Dual-Layered and Wavelength-Multiplexed Optical Barcode for High Data Storage

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Abstract

A novel barcode system design to achieve high data storage using more than one layer is introduced theoretically and tested partially in the laboratory. Compared to other existing barcode systems, diffraction gratings are used as core elements in the barcode symbol. As any other barcode system, the novel model requires a source of light, the barcode symbol and photodiode detectors. Theoretical background from optics has been used to design the entire system along with all the positioning of its components. After part-testing the design in laboratory, the barcode system design has been changed to achieve better results.

Experiments have showed that the initial proposed Light Emitting Diode (LED) source light cannot deliver 5mm spot light over a range of 50cm and therefore, white Light Amplification by Stimulated Emission of Radiation (LASER) light has been adopted as replacement. The diffractions from the barcode symbol are captured by detectors built with SI photo diodes, which are designed to detect this range of wavelengths. The barcode symbol is composed of small 5mm by 5mm grating modules and the largest possible symbol size defined is 80 modules (5cmx5cm). Experimental works have proved that intensity of the light can be used to uniquely identify each grating rather than the entire spectrum diffracted. A better design is proposed where the detectors are positioned under the barcode symbol and capture the light intensity of the first diffracted order. Theoretical investigations state that diffraction gratings with different lines per mm diffract different sets of wavelengths spectrum. This characteristic allows a set of unique gratings to be used in the barcode symbol which hence allow data to be represented or stored. Character (Char) sets are defined to help encode and decode data in the barcode symbol.

High data storage has been achieved through the use of two layers. Multiple layers offer the possibility to increase the number of unique sets of gratings which in turn increase the data representation capacity. Using two layers with 16 unique sets of gratings has proved to be able to store around 100 bytes of data. The system has the potential to use more than two layers and using 4 layers with 16 unique gratings per layer will achieve 200 bytes. The thesis has proved through theoretical and experimental work that diffraction gratings can be used in barcode system to represent data and multiple layers adds the benefit of increasing data storage. Further work is also suggested.

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I would like to take this opportunity to thank my supervisor Dr. Nicholas Ioannides for giving me the chance to do this research. I would also like to thank him again for all his support, motivation and guidance for the entire course of the project. His constructive feedback has helped me complete my research and contribute to knowledge.

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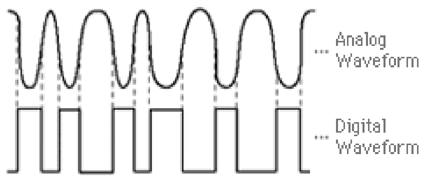
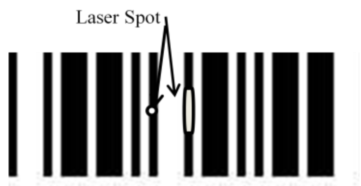
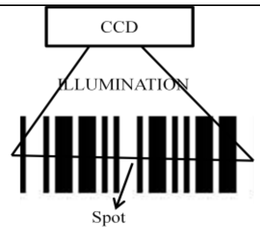
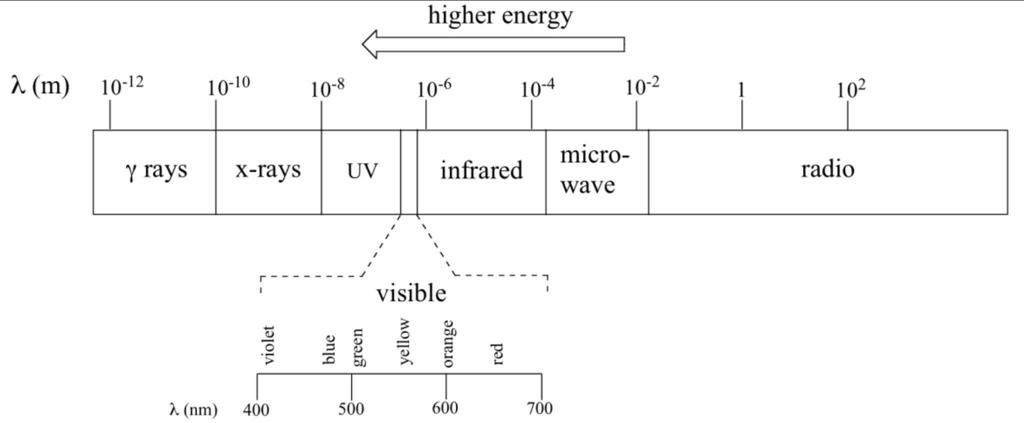
Glossary

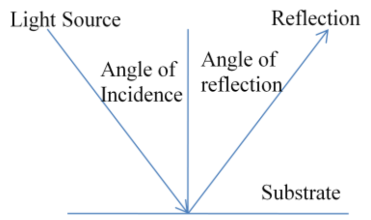
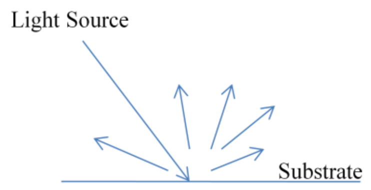
1D	First generation barcodes used in Supermarkets.
2D	Second generation barcodes mostly known as Matrix barcodes.
A	Amperes
ADC	Analogue to Digital Convertor
ASCII	American Standard Code for Information Interchange
CCD	Charge-Coupled Device
Char	Character
CPI	Cells per Inch
CYM	Cyan, Yellow, Magenta
DNA	Deoxyribonucleic Acid
DOF	Depth of Field
DVD	Digital Versatile Disc.
EAN	European Article Numbering
EDI	Electronic Data Interchange
FN	Facet Normal
GN	Grating Normal
HCCB	High capacity colour barcodes (Microsoft)
HLL	High Level Language
HSB	Hue Saturation brightness
ISBN	International Standard Book Number
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diode
Mems	Micro-Electro-Mechanical Systems
PM Codes	Paper Memory Codes
QLR	Quick Layered Response
RGB	Red Green Blue
RS	Reed-Solomon
RSS	Reduced Size Symbol
SI	Silicon
SNR	Signal-To-Noise Ratio
UCC	Uniform Code Council
UPC	Universal Product Code
UPS	United Parcel Service
USPS	United States Postal Service
V	Volts
XOR	Exclusive OR

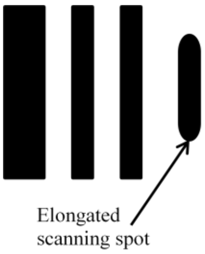
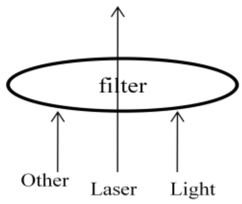
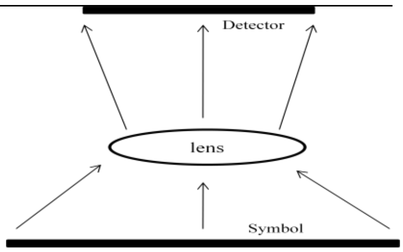
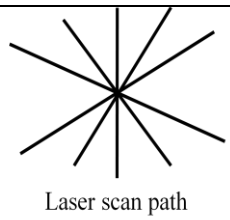
Scanner Glossary

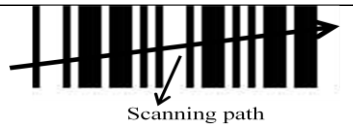
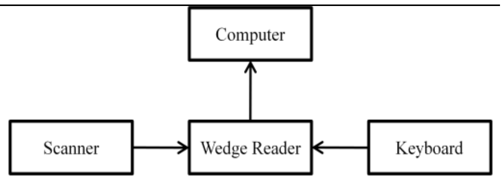
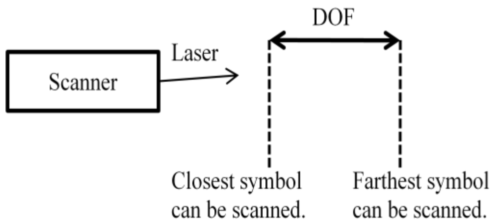
The table below introduces the scanner glossary. [21, 46, 47, 48]

Scanning means	This provides an interface to examine the reflected light from the symbol. It consists of mirrors, lens, sensors, or hand movement devices.	
A/D Convertor	Analogue to digital convertor converts analogue signal from the electro-optical system to digital signal.	
Processor	This processes digital data and decodes the data from the symbol and outputs it. The processor checks for validity and security of symbol. Symbols are processed using built-in software and user-defined algorithms.	
Wave shaper	This is part of A/D convertor which performs a better job of identifying edges of bars and spaces from the analogue signal.	
Illumination	This provides a way to transmit light to symbol. This can be led lights or laser light.	
Electro-optical System	This is an arrangement of the optical parts which scans the symbol. This includes illuminating the symbol and capturing the reflected light to produce the analogue data. Further details are given below for laser, Charged-Coupled Device (CCD) and 2D scanners.	
Laser Spot	Used in laser scanners; this represents the width of the narrowest module in a symbol to be examined.	
Spot	Used in CCD scanners; this refers to the area of the symbol being examined at a given time.	
Wavelength	Wavelength is the term used to represent different types of light which is a form of electromagnetic radiation	



Optical Reflectivity	This is a function of light source and characteristics of optical fibres used. Optical reflection is obtained from bars and spaces by lighting the symbols. Black bars and white spaces are used as standards as they are both adaptive to the wavelengths used in barcode systems and hence improve reflectivity.	
Light Sources	Readers use two wavelengths for scanning symbols; B633 (633nm) or B900 (900nm). Helium-neon lasers employ HeNe lasers operating at 633nm. Incandescent Light Source operates in the range of 600nm to 650nm depending on optical filters used. Monochromatic Visible LED operates between 630nm and 700nm. Infrared LED operates within 850nm and 920nm. White LED is used in 2D imaging devices.	
Specular Reflection	Beam of light is reflected such that angle of incidence=angle of reflection.	
Diffuse Reflection	Beam of light is reflected in different angles. This is due to dull, mate, non shiny surfaces.	
Photo-detector	This device collects the reflected light and outputs an analogue signal.	
Scan Length	This is the line or area the laser spot travels to scan a symbol	

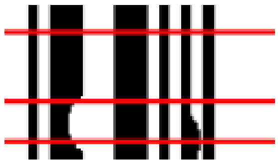
Resolution	This defines the laser spot to be ideally no wider or smaller than the smallest module width. If bar is too wide, two modules might be read as one module. Elongated spot scanning is adopted to correct printing defects. If spot is too small, then any small marks, edge roughness, points will be read as a bar.	
Mirrors	Mirrors are used to reflect light inside the laser scanner. Moving mirror is used to reflect the light on the symbol creating lines of laser spots and is also used to deflect the reflected light off the symbol to the photo detector. Mirrors are often coated based on optical components used to optimize light reflection. Oscillating mirrors are used in rastering scanners.	
Optical Filters	Filters are made up of glasses, gelatine or plastic and are placed in the light path of the laser. Filters absorb wavelengths of light. They are used to absorb the laser reflections and discard normal light condition wavelengths to improve scanning efficiency.	
Photodiode	This is a type of photo-detector used in CCD scanners. It normally defines the size of the narrowest module of a symbol. Photodiodes are arranged in array in different ways depending on CCD scanner's specification.	
Amplifier	The amplifier increases the signal power from the photodiodes.	
Lens	Lens converges or diverges a beam of light. Lenses are place in CCD and 2D imagers in between the detectors and the symbol to refract the reflected light from the symbol to the detector.	
Aperture	Aperture is a hole placed in front of the lens of a CCD camera to control the amount of light that enters the camera. Aperture is adjustable.	
Resolution	Resolution of a scanner is the narrowest bar or space the scanner can read. Using lenses, the laser beam is brought to match one module in a symbol.	
Omni-directional	A scanner which scans symbols in different scanning paths and any direction. It uses series of scan lines forming a starburst shown on the right.	

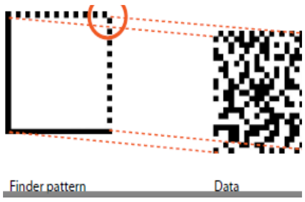
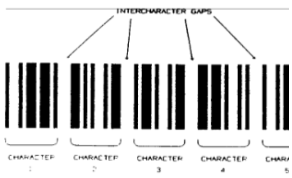
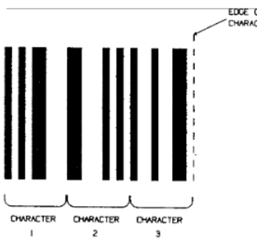
Orientation-Dependent	A fixed mount scanner which produces asingle line scan at a rate of about 50 to 1500 per second. Scanning line can be horizontal or vertical.	
Image Memory	Stores the image scanned to be processed by processor. This is used in 2D imager.	
Trigger	A button which tells the processor to take a scan of a symbol and to illuminate the symbol using a light source at the same time. This is used in 2D imager.	
Scan-Stitching	Parts of a symbol are scanned at different times and then stitched together by the processor to get a complete scan of the symbol.	
Wedge	This term describes scanners which are connected to a computer system in series with a keyboard. The keyboard can still be used normally.	
DOF	Depth of Field (DOF) describes the range of distance a symbol should be placed to be able to be scanned. It is a function of the module X dimensions. The larger the X value, the greater is the DOF and the smaller the X value, the smaller is the DOF.	

Symbology Glossary

The table below illustrates the symbology glossary. [24]

Bar	A bar is represented by the dark or black elements in a barcode
Space	The white or lighter elements in a barcode are called spaces.
Barcode Density	The density of the barcode refers to how much space is required for the needed characters (characters per Inch or centimetre). It also determines the storage capacity of a symbol.
Element (k)	Represent both a bar and a space.
Module (n)	A module is the smallest element of a barcode. The width of the single bars and spaces is a (mostly integer) multiple of the basic width of the module.
Module Width	The width of the barcode's smallest element in millimeter, in inches or in so-called mils (one mil = 1/1000 inch). The module width is usually abbreviated with the letter X.
X Dimension	Width of the barcode's smallest element (see Module width).
Quiet Zone	An area free of any printing or marks that precedes the start character of a barcode and follows the stop character. The required minimal size of the quiet zone depends on the barcode type. As a rule, the quiet zone should be ten times the dimension of the module width or at least 1/4 in (6.5 mm).
Human Readable Text	This term refers to the entire encoded information of a barcode shown in readable form. It is usually printed below the code. For 2D codes no human readable text is used.

Start and Stop Characters	Distinct characters used at the beginning and end of each barcode symbol that provide the scanner with start and stop reading instructions as well as scanning direction.	
Self-Checking Code	Self-checking code uses the same pattern for each character. For example, this can be five elements where two of these elements are wide and three are narrow. Any deviation from this pattern would result in an error.	
Check Digit	One or more characters included within the barcode which are used to perform a mathematical check to ensure the accuracy of the scanned data. Check digits are mandatory with certain codes or are even built into the symbology (as for Code-128)	
Bearer Bars	These are bars printed above and below the symbol. The bearer bars are eliminating partial reads (as drawn in the example on the right). Sometimes the complete symbol is surrounded by bearer bars (e.g. ITF-14).	
Substitution Error	Due to reading errors a character is replaced by another during scanning. Substitution errors can be excluded by adding a check digit.	
Synchronizing Bars	These bars are synchronizing the barcode reader. E.g. UPC-A and EAN-13 have synchronizing bars at the beginning, in the middle and at the end of the symbol.	
No-Read	A failure to decode, resulting in no output.	
Misread	The data output of a reader/decoder does not agree with the data encoded in the barcode field. This yields to substitution errors	
Character set	This term represents the range of data that can be encoded into a given symbol. Numeric – Can store numbers only. Alphanumeric – Can store numbers, special characters and alphabets. A shift code is used to allow the optical scanner and	

	algorithm recognise which character sets are being used.	
Optical Noise	This term refers to any factor that might result into misread while scanning a symbol.	
Finder Pattern	This is a small part of a symbol that help image-based scanning devices to locate the symbol in presence of optical noise.	
Self-clocking	This provides reference information to a scanner in order to measure relative edges of all elements in older symbologies.	
Bi-directional	A symbol that can be scanned from either right-to-left or left-to-right.	
Variable or Fixed	Variable symbol have no limit to their length and storage whereas fixed symbol are standardised barcode with fixed length.	
Discrete	In a discrete code, there are intercharacter gaps between each character encoded.	
Continuous	There are no gaps and each character is encoded one after another. In this type of symbology, each character ends with a space and the following character starts with a bar	

Definitions

Barcode Reader	Barcode reader mentioned in this project uses optical laser light to illuminate the barcode and then captures back the reflection/refraction of the light to read the barcode.
Conventional	Barcodes that are designed according to accepted standards.
Database	Database is a collection of files in an organised way where data can be accessed easily and quickly.
DataGlyph	A technique to encode data into pictures using different types of symbols.
Delta Code	This code has various element-widths where bars can be more than 2 times the width of a space and vice-versa.
Doped	Doped is the process of introducing impurities into an extremely pure semiconductor device.
EDI	EDI is a document used by big companies to send e-commerce orders or structured data to warehouses or to track orders.
Flux	Luminous Flux is a measure of light power in lumens.
HLL	High Level Language is a programming language which allows software to be written without a computer and in English language that is less technical and more understandable to all types of users.
Lumen	Lumen is the unit to measure the power of light.
Modular Code	A symbology which uses variable element widths represented in modules.
Optical Noise	This term refers to any types of disturbance that might stop a scanner or detector from reading a barcode.
Phosphor	This is a substance that exhibits or excites the phenomenon of luminescence.
Photon	A photon is a discrete bundle (quantum) of electromagnetic (or light) energy.
Plano Convex	This is a lens with a positive focal length.
Rastering	This term defines the area a scanner laser moves over a barcode to scan it using oscillating mirrors. The area covered is usually a square from left to right and top to bottom.
Security	Refers to techniques such as RFID tagging, data encryption, etc used to secure the data in barcodes which allows only the right recipient to get access to the data stored in barcodes.
Software	Software is a set of instructions given to a computer to perform some specific tasks.
Symbology	The process used to encrypt and store data in Barcodes.
Undoped	Undoped is contrary to doped, that is extremely pure.
Watt	Watt is the unit to measure Power.
Wavelength	Wavelength is used here to represent different types of light expressed in nanometres.
Width Code	A code which has 2 element widths where bars and spaces are narrow or wide.

Chapter 1

Introduction

Barcode mostly recognised as a series of black lines is a way to represent machine readable data that a can be read by an optical device and fed to a computer [1]. Two commonly types of barcodes used are linear which are of first generation (1D) [see fig 1.1] and matrix which are of second generation (2D) [see fig 1.2] whilst later generations have been research and developed but not commonly put in use [1]. 1D barcodes as shown [2] hold limited and little amount of data and are mainly used to uniquely identify products which are ranged from cheap in supermarkets to very expensive in boutiques. 2D barcode contains more data in two orthogonal axes and this allows more information to be represented compared to 1D [3]. Different types of 2D barcodes have been developed to represent different set of information [1]. The designs of 2D barcode along with the methods to store data are depicted in [4]. The main limitation of both generation of barcode is the lack of storing high capacity of data. Research in [5] explains the limitation in 2D barcodes to store data per unit area. Demands of high storage barcodes are in hospitals to record details on patient [14], biometric for individuals [15], Deoxyribonucleic Acid (DNA) to aid species identification [16], etc. The research questions are;

1. Is it possible to use diffraction grating as a barcode rather than paper?
2. Is it possible to create and design a barcode with two or several layers of gratings?

3. Is it possible to design a higher data storage barcode system than the existing ones?

The aim of this project is to merge two techniques to design a novel barcode system that will allow higher storage capacity. The first technique is wavelength-multiplexed from optic physics [6]. The second technique is the idea of using dual-layer storage [7] commonly known for DVD. The idea of dual layer is that data can be stored on the same medium but on two layers and this allows the capacity to be easily doubled [8]. However, coming back to barcodes, dual layer technique is possible on different mediums [9] amongst which one will be chosen to fit the structure of barcode. The second technique is to use different sets of colour to represent a 2D dimension barcode [10]. This approach is an extension to 2D barcodes which eliminates the limitation of data storage. The main challenge will be to merge these two mentioned techniques to get the new barcode with high data capacity storage.

Fig 1.1 1D barcode [20]

Fig 1.2 2D Barcode [20]

Furthermore, along with the design of a novel approach for a new barcode, an appropriate optical reader or camera is crucial. Upon research from related work, one that will work with the specification of the barcode will be selected. From optical physics, different components that form part of optical readers will be investigated and used to design better ones to be used in the new concept. For instance, optical filtering techniques used in photography which transmit light with a range of wavelength while blocking the remainder, will be researched and used [11] [12]. Another optical component to be investigated and used will be optical diffracting grating [13]. Diffraction grating splits light into different beams which travel in different directions depending on the spacing of the grating and wavelength of light so that grating acts as dispersive element [13]. These mentioned components and/or others from optic physics will be analysed and used in the development of the new barcode approach. Finally set of specifications will be given to define the new barcode system.

1.1 Reviewed Area of Potential Uses

Barcode system is best known for its practicability to uniquely identify products while 2D ones are being used by companies to refer to their specific website. This section depicts where the new technique of barcode can be applied in the future and includes the areas mentioned above in the introduction. Assumptions and proposals are made as to how the new barcode can be applied and replace existing techniques despite barcodes are not necessary to be currently in use in those areas. These proposals help to understand the real future need of the new barcode and hence promote this research and thesis.

Research in [14] proposed to use barcode for patient identification for blood transfusion where the system proved success. Adding to this, hospitals is the very first place where the new barcode system to be designed will prove its success. The need to store more data on each patient arises almost every day after each check-up. Normally, these data are stored on computer databases and each patient is given an ID. However, if each patient is rather given a barcode and this barcode can store a lot of information about the patient rather than just an unique identification. This will avoid data repetition if the patient is visiting a different hospital as patient's data will not be needed to be downloaded from a remote resource. Another benefit is quicker access to patient's details. More importantly, if network is down, data on patients can still be available remotely at any hospital. While the patient is out of country, the barcode can easily be used abroad to know the health history of the patient. Hence, this requires a barcode with high data storage which can store the patient's data along with required security and data encryption.

Research in [15] identified the use of barcode system for biometrics where a person's image and fingerprint were incorporated into the 2D barcode with its security. In addition, there are far more information that could be useful if stored on a barcode for biometrics.

For instance, criminal records, passport details and biometric information can be stored on a single barcode for each individual. Having all the information in one specific barcode will help identify and tackle criminals much easier. While leaving the country, previous details of individuals can instantly be retrieved at passport controls through the barcode. Again, information can be easily obtainable in any country to avoid criminal escapes. To store all the information, high storage barcode is needed.

Research in [16] explained the Barcode of Life Data System which aids the acquisition, storage, analysis and publication of DNA barcodes. Seven criteria were important to be measured for a species to have a barcode. Adding to these measure, there are other details that can prove to be vital to be stored on the barcode. For each species, heath history is crucial especially when different people are treating them. All these information require high data storage barcodes as most of the measures keep updating and keeping the old records make it good practice for future analysis.

Other industries such as car manufacture [19] will find the use of the barcode system more practical. The reason behind is that, for each car a set of specification can easily be fed onto a barcode and at each interval in the manufacture, the data is easily obtainable. Also, details of each part involved for each car design or model can be stored on the barcode. After car production, the barcode will be useful to identify specifications for any faulty parts to be replaced. Another place will be within worldwide retail companies. Data about clients and their previous buying history can be stored on barcodes. This will help creating orders more easily through the history data. To achieve this, high data storage barcode will be important.

1.2 Aims and Objectives

- To identify the data storage limitations of current 1-D and 2-D barcodes.
  - ✓ Review state of art 1D and 2D barcodes.
  - ✓ Research and understand basic fundamental of optic physics.
  - ✓ Review and identify the storage structure of both barcode generations.
  - ✓ Research for the need and future uses of high data storage barcodes in different area of businesses.

- To carry out a review of related work already done.
    - ✓ Review the development of latest coloured barcodes and the techniques involved.
    - ✓ Review state of art dual layer DVD technique applications in other places.

- To design and develop a novel approach of designing a new barcode that will use gratings in two layers.
    - ✓ Review different parts and their functions in an optical dual layer DVD.
    - ✓ Review different research done on new coloured barcodes and their ability to store data.
    - ✓ Review optical lasers or readers to understand the structure of different optical filtering techniques and optical diffraction gratings.
    - ✓ Review different optical readers and identify one to be used with new barcode.
    - ✓ Create specifications and design new dual-layer barcode.
    - ✓ Review existing optical readers and cameras.
    - ✓ Design a new source of optical light to illuminate barcode.
    - ✓ Design a new optical reader to read the light refracted from the barcode.

- To develop and test the technique that will incorporate data into the new dual layer barcode.
    - ✓ Review data storage techniques in existing generations of barcode system.
    - ✓ Define how gratings in the barcode will be used to store data.
    - ✓ Design pseudo code which will help optical reader decode data read from the barcode.
    - ✓ Create and specify how data will be stored into the barcode with the help of different character sets.
    - ✓ Specify the data capacity of the barcode system.

- To develop and test security technique that will be used in the barcode system.
    - ✓ Review security techniques in existing generations of barcode system.
    - ✓ Choose existing security techniques from previous barcode generations that will be used into the new barcode system.
    - ✓ Explain with samples how data will be secured with selected techniques.

- To test and evaluate the barcode system.
  - ✓ Perform practical work to test each component.
  - ✓ Compare each component against their desired specifications.
  - ✓ Compare the practical work results and review barcode system design.
  - ✓ Choose the best barcode system that will answer the thesis questions.
  - ✓ Provide further work recommendations based on evaluation results.

1.3 Methodology

- First method to be used is Literature review. Work and background related to this project will be deeply searched, analysed and reviewed for further understanding. Different work/methodologies carried out by different researches will be reviewed in depth and explained to make sure someone else's work is not being repeated. Background reading on Optical components along with all the mathematical formulae will be learned. Knowledge gained through previous studies on computer systems will be used to integrate the data storage techniques.

- Second method, the quantitative approach [17], will be adapted to gather information on several researches that are close to this one. This will obviously help identify and design the right dual-layered and wavelength-multiplexed techniques to be used. Also, this approach will help find and design the right optical reader. Qualitative [17] process is very crucial to aid in retrieving the required data from all the information collected through Literature Review and Quantitative process. This will help towards designing the right novel approach for the new barcode, to choose or modify an appropriate optical reader for the barcode and finally to tune both.

- Components will be designed and simulated using educational background gained though Literature reviews and qualifications obtained from past studies. The simulation of the barcode, reader and light source will be done using Optical theories and mathematical formulae. Each component designed will have its own set of specifications. Uses of tables, graphs and pictures will help to illustrate and explain each phase of the entire barcode system. Some components that will be available from manufacturing factories will be modelled and tested in the University Laboratory facilities. Practical work will also be conducted after system has been designed to test if the each component delivers its specification.

1.4 Deliverables

- Barcode systems currently in use in organisations and businesses will be analysed and explained in details. Pictures will be used to display the structures of barcodes and readers. The use of tables will aid to represent comparisons and capabilities of different barcode generation.

- Existing researches on state-of-the-art barcode systems will be identified and reviewed. Each research identified will be deeply analysed and explained. Results obtained will be compared with the aims and objectives and finally own conclusion will be drawn.

- Dual layer technique will be explained in detail along with its operation. The alignment and positioning of each layer will be designed. Mathematical analysis using the theory of optics will be used to establish viability of the technique. Each component will be designed with the help of mathematical equations. The concept of the entire barcode system will be provided alongside the positioning of each component.

- Following the design concept, the actual components will be simulated. Parts that will form each component will be chosen from existing manufacturing factories. However, the components will be completely designed from scratch and will be unique.

- Following the simulation of the barcode system, the data storage technique will be designed and incorporated. Use of Character sets will be defined to aid understand how data can be represented and stored. Data security will also be explained and samples will be provided to prove that they work. The barcode system data capacity will also be defined.

- Experimental work will be performed in the laboratory to test some of the components. The idea behind is to prove that the mentioned designs of the barcode system will work accordingly. During the practical work, other alternatives will be tried to aid tune the barcode system to achieve better results and performance.

- The results obtained will be analysed to ensure the objectives of the project is met. Future research will be identified and suggested.

1.5 Review of Thesis

Barcode is well known for its usage in retail industry to uniquely identify products and their prices while the second generation is mostly used for advertising companies. Chapter 1 simply introduces the history and the impact of different types of barcode generations in our lives. The research questions are defined and explained. Aims and objectives are set to help create a path throughout the research. Future potential uses of the new barcode system have been identified and explained for different organisations. Goals to be achieved at each phases are listed as deliverables and finally the methods to be used in the research are explained.

Different generations of existing barcodes are investigated in details in chapter 2. Different types of barcodes are compared and the results are given in tabular form. These barcodes are the ones that are being used currently in real life. Based on their structures, the limitations (including data storage) have been derived which explains the significance of doing this research. This project will aid to lift this limitation by integrating dual layer storage capabilities. Operations of optical barcodes have also been explained along with a clear description of how different optical components work, for instance wavelength, gratings, etc. To avoid repeating the same research, existing researches related to this one have been searched and analysed. This includes their aims and objectives, achieved targets, results, and recommendations. Tables, figures have been used to best clarify and display the work done by the researchers. Also, own conclusion on each related work found has been derived to clarify what has really been achieved and not.

Chapter 3 provides the design of the barcode system with the aid of a diagram. The system consists of four main components which are Light detection, Light Source, Gratings, and

Dual Layer. Design of the light detectors are given and explained. The guide to define the size and positioning of the detectors are defined. The choice of Light Source has been explained and argued. Mathematical analysis has aided to position the light source based on the gratings. The design of the barcode uses gratings as the two layers and a polycarbonate spacer. Specifications of the gratings to be used in the simulation process have been defined. The properties of the gratings have been modelled and reviewed.

Chapter 4 is the final design of the entire barcode system. Guidelines from chapter 3 have been used to prototype the components of the system. The light source has been designed with a powerful led chip, a convex lens and micro-electro-mechanical mirror to achieve 2D scanning. Two sets of five different gratings have been chosen to represent the modules of each layer. The detectors have been designed to capture the light diffraction. Each detector is different in sizes but contain the same parts. The final system prototype is also given with fix positions of each component, the specifications and any assumptions made.

Chapter 5 incorporates the data storage feature into the barcode system. Having designed the entire barcode system components in the previous chapter, this chapter completes the barcode system through the integration of the barcode data storage. The process of storing data into the barcode as well as decoding it is explained in details. Data character sets that will represent the data into the barcode gratings are created and referenced in Appendix B. Two main character sets defined are Extended American Standard Code for International Interchange (ASCII) and numeric. The data capacity of the barcode system is also defined. Finally, features such as security added to ensure data protection are explained.

Chapter 6 offers an alternative light source which is laser. LED has been the primary light source choice. Due to some complicated set-up required for LED to achieve the minimum 5mmx5mm light spot, laser has been chosen as an alternative source of light to be tested. The components in the laser light design are explained. White laser is still being researched. A proposal of how white led can be achieved from RGB (Red, Green, and Blue laser diodes) is given. A beam expander is used to increase the laser spot to the desired size of 5mm x 5mm. Challenges are discovered in the laser light source and explained. Some proposals aim to increase the achievable level of efficiency.

Chapter 7 involves practical work carried to test some components in the barcode system. The practical has been done in stepwise; starting with the light source, the gratings, the dual layers, and the finally the entire barcode design. Two components (LED and Laser) have been tested as the light source. Laser was introduced as an alternative because LED failed to generate the required light spot to illuminate one 5x5mm module which is one of the minimum requirements for the light source. The next experiment involves the grating itself which shows how a grating diffracts light and how the spectrum of light can be limited to a certain range of wavelengths. Two different gratings with different lines per mm have been used to simulate the dual layer. The positioning of the detector for the top layer is simulated using a white paper screen to prove the theory used in the design section works. Experimental work has showed that using two layers diffract the incident light through the first layer and then diffracted spectrum from the first layer is diffracted again. The result is undesired and does not allow data storage capability. To prevent this phenomenon, an alternative way of arranging the gratings for each layer has been proposed and tested. Alongside, a new barcode design has also been proposed to incorporate the change of the barcode symbol. This involves a new design and re-positioning of the detectors. The concept of coloured gratings which are of different wavelengths was proposed to replace the idea of using 5 sets of gratings per layer. This concept has been experimented and the resulted in various light intensity for each wavelength. The alternate way of positioning the gratings in the two layers where the top layer module sits in the middle of two bottom layer modules was tested and proved to be a failure. This is because the diffracted spectrum from the first layer is incident on two modules of the second layer at the same time and the final diffraction spectrums are difficult to analyse.

Chapter 8 analyses the proposed barcode design along with all the components, the experimental work, alternative proposals and then evaluates the best possible solutions and designs that will make the final barcode design more efficient. Each component's designs are analysed and compared to the original set of requirements defined in chapter 3. Better designs for some components are provided and chosen which improve efficiency of the system. Followed by some changes with the components, the entire design concept has been modified to adapt and incorporate the new specifications. Light Intensity is investigated and analysed to understand its importance in detecting the gratings. Data Storage has been analysed for the initial design and new technique has been proposed to be used.

Chapter 9 is the conclusion chapter which summarises the entire thesis and brings everything together. The thesis questions are answered using findings of the research. Recommendations are given which will aid apply the system effectively in future applications. Future work and further research have been identified and explained.

Chapter 2

Optical Barcode System

2.1 Barcode History

The uses of barcodes started with product identification in supermarkets and are nowadays spread widely in all businesses across the world due to its low cost production and its help in speeding identification processes. ‘The Bar Code Book’ [21] provides an overview of barcode history and is described below.

J.T. Kermode, in 1934, had the first barcode concept patent which described a card sorter. The patent however, used an arrangement of four parallel lines to uniquely identify products. In 1935, D.A. Young described another card sorting machine that used arrangement of optical marks in parallel for identification. The first fully documented explaining the benefits of an automated checkout was realised by Wallace Flint in 1932 as part of his master’s thesis at Harvard. Forty years after, around 1972 Flint used this standardization to actively invent the Universal Product Code (UPC) and its symbology.

In 1949, a new approach called Bull’s-eye code [22] [see fig 2.1] was described by Joe Woodland and Bernie Silver. This format consisted of circular line patterns with an archery target in the middle. In 1959, Girard Feissel came up with a code consisting of numbers 0-9 each made from parallel bar segments. However, such arrangements were proved to be more difficult to be read by scanners and different styled fonts used were harder for human to read. In 1972, an operating Bull’s-eye code with a scanner were developed by RCA and tested for 18-months in a Kroger Store in Cincinnati. This test provided valuable data for cost analysis and further system refinements.

In mid-1970 R.BertGookin, chairman of grocery industry help a committee to select a standard code and symbol. After several bar code technology proposals from different companies and different sets of printing tolerance tests were made by Battelle Memorial Institute, the UPC symbol was finally adapted as the grocery industry standard in the United States on 3rd of April 1973.

European Article Numbering (EAN) symbol was invented in December 1976 and adopted in the grocery industry in Europe. In 1971, the Plessey Company developed a bar code and reading system for use in Library Checkouts. Codabar that was used originally in libraries and continued in blood collection was invented in 1972 by Monarch Marking Systems. In 1974, Dr. David C. Allais developed this first alphanumeric bar code symbology named Code 39.

Low cost electronics and availability of smaller laser printers during the 1970s, allowed many companies to design their own bar code symbols with no standards for their own uses. In January 1982, Military Standard 1189 also known as Code 39 was developed followed by ANSI Standard MH10.8M that covered Code 39, Codabar and Interleaved 2 of 5. The latter known as UPC Shipping Container symbol was later adopted in 1984.

The attempts to reduce amount of space required for a car code symbol led to the invention of Code 128 by Ted Williams in 1981 and Code 93 by Dr. David C. Allais in 1982. Theses two technologies allowed labels to be 30% shorter than older bar code symbols. The U.S. Portal Service in the late 1980’s used software to change bar heights but with same width and developed a bar code symbology for common use on U.S letter.

In 1987, Dr. David C. Allais came up with Code 29 which is a nonconventional symbology but offered higher densities over other traditional bar code symbologies. This invention motivated Ted Williams in 1988 to introduce a similar barcode technique called Code 16k. PDF417 symbology designed by Symbol Technology came in 1990 and offered higher storage capacity over previous symbologies.

The world's first 2D Matrix barcode named Code one was introduced by Ted Williams in 1992. Code one was a novel "checkerboard style" 2D symbology that incorporated conventional bar code characteristics. United Parcel Service (UPS) invented Maxicode 2D symbology internally in 1993 and used it in their parcel tracking system.

In 1992 while crossing the English Channel, Ted Williams and Andy Longacre created a symbology suitable to indentify small objects and named it the creation Channel Code concepts. The latter led to the development of Reduced Size Symbol (RSS) with higher data capacity than UPC and EAN. The concept of merging conventional linear barcode with a 2D symoblogy was proposed by Sprague Ackley in 1997. The idea was to position a linear barcode in contact with a 2D one and finally, this evolved into EAN/UCC composite symbology. Ted Williams later used the composite technique to introduce Aztec Mesa symbology which included modifications from Andy Longacre.

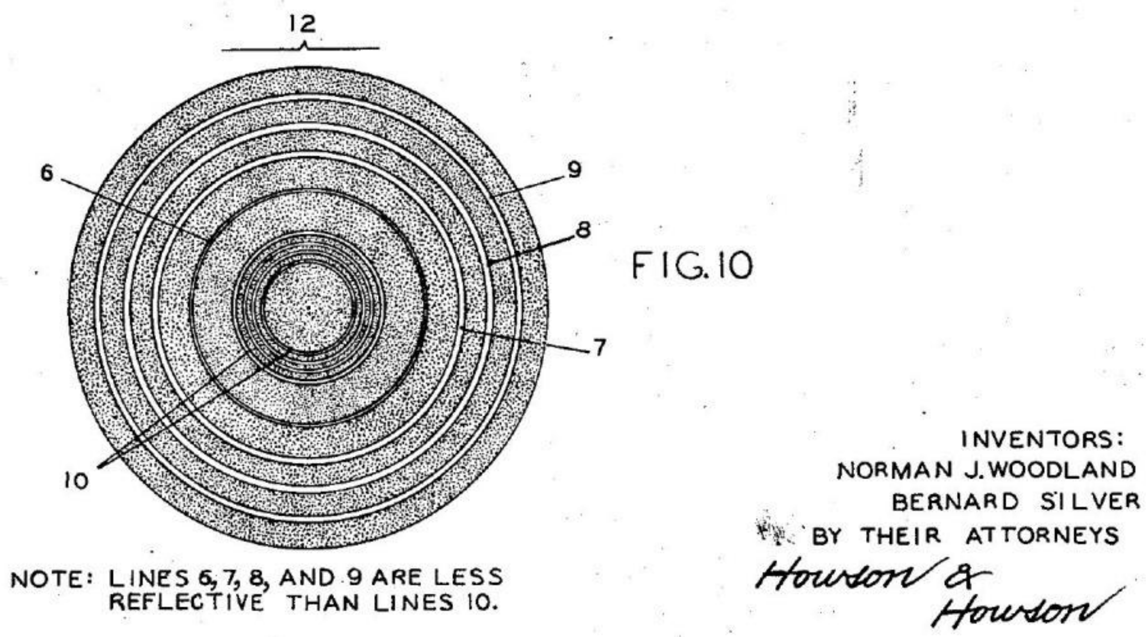


Fig 2.1 Bull's-eye Code [22]

2.2 Overview of Barcode System and Components

A barcode system can be classified into various components. The diagram below gives a basic idea of how each component in a barcode system works. Details of each component are given in next sections. However, printers and software have been excluded as they are not the main focus of this project.

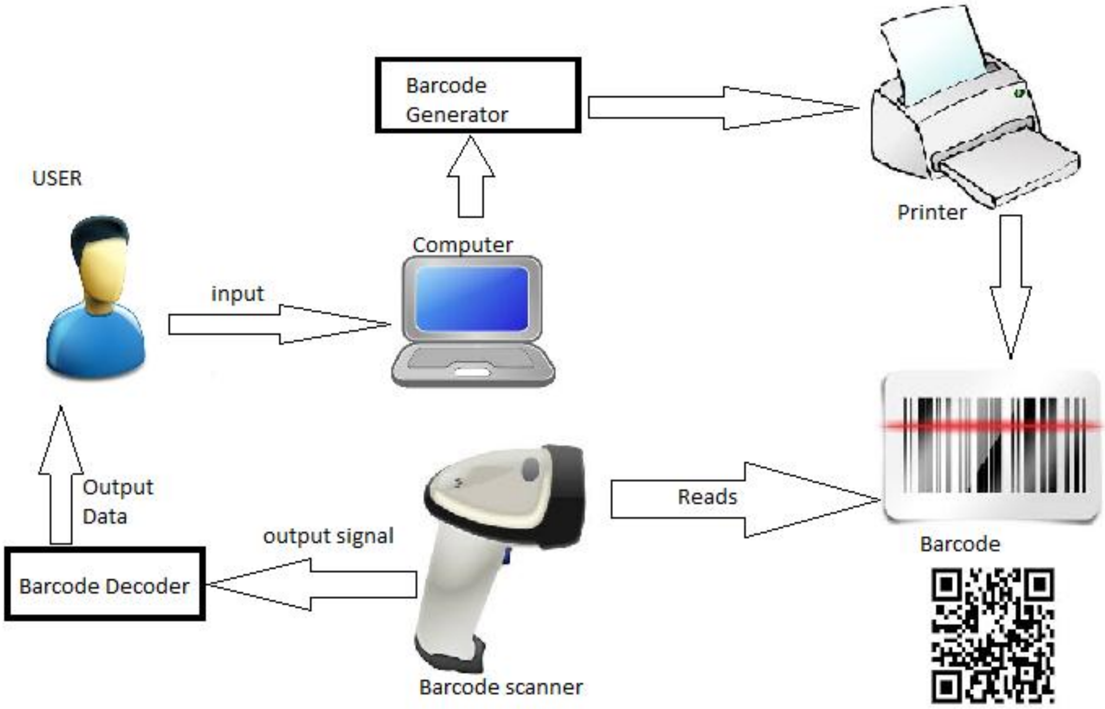


Fig 2.2 Barcode system

Input

Input is normally a way to feed the barcode generator with data that need to be stored in a symbol, for instance a product code, website, etc. A typical example is a keyboard.

Barcode generator

A barcode generator is software which encodes the data into bars and white spaces. The software has a conversion table for each type of symbology. The table aids the software to convert the encoded input data (0's and 1's) into the desired bars and white spaces to form the symbol. The generator also adds security features such as check digit to the symbol.

Printer

A printer typically a laser one or Ink Jet is used to print the barcode generated on products. Barcode can also be presented on digital screens or mobile phones. The printing resolution is very important to maintain the size of the barcode module across the whole symbol. The size of the one module has to match the 5x5mm laser spot.

Barcode

Barcode can be in 1D, 2D stacked or 2D matrix format. The data is stored in terms of symbols (black and white).

Reader

A reader is an optic device which uses the light optics' principles to read the barcode. Light of visible wavelength is used in 1D system, where a laser beam is transmitted on the barcode and moving mirrors are used to move the beam across the symbol. The reflection is then captured back to differentiate between bars and spaces. In 2D systems, a flash light is used to illuminate the symbol. A reader consisting of a series of photodiodes is used to capture the reflected light. Based on the reflection, the reader outputs signal to differentiate between bars and spaces.

Decoder Software

Decoder decodes the output signals from the reader into 0's and 1's. Security check is done to check validity of the data read. Decoder software is normally part of the optical reader.

Output

This is the information found and stored in the barcode. Output data can be used in various ways, for instance to open a website, to get the price of a product, etc.

2.3 Barcode Reader [21]

Various types of barcodes exist in different sizes and optical components. Depending on applications, some are fixed while some are hand-held moving ones. An optical reader uses light to detect for bars and spaces. Depending on applications, optic components described in the scanner glossary table in Glossary, are used to tune readers.

2.3.1 Barcode Scanner Basics

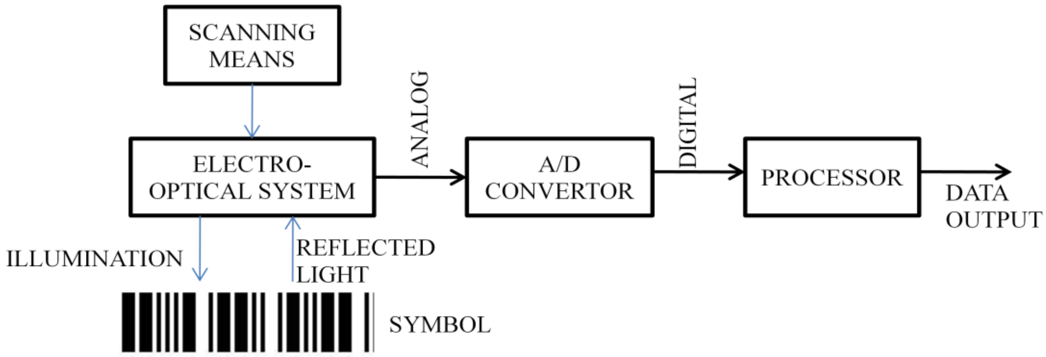


Fig. 2.3 Barcode Reader Framework [21]

A barcode reader performs three main operations;

1. **Light transmission**
   - Light is spread on the symbol using laser or flash light. In linear application, moving mirrors are used in readers to move the laser beam across the whole symbol forming a line of scanning. In 2D applications, flash light is used to illuminate the symbol. Photo-diodes are arranged to capture back the light reflected. Each module in a 2D symbol is read by one photodiode.

2. **Capture reflected light**
   - Light spread on the symbol is reflected back. The reader, with the use of lenses directs the reflected light to the photo-detector of the reader. The photo-detector then produces an analogue output based on the light received.

3. **Detection of Symbol**
   - A/D convertors are used to convert the signal into digital and feed them to the processor. The latter detects a symbol when the start/stop reference bars and spaces are read or received.

2.3.1.1 Laser Depth of Field [21]

Light beam in a laser reader varies in diameter. The beam diverges on two sides of a minimum point called the Waist or Focal point. The divergence of the beam on either side of the waist is symmetric. Beam Diameter, D represents the area the beam covers on the symbol and is a function of the waist diameter (d), light wavelength (λ) and the distance from the waist (Z).

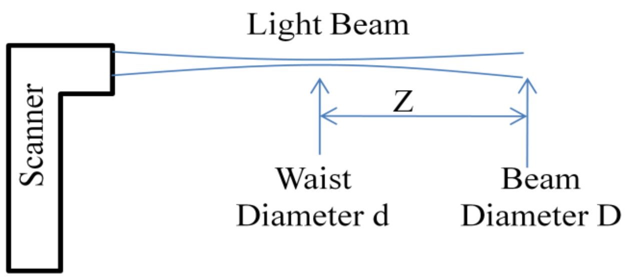


Fig 2.4 Laser Depth of Field

Diameter of Beam is calculated as follow:

$$D(mm) = \sqrt{d^2(mm) + Z^2\left(\frac{4\lambda^2}{\pi d}\right)} \quad , where\ Z\ in\ m\ , \lambda \text{ in nm}$$

Depth of field is the range between Z and D where D has not grown appreciably greater than the X grating module (5x5mm in the project application). Symbol can be decoded successfully if D is not greater than √2 times X dimensions. Minimum printing tolerance for X dimension is 0.8X. Taking d=0.8X, maximum D=(√2)/ 0.8 = 1.77 d. Replacing this in above equation gives,

$$DOF = \frac{58.3d^2}{\lambda} \quad d\ in\ mm\ , \lambda\ in\ nm$$

2.3.1.2 CCD DOF [21]

In CCD scanners, DOF is calculated using the magnifications, numerical aperture of the lens and the centre-to-centre spacing of the photodiodes used in the system.

$DOF = 2NsM(M+1)$ N= numerical aperture / M = magnification

s = photodiode centre-to-centre spacing

X dimension and a fill factor (B) are used to calculate the magnification of the lens. Fill factor is the measure of how much larger the X dimension is to the spacing of the photodiodes in the scanner; **M = X / (sB)**

Fill factor value is always between 2 and 3 and M value in most applications is >50. Therefore,

$$DOF = \frac{2N\,X^2}{sB^2}$$

Further detailed explanation is in [21].

2.3.2 Light Pens or Wands Scanner [21]

Wands and Light pens are the simplest and cheapest scanners. To scan a symbol, the device needs contact with the barcode and movement to cover the symbol area is done manually. Decoding is done as the light pen is moved over the symbol. The light beam is fixed in the housing. Successful scans depend on well trained people and errors are normally due to;

- Too slow scans.
- Stopping in the middle of the symbol.
- Missing the quiet zones.

2.3.3 Laser Scanner

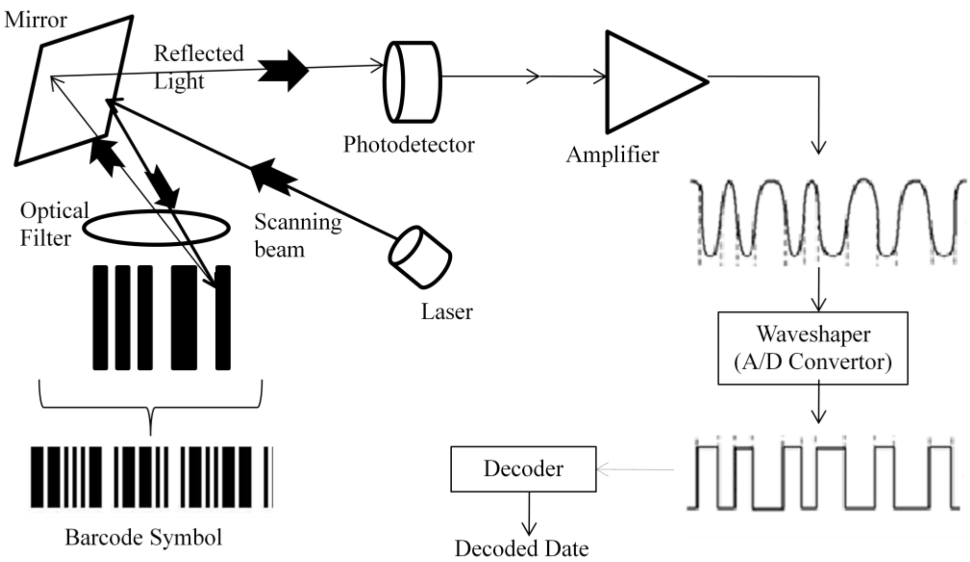


Fig 2.5 Laser Barcode Scanner

Two types of this laser barcode exist; hand-held and fixed. Different optical components used offers different options and ways of scanning symbols depending on applications. Most scanners use Helium Neon laser tubes for laser beam. Some housings use more than one mirror to reflect and direct light to specific components. Multiple laser lines are obtained through a moving or rotating mirror, polygons or holograms. Laser scanners read 1D barcodes while Rastering laser scanners allow 2D-stacked symbols to be read.

2.3.4 CCD Scanner

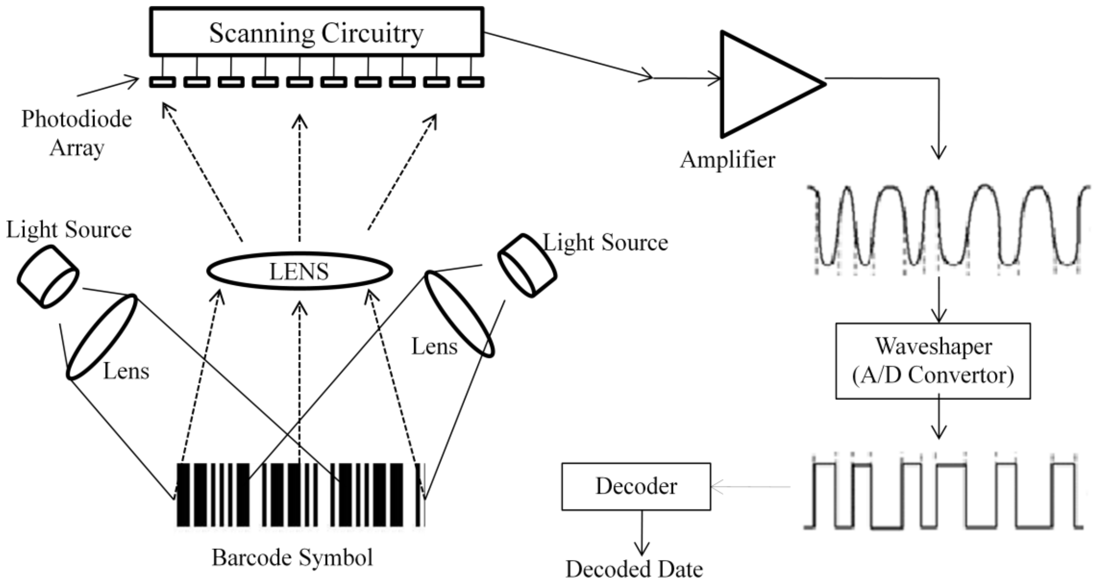


Fig 2.6 CCD Barcode Scanner [21]

Rather than scanning using a light beam, CCD scanners decodes a symbol by flooding light onto it and by capturing the reflected light as a whole. This is done through the use of CCD semiconductor technology used for the photodiode array sensor. Two photodiodes are arranged for each X module of a symbol. Unlike laser scanner, there are no moving mechanisms and the light reflected off the whole symbol is captured at the same time. This scanner is able to scan 1D barcodes and 2D barcode through the 2D arrangement of the photodiodes.

2.3.5 2D Imager

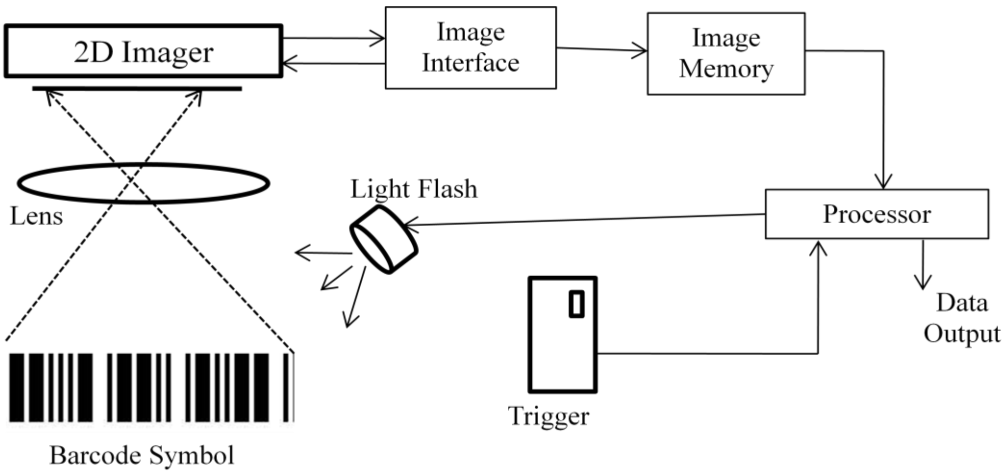


Fig 2.7 2D Imager [21]

2D imager uses special digital optical hardware to scan symbols by taking electronic pictures. Digital cameras are also known as 2D imager as the latter's basic components are those from a camera. Digital signal processing chip is used to compare and decode pictures of symbols. Image memory stores snaps of the pictures taken. Imager and image interface are the electro-optics of the scanner. Quality of picture taken is measured in pixels and depends on the sensors being used. Various qualities of sensors exists that can take high quality pictures but the choice of sensor types is based on its application.

2.4 Symbology

2.4.1 Introduction

Symbology represents the communication language between a symbol, optical scanner or image sensor equipment, printing device and a computer. Each type of bar code is assigned a unique symbology to represent its elements' arrangement and character coding techniques. Symbologies are **standardised**, set by American International Standards and other international standards, and **proprietary**, proposed and used by individual businesses around the world. The barcode glossary outlined in the Glossary section gives a very detailed explanation on the barcode properties and designs of both first and second generations. Starting from the initial barcode development up to the latest design, different barcode symbols developed along the way are explained. Some symbols are compared to each other while different versions of the same symbol are also explained. For most of the symbols, their applications in the current market are also mentioned.

2.4.2 Types of Symbols

Table 2.1 Barcode Configuration

Linear	This is known as 1D configuration which consists of parallel bars and spaces. However, bars can be either width-modulated or height modulated. A linear width-modulated barcode is very commonly in use and is referred to as a conventional bar code symbol. [22]	[20,26]
Circular	This configuration represents bars and spaces in concentric circles. [22]	[24,25]
2D Stacked	This uses multiple rows of width-modulated elements. Separator bars are sometimes used to separate adjacent rows. Optical scanners used for linear symbols are used to read this type of code. [22]	[20]
Composite	This type is a combination of stacked and linear barcode. The stacked barcode is place sometimes on top, in the middle or at the bottom of a linear code. This type however can only work with few 1D symbologies. This method allows fast scanning for linear part and more information for 2D part. [22]	[26]
2D Matrix	This encoded data in a two dimensional pattern. It uses cells to store data and this can be either black or white. Special equipments having similar resolution in vertical and horizontal axes are used to print and read the code. This is referred to as area symbologies.[22]	[26]

2.4.3 1D Barcode and Applications

Code 39

Code 39, a 2-width, was the first alphanumeric symbol developed. Each character is encoded using three five bars and four spaces combining 9 elements. Three of the elements are wide and six are narrow. Each character starts/ends with a bar while the start and end character uses an asterisk ("*"). This symbology was used in applications such as ID badges, industrial labelling, government labelling and in the Health Industry. It is currently being used as Vehicle Identification Number (VIN).[21,27]

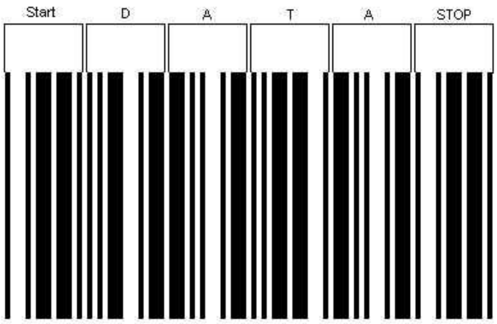


Fig 2.8 Code 39 [29]

Interleaved 2 of 5

This symbol, a 2-width, encodes two digits; one in the bar and one in the spaces. For one character there are five bars and the next one has 5 spaces. Two bars/spaces are wide and three bars/spaces are narrow. Bearer bars are used to avoid partial scans. Interleaved 2 of 5 barcodes are used in the distribution industry to label boxes of retail products. [21]

Fig 2.9 Interleaved 2 of 5 [30,32]

Codabar

Codabar encodes each character into four bars and three spaces. Traditional Codabar used variable widths elements while rationalized Codabar (described here) uses 2-width element. Each character is represented into one wide bar, one wide space and all the rest as narrow. There are four types of start and stop codes known as A, B, C and D. Application of this symbology includes library book tracking system, blood banks forms and air parcel express services (FedEx Air bills). [21,28]

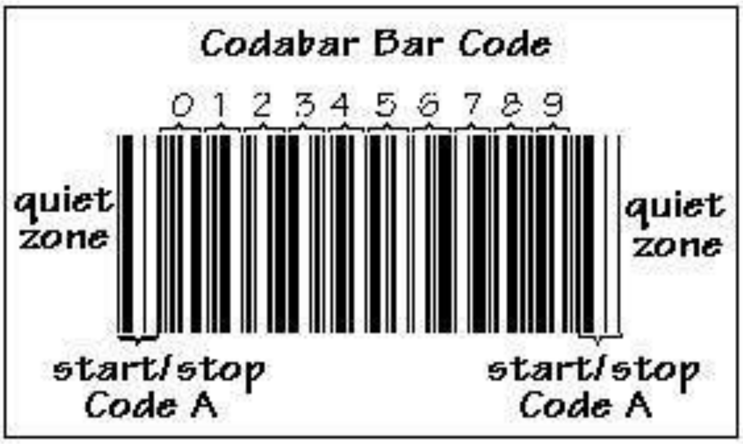


Fig 2.10 Rationalized Codabar [32]

Code 128

Code 128 uses variable element-widths and comprises of 11 modules for each character. The latter has three bars and three spaces making a code 128 a (11,3) symbol. Each character starts with a bar and ends with a space. This symbology allows three different character sets to be represented. The use of shift codes allows the scanner to detect the character set currently in use. Code 128 is common used by United States Postal Service (USPS) and by supply chain to identify product containers and pallets. [21,27,28]

Fig 2.11 Code 128 [31]

Code 93

Code 93, a modular code, has nine modules with either bars or spaces. Each character contains three bars and three spaces making it a (9,3) code. Shift characters (S1, S2, S3, S4) are used to represent all 128 ASCII codes. The start and stop characters are the same but code 93 uses a termination bar at the end. Code 93 is commonly used by Canada Post to encode supplementary delivery information. [21,27]

Code 93i is an extension to code 93 which allows international characters to be encoded. Special start and stop characters are used to define four modes;

Table 2.2 Code 93i modes

Code 93	Starts/ends with code 93 normal characters
93i	Starts with code 93 character / ends with 93i character
93i-EC	Starts with 93i character / ends with 93 character
93i Composite	Starts / ends with 93i character

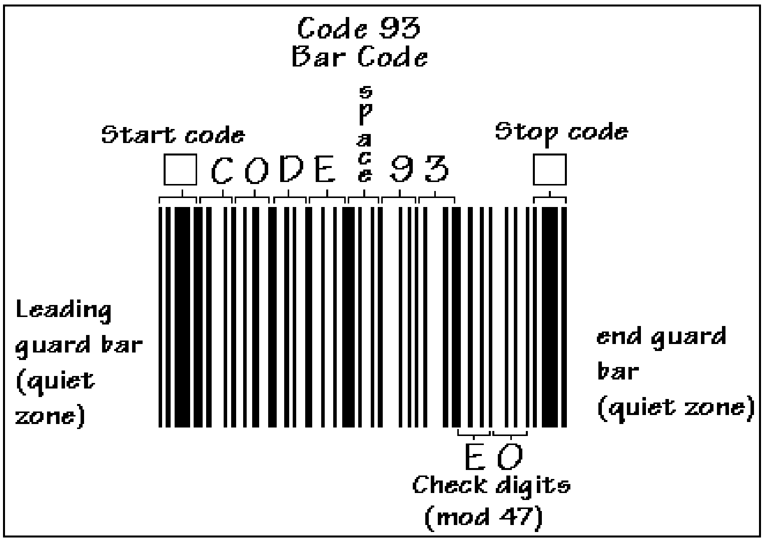


Fig 2.12 Code 93 [32]

2 of 5 Code

2 of 5 Code is a 2-width symbol with five bars and spaces to separate them. Data is stored in bars only where narrow ones represent 0 and wide ones represent 1. Start and stop characters are shortened to three bars and spaces in-between. Applications of this symbology were in 1960s where it has been used for warehouse sort systems, photofinishing envelope identification and airline numbered airline tickets. [21]

Fig 2.13 2 of 5 Code [27]

Code 11

Code 11 uses three different bar widths and two space widths. The symbol’s name was derived from the 11 different data characters that can be represented along with the stop and start characters. Code 11 was used to label telecommunication components and equipments. [27]

Fig 2.14 Code 11 [32]

UPC Version A

UPC A is mainly used to identify products at the checkout in supermarkets in USA. Characters are encoded within two bars and two spaces within seven modules making UPC a (7,2) code. UPC provides three different character sets (A,B,C). Guard bars are of different heights compared to data bars. Two centre guard bars separate the data in between the barcode and two more guard bars on each side are the start and stop characters. Data in both halves are the same but however, the first half is encoded using a set character A while second half on the right is encoded using a character set C. [21,27]

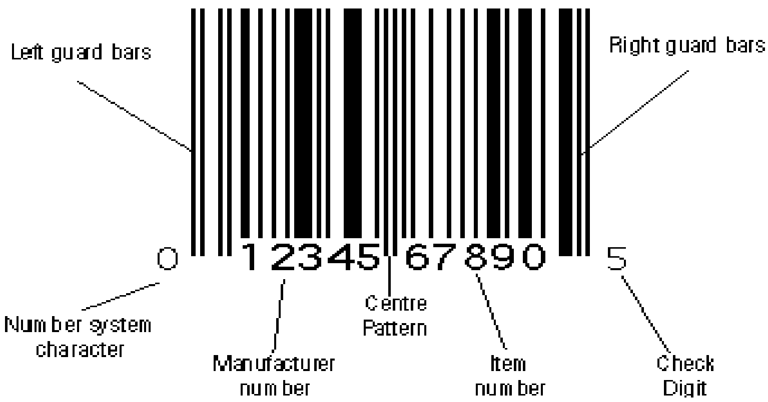


Fig 2.15 UPC A [33]

UPC Version E

UPC E is a compressed version of UPC A. The last digit represents the compression mode and there are two guard bars on each side known as start and stop characters. Guard bars are of different heights compared to data bars. UPC E uses characters from character sets A and B. UPC E are used on small items in supermarkets in USA. [21,27]

Fig 2.16 UPC E [33]

EAN

EAN is a superset of UPC and uses the three character sets from UPC. EAN 13 is the same as UPC A except that the half left hand side of the symbol is encoded in the same manner as UPC E. EAN 8 is encoded using same technique as UPC A but with only 4 digits on each side. EAN versions 13 and 8 are both used to identify products at point of sale in Europe’s supermarkets. International Standard Book Number (ISBN) is produced using EAN 13. [21]

Fig 2.17 EAN-13 [32]

Fig 2.18 EAN-8 [32]

RSS

RSS is an alternative to UPC that allows more information to be encoded and has different versions. The first digit in the symbol determines if symbol is linear (0) or has a 2D symbol (1) attached.

RSS-14 has 8 regions comprising of left/right guard pattern, left and right finder patterns, and 4 data character with different (n,k) values.

Fig 2.19 RSS-14 [21]

RSS Limited is composed of 5 regions within 74 modules with left/right guard patterns, one check character and two characters with different (n,k) values.

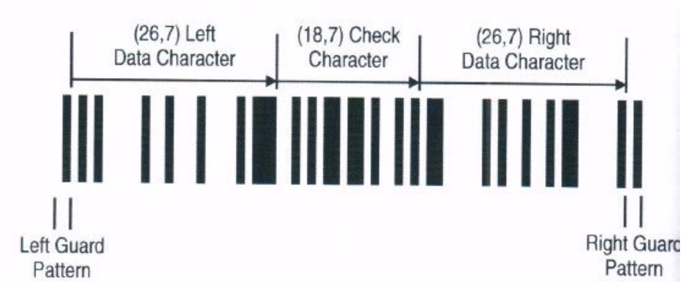


Fig 2.20 RSS Limited [21]

RSS expanded contains 11 regions broken into three triplets. Each triplet includes 1 check character, finder patter and one data character. All characters have the same (17,4) format.

Fig 2.21 RSS Expanded [21]

Miscellaneous

There are many more linear symbologies shown in [20] that have not been described here. Only the most important related to the project's work and commonly used ones have been picked up. Others symbols exists which are a re-presentation of the ones described above, where the same methods have been re-applied to develop new ones.

2.4.4 2D Stacked Barcode and Applications

Code 49

Code 49 uses 1 module to separate each row and minimum of 8 modules for bar heights. Each word in a row encodes 2 characters within a (16,4) format. The rows in the symbol can be scanned in any order as the reader keeps track of the row numbers and number of rows to expect. After each row is read a click is heard and a beep after final reading of whole symbol. Numeric mode allows 5 digits to be encoded instead of 3 alphanumeric characters. Code 49 was designed to label small items but was hardly used as newer techniques were developed. [21]

Fig 2.22 Code 49 [35]

Codablock

Codablock combined Code 39 symbology into different rows along with separator bars and row identifiers. An implementation of four rows codablock holding 18 characters was offered but not used due to its low density and high overhead. Codablock F was however introduced which combined code 128 symbol in rows. Additional characters are used to identify the rows. [21]

Fig 2.23 Codablock [35]

Code 16k

Code 16k has a similar structure to code 49. Characters are encoded using a reverse method (bars are white, spaces are black) of code 128 within (11,3) pattern. Each character has three spaces and three bars and start with a space. Code 16k is a multi-widths element. Code 16k offers less density compared to code 49 at start of message but higher (double) density for long messages. Each row has its own start and stop characters. Code 16k designed to extend code 49 storage was not widely used. [21]

Fig 2.24 Code 16k [35]

PDF417

PDF417 is a combination of 2D Stacked and 2D Matrix (explained in later sections) structures. Each character (value between 0 and 928), known as codeword, uses 4 bars and 4 spaces within 17 modules (17,4) and multi-widths elements. Three different character sets known as clusters are provided and each three rows uses one of each and repeat the same pattern for next three rows. This structure allows readers to differentiate between different rows and eliminates the use of row separators. PDF417 offers three encoding method. PDF417 is used by postal services for parcel delivery and by airline industry on boarding passes. [21, 37]

Macro PDF417 is a technique which combines about 99,999 PDF417 symbols linked together in a large file. [21]

Table 2.3 PDF417 Compression Techniques [21]

Text Compaction Mode (TC)	Uses '10 to base 900 conversion' capable of packing just under 3 digital digits into one character.	EXC Alpha- Starts in upper case EXC Lower- Starts in lower case EXC Mixed- Numeric and other punctuation EXC Punctuation- Punctuation and Bracket Characters
Byte Compaction Mode (BC)	Uses '256 to base 900 conversion'	Multiples of 6 bytes are encoded in one codeword. 5 or less bytes are encoded each in a codeword.
Numeric Compaction Mode (NC)	Uses '10 to base 900 conversion' capable of packing just under 3 digital digits into one character.	If symbol is not filled by available data, codeword 900 is used as a pad character to fill the symbol.

Start Pattern | Left Row Indicator | Data Codewords | Right Row Indicator | Stop Pattern

Fig 2.25 PDF417 [21]

Datastrip

Datastrip is a very high security 2D stacked barcode. The target of this symbology was to provide handheld individual's identity solutions. Unfortunately, the specification is not given due to its uses in highly secured applications, but [21] states that the data capacity is 2,100 bytes with unspecified X dimensions. The application is mainly for Identity management and is used as follows;

Table 2.4 Datastrip Applications [34]

Government	Passports, ePassports, visas, national ID cards, drivers licenses, voter registration cards, social security cards
Military	ID verification and security at military bases / Staff ID verification for Air Force, Army and Navy bases
Law Enforcement	Roadside drivers license and fingerprint checks / Passport or ID checks for suspects
Commercial	Access controls for employees / Remote reading of Employee ID cards at control points.
Education	Student, staff ad visitor Ids / ID verification for attendance, exam taking and facility access.
Health Care	Patient medical cards, employee ID cards.
Financial	Savings cards, employee ID cards
Transportation	Employee ID for airports an seaports / seafarer ID cards / Commercial driver's license / Trusted traveller ID programs.
Public Safety and Justice	Prison Ids for visitors, employees and prisoners / Identifications for individual on parole for drug testing and meeting with parole officers.
Hospitality	Guest ID and VIP pass cards at events.

Fig 2.26 Datastrip [36]

UltraCode

Character is encoded using 14 rectangular modules (2 in length x 7 in height) as a series of tiles. Module has height value of 2 and width value of 1. One top row of 1X is used for scanner alignment and 2X row is used for clocking. Modules are coloured to represent finder patterns, clock pattern, data, alignment pattern and overhead characters. Ultra code was designed to overcome the issue inherent on direct marking of packages. [21]

Fig 2.27 UltraCode [36]

Miscellaneous

There are many more linear symbologies shown in [20] that have not been described here. Only the most important related to the project's work and commonly used ones have been picked up. Others symbols exist which are a re-presentation of the ones described above, where the same methods have been re-applied to develop new ones.

2.4.5 2D Barcodes and Application

Code One

Code One has 10 versions and 14 different sizes. Each version has its own unique recognition pattern and finder pattern.Data is stored on the top or/and bottom of the finder path in arrays of light or dark data modules (equivalent to X dimensions). Some versions require quiet zone of at least 1X. Code One has different code sets shown below; [21]

Table 2.5 Code One Encoding [21]

ASCII	Full ASCII Data	One ASCII character is encoded per symbol character. Extended ASCII uses Function character as shift/Latch
C40	Mostly uppercase alphanumeric data	3 alphanumeric characters are encoded per symbol character
Decimal	Numeric data	2 digits are encoded per symbol character.
Text	Mostly lowercase text data	3 alphanumeric characters are encoded per symbol character
EDI	EDI data set	One ASCII character is encoded per symbol character.
Byte	Binary data	One byte (8 bits) are encoded per symbol character.

Fig 2.28 Code One [35]

Data Matrix

This symbol represents arrays of data cells (white or dark) within a perimeter pattern. The latter comprises of two solid lines forming an **L** shape and two dashes edges. The first version was called ECC000 where the upper right hand corner cell is dark. The latest version is ECC 200 where the upper right hand corner is light. The symbol is divided into data regions separated by alignment patterns. Quiet zone of 1X is required on four sides. Data matrix is used everywhere in the world in different applications as it is free to adapt. Main uses are by printed media, US postal service, aviation, Ford Motor Company, US Department of Defence, etc. Data encoding methods (ECC 200) are as follows; [21,27]

Table 2.6 Data Matrix Encoding [21]

ASCII	Full ASCII Data Double digits numeric	4 bits (numeric) / 8 bits(ASCII) / 16 bits (Extended ASCII) per character	A latch character is used to switch to a different encoding set.
C40	Primarily uppercase alphanumeric data	5.3 bits per character	3 alphanumeric characters are encoded into two codewords. Unshift character is used to switch back to ASCII encoding.
Text	Primarily lowercase alphanumeric data	5.3 bits per character	3 alphanumeric characters are encoded into two codewords. (similar to C40) Unlatch character is used to switch back to ASCII encoding.
X12	ANSI X12 EDI data set	5.3 bits per character	3 alphanumeric characters are encoded into two codewords..
EDIFACT	ASCII values 32-94	6 bits per character	4 characters are encoded into 3 data matrix codewords. Unlatch character is used to switch back to ASCII encoding.
Base 256	Byte value 0-255	8 bits per character	When switching to this mode, the first one or two codewords define the length of data field in bytes.

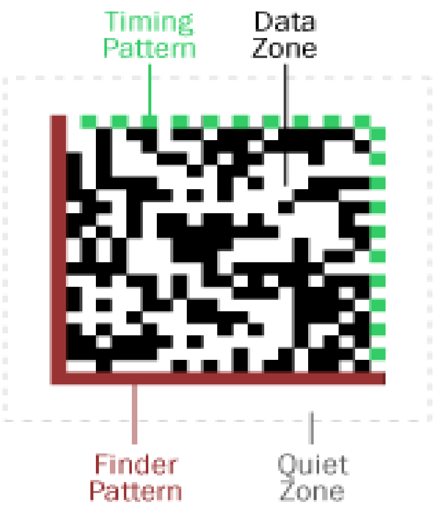


Fig 2.29 Data Matrix [39]

Maxi Code

Maxi Code represents rows of hexagonal elements arranged around a set of three concentric lines. The three circles found in the middle of the code is the finder pattern. Quiet zone of at least 1X is mandatory on all sides. Symbology represents two messages in each symbol. There are five different code sets each with 64 6-bit character patterns. Bits 3 through 6 represent the mode of the symbol and there are 6 different modes. This symbology has 15 control characters (non-data) with no ASCII values which are used to send special functions or send specific data to a host computer. Maxi Code allows up to 8 symbols to be appended in a structured format. Structured Append symbol is indicated by a sequence of two codewords in specific positions depending on the mode. Pad characters are used to fill up symbols. MaxiCode is mainly used for shipping packages by UPS. [21]

Fig 2.30 MaxiCode [32]

QR Code

QR code represents data in arrays of modules in square arrangements and functions patterns. The latter are three square finder patterns, one square alignment pattern, separator and timing pattern. Codewords are 8-bit lengths. A quiet zone of at least 4X is required on all sides. Two versions of QR exist and the Version 2 which provides extra enhanced features is described here. There are various sizes depending on applications and the only difference is 4X per side. Pad character is used to fill excess capacity. Up to 16 symbols are allowed to be appended in a structured format. QR code was designed by Toyota Car Manufacturer in Japan to be used with identification of automotive parts. QR has now spread worldwide and is being used for marketing by various companies. Data is encoded in four modes; [21,27]

Table 2.7 QR Code Encoding [21]

Numeric Mode	Digits 0-9 is grouped into 3 decimal digits and then encoded as 10-bit character
Alphanumeric Mode	Data is grouped into pairs and then encoded as 11-bit character. If number of message characters is not even, final character is encoded as 6-bit. For each pair, first character is multiplied by 45 and then added to second character. Finally sum is encoded as 11-bit character.
Byte Mode	Data is encoded as 8-bit per character
Kanji Mode	A shift JIS system is used to encode data. Each 2-byte character value is compressed into 13-bit codeword. Symbol mode and length indicator is then appended to binary data. FNC1 is used in some applications.

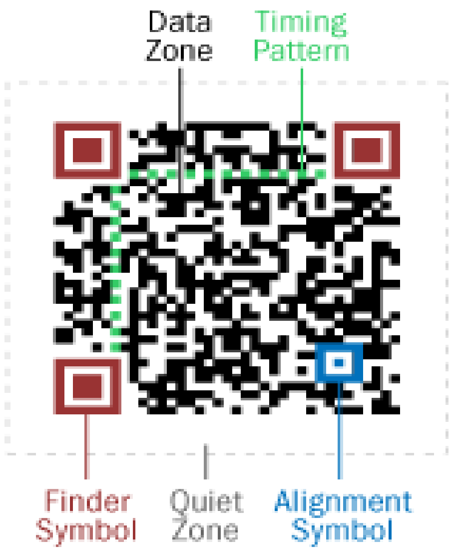


Fig 2.31 QR Code [39]

Aztec Code

Aztec code represents data in form of square modules around a square ‘bull’s-eye’ finder pattern. Two versions are defined; Compact and Full-range. Compact version has up to 4 layers of 2 module data and 3 ring finder pattern, while full-range version has up to 32 layers of 2X data and 4 rings finder pattern. Core symbol refers to the area consisting of finder pattern, orientation bits and a mode message. Mode message includes the number of data layers and data words. Four 3X orientation pattern surrounds the finder path. Aztec encodes data into 5-bits data word and has 5 different character sets. Additional features such as Reflectance reversal (colours black and white may be switched), mirror image (symbols printed in form of mirror image can be decoded), structured append (up to 16 symbols), extended channel interpretation (using ECI other character sets are optional), Reader initialisation (special form which initialise reading equipments) and Aztec Runes (set of 256 small symbols) are available. Aztec Code is used as a marker of small items. Poland uses Aztec in car registration documents. Other applications include transportation, security safeguard, mobile messages, boarding passes (Heathrow Express), etc. [21,41]

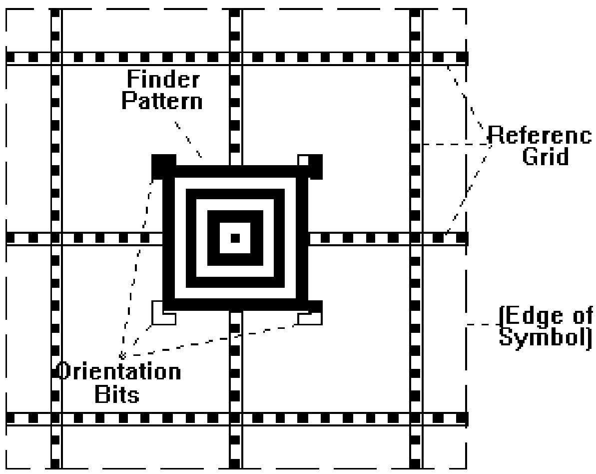


Fig 2.32 Aztec Code [40]

Miscellaneous

There are many more 2D symbologies shown in [20] that have not been described here. Only the most important related to the project’s work and commonly used ones have been picked up. Others proprietary symbols exists which are a re-presentation of the ones described above, where the same methods have been re-applied to develop new ones.

2.5 Data Storage and Security

2.5.1 Information Content of bar codes [38]

Information Content per module is defined below if a code has *n* modules and can generate *S(n)* code words;

$$H(n) = \frac{1}{n} log_2 S(n) = \frac{1}{x} H(n) \qquad (1)$$

Density of a code (in bits per unit length) is defined below if a width *W* is used to print *n* modules; (*X*= module width)

$$D(n) = \frac{1}{w} log_2 S(n) = \frac{1}{x} H(n) \qquad (2)$$

A 'delta code' (format (n,k)) can encode up to 2^n code words and has density information as;

$$D_\delta(n) = \frac{1}{w} log_2(2^n) = \frac{n}{xw} = \frac{1}{x} \qquad (3)$$

In a 2-widths code, number of effective modules is *n-j*, where *j* is the number of bits set to 1. Number of possible code words is;

$$S_w(n) = \sum_{j=0}^{n/2} \begin{bmatrix} n-j \\ j \end{bmatrix} \qquad (4)$$

(4) is equal to *nth* Fibonacci number, given by;

$$f_n = \frac{1}{\sqrt{5}} \left[\left[\frac{1+\sqrt{5}}{2} \right]^{n+1} - \left[\frac{1-\sqrt{5}}{2} \right]^{n+1} \right] \qquad (5)$$

In (5), as *n* increases, the second term goes to zero. For (*n*>5), the following gives a good approximation;

$$S_w(n) \approx 0.4472 \times (1.618)^{n+1} \qquad (6)$$

Density of unrestricted width code is therefore;

$$D_w(n) = \frac{1}{w} log_2 S_w(n) \approx \frac{1}{x}\ log_2 1.618 + \frac{log_2(1.618\ \times\ 0.4472)}{w}$$

OR

$$D_w(n) \approx \frac{0.694}{x} - \frac{0.467}{w} \qquad (7)$$

Maximum number of code words in a (n,k) ‘delta code’ is given as;

$$S(n,k) = \begin{bmatrix} n-1 \\ 2k-1 \end{bmatrix} = \frac{(n-1)(n-2)\dots(n-2k+1)}{(2k-1)(2k-2)\dots 3\cdot 2} \qquad (8)$$

Information content for ‘delta codes’ is given as;

$$H(n,k) = \frac{1}{n}\ log_2 \begin{bmatrix} n-1 \\ 2k-1 \end{bmatrix}$$

$$= \frac{1}{n} \sum_{i=1}^{2k-1} [log_2(n-i) - \ log_2(i)] = \frac{1}{n} \sum_{i=1}^{2k-1} log_2\left(\frac{n}{i} - 1\right) \qquad (9)$$

For a given *n*, *S* is maximum when *2k-1* is exactly half of *n-1*, which implies *n-1 =2(2k-1)* or ;

$$n = 4k - 1 \qquad (10)$$

Codes which satisfy equation (10) are called Symmetric Codes.
Thus for symmetric codes where *n=4k-1*, equation (8) yields;

$$S_s(n) = \begin{bmatrix} n-1 \\ \frac{n-1}{2} \end{bmatrix} = \frac{2^n}{\sqrt{2\pi(n-1)}} \qquad (11)$$

Equation (11) shows the loss factor of (n,k) codes compared to maximum of 2^n for ‘delta codes’ and the loss factor is given as;

$$Loss\ Factor = \frac{1}{\sqrt{2\pi(n-1)}}$$

Dividing the binary logarithm of *S* by *n* gives;

$$H_s(n) \approx 1 - \frac{log_2[2\pi(n-1)]}{2n} \qquad (12)$$

(12) shows that as n goes infinite, *H(n)* goes 1 which is the maximum theoretical information content. Thus, equation of density is given as;

$$D_s(n) = \frac{1}{x} - \frac{log_2[2\pi(n-1)]}{2w} \qquad (13)$$

Linear Efficiency of a symbol is given as; [21]

$$\frac{Bits\ of\ data\ in\ symbol}{Length\ of\ symbol\ in\ modules} \times 100\% \qquad (14)$$

Area Efficiency of 2D symbol is given as; [21]

$$\frac{Bits\ of\ data\ in\ symbol}{Area\ of\ symbol\ in\ square\ modules} \times 100\% \qquad (15)$$

Capacity of (m,w) width code is given as;

$$S_w(m,w) = \begin{bmatrix} m \\ w \end{bmatrix} = \frac{m(m-1)\ldots m(m-w+1)}{w(w-1)\ldots.\ 3\cdot 2} \qquad (16)$$

Information content of width code is given as; (*m*+*wr)* is the code length where *r* is the ratio of wide over narrow minus one)

$$H_w(m,w) = \frac{1}{m+w\cdot r} log_2 S \qquad (17)$$

2.5.1.1 1D Data Storage

Table 2.8 1D Data Storage [20, 21, 26]

Symbology	Type	Length	Character set	Density / Capacity
Code 39	Alpha-numeric	Variable	10 digits, 26 uppercase letters, 7 special char	9.8 characters per inch (x=7.5mil)
Interleaved 2 of 5	Numeric	Variable	Digits 0-9	High density, 18 digits per inch (x=7.5mil), maximum of 14 digits in one symbol
Rationalised Codabar	Alpha-numeric	Variable	10 digits, 6 special char	12.8 char per inch (x=7.5mil)
Code 128	Alpha-numeric	Variable	107 characters including four function/four code set selection/three start char.	Low density, 12.1 characters or 24.2 numeric digits per inch (x=7.5mil), Maximum of 48 char in one symbol
Code 93	Alpha-numeric	Variable	26 letters, 10 digits, 7 special char	High density, 14.8 char per inch (x=7.5mil)
Code 93i	Alpha-numeric	Variable	Full and extended ASCII char / 65,536 Unicode Char	High density , 14.8 char per inch
2 of 5 Code	Numeric	Variable	Digits 0-9	High density, 18 digits per inch (x=7.5mil), 14 digits in one symbol
Code 11	Numeric	Variable	10 digits, 1 special character	High density, 18 digits per inch (x=7.5mil)
Postnet Code	Numeric	Variable	0-9 digits	Low density, maximum of 12 digits in one symbol.
Four State Code	Alpha-numeric	Variable	0-9 digits, A-Z letters	Low density, maximum of 31 char in one symbol
UPC A	Numeric	Fixed	0-9 digits	13 digits
UPC E	Numeric	Fixed	0-9 digits	8 digits
EAN 13	Numeric	Fixed	0-9 digits	13 digits
EAN 8	Numeric	Fixed	0-9 digits	8 digits
RSS 14	Numeric	Fixed	0-9 digits	Application Identifier (01) + 14 digits
RSS Limited	Numeric	Fixed	0-9 digits	Application Identifier (01) + 14 digits
RSS Extended	Alpha-numeric	Variable	74 numeric or 41 alphabetic	maximum of 22 char in a symbol

2.5.1.2 2D Stacked Data Storage

Table 2.9 2D Stacked Data Storage [21]

Symbology	Type	Length	Data value	Row	Data Capacity / Density
Code 49	Alpha-numeric / continuous	Fixed (70 modules)- Maximum of 4 words (8 characters) by 8 rows	Full 128 ASCII set, including 3 function and 3 shift characters	2-8	Maximum of 49 alphanumeric or 81 numeric characters. 93.3 alphanumeric / 154.3 numeric per inch. (X=7.5mil)
Codablock F	Alpha-numeric / continuous	Fixed	Full ASCII characters	2-44	Maximum of 62 characters per row. (see code 128 for density per row)
Code 16k	Alpha-numeric / continuous	Fixed, 70 modules / 5 characters per row	107 characters. Full ASCII set using 3 character sets.	2-16	Maximum of 77 ASCII or 154 numeric characters. 146.7 alphanumeric / 293.3 numeric per inch. (X=7.5mil)
PDF417	Alpha-numeric / Binary Data / Continuous	Variable, 90X to 583X	128 ASCII / 128 Extended ASCII / 8-bit binary data	3-90	1850 text characters / 2710 digits / 1108 bytes.
Micro PDF417	Alpha-numeric/ binary data / continuous	Different fixed sizes (40X, 57X, 84X or 101X)	128 ASCII / 128 Extended ASCII / 8-bit binary data	4-44	Maximum of 250 text characters, 366 digits, or 150 bytes.
UltraCode	Alpha-numeric/ binary data / continuous	Variable length / fixed height	128 ASCII / 128 16-bit Unicode characters / 8-bit binary data	7	Approximation of 193 Uppercase English characters / 64 Japanese, Chinese or Korean /307 decimal digits / 124 bytes over 5 inches using X=10mil

2.5.1.3 2D Data Storage

Table 2.10 2D Matrix Data Storage [21]

Symbology	Size	Data value	Capacity / Density
Code One	From (9X by 13X) to (134X by 148X)	Full 256 ASCII set / 8 bit binary / 1 Pad or Message separator	Maximum of 2218 text characters / 3550 digits / 1478 bytes.
Data Matrix Mode ECC 200	From (10X by 10X) to (144X by 144X)	Full 256 ASCII set / All ISO characters / All EBCDIC characters	Maximum of 2335 alpha numeric characters / 3116 numeric digits
Maxicode	Fixed, (1.11 inch by 1.054 inch)	Full 256 ASCII characters	Maximum of 93 Characters.
Aztec Code	Variable, 90X to 583X	First 0-127 ASCII set / ISO 8859-1 values 128-255 / All 8-bit values / Latin Alphabet No.1	3,067 alphabetic characters / 2710 digits / 1914 bytes of data.
QR Code	Fixed, (21X by 21X) or (177X by 177X)	Numeric, Alphanumeric Data and 9 special symbol, 8-bit data, Kanji characters.	Maximum of 4,296 alphanumeric characters, or 7,089 numeric digits.

2.5.2 Data Security

2.5.2.1 Modulo

Modulo is a technique that is used to validate a code transmitted. A division is made to the sum calculated using a specific weight multiplied by the data code to be transmitted. The remainder of the calculation is used as the check digit to validate the code on the receiving end. For instance, if modulo 4 is used and the sum is 18, then the check digit is the remainder of 18/4 which is 2. Modulo does not correct corrupted data.

2.5.2.2 Reed-Solomon

Reed-Solomon (RS) is an error-correction technique. A complicated mathematical calculation is done with the data transmitted to obtain the RS code. RS is a non binary and cyclic code. It allows corrupted characters to be recovered. RS defines a polynomial field based on the data to be transferred and use this field to calculate the RS code. If n bits of data need to be sent, the code sent is defined as n+2k where 2k is the RS code. Corrupted bits of no more than k bits can be corrected and retrieved if data is corrupted upon transmission. More in-depth details are given in [44] [45].

2.5.2.3 Symbols Security

Table 2.11 Data Security 1 [21]

Symbology	Check Character / Technique	Description
Code 39	Optional 1 digit Modulo 43	The sum of all data values is divided by 43. Remainder is the check digit.
Interleaved 2 of 5	1 check digit and 1 optional for parity check Modulo 10 Even Parity	Sum of odd positioned digits is added to (sum of even positioned digits X 3). The smallest value added to this sum to make it multiple of 10 is the check digit. If total number of digits is odd, a non-significant zero is added to make it even.
Code 128	1 Character Modulo 103	Each character is multiplied by a value starting from one and increment in value by 1 (1^{st} X 1, 2^{nd} X 2, 3^{rd} X 3, etc). The sums are added and then divided by 103. Remainder is the check digit.
Code 93	2 Characters Modulo 47	Data: E, sp, 9, 3, C, K Data Value: 14, 38, 9, 3 C Weight: 4 (sp), 3 (9), 2 (3), 1 (C) K Weight: 5 (sp), 4 (9), 3 (3), 2 (C), 1 (K) C= remainder of [((1x3)+(2x9)+(3x38)+(4x14))/47] K= remainder of [((1xC)+(2x3)+(3x9)+(4x38)+(5x14))/47]
Code 93i	2 Characters Modulo 53, 6 Reed-Solomon Characters	Same as Code 93 except sums are divided by 53 instead of 47. RS has three characters following start character and three preceding the stop character, and can recover 2 data characters.
Code 11	1 or 2 Digits Modulo 11	-Check digits are calculated using same technique as in code 93. [43]
Postnet Code	5 bars check digit	Check digit is the value added to the sum of all digits to make it a multiple of 10.
UPC A (GTIN-12)	1 Digit Modulo 10	[42]
EAN 13 (GTIN-13)	1 Digit Modulo 10	
EAN 8 (GTIN-8)	1 Digit Modulo 10	
RSS 14 (GTIN-14)	1 Digit Modulo 10	

ID Key Format	Digit positions																	
GTIN-8											N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8
GTIN-12							N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	N_9	N_{10}	N_{11}	N_{12}
GTIN-13						N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	N_9	N_{10}	N_{11}	N_{12}	N_{13}
GTIN-14					N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	N_9	N_{10}	N_{11}	N_{12}	N_{13}	N_{14}
SSCC	N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	N_9	N_{10}	N_{11}	N_{12}	N_{13}	N_{14}	N_{15}	N_{16}	N_{17}	N_{18}
Step 1: Multiply value of each position by																		
	x3	x1	x3	x1	x3	x1	x3	x1	x3	x1	x3	x1	x3	x1	x3	x1	x3	
Step 2: Add results together to create **sum**																		
Step 3: Subtract **sum** from the next highest multiple of ten = ***Check digit***																		

Symbology	Check Character / Technique	Description
UPC E	1 Digit Modulo 10	Check digit is calculated from UPC A and then data is compressed to UPC E mode.

Table 2.12 Data Security 2 [21]

Symbology	**Check Character / Technique**	**Description**
RSS Limited	1 Digit Modulo 10	Check digit is calculated from RSS-14 and then data is compressed to RSS Limited mode.
RSS Extended	1 Character Modulo 10	Check digit contains length of symbol and checksum. The latter is calculated using same technique as RSS-14.
Code 49	2 or 3 check words Modulo 2401, Row 1-7 has mixed even and odd parity words. Last row has all even parity words.	2 check words (X, Y) for rows <=6, 3 check words (X, Y, Z) if rows >6. $Z = (Z_{00}\ C_{r7} + \sum_{i=1}^{r-1} \sum_{j=1}^{4} Z_{ij}W_{ij})$ MOD 2401 $Y = (Y_{00}\ C_{r7} + \sum_{i=1}^{r-1} \sum_{j=1}^{4} Y_{ij}W_{ij} + Y_{r1}\ W_{r1})$ MOD 2401 $X = (X_{00}\ C_{r7} + \sum_{i=1}^{r-1} \sum_{j=1}^{4} X_{ij}W_{ij} + X_{r1}\ W_{r1} + X_{r2}\ W_{r2})$ MOD 2401 r is number of rows and values are obtained from a specified table shown in [21].
Codablock F	Modulo103 in each row	Code 128 check digit in each row.
Code 16k	2 last characters in last row. Modulo 107	7th character in last row is modulo 107 of the sum of preceding characters' values multiply by an ascending value starting from 2. 8th character in last row is modulo 107 of the sum of preceding characters' values multiply by an ascending value starting from 1 including 7th character.
PDF417	Reed Solomon	Optional, 2-512 characters per symbol
Micro PDF417	Reed Solomon	7-50 characters (per row by column combination)
UltraCode	Reed Solomon	1 tile = 14 modules
Code One	Reed Solomon	4 to 560 characters per symbol
Data Matrix (ECC 200)	Reed Solomon	5 to 620 code words
Maxicode	Reed Solomon	2 levels of security
Aztec Code	Reed Solomon	5-95% of data region (normally 23% plus 3 codewords)
QR Code	Reed Solomon	4 levels of security ; L =7% OR M =15% OR Q =25% OR H =30% of symbol codewords.

2.6 State-of-the-art Optical Barcode Systems

This section reviews various researches and other articles that intend to answer the questions of this thesis. The main objective here is to avoid repeating a research that has already been done. So far, researches that have been done to improve 1D and 2D barcodes storage are colour barcode technology sometimes known as 3D barcodes. Alongside the colour technology, some researchers have used technique such as different module shapes and several layers to improve data storage. Other technologies that intend to replace barcodes completely such as RFID will be briefly compared in section 2.7 as they are outside the scope of the thesis question and they are not optical techniques. Hence, State-of-the-art colour barcode systems that have been researched, analysed, reviewed, referenced and summarised below are mainly colour techniques and several layered-barcode.

2.6.1 High Capacity Colour Barcodes (HCCB) Barcodes

HCCB also known as Microsoft Tag is the most popular colour barcode currently in use by retail businesses [50]. HCCB uses four or eight colours to encode data in triangular shapes as shown in Figure 2.33. The space each type of barcode requires to store 1 byte of data is shown in Figure 2.34. The triangle module reduces the cell size required to store 1 bit. The data capacity per square inch of an 8-colour HCCB is defined by Microsoft as 2000 binary bytes or 3500 alphabetical characters using a 600dpi printer and scanner. HCCB uses a pallet of the colours used for data encoding at the bottom right corner so that decoders can validate barcode read. Four separator lines are used to locate barcode. Each row of data is separated by a white line.

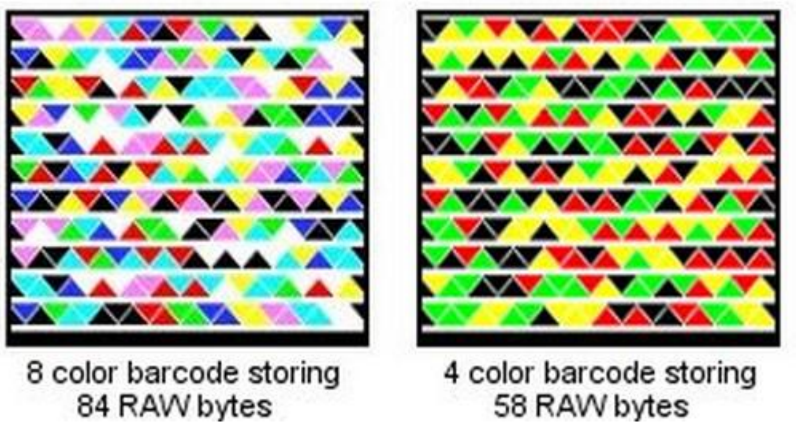


Fig 2.33 4-colour and 8-colour HCCB **[49]**

***RAW bytes refer to unprocessed or uncompressed data**

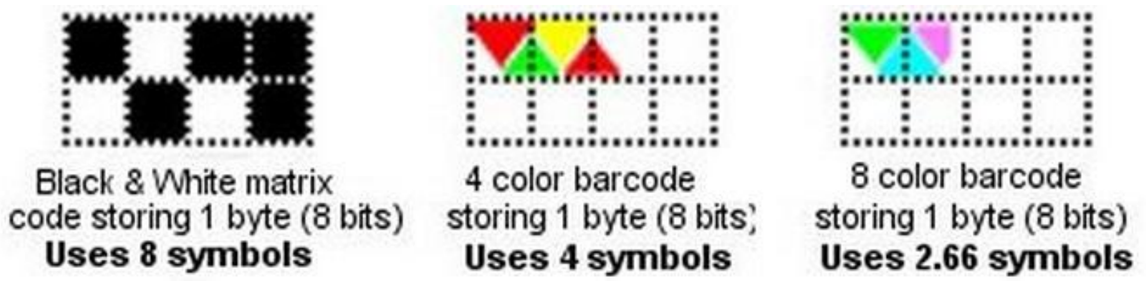


Fig 2.34 HCCB Data Symbols **[49]**

HCCB proves that barcodes using different colours to represent different wavelengths of light has been researched and introduced. The use of a white light illuminates each module with a different wavelength of light and the diffracted light is captured by a scanner which finally read the wavelength of the particular module in the HCCB. The new proposed barcode symbol in this research diffracts white light into a spectrum of light. Diffraction gratings are used instead of modules with specific light wavelength.

2.6.2 Paper Memory (PM) Code [51]

PM code is a layered barcode which consists of several layers of 2D Matrix colour barcode. The latter uses the same characteristics of 2D Matrix Barcodes but instead, replaces the black and white modules with colours to encode more data as in HCCB. Data is encoded in different 2D Matrix colour barcode and then the resultant PM code is generated by compiling all the Matrix barcodes together. One module in the PM code will either be one colour or the resultant mixed colour from the several layers as shown in Figure 3.3. Amount of data that can be encoded in a PM code will depend on the colours and number of layers used but will obviously be much higher than HCCB. As mentioned in [52] decoding software uses a colour conversion algorithm that combines RGB and Hue Saturation Brightness (HSB) colour spaces. This algorithm allows the decoder to identify each colour cell in each layer which enables each layer to be decoded individually and finally the whole PM code.

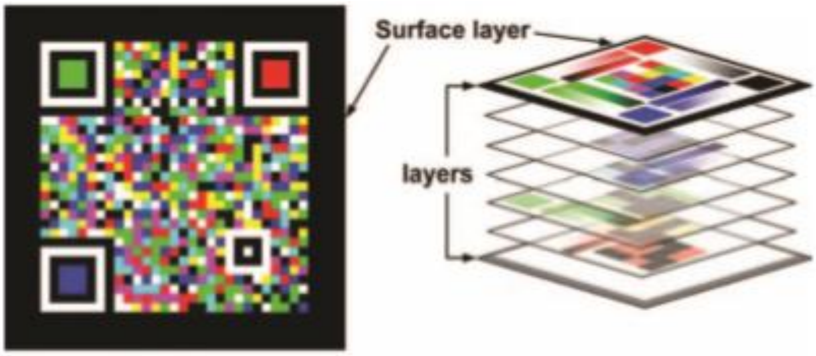


Fig 2.35 PM code **[52]**

Compared to my work, this technique reflects the design of the dual-layered barcode. PM code consists of several more layers than the one in this project. No testing of the code was found that could prove its success. Writer in [53] claims that using 17000 colours requires very complex error corrections and is very sensitive to noise in the colour spectrum. Due to lack of resources, this barcode is considered to have been unsuccessful. Hence, the idea behind the layered structure will be used in my project but again using diffraction grating is still a new concept in my project.

2.6.3 Quick Layered Response (QLR) Barcode

QLR Barcode [53] was designed to use the same layered-structure as PM code. However, QLR uses only three colours (Red Green Blue (RGB)) and three layers of Quick Response (QR) colour Codes as shown in Figure 2.36. The idea of using Coloured QR barcodes is not to encode more data but instead to separate them in three layers. One coloured QR barcode will be exactly the same as a traditional 2D QR barcode. A QLR barcode will encode a maximum data of 12,888 alphanumeric characters, or 21,267 numeric digits, which is three times QR code capacity.

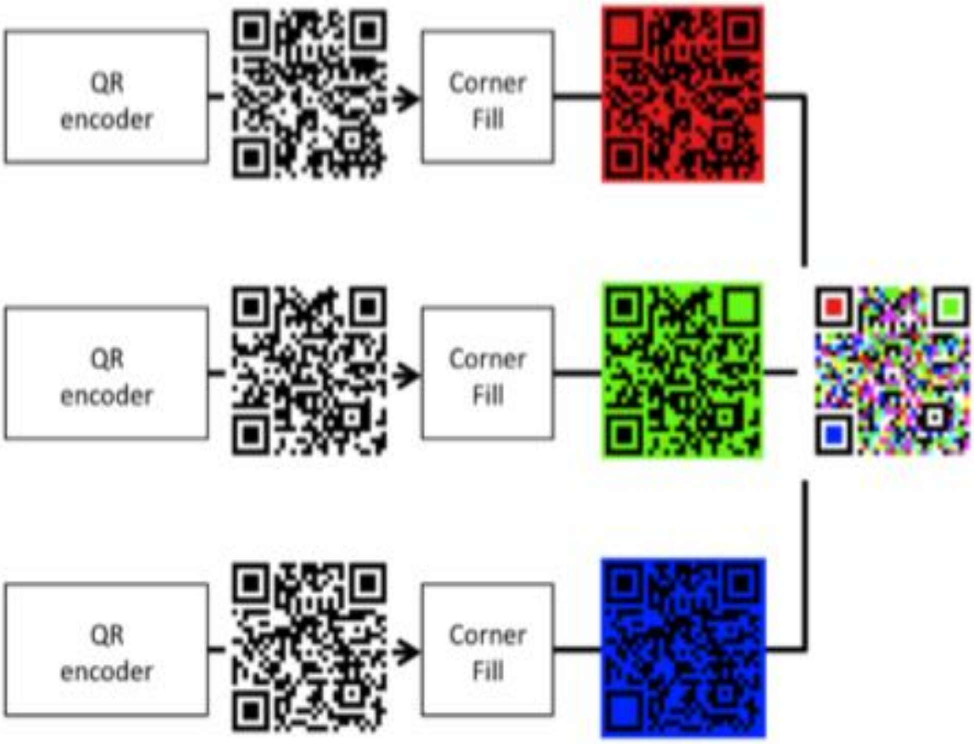


Fig 2.36 QLR CODE **[53]**

The three corners with the RGB colours are used to detect the code as well as differentiate it with QR codes. A matrix calculation is used to detect and decode the layers respectively and is given as, [53]

$$A \times [tl, tr, bl] = [r, g, b] \qquad (1)$$

where A is our linear transformation and *tl, tr, and bl* are the top left, top right and bottom left sampled corner colours, respectively.

$$A \times \begin{bmatrix} tlR & trR & blR \\ tlG & trG & blG \\ tlB & trB & blB \end{bmatrix} = \begin{bmatrix} 255 & 0 & 0 \\ 0 & 255 & 0 \\ 0 & 0 & 255 \end{bmatrix}$$

$$A = \frac{1}{255} \begin{bmatrix} tlR & trR & blR \\ tlG & trG & blG \\ tlB & trB & blB \end{bmatrix}^{-1}$$

Using a simple formula for the inverse of a matrix

$$M^{-1} = \frac{adj\ (M)}{|M|} \qquad (2)$$

Paper claims that encoding and decoding tests were conducted and successful despite no evidence was given. The decoding process is done by java software. Compared to my work, the layered strategy in this paper might help to design the dual layer barcode in my project. However, decoding process of each colour will instead be based on the diffracted wavelengths obtained from gratings. My work will aim at using two layers of gratings where gratings in each layer will diffract one module into a spectrum of light wavelengths. A wider range of wavelengths per module could allow extra storage capacity compared to QLR code.

2.6.4 DataGlyph [54]

Dataglyph is a technique of hiding highly confidential digital data using symbols or dots in pictures [55]. Data glyph is mainly used by companies to prevent counterfeit. OrhanBulan, Student Member, IEEE, Gaurav Sharma, Senior Member, IEEE, and Vishal Monga, Member, IEEE used the dataglyph's technique to design a way to embed data into gray-scale pictures using elongated dots [56]. Following this concept, OrhanBulan and Gaurav Sharma extended the approach to coloured picture [57], hence calling this technique as High Capacity Image Barcodes. Using coloured pictures, OrhanBulan and Gaurav Sharma designed a high coloured barcode [54] using elliptical shapes with three colour separation. After a review regarding issues with the colours scattering spectral, a newer version [54] was introduced using only 2 colours out of the initial three colours.

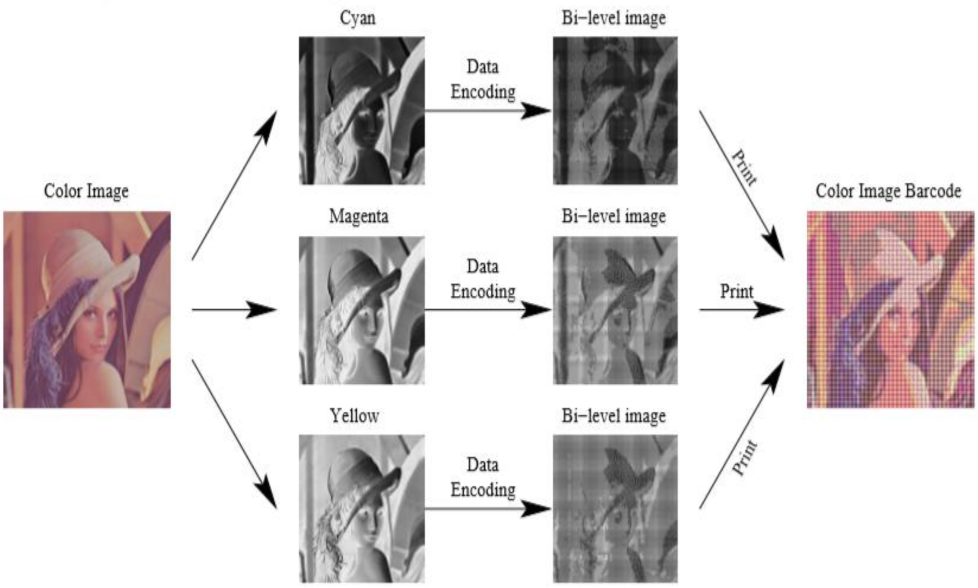


Fig 2.37 Image Barcode **[57]**

In [57], the barcode uses three colours Cyan (C), Magenta (M), and Yellow(Y) available from colour printers to separate three layers. Data is broken into three parts and encoded into three layers and colours. The layer itself is made using elongated dots formally used in [56] to hide data. The shape is modulated to form binary modulation allowing 1 bit per cell or 4-ary modulation allowing 2 bits per cell. One cell is the minimum size that can be detected by a laser scanner normally used as the reader. Three lights Red (R), Green (G), and Blue (B), are used by the scanner in turn to capture each layer in different channels. Below are some pictures to give a better idea of how the technique works theoretically as well as a table showing the data capacity.

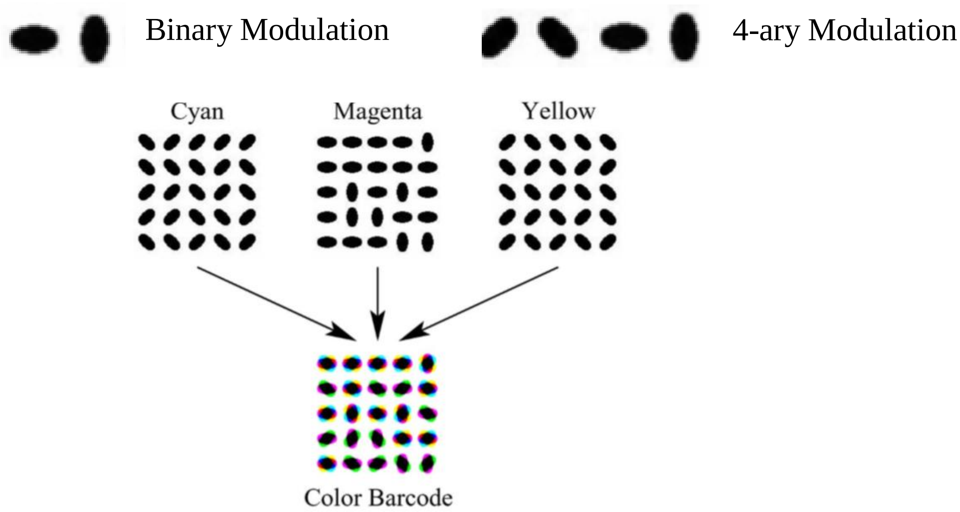


Fig 2.38 High Capacity Barcode: Per Channel Data Encoding **[57]**

Table 2.13 High Capacity Barcode: Per Channel Data Encoding Data Capacity **[57]**

	HP Color Laserjet 4700		**Xerox iGen3**		**Xerox DocuColor 800**	
	Payload Density (Bytes/in^2)	Code Rate	Payload Density (Bytes/in^2)	Code Rate	Payload Density (Bytes/in^2)	Code Rate
75 cpi	1757	5 / 6	1898	9 / 10	1898	9 / 10
100cpi	2812	3 / 4	3000	4 / 5	3333	8 / 9

[54] is an extension to [57] where better cells per inch are achieved per inch square and two colours are used to reduce colour spectral scattering mentioned in [57]. The technique is the same as in [57] but however due to addition of elliptical dot array, the new high colour barcode symbology offers higher data storage as shown bellow. The writer concludes that the two-colour mixtures of the Cyan and Yellow colorant channels used

widely in digital printers can easily be separated using the red and blue channels of common desktop RGB scanners due to their complementary spectral characteristics [54].

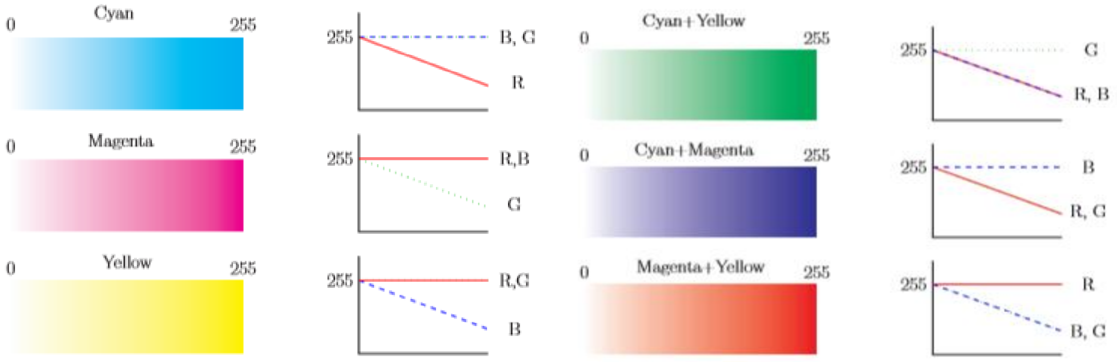


Fig 2.39 Colour Separations **[54]**

Table 2.14 High Capacity Barcode using Dot Orientation and Colour Separability Data Capacity **[57]**

Modulation	Scanner Res. (dpi)	SER	Bits/inch sq.
Binary	1200	0.0201	28,800
Binary	2400	0.0047	28,800
4 - *ary*	1200	0.1316	57,600
4 - *ary*	2400	0.0559	57,600

This research is the closest work done compared to mine. The dual layer in my design will use the same colour combination technique. However, the dataglyphs shapes used to store the data in each layer limits the amount of storage capacity. Compared to this research, my work will look towards designing or using an existing 2D format such as HCCB or QR code that will store more data compared to the dot orientation. The writer uses one colour for each layer whereas my work will look to extend the use of different colours in a each layer to extend the data capacity. Again as mentioned before, grating which will diffract more colours will aid towards higher number of colours per module and thus higher data storage. However, some basics from this research might be considered during the design of the new novel barcode.

2.6.5 Other Barcodes

This section outlines and references some other researchers who developed barcode symbologies to increase data storage capacity compared to 1D and 2D barcodes. After the invention of HCCB, further researches were carried out to try and use more colours to represent more data and increase densities. Writer in [58] created an approach to use 24 colours instead of 8-colour HCCB and eliminated the use of colour references used by HCCB. Writer in [61] designed an approach where even more colours are used with an increased density than any existing 2D barcode. Writer in [60] used the QR barcode with colours to increase density and data storage.

Apart from using more colours, some researchers came with ideas of using more than one barcode to represent a larger amount of data. Instead of using a single barcode, data is split to be stored and represented into several barcodes. Writers in [59] and [63] used this approach to split and store data in a series of barcodes. The camera reading the barcodes, are normally handheld and moved across the whole symbol to read all barcode in a sequence.

Along with colours, research in [62] used the idea of adding the usage of different shapes in one symbol. The idea used was to have a set of shapes and a set of colours. Each colour and shape would represent one character. This technique was highly dependent on the decoding software.

None of these techniques compares to my work but except the goal of extending the storage capacity of 2D barcodes. The idea to mention them is to give the reader an idea of how researchers have developed ideas based on previous existing barcodes to achieve higher data storage.

2.7 RFID [98]

Radio Frequency Identification is the technology that uses microchips referred to as tags to store data in objects. The concept is simple where tags are used to store data and a RFID reader with an antenna is used to detect and capture the data from the objects. The communication between the tags and readers use Radio Waves. Two types of tags exist; passive and active. This technology is used in different applications and some are as follows;

1. To replace barcodes to uniquely identify products in supermarkets.
2. To track objects or devices.
3. Implanted in humans to use as identity.

Active tags are used with applications where the object and the reader are located over long distances. They normally operate at 455 MHz, 2.45 GHz or 5.8 GHz and have an operating range of 60 to 300 feet. Two types of active tags are transponders and beacons. Transponders normally are dormant and when it receives a signal from a detector, it then sends the unique identification number or other data to the reader. This helps save power. Beacons are tags used to track a lost object. The beacon keeps broadcasting its signals at regular intervals for a reader to pickup up the signal and recovers the lost object.

Passive tags do not normally transmit any signal and have no power. They are much cheaper than active tags. The operating range is from few inches to 30 feet which is much smaller compared to active tags. The passive transponder consists of a microchip attached to an antenna which can be packaged in many different ways such as printable RFID label, smart label or on a substrate creating a label. They can operate at low, high or ultra-high frequencies. Different frequencies are application-dependent as the higher the frequencies the more chances for the signal to bounce off objects.

Below is a brief comparison between RFID technology, 1D/2D/coloured barcodes and the new barcode system is given below;

1. RFID is more expensive than normal 1D/2D/coloured barcodes and thus remains less favourable. However, the new barcode system will be more expensive than all of them as customized gratings cost more than tags.
2. RFID allows data to be modified but 1D/2D/coloured barcodes as well as the new barcode system cannot be modified and will need to be re-created.
3. RFID uses radio waves whereas 1D/2D/coloured and the new barcode system uses optical light to read the data. Radio waves can be interacted and read by other sources which. RFID require strong security, thus compromising data storage.
4. RFID hold up to 2 Kb [98] whereas 1D/2D/coloured hold more data (QR Code can hold around 2.9 Kb) and the new barcode system have the potential to hold around 200 bytes.

RFID is a very good technology which uses a different method of tagging and unique identification compare to traditional barcode. This research is to develop a completely different technology of barcode system which differs from RFID as it uses light to read the barcode and it uses gratings to store/represent data.

2.8 Summary

This chapter covers two sections of the project; the entire detailed explanation of existing barcode system and review of researches related to the question of this project already researched and completed. The first section is an introduction to the history of barcode detailing the different generations from its existence up till now. An overview of Barcode system and its components is given along with detailed explanation of each component. This section explains how the barcode system works to read a symbol and create/print a symbol. Three different generations of barcodes are explained and they are 1D, 2D and coloured barcodes. Existing types of these barcode generations are compared and explained in detail. Tables are used to illustrate the specifications of each of the types of barcode generation symbology. The data capacity along with their character sets for the symbols are also compared in tabular form. The data security used in existing barcode systems is also explained and a table defines the security techniques associated with the different symbol types.

The second phase is to ensure that work already researched in the past does not answer the question of this project. The most related researches are briefly explained. The aims and objectives, questions, work carried by the authors and the results are given and compared against the questions of this project to ensure they have not been answered. Most of researches compared have developed coloured and layered barcode systems. However, the use of gratings in a barcode system was never researched before. The study of previous related researches proves that this project proposes a barcode system that has not been developed in the past. This new design clearly involves the use of diffraction gratings proposed on two layers and the use of wavelength-multiplexed technique achieve data storage.

Chapter 3

Wavelength Multiplexed and Dual Layer Barcode Design

This chapter provides a design of the whole new barcode system. The entire system is broken into 4 main components (Light Source, Light Detector, Barcode, and Dual Layer). Diffraction of grating occurs in many diffracting orders. This concept will only focus on the first diffraction order in order to prove that the technique mentioned works. Further diffraction orders will be considered later in the project or in future work.

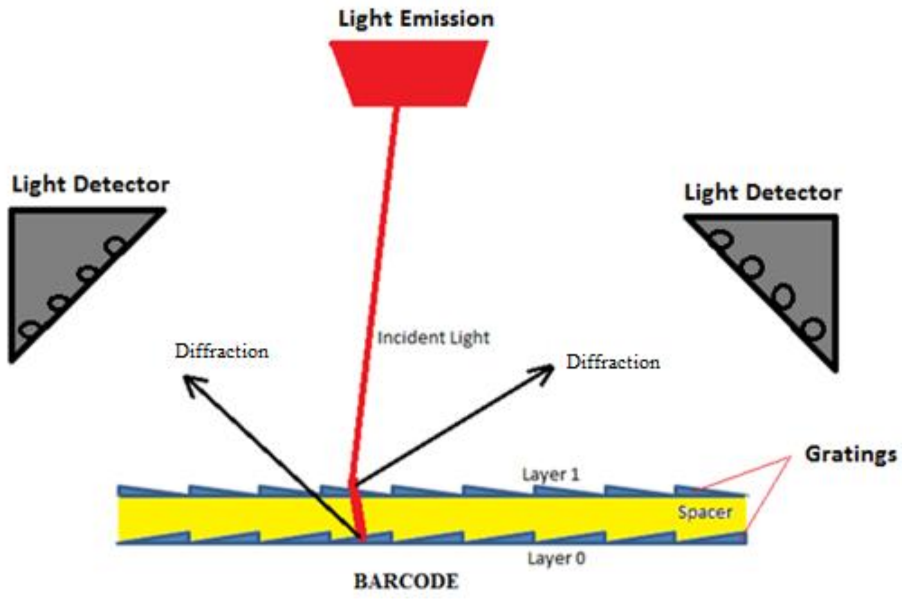


Fig 3.0 Barcode System Design

In simple terms, the system will operate by illuminating the barcode with a light. The latter will illuminate the gratings which will then be diffracted into various directions and wavelengths. Finally the light diffracted will be read by light detectors and then decoded to read the data stored in the barcode. To start, the barcode itself will be designed using gratings with different properties. Gratings are best known for their ability to diffract light into various wavelengths and direction. This feature allows gratings to be differentiated with each other, thus enabling data storage. Two layers of grating will enhance the data storage and polycarbonate will be used to add a spacer in between the layers. Each grating will be designed to diffract light in each direction. The first grating will be semi transparent and semi reflective to allow the incident light to reach the second layer. Light detection will comprised of two detectors on each side of the barcode. The detectors will be made of arrays of photodiodes to capture the broad wavelength diffracted from the barcode. The light source to be used will be white LED. The rays of the light will be focussed onto the gratings using lenses and rotating mirrors. The designs of the four components are explained in details below.

3.1 Light Detection

The only way to read the gratings or data to be stored on the new barcode is via light detection. Gratings with different properties will be used to diffract incident light from the LED into different directions and wavelengths. Detectors with arrays of photodiodes will be crucial to detect and read the light diffraction from the gratings. Along with the barcode design, it is essential to design a proper detector which will adapt to the barcode design and work appropriately to ensure the light diffraction is not lost but instead read and output as required. This section defines specifications and guidelines to help design the detector.

3.1.1 Photodiodes

Photodiode is a semi-conductor light detector that converts the received incident light power into current signals which is converted into voltage for measurement. Photodiodes are low cost and offers detection of visible to near-IR wavelength detection. They have very fast response times, low noises, lightweight and can be designed to meet requirements of many applications [65]. Three types of photodiodes exist; PN junction diode, PIN photodiode and avalanche photodiode [64]. In this project, PIN photodiode will be used to capture the light refracted from the barcode. SI pin photodiode offers a response with wavelength of about 200 nm to 1100nm and hence will be used in this design. An array of photodiodes will be used to pick up different light wavelengths which travel in different directions due to the small size of one single diode.

3.1.1.1 PIN Photodiodes

A PIN photodiode is one with an intrinsic undoped region between the p and n regions (both doped) as shown below. The top surface is coated to stop any light reflection.

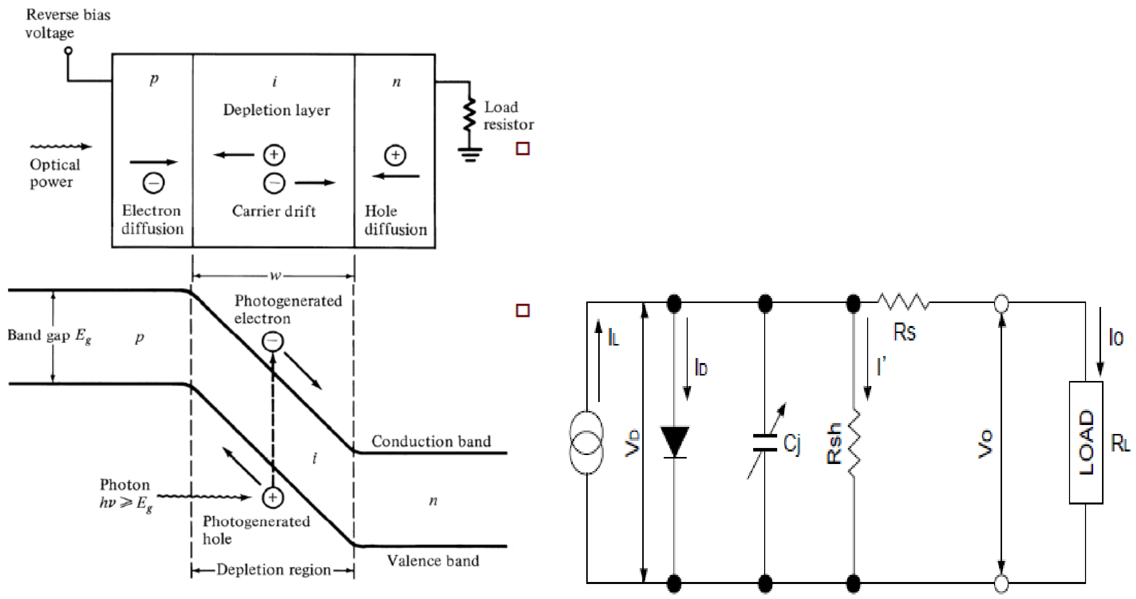


Fig 3.1 PIN Photodiode and Circuit [66][67]

3.1.1.2 Operation

When light strikes the surface of the diode, the electrons become stimulated and get pulled towards the conduction band, leaving holes in their place in the valence area. This occurs only if the light energy is higher than the band gap energy. The pairs of electrons and holes occur throughout the P, I and N layers. In the depletion (intrinsic) layer, the electric field accelerates the electrons towards the N-layer and holes towards the P-layer. At this time, holes are diffused through the N layer up to the depletion and collected in the P-layer valence band. This is how the electron-hole pairs are collected in the P and N layers. A positive charge is resulted in the P-layer and negative in the N-layer. An external circuit is used to allow electrons to flow away from the N-layer and the holes away from the P-layer towards the respective opposite electrodes. The electrons and holes are called carriers as they generate a current flow in the semiconductor device [66]. P-N and PIN diodes work in the same principle. Intrinsic used in PIN is thicker and generate more electron-hole pairs which results in better efficiency. Further advantages are explained in [64] [67].

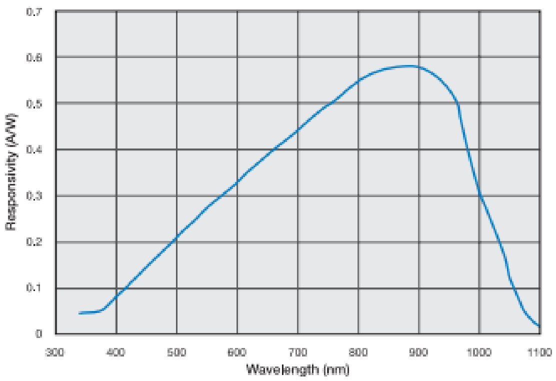
Two modes of operation exist;

1. Photovoltaic mode. This mode is known as zero-bias where the photocurrent is restricted and a voltage is build up. There is no external power. [64]
2. Photo conductive. This mode allows the use of reverse-biasing. Using an external reverse voltage, the frequency response and linearity is improved. [66]

3.1.2 Design Considerations

The choice of PIN photodiodes is based on their capabilities and, here some of the main specifications considered are described.

Table 3.1 Photodiode Design Considerations [66]

Responsivity	Responsivity depends on wavelength of incident light and is a ratio between the incident optical power and the resultant current output. This is quoted in Ampere / Watts (A W^{-1}).
Spectral Response	This represents the relation between responsivity and wavelength. This provides vital information when selecting a photodiode for an application, especially to check the compatibility of the light emitter used. A graph below is an example of a Silicon (SI) PIN photodiode, but however every detector has its own spectral response.  **Fig 3.2** Spectral Response of SI Pin Photodiode
Signal detection Threshold	Two factors affect the minimum signals the detector can pick up and has to be considered are: -A dark current is a small current that flows in absence of incident light and

	when a reverse voltage is applied to a photodiode. (available in data sheets) -Noise Equivalent power is the amount of light equivalent to the noise level of a detector. (available in data sheets)

3.1.3 Photodiode Implementation

The main consideration for a detector is the type of photodiodes. As mentioned above, silicon is the right choice due to its capability of detecting the whole visible light spectrum. The light diffracted from the gratings would result in different wavelengths and directions. Having a single photodiode will not be enough to detect the whole range of the light. Thus, a SI photo diode array will be considered for this application. Next considerations are the size of the photodiode, which is the number of diodes, and the positioning. All of these criteria are explained below briefly and offers a good understanding whilst designing the barcode system.

3.1.3.1 Photodiode Array

A photodiode array is simply an arrangement of photodiodes in arrays. This is very practical to detect various lights diffracted from a grating where the wavelengths of the incident light are received in various angles from the grating. A photodiode array can consists from 16 to 200 photodiodes depending on applications and one is readily available from the market. [64]

3.1.3.2 Photodiode Size

The size of the photodiode plays a fundamental role into the detection phase. The more diodes, the more accurate and more readings can be obtained while a smaller detector might result in some wavelengths not being detected. However, having a too big detector might deter the performance by detecting light from other sources. To have a good estimate, the positioning of the detector need to be known as well as the size between the minimum and maximum wavelengths of the output light from the gratings. Achieving readings (outputs) of at least two diodes per wavelengths in the spectrum would be the target.

3.1.3.3 Photodiode Positioning

The application requires two detectors of the same type. Light diffracted from 1st layer will be picked up by one detector on one side while the light from the 2nd layer will be picked up by detector on the other side. The main criteria require the detectors to be placed in a position where all the light diffracted from the whole barcode are detected.

This requires the orientation of the detectors and the distance between the barcode to be adjusted. Below are some basic calculations and values which will be used to help positioning the detectors in the perfect place.

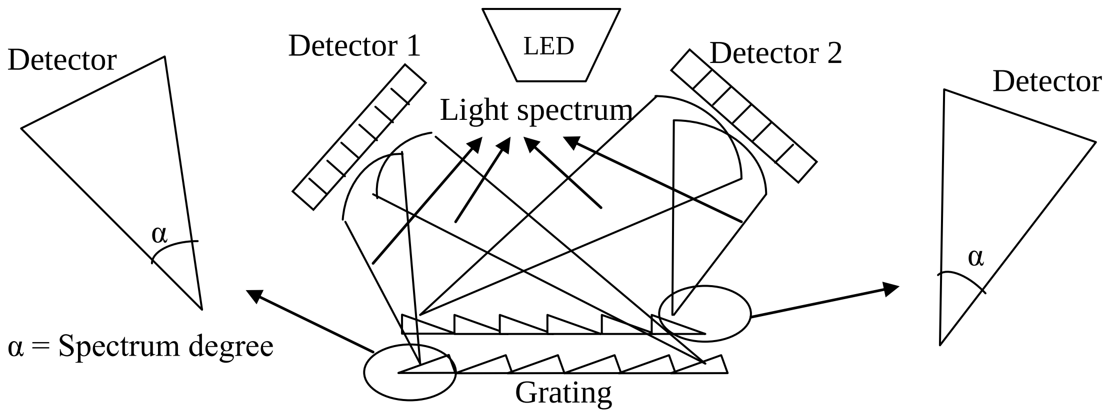
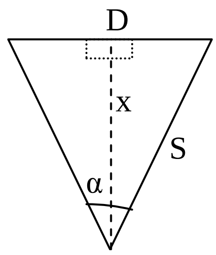


Fig 3.3 Detector Positioning

The two triangles give an idea of the spectrum diffracted from the grating towards the detector. As mentioned above, only the first diffraction order is being considered. This demonstrates that the further the detector is placed, the bigger it should be to detect the minimum and maximum wavelengths. Considering the detector orientation is placed perpendicular and in the middle of one grating module, a close idea of the size of detector can be obtained compared to the distance it is placed from the grating.

$$D = 2\left(\sqrt{S^2 - X^2}\right)$$

$$S = \frac{X}{\cos\frac{\alpha}{2}}$$



D = Detector Length

α = Spectrum Angle

x = distance between detector and grating

Table 3.2 Detector Positioning Values

α (degree)	X(cm)	D(cm)
5	10	0.9
5	20	1.7
5	30	2.6
5	40	3.5
5	50	4.4
5	60	5.2

α (degree)	X(cm)	D(cm)
25	10	4.4
25	20	8.9
25	30	13.3
25	40	17.7
25	50	22.2
25	60	26.6

α (degree)	X(cm)	D(cm)
40	10	7.3
40	20	14.6
40	30	21.8
40	40	29.1
40	50	36.4
40	60	43.7

α (degree)	X(cm)	D(cm)
55	10	10.4
55	20	20.8

α (degree)	X(cm)	D(cm)
70	10	14.0
70	20	28.0

α (degree)	X(cm)	D(cm)
85	10	18.3
85	20	36.7

55	30	31.2	70	30	42.0	85	30	55.0
55	40	41.6	70	40	56.0	85	40	73.3
55	50	52.1	70	50	70.0	85	50	91.6
55	60	62.5	70	60	84.0	85	60	110.0

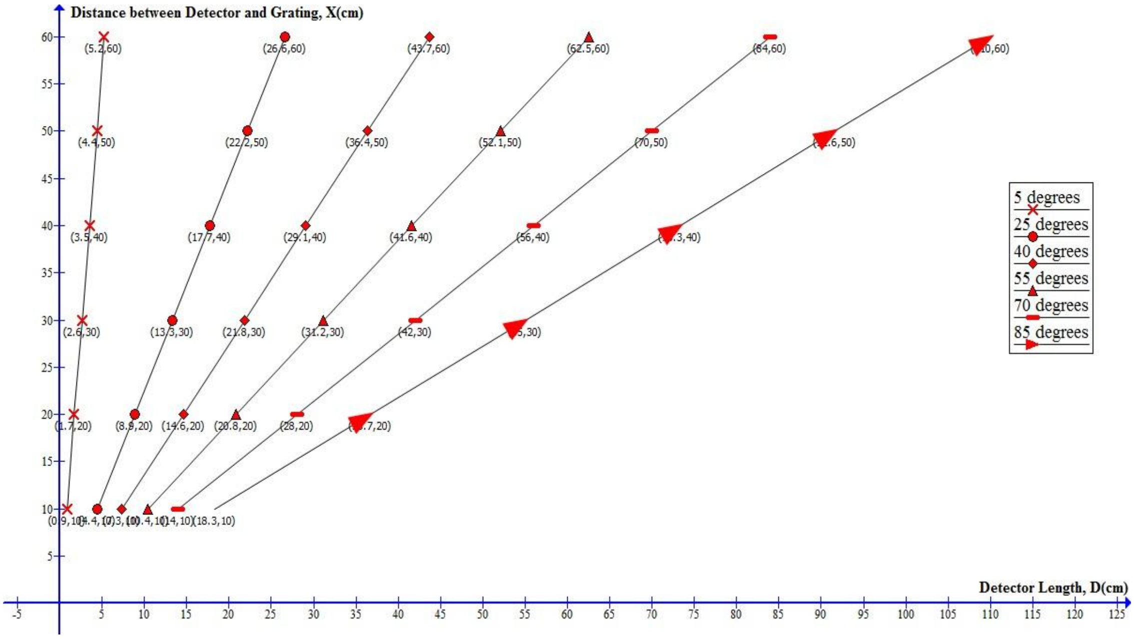


Fig 3.4 Detector Positioning Guide Graph

3.2 Light Source

Light is a crucial factor of any optical system. In my design, light is needed to illuminate the barcodes which will aid the detector to read them. Two main light source mostly used in optics are LASER and LED. In the new barcode system, the data will be stored in gratings. To read the data, light will be incident on the grating and the resulting diffraction of different wavelengths will be captured by a photodiode array.

The use of white light allows the full range of visible wavelength to be diffracted from a grating. This phenomenon encourages data storage by enabling different light wavelengths from the full spectrum to be represented by a unique set of data or binary code. LED light, for now, is considered to be more favourable in this new concept for its ability to generate white light.

Laser is used in most advanced optics components in various industries ranging from health to retailing and is always considered as the first choice in most optoelectronic designs. However, lasers are monochromatic and can only emit one wavelength per laser. [68]

3.2.2 LED

LED is a semi-conductor device that converts electricity to light using diodes. It uses the technique as photodiode but vice-versa as explained below. Two different designs of LED exist; one for low power requiring lower heat dissipation technique and one for high power requiring high power dissipation.

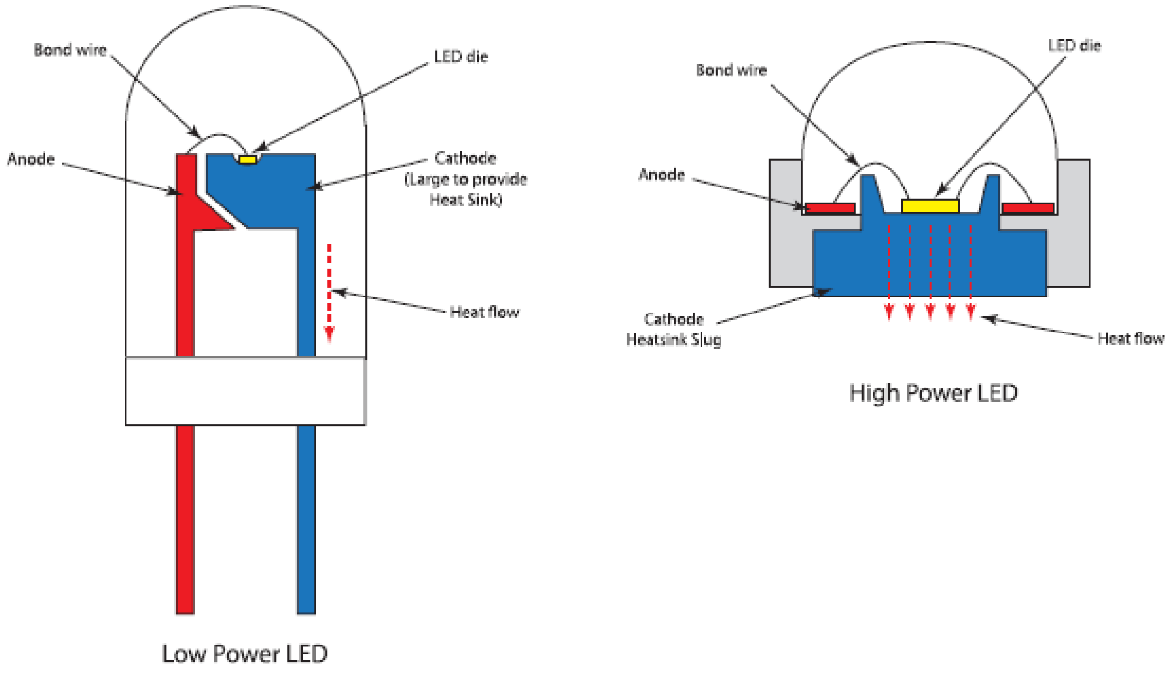


Fig 3.5 LED Designs [69]

3.2.2.1 LED Operation

As in photodiode, the LED component consists of the P-type material, N-type material, conduction band, valence band and the power supply.

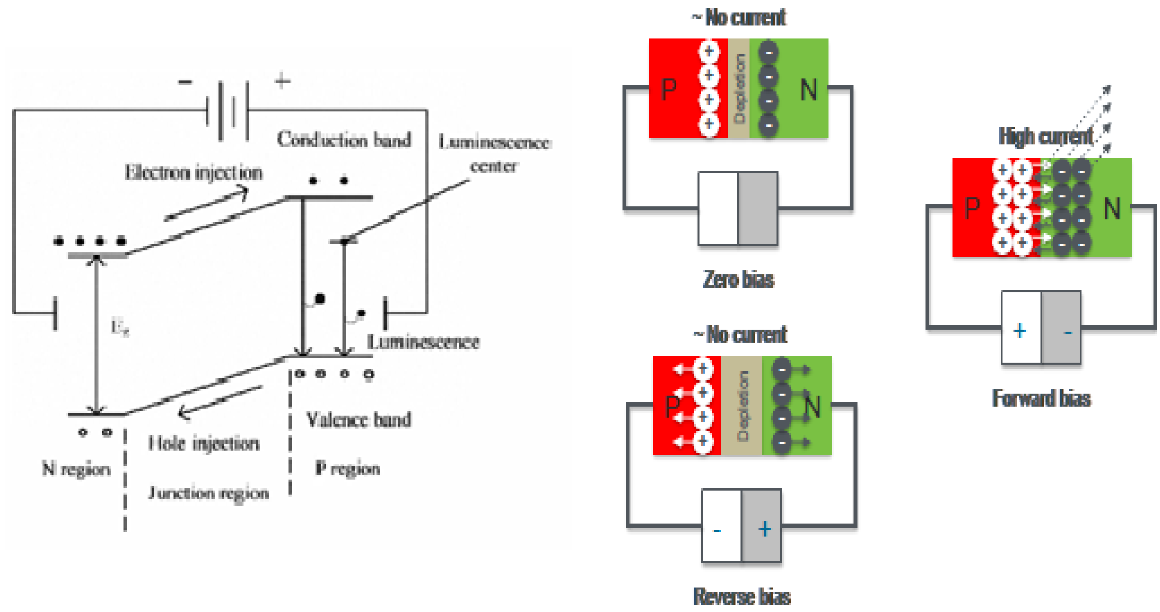


Fig 3.6 LED Principles [70]

The P region contains excess of holes while the N region contains excess of electrons. Conduction band contains higher energy while valence band contains low energy electrons. When no current is supplied, the electrons inject towards the holes in a region in the middle called depletion. In this area, the electrons are cancelled out and hence form as an insulator to the diode (no current flow). This is called as zero bias. In reverse bias where again there is no current, but the power supply is connected (+ve to N, -ve to P), the electrons moves away from the holes and hence creating the insulation depletion zone [70].

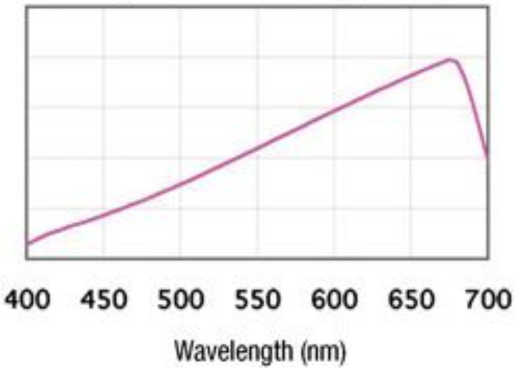
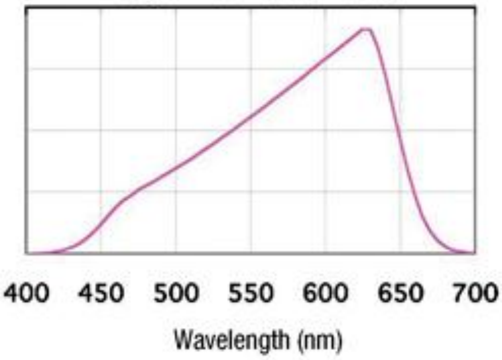
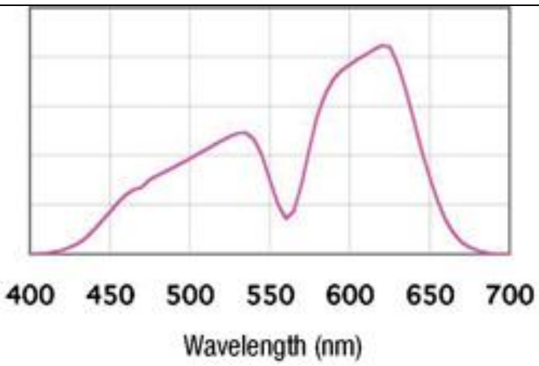
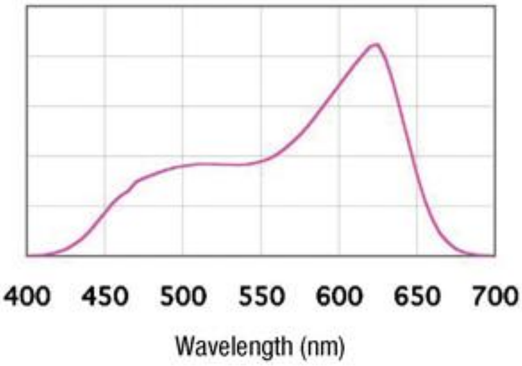
Light is produced in the forward bias mode. This is when the power supply connections are reversed compared to reverse bias. Then, the holes in the P region are powered by more energy. When electrons with higher energy are injected towards the P region, they are dropped into the holes with lower energy. The excess energy is emitted as a photon, which is light. The energy difference or height of the electron falling into the hole determines the frequency of the light photon [69]. LED in some ways has the following advantages compared to other sources of light, for instance incandescent, halogen, lasers and fluorescent;

- Produces more lumens per watt and requires lower current voltage resulting in low power consumption.
- Low power means lower heat.
- Contain no mercury which makes it cheap and has longer life.
- Small, light and very practical to fit any application.

3.2.2.2 White LED

As stated above, the main reason for choosing LED is due to its capability of emitting white light which is crucial in my design application. White light operates over a broad range of wavelength which is required for the barcode application, for instance from 300nm to 700nm. Different techniques to create white led exists and range from single chip to four chip LED from different sources. [70] and [77] illustrate some of them. Phosphor is a common compound used to generate different types of white LED as shown in the following table.

Table 3.3 Examples of Phosphor-White LEDs [77]

Phosphor model 400-700 (PHOS-1)	
Phosphor 450-650 (PHOS-2)	
Phosphor 445-645 with narrow valley (PHOS-3)	
Phosphor 445-645 with broad valley (PHOS-4)	

3.2.3 Application Considerations

The choice of LED depends on various applications and some factors that are considered are as follows;

Table 3.4 LED Choice Consideration [17]

Thermal Management	This term relates to the management of heat in a LED component. Depending on the power and time-usage of LED, the heat generated has to be dissipated effectively. Excess heat affects LED performances and these include colour shifts, reduced light output, lumen or light loss and shortened life.
Junction Temperature	This is the temperature of the actual semi-conductor. Three main factors which affect this are: the drive current, thermal path and ambient temperature. The higher the current, the higher will be the generated heat. Thermal path and ambient temperature determine the amount of heat that can be removed from the chip to the surroundings.
Correlated Colour Temperature	This is a measure in Kelvin, used to describe the appearance of white light source. It indicates if a light source appear more yellow/gold/orange or more blue in terms of shades of white. Warm white and cool white are defined using this measure.
Luminous Efficacy	This is an important indicator of energy efficiency. The latter measures the amount of light produced for each watt of electricity consumed by the LED in lumens per watt (lm/W).

3.2.4 Light Source Design Theory

This section describes two ways of how to use the LED light source to illuminate the gratings. The first method considered is to use the LED as a flash light on the whole barcode and capturing the reflected lights using the photodiode. The second method to be considered is to illuminate each module at a time using a single beam of the LED light. Various characteristics are considered and explained that impacts the entire system;

1. The minimum distance between the LED source light and the barcode symbol.
2. The position of the LED light to ensure the entire barcode is illuminated.

3.2.4.1 Flash Light LED

Flash LED illuminates the entire barcode at once and at specific intervals of time. The setup of the flash light is simple and is easily available from market. A switch would be used to operate the flash. The principle is very easy but do not meet the requirements of this new barcode concept. The flash light illuminates the entire barcode at the same time and the resulting diffracted spectrum captured by the detectors will be from the entire barcode. This phenomenon will make it difficult for the detectors to distinguish diffracted spectrums from each module of the barcode. Data storage requires each module to be identified uniquely by the detectors.

3.2.4.2 Beam LED

To generate a beam would need the use of lenses and mirrors. A brief idea of the design is suggested below while the next chapter will simulate the one which will be used. This method will be more ideal as each module will be illuminated and decodes in sequence which allow detector to easily read the barcode.

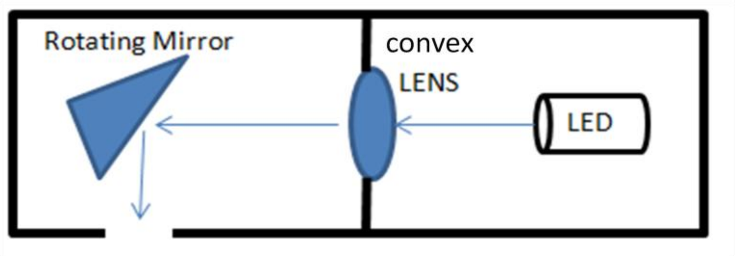


Fig 3.7 Beam LED Design

The idea is to create a beam of minimal width which will increase the number of modules in the barcode as well as storage. On the other hand, the beam has to be strong to be able to reach the whole surface of the barcode. A convex lens will be used to focus the LED light beam into a smaller beam which would match the module size of the barcode onto a rotating (mems) mirror. The mirror in turn will reflect the beam from the lens onto the barcode. The rotating feature will aid the beam of light to illuminate the entire symbol from the starting module till the end. Whilst each module is being illuminated, the modules on the second layer will in turn be illuminated by the incident light which refracts through the first layer.

3.2.4.3 LED Position

Ideally the LED would be positioned on top of the barcode to help illuminate the gratings of the barcode. Also this positioning will direct the incident light from the LED towards the gratings to allow the diffraction to occur. The next important factor that needs to be considered will be the distance the source light and the barcode. The criteria to help define this distance are the power of the LED diode (in lumens) and desired incident angles for the barcode.

Power

LED in various numbers of lumens are readily available from the market. The higher lumens the LED can produce, the more powerful light it can generate resulting in longer distances. However, high powered LEDs have a bad effect on power consumption and price. Depending on the minimum safe distance specified in the next section, an ideal LED diode will be chosen to match the requirements of the barcode system. The right component will be detailed in the simulation chapter.

Distance

The idea is to place the gratings in such a position so that the light is diffracted in a specific direction where the detector will be placed. This distance will affect the incident light on the gratings. As shown below, the higher the LED is, the difference of incident angles between the modules of the barcode will be higher.

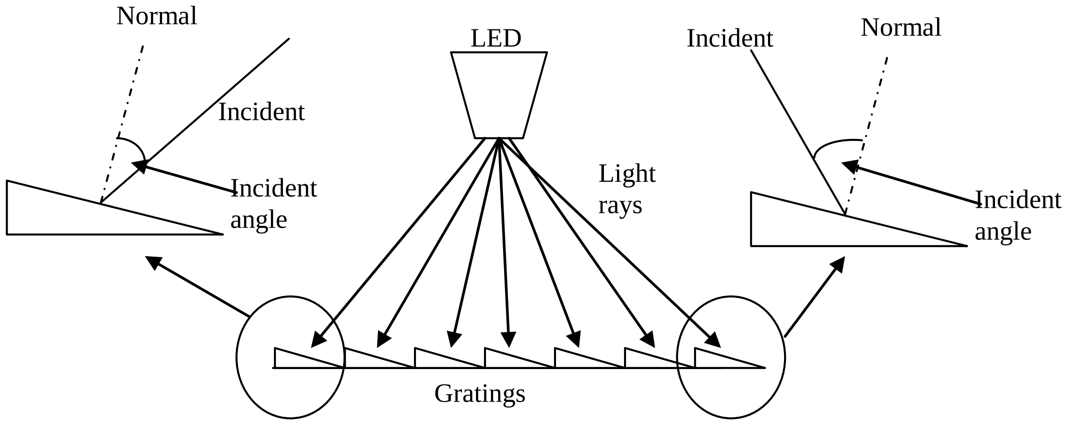
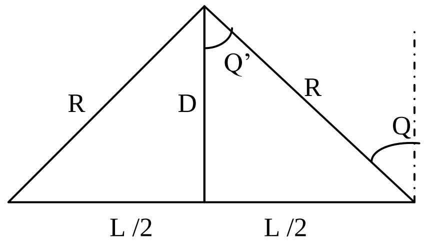


Fig 3.8 LED Positioning

Suppose distance between LED and grating is D (cm), Grating length is L , Incident angle as Q (degrees), Ray light as R (cm) and that the LED is placed above the middle of the grating, then the values obtained are as follow;



$$Q' = Q,\ Cos\ Q' = D/R$$

$$R = \sqrt{D^2 + \left(L/_2\right)^2}$$

Using the above method helps to calculate the impact on incident angles for modules of different barcode lengths and for different distances between LED and barcode. The idea here is to have a minimum deviation in incident angle between the modules closest to the barcode and the ones furthest. This will allow light from all modules to diffract nearly in the same directions and helps to ease the process of positioning the detector. Below are some values.

Table 3.5 LED Distance Values

D (cm)	L/2 (cm)	i (degree)	D (cm)	L/2 (cm)	i (degree)	D (cm)	L/2 (cm)	i (degree)
10	0.5	2.9	20	0.5	1.4	30	0.5	1.0
10	1	5.7	20	1	2.9	30	1	1.9
10	1.5	8.5	20	1.5	4.3	30	1.5	2.9
10	2	11.3	20	2	5.7	30	2	3.8
10	2.5	14.0	20	2.5	7.1	30	2.5	4.8
10	3	16.7	20	3	8.5	30	3	5.7
10	3.5	19.3	20	3.5	9.9	30	3.5	6.7
10	4	21.8	20	4	11.3	30	4	7.6
D (cm)	L/2 (cm)	i (degree)	D (cm)	L/2 (cm)	i (degree)	D (cm)	L/2 (cm)	i (degree)
40	0.5	0.7	50	0.5	0.6	60	0.5	0.5
40	1	1.4	50	1	1.1	60	1	1.0
40	1.5	2.1	50	1.5	1.7	60	1.5	1.4
40	2	2.9	50	2	2.3	60	2	1.9
40	2.5	3.6	50	2.5	2.9	60	2.5	2.4
40	3	4.3	50	3	3.4	60	3	2.9
40	3.5	5.0	50	3.5	4.0	60	3.5	3.3
40	4	5.7	50	4	4.6	60	4	3.8

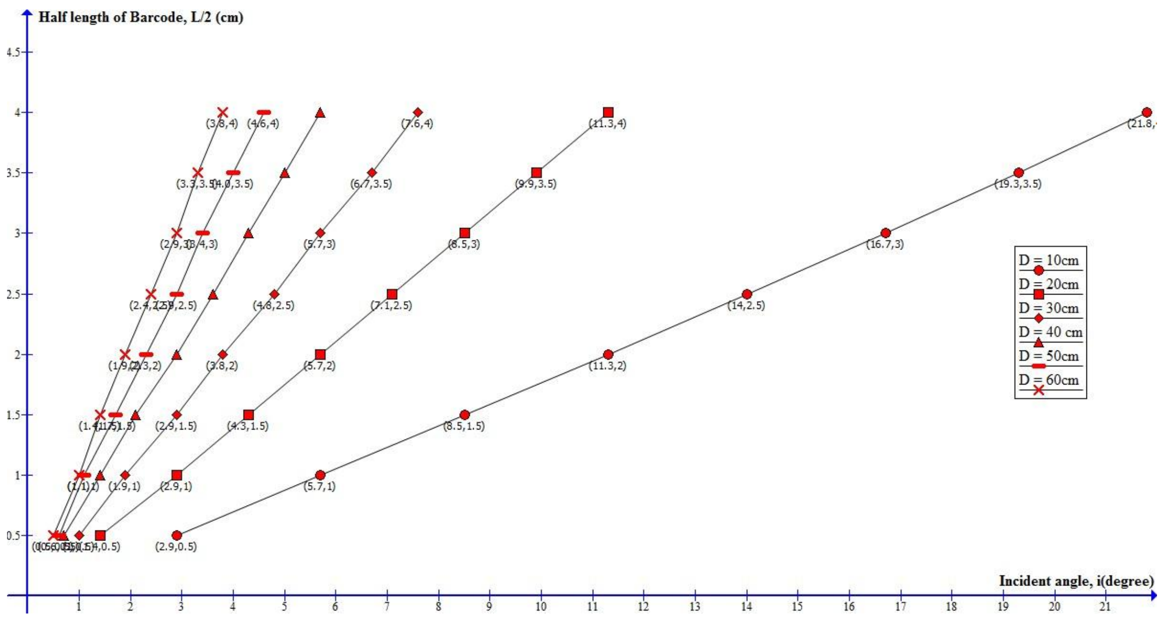


Fig 3.9 LED Positioning Guide Graph

3.3 Diffraction Gratings

A diffraction grating is an optical element which splits light composed of different or single wavelengths and diffracts them at different angles. A grating is made up using slits/grooves at fixed distance which upon light diffraction, change the amplitude or phase of the light to have different wavelengths into different directions due to periodic variation in the refractive index near the surface region of the grating [72]. Two common types of diffraction exists; Master and Replica. Master known as the original is one which is created from scratch by the method of ruling or holographic (explained below). Replica is a precision process which allows a large number of gratings to be produced using a single master grating (ruled or holographic). The three dimensional topography of the master grating is transferred onto another substrate [73]. Replica gratings are much cheaper to produce and are so good compared to master gratings that they are used to reproduce other replicas.

Ruling is a technique where a diamond tool mounted on a ruling engine is used to physically burn grooves against a thin reflective coating of evaporated metal on a plane or concave surface. Holographic involves photolithographic process where the photographic recording of stationary interference fringe fields on a substrate [72]. The latter is coated with a photosensitive material and is positioned between the intersecting monochromatic and coherent beams of light from a laser. The laser beams intersection generates a sinusoidal intensity pattern of parallel and equally spaced interference fringes in the photosensitive material. Intensity pattern finally becomes a surface pattern after being immersed in solvent [73].

Two main types of dispersing systems are Reflective and Transmission. Reflective gratings contains a reflective material that reflects the diffracted light on the same side as the incident light while transmission gratings allows the light to pass through the grating and diffracts it as it leaves the grating on the opposite side. Both will be considered in this application. A new design might be considered to adapt both characteristics in a single grating to adapt to the dual layer barcode where the first layer will partly reflect and transmit the light and the second layer will only reflect the light. Other types of gratings exist such as prisms, echelles, etc [72] but will not be used here.

3.3.1 Physics of Diffraction Gratings

The physics of grating defines all the aspects and characteristics that design and create the grating itself. This section however will only explain the main ones that are used to choose a diffraction grating.

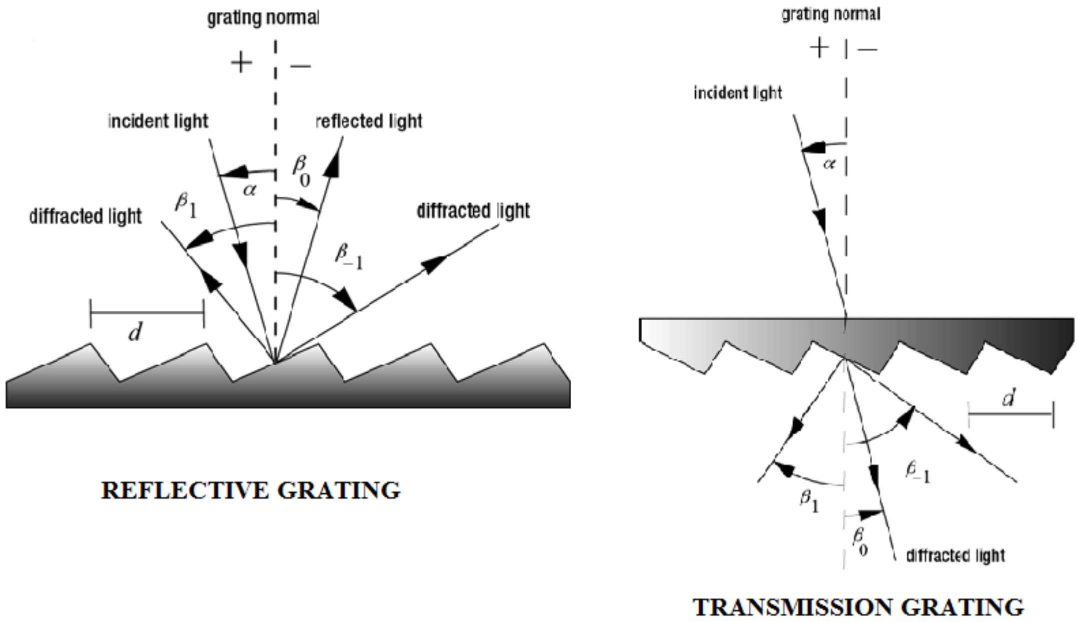


Fig 3.10 Diffraction Gratings [72]

3.3.1.1 Equation

The figure above illustrated the different factors that are considered to calculate light diffraction. The grating normal is an imaginary line drawn perpendicular to the grating to measure the angle of incidence and diffraction. The right hand side is always negative and left hand side positive. The Diffraction Equation is;

$$\boldsymbol{m\lambda = d(\sin\alpha \ \pm \ \sin\beta)}$$

m = diffraction order
λ = Diffracted wavelength
d= $\frac{1}{G}$, G = Number of grooves per mm
α = Incident angle
β = Diffracted angle

Littrow configuration is a special situation where the light is diffracted in the same directions as the incident light. This means that angle α = angle β, then the formula is;

$$\boldsymbol{m\lambda = 2d(\sin\alpha)}$$

3.3.1.2 Diffraction Orders

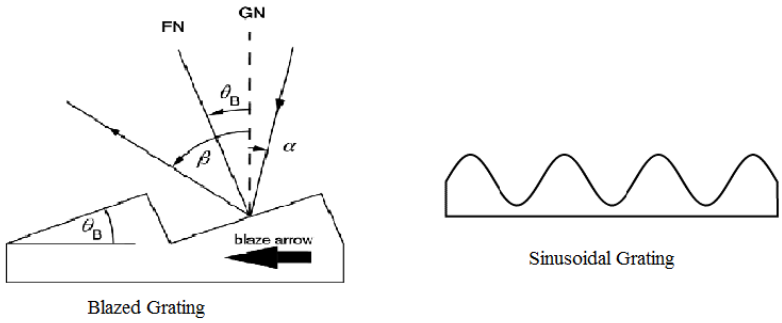
More than one diffraction angle β can be satisfied by the grating equation if angle α, d and λ are constant. For instance, at an angle β, both λ=300 nm and 600 nm can be satisfied for m=1 and 2. Both positive and negative orders exist depending on retarded or advanced rays. For m=0, this is a pure reflection (α =β) or transmit (β=0) of the incident light without any change. The maximum number of diffraction orders of a grating is based on the spacing grooves, d and the diffracted wavelength. Spectra of all orders m exists for; [72]

$$\boldsymbol{-2d} < m\lambda < 2\boldsymbol{d}, \quad \boldsymbol{m\ an\ integer}$$

Two types of orders exist. First, the Free Spectral order is where the diffracted light of each order are not overlapped by each other. Secondly, the Overlapping Order is where some light diffracted from the second order will overlap light diffracted by the previous and following order.

3.3.1.3 Grooves

Grooves are small slits in the gratings that combine diffracted light to form wave fronts. The ranges of wavelength and diffraction orders are determined by the number of grooves per mm in the grating. Two types of grooves profiles are Blaze and Sinusoidal. The idea of different profiles is to improve efficiency and having different profiles is to adapt different types of gratings (ruled, holographic or replicas).



*Q_B represents the angle between the grating normal and facet normal.

Fig 3.11 Groove Profile [72]

Blazed are triangular formed gratings to control over magnitude and variation of diffracted energy with wavelength [72]. If the Facet Normal (FN) bisects the angle between the incident and diffracted light, then the grating is said to be in glaze condition. The blaze angle Q_B can be change to improve efficiencies of different applications. The blaze arrow points from the FN to the bisector angle of incident and diffraction.

Sinusoidal grooves are obtained using the interferometric (holographic) recording techniques. The efficiency of this profile depends on the ratio of the groove height and groove spacing. Lower values of the ratio are for lower modulation gratings while higher values are for higher modulation gratings [72].

3.3.2 Design Considerations

Diffraction gratings can be tailored to adapt different types of applications. Various features and factors are considered to design the desired gratings. The table on the next page depicts some of the factors that are to be considered while designing the diffraction gratings for the barcode design.

Table 3.6 Diffraction Granting Design Factors [72][73]

Wavelength Range	In any application, this is the minimum factor to consider. It describes the output light spectrum diffracted by the grating representing the minimum and maximum wavelengths that the grating can produce. The range is easily influenced by other factors such as the material coating (e.g. Silicon for visible light) and the mounting (i.e. the incident light angle)
Peak Wavelength	Peak wavelength describes the highest wavelength efficiency a diffraction grating can output. Out of the whole wavelengths' range, the highest wavelength's energy captured by a photo detector would be the peak wavelength of the grating. This factor is easily influenced by the number of grooves per mm in the diffraction grating.
Dispersing System	Dispersion is an important factor to consider. Depending on where incident light need to be diffracted and directed, some applications require transmission grating, some others require reflective while some require both transmission and reflective gratings.
Efficiency	Ruled grating offer higher efficiency than holographic ones. Efficiency is the energy flow of the light diffracted from the grating towards the detector. Coatings on gratings influence efficiency and Groove profiles are used to provide better efficiency for specified wavelength. (e.g. Blazed grating uses Littrow principle to generate high efficiency)
Resolving Power	This factor refers to the ability of the grating to separate two wavelengths. The higher the resolving power the more efficient for this application as higher readings can be achieved and this also helps higher data storage.
Stray Light	Stray light are unwanted light that are received by the detector other than the gratin. This can be due to defects of gratings or other components in the design that contributes to light. Signal-To-Noise Ratio (SNR) is used to calculate the ration of diffracted energy to unwanted light energy in applications.
Mounting	Mounting is the platform on which the grating is placed. This factor will influence the grating normal which will be used to calculate the diffracted light in various angles. Having a tilted mounting will for instance help direct the diffracted wavelengths to a desired location.
Groove Spacing	Groove spacing influences the wavelength range. Using gratings coated with the same material with different groove spacing will achieve different wavelength ranges.
Grating Size	Size of grating is crucial for any design and it is dictated by the light throughput desired [72]. In this case, the design of the minimal size of the grating should be able to match the light from the LED source.

3.3.3 Grating Design Theory

The new barcode is the key objective of the project and will be designed using diffraction grating on two layers. Both layers are expected to work in the same way while the only difference would be that each of them will diffract light in opposite directions. The dual-layer technique will be explained in the next section. The main objective of the diffraction gratings is to be able to diffract light in a specific area where the detectors are able to read them. Grating specifications to be used will be given in next chapter after simulations while data storage will be in also later chapters.

3.3.3.1 Mounting and Size

The mounting of the grating will aid to diffract the light from each grating into the desired direction. The mounting will look like a saw tooth as shown below. The size of each saw tooth is crucial as this will represent one cell of the barcode. The size will be a factor of both the minimum size of grating that can be created and the light source spot diameter. The smaller the resulting size of one saw tooth will result into a higher capacity barcode while a larger size will result into a lesser capacity barcode. The size of the whole barcode is also important to ensure that the latter is practical for use and also to ensure that all diffracted light is captured by the detector.

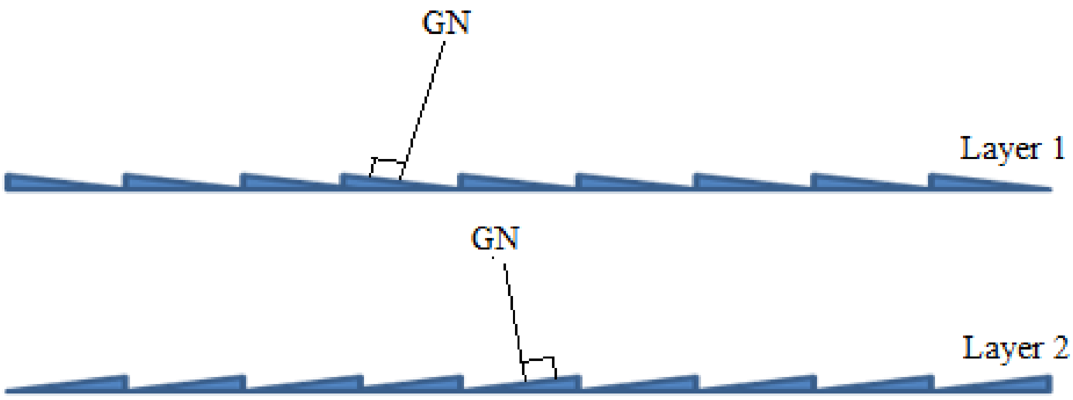


Fig 3.12 Grating Mounting

3.3.3.2 Light Diffraction

Light diffracted from layer 1 and 2 must reach the detectors on each side. Detectors vary in sizes, but having all the diffracted light in a smaller area will benefit the design from having a smaller detector.

$$m\lambda = d(\sin\alpha \pm \sin\beta)$$

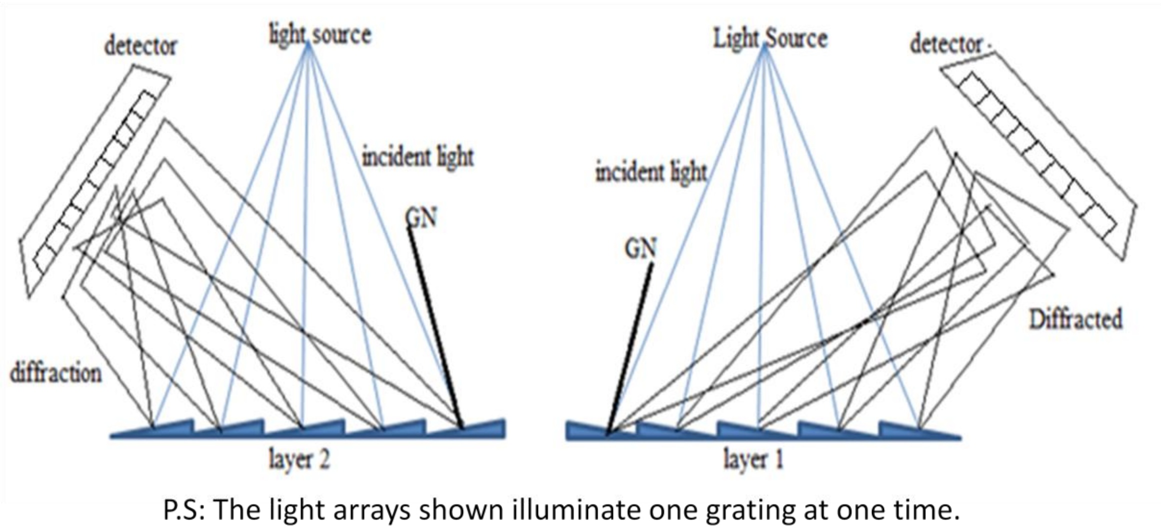


Fig 3.13 Light Diffraction

Based on incident angle, the grating grooves and the order number, the angle for the range of required diffracted light can be calculated using the diffracted formula. Below represents the relation between different values of incident angles due to the movement of the light source, changing the grating mounting inclination, or having a bigger size barcode. The minimum and maximum desired wavelength will be used for calculation as the middle range is expected to lie in-between. The same value of grooves per mm will be considered here, while in the data storage chapter; different values will be used to show the different outcomes of diffracted light. Order number 1 and -1 will only be considered.

Table 3.7 Light Diffraction

m λ = d (sin i +/- sin r) **n=500 lines per mm** **d = 2 x 10 -6**

λ (nm)		400	450	500	550	600	650	700	750	Range*
i = 0	m=1	11.5	13	14.5	16	17.5	19	20.5	22	10.5
	m=-1	-11.5	-13	-14.5	-16	-17.5	-19	-20.5	-22	-10.5
i = -20°	m=1	32	34.5	36.3	38.1	40	41.8	43.8	45.8	13.8
	m=-1	-32	-34.5	-36.3	-38.1	-40	-41.8	-43.8	-45.8	-13.8
i = -10°	m=1	22	23.5	25.1	26.7	28.3	29.9	31.6	33.3	11.3
	m=-1	-22	-23.5	-25.1	-26.7	-28.3	-29.9	-31.6	-33.3	-11.3
i = 10°	m=1	1.5	2.9	4.4	5.8	7.2	8.7	10.1	11.6	10.1
	m=-1	-1.5	-2.9	-4.4	-5.8	-7.2	-8.7	-10.1	-11.6	-10.1
i = 20°	m=1	-8.2	-6.7	-5.3	-3.8	-2.4	-1	0.5	1.9	10.1
	m=-1	8.2	6.7	5.3	3.8	2.4	1	-0.5	-1.9	-10.1

* Range is the angle between the minimum and maximum required light diffraction. The range will change as the number of lines per mm increases as this will be shown in later chapters.

Assume that the diffraction from the middle of the barcode (i=0) will hit the middle of the detector. Based on the light source positioning (section 3.2), assume that the maximum difference between the middle barcode and the end is 20 degrees on each side. Using the values and calculations from sections 3.2 and 3.1 can easily help to arrange all the components. The grating mounting can be inclined to have a desired incident angle that will diffract light in a specific angle towards the detector.

3.3.3.3 Challenges

The main challenge is the positioning of the detectors. Different types of gratings will diffract light in different angles and directions. Calibration is required each time a different type of grating is being used and if the light source is moved. Second challenge is the number of diffraction orders generated by the diffraction. Noise in the system is a challenge and this refers to unwanted light (natural light or light from other sources) Signal-to-Noise (SNR) is used to calculate noise level in db. Also, a bigger detector might pick up the light from the unwanted negative/positive orders if the diffraction angle is small.

3.4 Dual Layer

The second part of the design is to have the barcode on two layers one on top of the other. The idea of having two layers is to double the amount of data a single layer grating would hold. The technique is fairly simple and straight forward. Using a semi reflective first layer will easily diffract (towards detector) and transmit (towards second layer) the light at the same time. This technique is copied from the framework of a dual Layer DVD (explained below). Below shows a design of the two layers and the different parts are explained in the following sections.

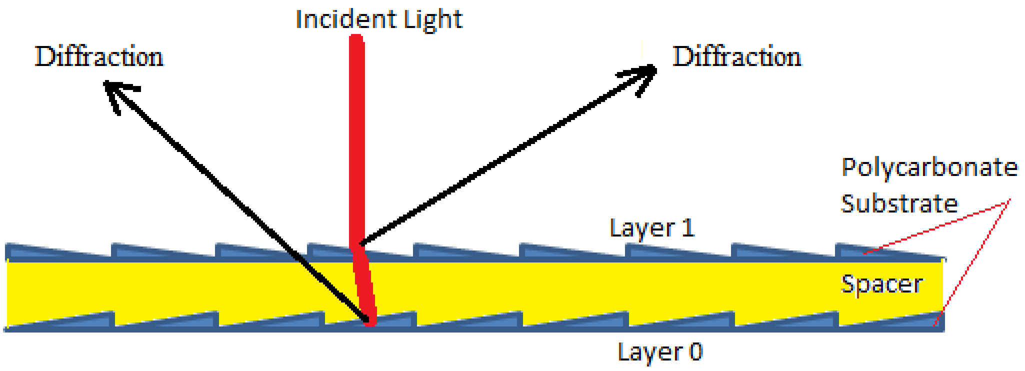


Fig 3.14 Dual Layer Design

3.4.1 Dual Layer Operation

The idea of using dual layer comes from the state-of-art DVD technology [74]. The structure of a DVD is shown below where the first layer is coated with semi transparent metal reflector to allow the laser to reach the second layer. Spacers are used to separate the layers and are transparent. Spacers are optical transparent materials designed to adapt to the laser requirements. Polycarbonate used to protect the layers is a strong material made of plastic and scratch resistant. Recording and reading of the layers requires the reader to focus the laser on each layer at each time [73]. Thin coatings or thin films are used to change the physical or optical properties of materials. Different coating materials contain different types of refractive index that will make the substrate act differently. The use of specific material coating for an optical system is dependent on its specification and requirement. Handbook in [76] offers a detailed guidance on different types of coating.

The dual layer barcode will inherit the components from a DVD. As shown above in the picture, the first layer will be coated with a thin semi transparent layer. The layers will be separated by a spacer (as used in a DVD), and the second layer will be reflective. When light is illuminated on the top layer, the light will be diffracted to the first detector and the second layer. Having the two layers close to each other will reduce the unwanted effects generated when the light from the LED passes through the first layer to reach the second one.

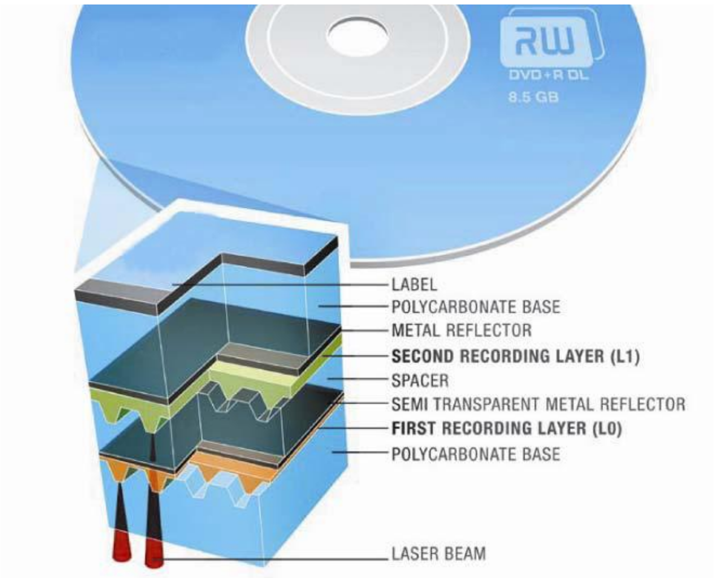


Fig 3.15 DVD Components [75]

3.4.2 Challenges

The main consideration would be the material itself that will be used as the spacer and also the polycarbonate. The refractive index of all the materials has to be considered to ensure light is directed in the desired path. The power of the incident light has to be considered. The thin semi reflective coating choice is very crucial to increase diffraction efficiency.

The next challenge of the dual layer is the light diffraction of the second layer. The diffracted light will have to go through the spacer and first layer before reaching the second detector. Some light will be lost due to scattering or being absorbed in the semi reflective coating. The effect of the first layer gratings on the diffracted light from the second layer has to be considered to avoid loss of the light.

3.5 Summary

This chapter explains and provide a guide to design the new wavelength-multiplexed and dual layer barcode design which comprises of 3 main components; the dual layer Barcode the Light Source, the Light Detection. Light Source is placed on top of the barcode to allow the incident light reach the gratings of the barcode and the Light Detectors are placed one on each side of the barcode to capture the diffracted light. An approach about the positioning of each component have been calculated and defined. Parts needed to design the individual components have been explained. The Light Source chosen for the application is white LED. SI photodiodes have been chosen to detect the diffractions from the gratings. Each of the two detectors contain arrays of SI photodiodes and are of different sizes which depend on the diffraction angles of each layer. Maximising the number of photodiodes allows better reading values of the light. The Size of the detectors has been defined and is normally related to the properties of gratings and the distance between the detector and the barcode. The barcode is made of gratings. The barcode is broken into modules and each module is represented using different gratings with different properties that diffract light in different directions and wavelengths. Two layers of the gratings are used with a polycarbonate spacer in between to form the dual layer barcode and this feature enhances the data storage. Light diffracted from the first grating is directed towards one detector on one side while light from the second grating is directed to the detector on the other side. Design considerations for each component have been given.

The following chapter will be the creation of the whole system with each component. The guides and design considerations given in this chapter will aid to design the components as well as to choose the parts that will simulate the system. Positioning of the light source and detectors will be defined. A finalised detailed specification of each component will be defined in the next chapter.

Chapter 4

Barcode Simulation

Following the design recommendations of the barcode system, this chapter illustrates the simulation of the entire system. The arrangement of each component is given based on assumptions derived to meet all the design requirements set in the previous chapter. Specifications and assumptions for each component (Light Source, Barcode, and Detector) are given. Each component has been designed from parts available from the current market. The arrangement for each component is calculated from the optical mathematical formulae defined in previous chapter. The last section provides the final design of the whole system with the specific arrangement of each component. Tables and pictures help to summarise results.

4.1 Light Source

White LED is readily available with a lot of different specifications, sizes and prices from the market. However, only buying a single LED light will not be able to illuminate the barcode as specified and required. This section explains how the LED output light can be customised to meet the system illumination requirements. The design of the light source along with the components is given below.

4.1.1 LED

The chosen LED is White Lightening Unencapsulated High Brightness from Luminus [78] and some of its features are;

- High surface brightness and high optical output.
- High thermal conductivity package and mercury free.
- Exclusive photonic lattice technology for high efficiency and uniform emission.

Fig 4.1 White LED CBT-90 [78]

Table 4.1: LED Specification [78]

Dimensions (mm x mm)	**Input Power**	**Typical Voltage**	**Nominal Current**	**Max Current**	**Colour**	**Typical flux (lumens)**
28 X 27	30 W	3.6 V	9.0 A	13.5 A	Cool White	1600-2250

Please refer to appendix A for more data and information.

A light output table is given below to help understand LED power compared to incandescent and compact fluorescent.

Table 4.2: Light Output Comparison [79]

Electrical power equivalents for differing lamps			
Minimum light output (lumens)	**Electrical power consumption (watts)**		
	Incandescent	**Compact fluorescent**	**LED**
450	40	9–11	6–8
800	60	13–15	9–12
1,100	75	18–20	13–16
1,600	100	24–28	18–22
2,400	150	30–52	30
3,100	200	49–75	32
4,000	300	75–100	40.5

4.1.2 Micro-Electro-Mechanical-Systems (Mems) Mirror

The mems mirror is the key component that will direct the light onto the barcode to help illuminate each module at a time and in 2-D. The chosen mirror is called a mems steering mirror with no coated glasses from Sercalo Microtechnology Ltd.

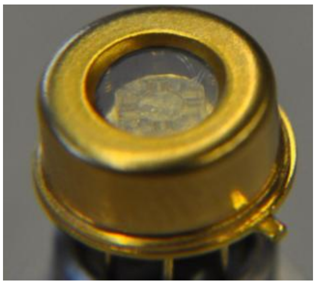


Fig 4.2 MEMs Mirror [80]

Some specifications are illustrated below whilst the data sheet is available in Appendix A.

Table 4.3: Mems Mirror Specification [80]

Mirror Size	Max Voltage	Coating	X axis Tilt	Y axis Tilt
2 x 2.5(mm^2)	70V	none	±4.5 degrees	±2.5 degrees

4.1.3 Convex Lens

The Convex lens will focus the light into a thin beam onto the mems mirror. The chosen one is Plastic Convex Lens from Comar shown below.

Fig 4.3 Plastic Lens [81]

The lens is available with a range of sizes and focus lengths. The chosen one is item code ‘33PP09’ and the specifications are;

Table 4.4: Lens Specification [81]

Focal Length	**Diameter**	**Aperture**	**Back Flare**	**Material**	**Form**
32.7mm	9mm	9mm	30.6mm	Acrylic	Plano convex

4.1.4 Light Source Prototype

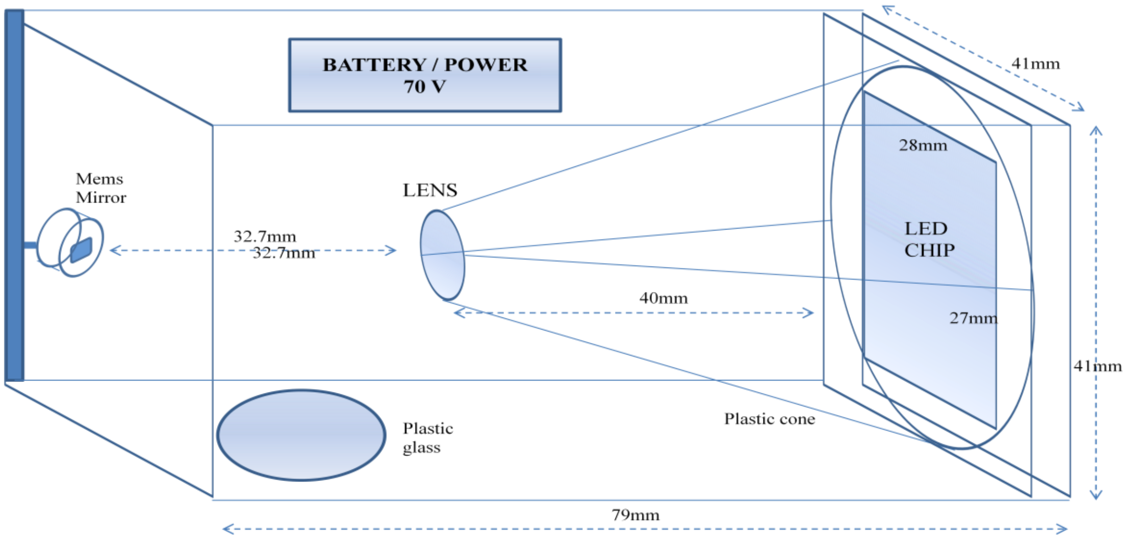


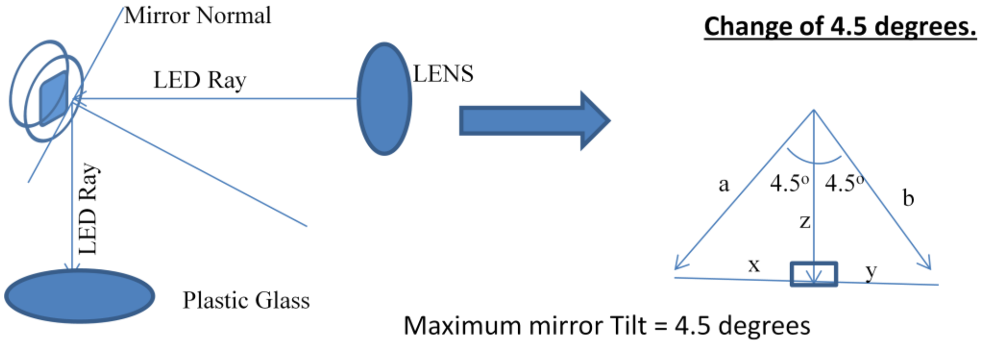
Fig 4.4 Light Source Prototype

4.1.4.1 Specifications

- The size is around 79x41x41 mm (Length x Height x Depth).
- Behind the LED and behind the mems mirror on each ends, is the space for wiring.
- The plastic cone is made of plastic and black in colour to reflect and refract the light towards the lens. The cone is sealed with one side is the lens and the other side is the led chip. The distance between the lens and the LED is around 40mm but can be shortened.
- The mems mirror is placed at the focal length of the lens and at the end of the other side. It lies in the middle of the left panel tilted facing down and perpendicular to the lens.
- The plastic glass allows the light to escape and illuminate the barcode. It is placed below the mems mirror and the size of the plastic glass is calculated as shown in 4.1.4.2. Coatings will stop natural light from entering the box. However such coating will differ upon real experience.

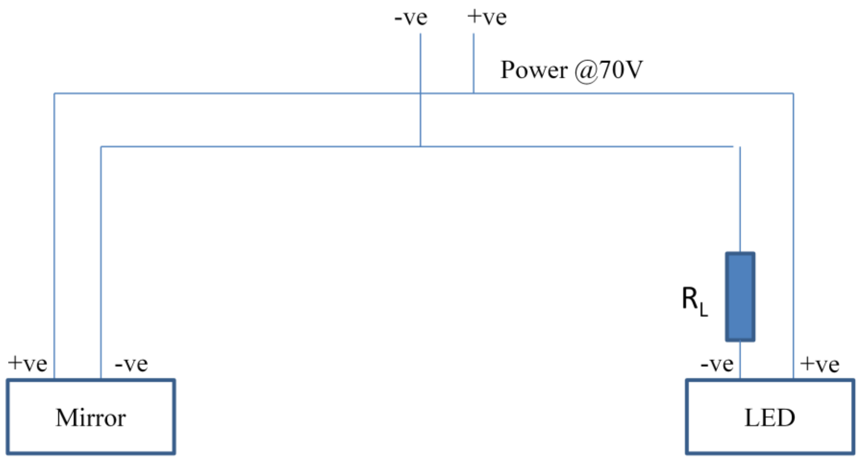
- Resistors are used to control the current flow to each component. The wiring diagram is given in section 4.1.4.3 along with the calculations for the resistors and main power supply.

4.1.4.2 Plastic glass size



Maximum mirror Tilt = 4.5 degrees
Cos 4.5 = z/a = z/b
Z= distance between mirror and plastic glass = half the size of the light source length = 20.5mm
X^2=square roof of ($z^2 – a^2$)
x=y= 1.6mm
Minimum Radius of the glass= x = y = 1.6mm.

4.1.4.3 Wiring



Max Current for mirror = 70V

Max Current for LED= 13.5 A
Power = 70V
R_L = 70/13.5 = 5.2 Ohms

Fig 4.5 Light Source Wiring

4.2 Barcode

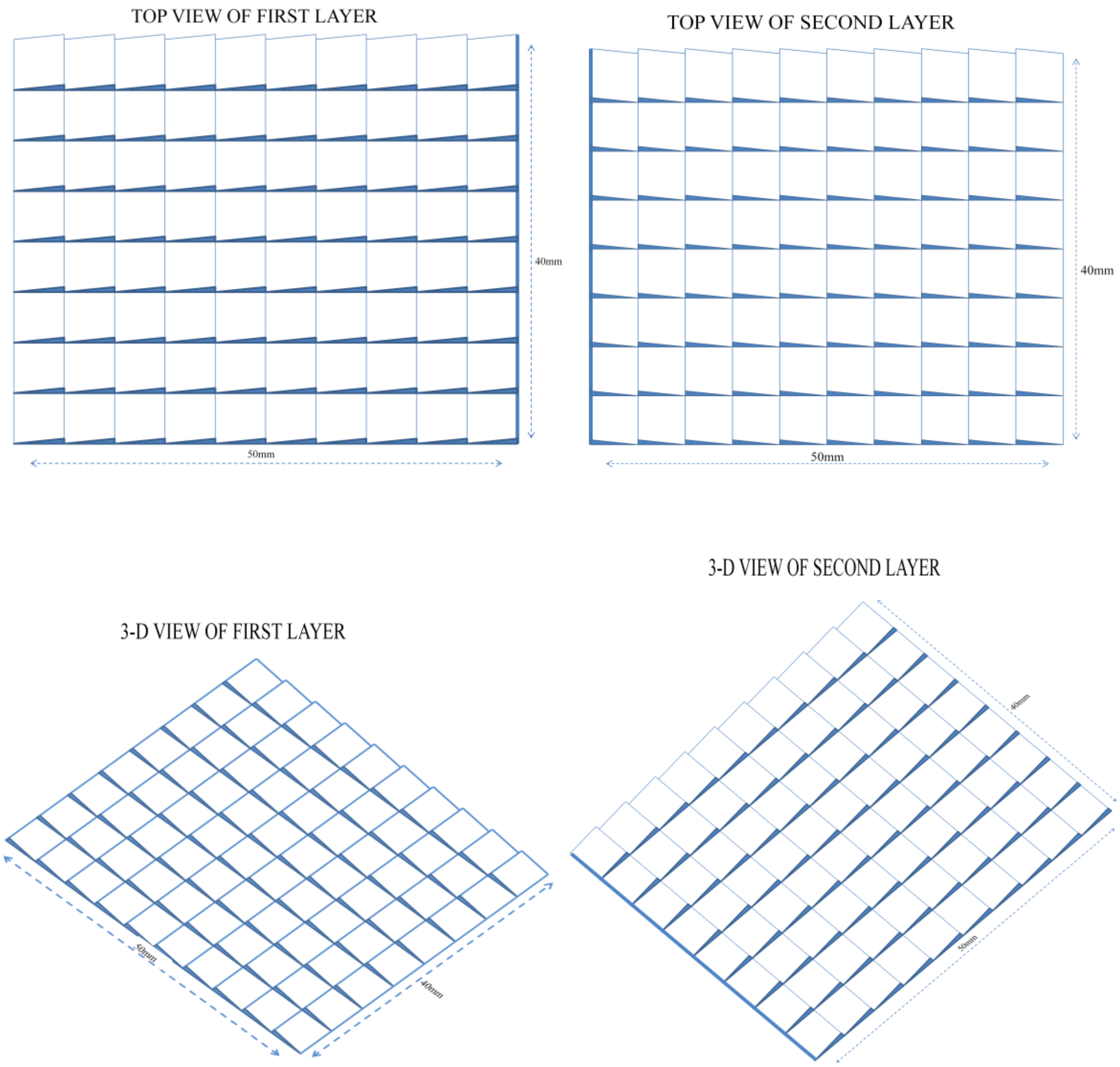


Fig 4.6 Barcode Prototype

As shown in previous chapter, the idea is to have 2 layers with each one diffracting the light on opposite side. The barcode mounts are as shown above. Each square represent one module of 5mm by 5mm. Each of these modules will contain gratings with different specifications which will allow data storage. The size of the barcode is assumed as 10 x 9 modules resulting in 180 modules. The maximum size will depend on how far the light source can be placed on top of the barcode and this is shown in the last section. The modules of each layer are slightly oriented towards their light detectors on each side to ensure the light is diffracted in the right direction to reach the right detectors. The orientation will depend on the barcode system and is shown below.

4.2.1 Barcode Materials

The material chosen for the barcode mount for each layer is polycarbonate. Polycarbonate is a very popular type of plastic which can easily be moulded and formed into very thin layers of around 0.1mm. Polycarbonate has a refractive index of 1.585. The picture below depicts an idea of how the modules of each layer will be arranged. The top module will sit on top of the bottom layer and polycarbonate will be used to fill the gap. Some measurements based on the calculations done in previous chapter. One barcode module will be 5mm of length and the heights of each layers' modules are specified to diffract the light towards the detectors.

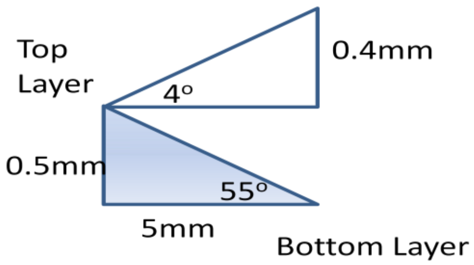


Fig 4.7 Polycarbonate Size

The top layer will be made semi reflective which means the incident light will be partially diffracted to the left detector and will also be partially transmitted to the bottom layer. Semi reflective films are used to create semi-reflective gratings, and these films are dyed within a metallised layer which has a reflective, but not mirrored surface [83]. The gratings for the bottom layer will be reflective which means all the incident light will be refracted to the detector on the right.

4.2.2 Gratings

Each module of 5x5(mm) will contain a different grating of different lines per mm which will diffract different set of wavelengths in different directions. Below is a selection of gratings that will be used in each module along with their specifications. The light source is assumed to be fixed on top of the barcode and in the middle. Five different types of gratings have been chosen with different set of number of lines per mm for each layer. Each of them will diffract a limited series of wavelengths which will be captured by the light detector. For the first layer, the modules are oriented to diffract the light to the left and vice-versa for the second layer.

Table 4.5: Top Layer Grating Selection

Number of Lines/mm	2800	1800	1350	1100	900
Wavelengths (nm)	300	300-450	300-600	300-750	300-900

*300 nm is the minimum required wavelength although shorter will be diffracted.

Table 4.6: Bottom Layer Grating Selection

Number of Lines/mm	5300	3500	2600	2100	1700
Wavelengths (nm)	300	300-450	300-600	300-750	300-900

*300 nm is the minimum requires wavelength although shorter will be diffracted.

Section 3.2.3.3 gives the calculations which explain the incident light differences between each ends of a barcode. For this size of barcode (5cm in length) and assuming that the distance between the light source and the middle of the barcode is 50cm, the following applies for the top layer;

- Top layer (x-axis); from the middle of the barcode to the right side, the maximum difference is +2.9 degree and -2.9 degree to the left end.
- Bottom layer (x-axis); from the middle of the barcode to the left side, the maximum difference is +2.9 degree and -2.9 degree to the right end.
- Top layer (y-axis); from the middle of the barcode to the top end side, the maximum difference is +2.3 degree and -2.3 degree to the bottom end.
- Top layer (y-axis); from the middle of the barcode to the top end side, the maximum difference is +2.3 degree and -2.3 degree to the bottom end.

Please note that the incident will be refracted for the bottom layer and will depend on the top layer incident angles and the polycarbonate refractive index. Values are given in section 4.2.2.2.

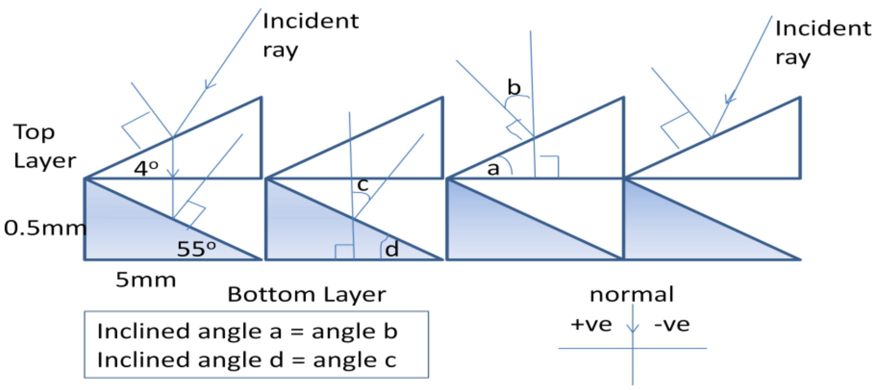


Fig 4.8 Incident and Module Orientation Angles

Figure 4.9 below outlines a slightly different set-up of the barcode grating mount. The bottom layer has been moved to the right slightly by half a module size (2.5mm). The idea here is to try a different arrangement of the layers to analyse if better results can be achieved from the change in the diffracted light. As shown in the figure below, moving the bottom layer means that the start of each module will be in-between the top layer module. The principle behind the barcode system is to illuminate one module at one time and to capture the diffracted spectrum of each layer on 2 separate detectors. To achieve this, the incident light from the LED source is converged to match the size of each module. The new set-up in figure 4.9 will not allow the system to operate according to its principle. The incident rays from the top layer module will be propagated into two modules in the bottom layer, hence ending up having diffraction from two bottom layer modules at the same time. So, for this reason, the idea of having the bottom layer modules not lined up with the top layer will be disregarded in this project.

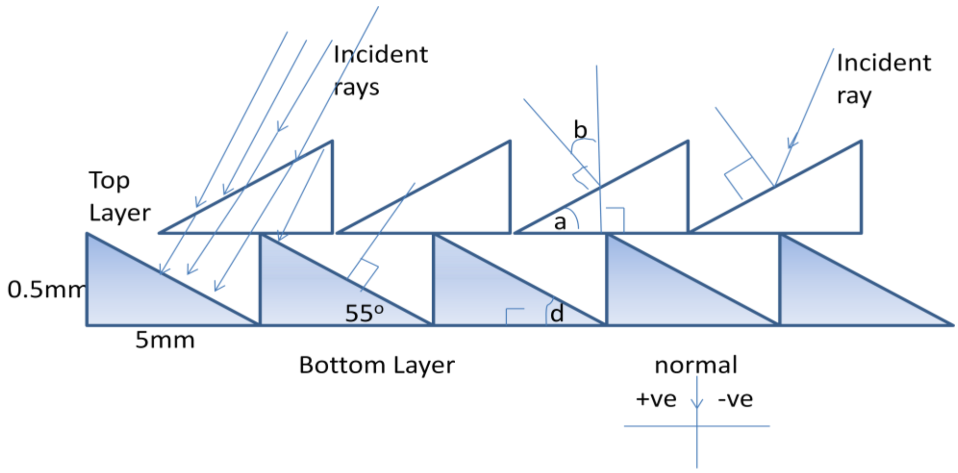


Fig 4.9 Barcode Layers Alternate Mounting

4.2.2.1 Top Layer

The orientation for each module of the top layer is 4 degrees. Having the light source in the perpendicular to the middle of the barcode means that the incident angle on the middle module is -4 degrees (=inclination angle); the incident angle for the left hand side is -3 + -4 = -7 degrees; and the incident for the right hand side will be 3-4 = -1 degrees. The order of diffraction for the top layer is assumed to be 1. The tables below show that the set of wavelengths that are diffracted using the selected five sets of gratings along with the minimum and maximum incident values, and refracted angles.

Table 4.7: Top Layer Grating Specifications

$m\lambda = d(\sin i + \sin r)$ [see section 3.3.1.1]
m=1 for top layer
Mount Orientation = 4 degrees
n (l/mm)= 900

	i=-1	i=-4	i=-7
λ (nm)	r	r	r
300	16.7	19.9	23.1
450	25.0	28.4	31.8
600	33.8	37.6	41.5
750	43.8	48.2	52.8
900	55.8	61.6	68.7

n(l/mm)= 1100

	i= -1	i= -4	i= -7
λ (nm)	r	r	r
300	20.3	23.6	26.9
450	30.8	34.4	38.1
600	42.6	46.9	51.4
750	57.4	63.5	71.3
900	#NUM!	#NUM!	#NUM!

n(l/mm)= 1350

	i= -1	i= -4	i= -7
λ (nm)	r	r	r
300	25.0	28.4	31.8
450	38.6	42.6	46.8
600	55.8	61.6	68.7
750	#NUM!	#NUM!	#NUM!
900	#NUM!	#NUM!	#NUM!

n(l/mm)= 1800

	i= -1	i= -4	i= -7
λ (nm)	r	r	r
300	33.8	37.6	41.5
450	55.8	61.6	68.7
600	#NUM!	#NUM!	#NUM!
750	#NUM!	#NUM!	#NUM!
900	#NUM!	#NUM!	#NUM!

n(l/mm)= 2800

	i= -1	i= -4	i= -7
λ (nm)	r	r	r
300	55.8	61.6	67.8
450	#NUM!	#NUM!	#NUM!
600	#NUM!	#NUM!	#NUM!
750	#NUM!	#NUM!	#NUM!
900	#NUM!	#NUM!	#NUM!

Values of incident angle, i and refraction angle, r are in degrees.

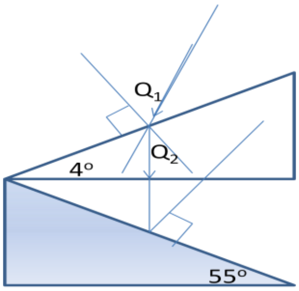
The value '#NUM!' means the specific wavelength is not part of the diffraction order.

4.2.2.2 Bottom Layer

The orientation for each module of the bottom layer is 55 degrees. The order of diffraction to be considered will be 1. For the bottom layer, the incident angles will due to refractive index of polycarbonate. Using Snell's law of refraction, $n_1 \sin Q_1 = n_2 \sin Q_2$, the incident angles are obtained.

Using Snell's Law, $n_1 \sin Q_1 = n_2 \sin Q_2$
n of air = 1.0 , n of polycarbonate = 1.585

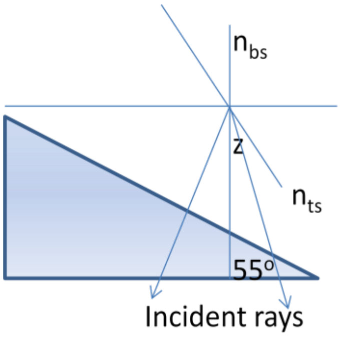
Middle of Barcode,	Right of Barcode,	Left of Barcode,
Incident $= Q_1 = 4$	Incident $= Q_1 = 1$	Incident $= Q_1 = 7$
$Q_2 = 2.5$	$Q_2 = 5.3$	$Q_2 = 1.6$



n_{ts}= Normal of top layer mount surface
n_{bs} = Normal of base of mounts of both layers
Z =angle between n_{bs} and n_{ts} = inclined first layer mount = 4º,
Q_2 = angle between n_{ts} and diffracted incident rays.
C= angle between n_{bs} and diffracted rays.

$Q_2 = 2.5º$	$Q_2 = 5.3º$	$Q_2 = 1.6º$
C= 1.5º (right of n_{bs})	C=1.3º (left of n_{bs})	C=2.4º (right of n_{bs})

Using the same principles of orientation as for the top layer, the mount is inclined 55 degrees which results in the following incident values mentioned below.



- In the middle, incident angle will be -4 degrees (top layer) and +56.5 degrees (bottom layer) [shown above],
- At the end of the right hand side, incident angle will be -1 degrees (top layer) and +53.7 degrees (bottom layer),
- At the end of the left hand side, incident angle will be -7 degrees (top layer) and +57.4 degrees (bottom layer).

The tables below show the same chosen gratings with their diffracted wavelengths, minimum and maximum incident values, and refracted angles.

Table 4.8: Bottom Layer Grating Specifications

m λ = d (sin i + sin r) [see section 3.3.1.1]			
m= 1 for bottom layer			
Mount Orientation = 55 degrees			
n(l/mm)=	**1700**		
	i= 53.7	**i= 56.4**	**i= 57.4**
λ (nm)	**r**	**r**	**r**
300	-17.2	-18.9	-19.4
450	-2.3	-4.0	-4.4
600	12.4	10.7	10.3
750	28.0	26.2	25.7
900	46.4	44.1	43.5

n(l/mm)=	**2100**		
	i=53.7	**i=56.5**	**i=57.4**
λ (nm)	**r**	**r**	**r**
300	-10.1	-11.8	-12.2
450	8	6.4	5.9
600	27.0	25.2	24.7
750	50.3	47.8	47.1
900	#NUM!	#NUM!	#NUM!

n(l/mm)=	**2600**		
	i=53.7	**i=56.5**	**i=57.4**
λ (nm)	**r**	**r**	**r**
300	-1.5	-3.1	-3.6
450	21.3	19.6	19.1
600	48.9	48.6	45.9
750	#NUM!	#NUM!	#NUM!
900	#NUM!	#NUM!	#NUM!

n(l/mm)=	**3500**		
	i=53.7	**i=56.5**	**i=57.4**
λ (nm)	**r**	**r**	**r**
300	14.1	12.5	12.0
450	50.3	47.8	47.1
600	#NUM!	#NUM!	#NUM!
750	#NUM!	#NUM!	#NUM!
900	#NUM!	#NUM!	#NUM!

n(l/mm)=	**5300**		
	i=53.7	**i=56.5**	**i=57.4**
λ (nm)	**r**	**r**	**r**
300	51.6	49.1	48.4
450	#NUM!	#NUM!	#NUM!
600	#NUM!	#NUM!	#NUM!
750	#NUM!	#NUM!	#NUM!
900	#NUM!	#NUM!	#NUM!

Values of incident angle, i and refraction angle, r are in degrees.

The value '#NUM!' means the specific wavelength is not part of the diffraction order.

4.2.3 Diffracted Spectrum

Diffracted spectrum is the diffraction that occurs from the barcode modules. For each layer, the spectrum angles for one specific grating will be the same for each modules. The longest wavelength that can each grating can diffract will be required to reach the detector. Te longest wavelength for each layers and each grating is the maximum angle shown in tables 4.7 and 4.8. The other shorter wavelengths will not be considered due to the fact that far too big detector will be required to capture the whole spectrum (see Fig.3.3). The data coding will cover this in more details n the next chapter.

4.2.3.1 Top Layer

The maximum incidence angle for the right end module is 55.8^{o} and maximum angle for the left end module is 71.3^{o} which can easily be read from **table 4.7.** Below is a figure to illustrate the angles. Angle R_s represents the range of diffracted light that is required to reach the detector. This value R_s is 15.5^{o} obtained by subtracting the maximum of the right end module from the maximum of the left end module.

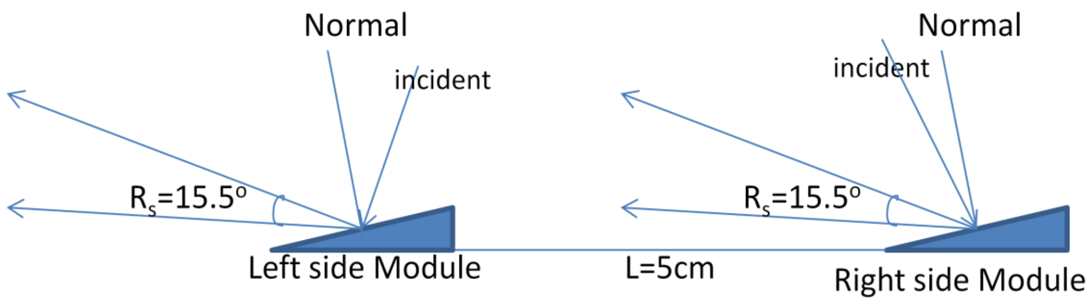


Fig 4.10 Top Layer Spectrum

4.2.3.2 Bottom Layer

After diffraction, the spectrum will have to exit from the polycarbonate with a refractive index of 1.585 into the air with a refractive index of 1. This change will alter the direction of the spectrum. Also the exit into the air will be through the top modules which are inclined 4 degrees. Below is a figure to help understand the angles.

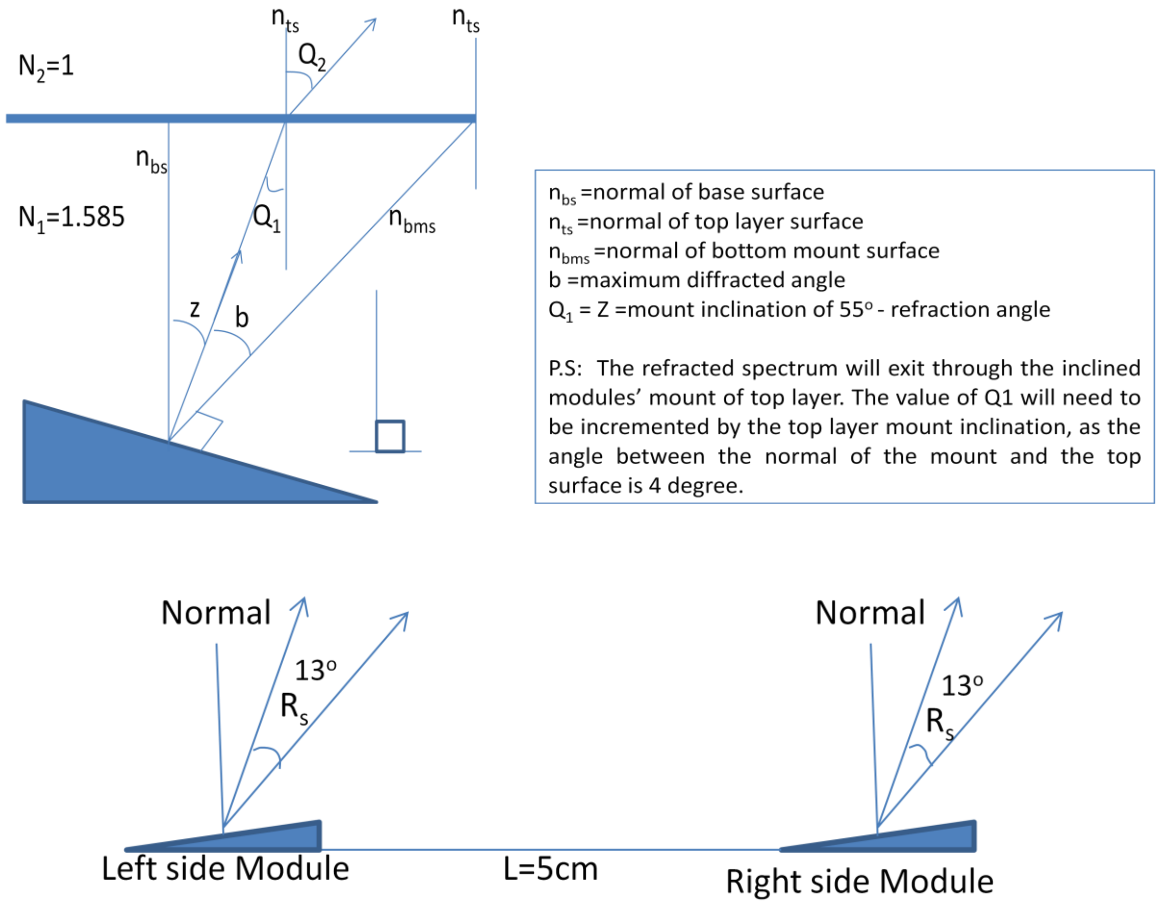


Fig 4.11 Bottom Layer Spectrum

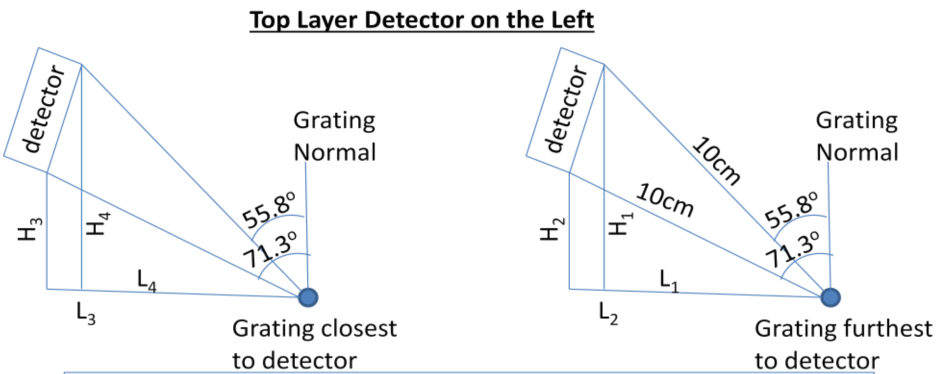
The maximum refractive angle for the right end module is 51.6 and maximum angle for the left end module is 43.5 which can easily be read from **table 4.8.** Using Snell's law of refraction, the exit angles Q_2 for each ends are as follows;

Z + b = inclined angle = 55°	Z + b = inclined angle = 55°
For b = **43.5°** ,	For b = **51.6°** ,
Q_1 = Z = 55°- 43.5° = 11.5°	Q_1 = Z = 55°- 51.6° = 3.4°
Q_1 for top layer module = 11.5° + 4° = 15.4°	Q_1 for top layer module = 3.4° + 4° = 7.4°
Q_2 = Sin^{-1} (sin 15.4 * 1.585) = **25°**	Q_2 = Sin^{-1} (sin 7.4 * 1.585) = **12°**

4.3 Light Detector

A wide range of photodiode modules are available on the market with the required Si photodiode. However, all the modules come with just one photodiode which is of maximum sensitive area of 100mm^2. Array of photodiodes are available but in small sizes not suitable for this application. Instead, a module with an array of large sensitivity area photodiodes will be customised to meet the requirements of the barcode system will be designed. The size is crucial to ensure the required diffracted wavelength is captured by the detector. Te positioning of the detectors is important to calculate the minimum required size.

The grating is tilted 4 degrees and the height between the grating surface and the barcode surface above the barcode surface is 0.2mm which can be neglected. It is assumed that the light source is 50cm above the middle of the barcode. The top end of the detector should be 3.3cm on the left of the barcode grating closest to it and 8.3cm high from the barcode surface. The lower end of the detector should be 4.5cm on the left of the barcode grating closest to it and 1.5cm high from the barcode surface. Minimum size of the detector should be of 4.3cm x 4.3cm as shown below to capture diffractions from the top layer.



- L_1, L_4 = Length between grating and top end of detector
- L_2, L_3 = Length between grating and top bottom of detector.
- H_1, H_4 = maximum height between grating and detector
- H_2, H_3 = minimum height between grating and detector.

L_1 = 8.3cm	L_2 = 9.5cm	L_3 = 4.5cm	L_4 = 3.3cm
H_1 = 5.6cm	H_2 = 3.1cm	H_3 = 1.5cm	H_4 = 2.3cm

Fig 4.12 Top Layer Detector Size

The grating is tilted 4 degrees and the height between the grating surface and the barcode surface above the barcode surface is 0.2mm which can be neglected. It is assumed that the light source is 50cm above the middle of the barcode. The top end of the bottom detector should be 3.3cm on the right of the barcode grating closest to it and 39cm high on top of the barcode. The lower end of the detector should be 5.3cm on the left of the barcode grating closest to it and 11.4cm high from the barcode surface. Minimum size of the detector should be 27.7cm by 27.7cm to capture the diffractions of all the bottom layer modules.

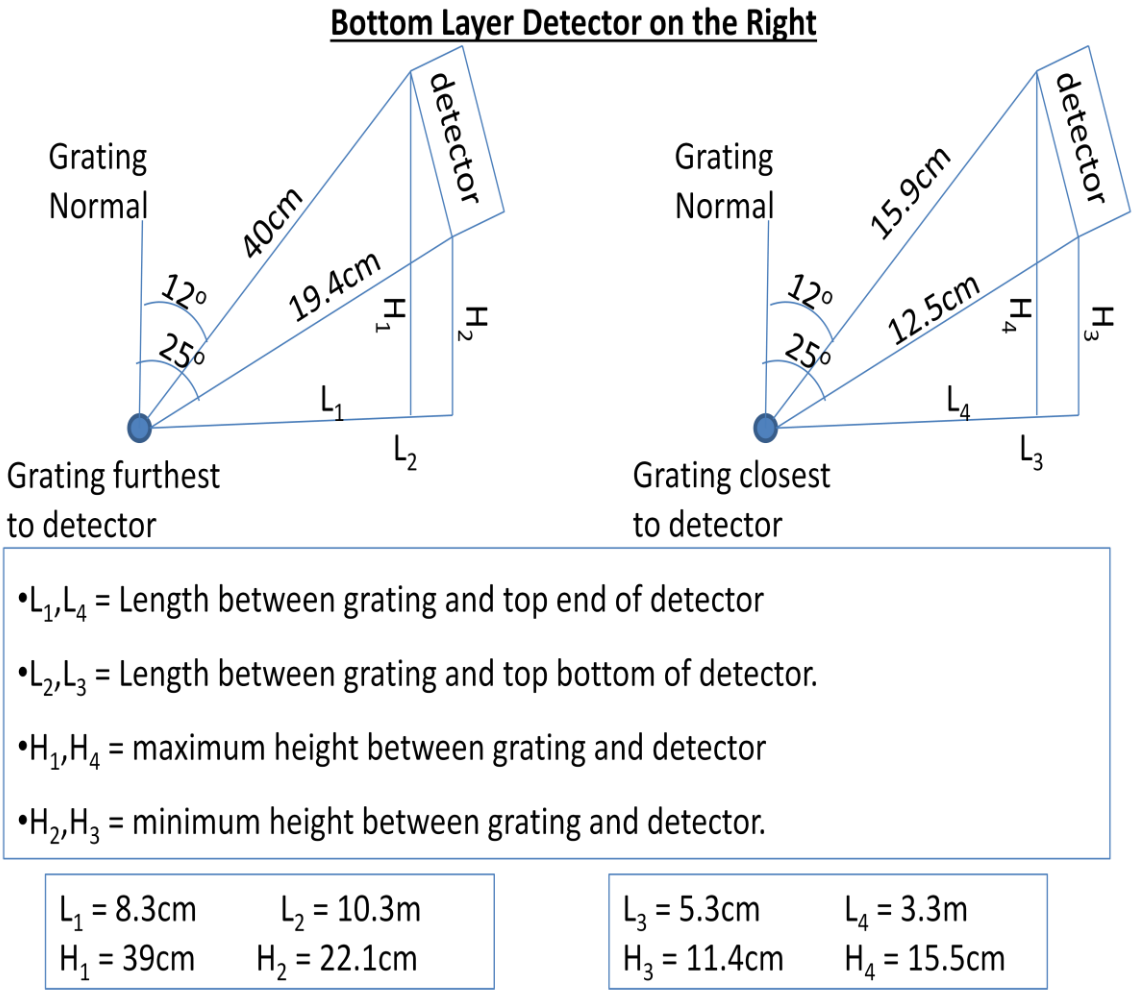


Fig 4.13 Bottom Layer Detector Size

4.3.1 Photodiode and other Components

4.3.1.1 Photodiode

The chosen photodiode for this application is a silicon red enhanced one from API laser components and is shown below. The diode has a big sensitivity area and is designed for low capacitance and high speed applications.[84]. Data sheet is in Appendix A.

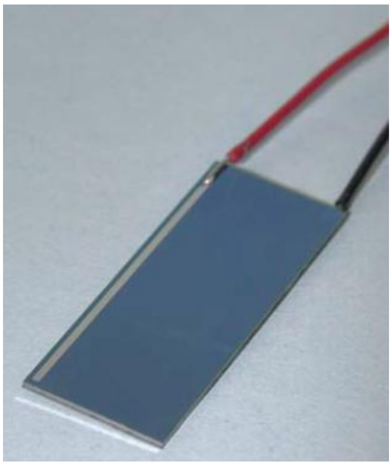


Fig 4.14 Silicon Photodiode [84]

4.3.1.2 Specification

Table 4.9: Photodiode Specifications [84]

Photosensitive area (mm^2)	Response time (V_R=5V)	Output	Connection	Supply voltage	Operating condition
9.25 x 25.17	150ns	Analogue	PVC wire	5V	-40° to +100°

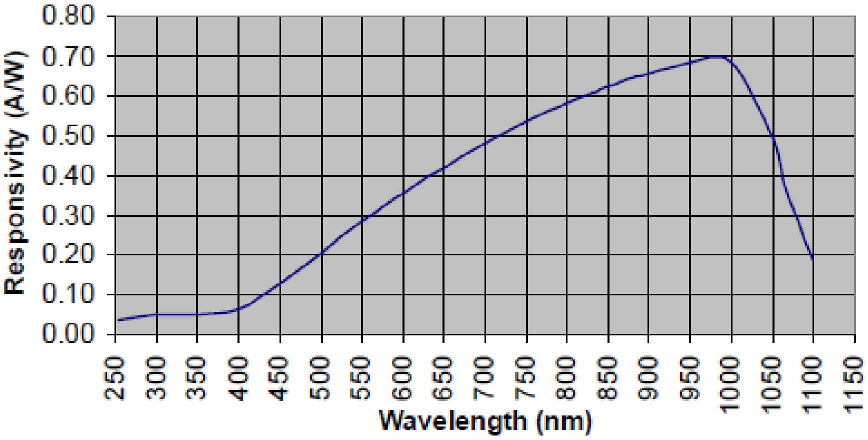


Fig 4.15 Silicon Spectral Response [84]

4.3.1.3 Analogue to Digital Convertor

The output from the photodiode is analogue. An ADC will be used to convert the signal into digital so that other devices such as computer can understand. One detector will consist of a minimum of 18 photodiode which will require 3 Analogue-to-Digital Convertors (ADCs) of 8 channels and the other detector will require 42 ADCs for 336 diodes. Below is the choice of an 8 channel ADC from Linear Technology [85]. Datasheet is in Appendix A.

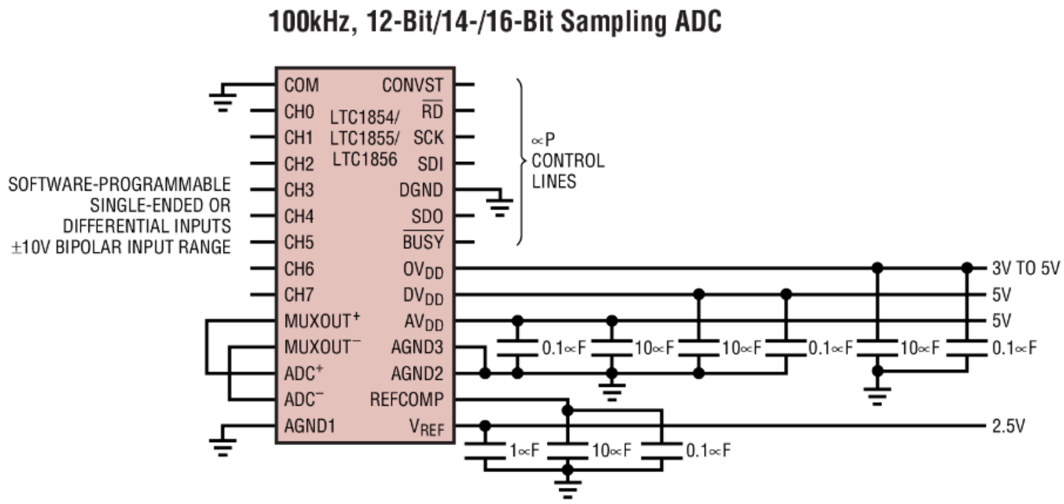


Fig 4.16 ADC 8-Channel [85]

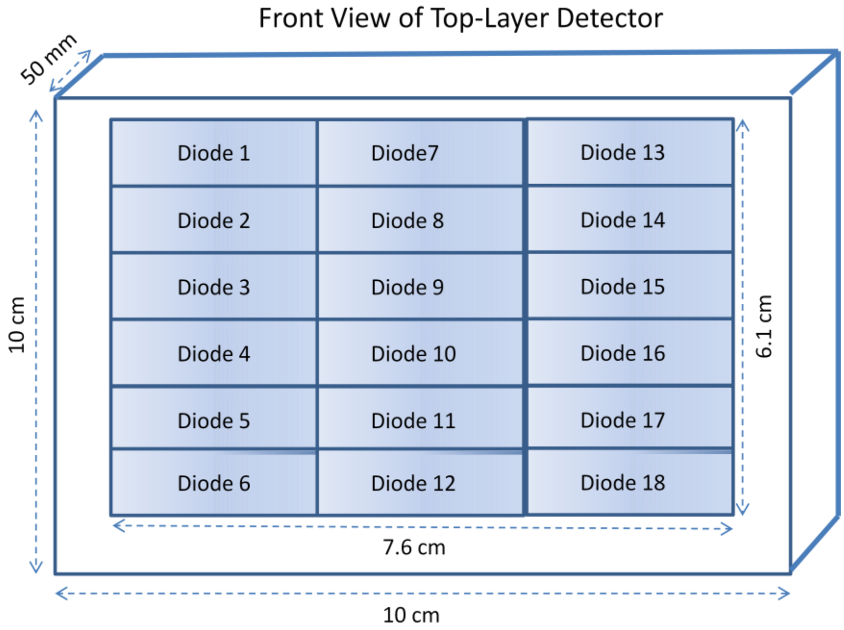
Table 4.9: ADC Specifications [85]

Power Supply	Sample Rate	Channels	Input Range	Power Dissipation
5V	100ksps	8 multiplexer	±10V	40mW

4.3.2 Prototype

Top layer detector will have 18 photodiodes and bottom detector will have 336 which will cover the required minimum size to detect the diffracted light from the barcode. Below is a design of the detectors. The connection circuit will be behind the photodiodes. Each photodiode will have its own circuit. The 8-channel ADCs will be inside the box as well. The output signal for each photodiode will be behind the detector box. A port to drive power to the detector is at the back also. The power will be 15V for the detectors, where

5v will be for the ADCs, and 5V will be for the photodiodes (used to cancel the dark current).



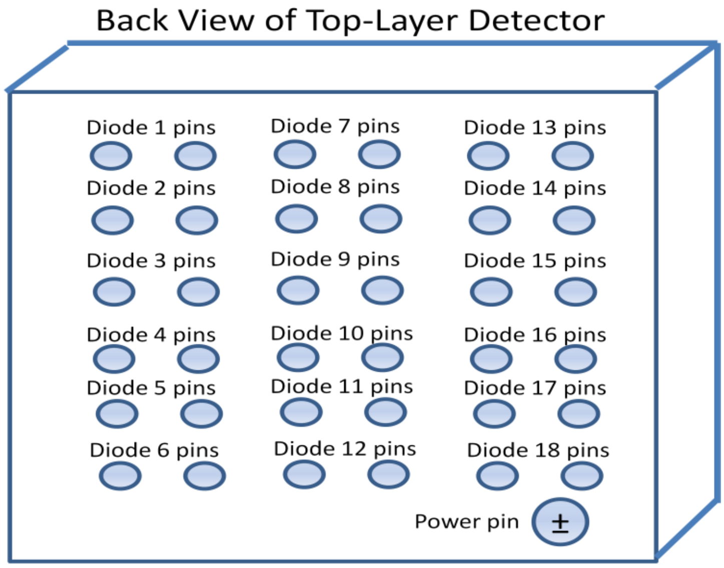


Fig 4.17 Top-Layer Detector Prototype

The bottom layer detector will be of same model as the top-layer. It will consist of 336 diodes to cover an area of at least 27.2cm by 27.2cm. The front view is given below with the dimensions. Back side will be the same as the top layer detector but with more output ports.

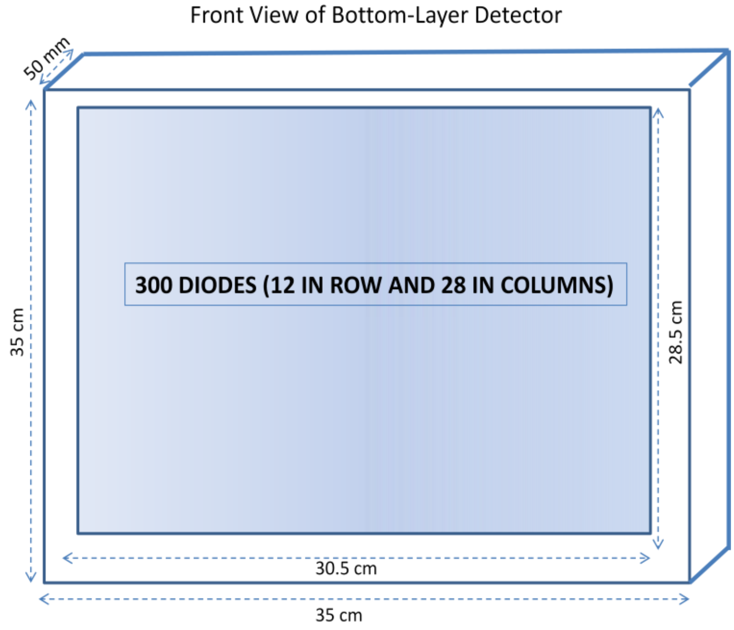


Fig 4.18 Bottom-Layer Detector Prototype

A diagram of the circuit of one the photodiode is shown below to give an overview. More details about the components in the circuit can be found in [86].

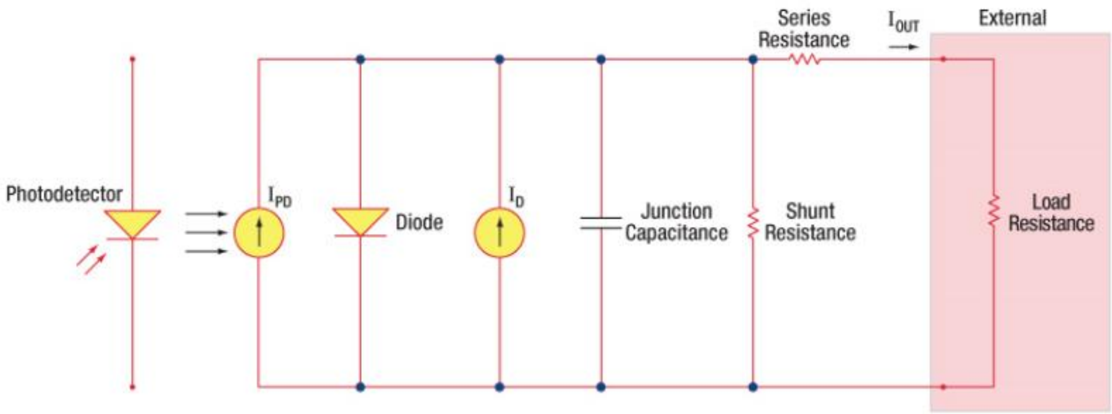


Fig 4.19 Photodiode Circuit [86]

4.4 Summary

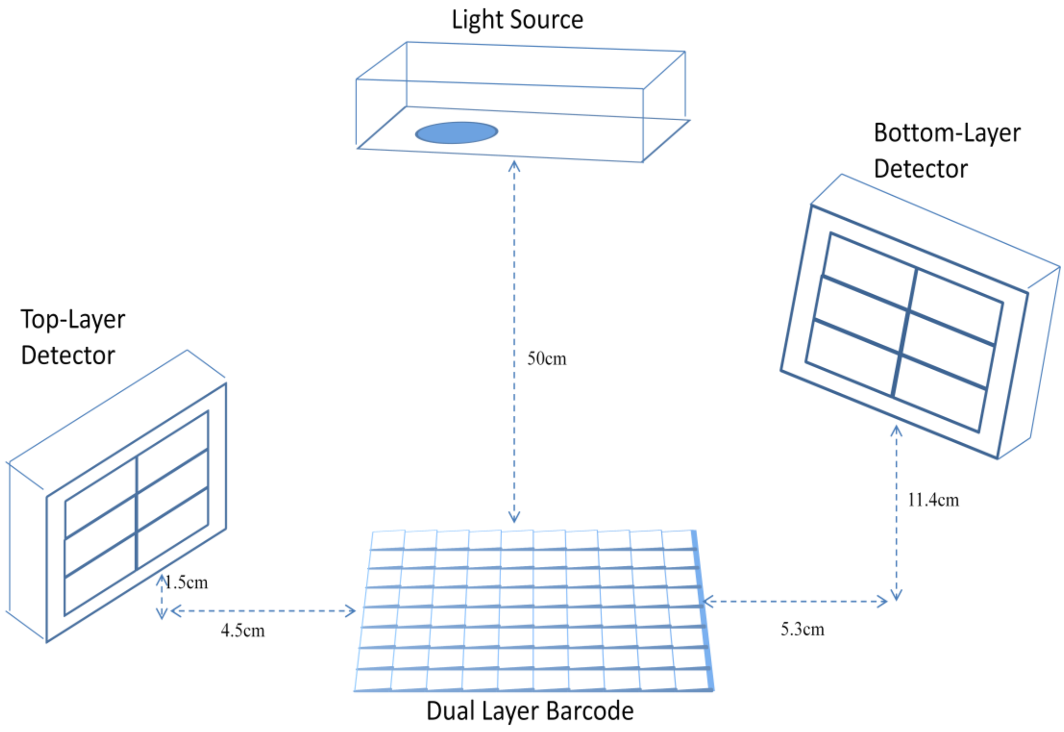


Fig 4.20 Barcode System Prototype

The above diagram is the final prototype of the whole barcode system with all of its components. It is assumed that all the components positions are fixed relative to each other. The light source has to be at least 50cm from the barcode as defined in chapter 3 and in the middle. The detector on the left has to be 4.5cm from the barcode and 1.5cm high. The barcode on the right hand side for the bottom layer has to be 5.3cm from the barcode and 11.4cm high.

This chapter simulates the entire barcode system. With the help of the previous chapter, each component has been designed and prototyped. Off market powerful Led chip has been used to design the light source along with a convex lens and mems mirror to illuminate the barcode. Two sets of five diffraction gratings have been selected to represent the modules for each layer of the barcode. Based on the light diffraction, each detector has been designed with different specifications and sizes. However, they both have similar components such as photodiodes, circuits and ADCs. Positioning is based on mathematical calculations to ensure the entire barcode is illuminated and the light diffraction is picked up by the detectors. The next chapter will focus on the data storage of the barcode based on the diffracted light.

Chapter 5

Data Storage

Following the design concept of the barcode system in the previous chapter, the next requirement in the project is to be able to store data in the barcode as well as retrieve it. This Chapter explains the types of data that can be stored in the gratings and the ways the data is read and decoded. To start with, the outputs of the detectors are analysed and understood. These outputs are mapped with set of binary bits to allow data storage. Characters are then in turn mapped to binary bits to be stored. Two set of data character are chosen for the barcode system and they are EXTENDED ASCII Character Set and Numeric Character Set. Each character is mapped with a unique binary code that is represented into the gratings. Algorithm is defined to help understand how data read from the detectors is dealt with and decoded. Finders Patterns are defined to aid detectors detect the start and end of the barcode. Data security is very important in any data access system including this barcode system. Two basic levels of security are chosen. One choice is to check for data errors while the other one checks for data errors and correct it. Capabilities and data capacity of the barcode is determined according to different security features.

5.1 Data Integration

This section explains the crucial link between the gratings and data in the barcode system. Starting from a detailed explanation of different types of data required, followed by the features and limitations of the grating storage capabilities, the possibility of merging the data into the barcode is defined. The final sub section explains how the data is read from the gratings without or with minimum errors.

5.1.1 Data

Before the existence of computers, information was stored on papers for future reference and use. When computer systems were discovered, papers were replaced by electronics known as hard drive to store information. Data represent information saved into computer hard drives. In computer low level language, data is converted into strings of 1s and 0s using computer conversion tables and algorithms before being stored. In this context, colours detected from gratings will be converted to 0s and 1s to represent data.

5.1.1.1 Types of Data

Data can exist in any form and languages. Based on different applications, different types of data are defined with different characteristics. Having different types of data allow the use of only required characters for specific applications which help to increase data storage and increase efficiency (for instance, barcode system in supermarket can only use numeric). Data types are not limited and are still being developed by various people around the world for different. However, below is a table of the most common types used;

Table 5.1: Data Types

TYPES	EXAMPLE
Numeric	Numbers 0-9
Text	Letters A-Z
Special Characters	Other characters than number and letters (e.g. *, %, $, etc)

The above basic types of data will be used in this project to demonstrate the storage capabilities of the barcode system. Other forms of data and further complex definition of data is beyond the scope of this project. However, the design of the barcode system will adapt to store any types of data for any application and this will be explained in the next sections.

5.1.2 Gratings

As demonstrated in the previous chapter, the barcode is formed using a collection of gratings with different characteristics. Picture 5.1 below shows the barcode segmented into very small modules of the same size (5mm x 5mm). Gratings offer the feature of wavelength-multiplexing, the right technique to store and represent data in the barcode system. The idea is to create an array of modules with the gratings. Each module will be able to consist of a grating with a different characteristic. This will enable each module to be different from each other, thus allowing representation of different sets of data.

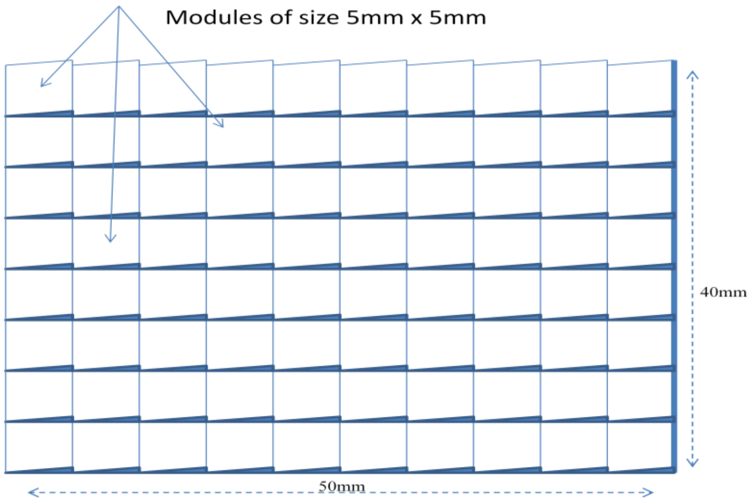


Fig 5.1 Barcode Modules

The idea is to illuminate the grating which will diffract the light into a spectrum of wavelengths that can be captured back by light detectors. The chosen wavelengths are visible light ranging from 300nm to 900nm. A number of gratings with the help of different number of lines per mm are readily available to offer any wavelengths between the chosen ranges, which will in turn allow a number of unique gratings to be available for the barcode system. The higher the number of unique grating can be introduced in the barcode, the higher the data storage can be stored. In this application, only a small set of gratings with different characteristics such as l/mm will be introduced and tested.

5.1.3 Data Merging

This sub-section explains the marriage between the data and the grating modules. In computing, data is stored in 0s and 1s. This same technique will be used here but instead as a reference. In simpler terms, the gratings will represent a series of 0s and 1s which will then be used to represent characters. As in previous generations of barcode, the same technique is more or less applicable in this barcode system approach. To start with, the entire barcode will be considered into smaller modules as shown in previous section. Each module has the ability to hold 5 unique gratings resulting in 5 unique series of 0s and 1s. In computer terms, 2 binary bits offer 2^2=4 options, and 3 bits offer 2^3=6 options. In this case, each grating for each module will represent two bits as shown in table below. The fifth grating is used as the finder path. Once detected at the start of the barcode, the top layer detector recognise the barcode and once detected by the bottom layer barcode, the end is of the barcode reading is acknowledged. Reading of the barcode will never start unless the 300nm wavelength is read and again will not stop until the 300nm wavelength is read again by the bottom layer detector. This feature ensures that the entire system is placed in their optimum positions to ensure all the wavelengths detected are correct.

Table 5.2: Bits per Module

Wavelengths nm	TOP LAYER		BOTTOM LAYER	
	Binary Bits	**Grating Name**	**Binary Bits**	**Grating Name**
300nm-900nm	00	T-A	00	B-A
300nm-750nm	01	T-B	01	B-B
300nm-600nm	10	T-C	10	B-C
300nm-450nm	11	T-D	11	B-D
300nm	Finder path	T-S	End of barcode	B-E

To clarify, each of the above range of wavelengths is achievable by a unique grating and the selections of the gratings are made using the reference Character Sets in the following sections.

The next important part is the detection of the diffracted spectrum from the gratings and its relation with the binary bits. Two main important questions that are raised are;

- How will the system map the output from the detectors with the binary bits?
- How can characters be stored into the barcode modules and how many characters will the barcode represent or store?

The answer to the first question is to use software. The only way to help the detectors understand the output values is to offer them a database to compare and check. Below is an idea of the software in terms on algorithm that will create the bridge between the detectors' reading and the output value. The second question is very crucial as this will determine if data can be stored in the modules or just binary bits. For this challenge, modules will be combined to allow represent characters that require 2 or more binary bits to be represented. To make it simpler, character sets have been defined in the next sub-section to show the different characters that can be stored in the barcode system.

5.1.3.1 Algorithm

Software is crucial to help decode the input value from the detectors. Despite that this project does not focus on software of the barcode system, a small algorithm along with a quick explanation is given to help understand how the data storage will be interpreted within the system. The desired expected outputs from the gratings are given below in a tabular form.

Table 5.3: Barcode Module Outputs

TOP LAYER **Grating with n(l/mm)**	**BOTTOM LAYER** **Grating with n(l/mm)**	**Wavelengths range**
900	1700	300nm-900nm
1100	2100	300nm-750nm
1350	2600	300nm-600nm
1800	3500	300nm-450nm
2800	5300	300nm

<u>Decoding reading from each grating</u>

Module name: grating_module( )

Define an array of integer input

Store inputs from each photodiode to each array in input

Define integer maximum value and minimum value

Calculate highest value in input arrays and assign to maximum value variable

Calculate lowest value in input arrays and assign to minimum value variable

If maximum value < or = 900;

Return binary(0,0);

If maximum value < or = 750;

Return binary(0,1);

If maximum value < or = 600;

Return binary(1,0);

If maximum value < or = 450;

Return binary(1,1);

If maximum value < or = 300;

Return start_end(finder path)

The algorithm above is an idea or guide to write the software that will interpret the wavelengths detected by the photodiodes from both detectors. Each module read will go through this algorithm to decode its binary bits. Return binary(0,0) means to send the bits value 00 to binary module where all the bits can be combined to form a series of 0s and 1s. The finder path will instruct the computer to start and to stop reading the barcode modules. Different modules are used to compare the series of 0s and 1s with databases that contain the characters along with their binary equivalent and output the desired character. The compression algorithm will be different for different applications and will not be given here. The picture below summarises this process.

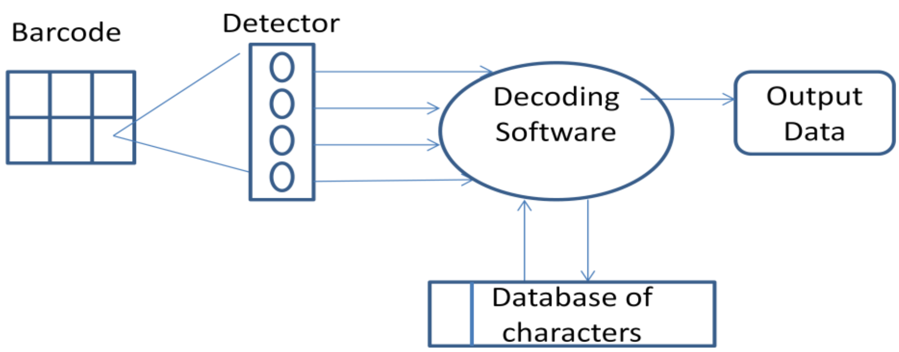


Fig 5.2 Signal Decoding from Detector

5.1.3.2 Character Set

The character set is a selection of characters that are used in different applications, for instance numeric values for a supermarket's products identification. The idea of having tailored set of characters is to maximise data storage as characters not in use will not be allocated a binary equivalent. However, many more sets of characters exist in different languages and sizes. ASCII, Extended ASCII and Numeric Character Sets are the most common tables used worldwide. Hence, these two sets will be converted to be adapted in the barcode system. The final conversion character sets will be stored in the database file that will help storing data and also help the decoding software output the appropriate characters. Characters are normally converted into binary before storage in computing and this technique is also used here. However, to allow better representation of binary numbers, the technique hexadecimal is adopted. Hexadecimal encapsulate 4 numeric bits into one, which allow long strings of binary number to be shortened for better presentation. Refer to Appendix B for detailed explanation on binary and hexadecimal conversion technique and a full reference table. Appendix B also explains how many bits are required to represent a set of characters.

Table 5.4: Hexadecimal Grating Equivalent

Hexadecimal Number	Binary	Top Layer Grating	Bottom Layer Grating
0	0000	T-A,T-A	B-A,B-A
1	0001	T-A,T-B	B-A,B-B
2	0010	T-A,T-C	B-A,B-C
3	0011	T-A,T-D	B-A,B-D
4	0100	T-B,T-A	B-B,B-A
5	0101	T-B,T-B	B-B,B-B
6	0110	T-B,T-C	B-B,B-C
7	0111	T-B,T-D	B-B,B-D
8	1000	T-C,T-A	B-C,B-A
9	1001	T-C,T-B	B-C,B-B
A	1010	T-C,T-C	B-C,B-C
B	1011	T-B,T-D	B-B,B-D
C	1100	T-D,T-A	B-D,B-A
D	1101	T-D,T-B	B-D,B-B
E	1110	T-D,T-C	B-D,B-C
F	1111	T-D,T-D	B-D,B-D

ASCII and Extended character sets contain 256 characters. They require 1 whole byte which is 8 bits to represent one character. Each grating module can represent 2 bits, hence needing 4 modules per character or byte. However, using numeric character set, only 2 modules are required for each number allowing more data to be stored.

Table 5.5: Numeric Character Set

Number	Hexadecimal Number	Top Layer Grating	Bottom Layer Grating
0	0	T-A,T-A	B-A,B-A
1	1	T-A,T-B	B-A,B-B
2	2	T-A,T-C	B-A,B-C
3	3	T-A,T-D	B-A,B-D
4	4	T-B,T-A	B-B,B-A
5	5	T-B,T-B	B-B,B-B
6	6	T-B,T-C	B-B,B-C
7	7	T-B,T-D	B-B,B-D
8	8	T-C,T-A	B-C,B-A
9	9	T-C,T-B	B-C,B-B

The FULL ASCII Character Set is shown in Appendix B.

5.2 Data Security [21]

The main criteria for any barcode system to be perfect, is its ability to successfully read all the data stored in the symbol accurately and rapidly. Data security offers various techniques to help detect if the accurate data is read and also offers ways to correct the data errors found. Unlike other barcode systems where symbols are printed in ink on papers, this novel model instead have gratings placed in small modules like fish scales. The gratings are cut in one size for all the modules compared to other barcode models, where different line widths are used. Colour barcodes tend to fade whilst grating will never fade or face any change in their original specification (lines per mm). To conclude, gratings are more secure than any other generations of barcodes, making this barcode system more secure.

However, despite having the best components in a barcode system, there are always disturbances in the system that will prevent the detectors from picking up the right output signal from the barcodes. Some disturbances are as follows;

- Damaged gratings will diffract light in undesired directions and wavelengths. The spectrum detected by the detectors will be converted into wrong data.

- Light from surroundings might disturb the incident LED light onto the gratings and therefore, again result in undesired diffracted wavelengths and directions.

- Dusts or other substances that might fall on the barcode will block some diffracted light which will break the sequence and finally result in wrong data being read.

- Slight or big movement of the components will prevent the barcode from being read in the right sequence, hence resulting again in the wrong data being read.

For this barcode system, two basic data security features are chosen and they are check characters and error correction.

5.2.1 Check Character

Check character is a technique that checks for data errors in a barcode. An additional character called modulo 43, is used to hold a check digit that is mathematically calculated using a set of characters and this check character is placed at the end. This barcode system will have two check characters for each layer. First and last grating in each layer are for finder paths and end. This leaves 79 gratings in each layers resulting in total of 39.5 characters. The mathematical process for the modulo 43 check character is as follows;

- The hexadecimal value of each character from the character set table will be added together. For hexadecimal letters a-d, the values are shown in table 5.8 below and their additions for a character are; 2d = 2+13 = 15, AE = 10+ 14 = 24.

- Then, the total sum is divided by 43.

- The Remainder is used as the check digit.

- Finally, the character's hexadecimal value from the character set that matches the check digit is used as the check character that is stored.

2 gratings per numeric and 3 check characters per layer is required for Check Character implementation. For numeric character set, the final value is added together and then compared with its value in the character set. For instance, if the remainder comes to 41, then 4 is added to 1 resulting in 5.

Table 5.6: Check Character Value Set

Hexadecimal	**Character Value**
A	10
B	11
C	12
D	13
E	14
F	15

5.2.1.1 ASCII Character Set Example

Consider the message "**CHARACTER-43**". From character set table 5.7, CHARACTER-43 in hexadecimals are;

CHARACTER-43 = 43 , 48 , 41 , 52 , 41 , 43 , 54 , 45 , 52 , **2d** , 34 , 33
Sum = 43+48+41+52+41+43+54+45+52+ **2+13** +34+33 = 501
Division = 501/43 = 11 remainder 28
Check digit =28
From character set, hexadecimal 28 is equal to character (

Final message is "**CHARACTER-43(**"

5.2.1.2 Numeric Character Set Example

Consider the numeric "**45679A0BE**". From numeric set table 5.7, **45679A0BE** in hexadecimals are;

45679A0BE = 4 , 5 , 6 , 7 , 9 , 10 , 0 , 11 , 15
Sum = 4 + 5 + 6 + 7 + 9 + 10 + 0 + 11 + 15 = 67

Division = 67/43 = 1 remainder 24

Check digit =24

Check digit is added together, 2 + 4 = 6

From numeric set, hexadecimal 6 is equivalent to numeric 6

Final message is "**45679A0BE6**"

5.2.2 Error Correction

This technique provides the features of finding data errors in barcodes along with the capability to correct the error. This method encapsulates extra bits to a series of data bits which are then encoded in one block of data. Three extra bits are added to a four bit block to have a coded 7-bit block of data. The three bits added are obtained by encoding the 4-bit original data in three ways. When, the 7-bit block is decoded, the three bits are then compared against the encoded ones. Out of the three choices, if one is not matched, then it is easy to change the bit to correct the data error. The main disadvantage of this technique is that it uses a lot of bits. A 4-bit codeword requires 7 bits of data storage which is nearly 75% extra. Below is an example based on Linear Block Coding.

- Consider a block of 4-bit data (2 grating in this barcode system). There are 16 distinct data set and each bit is assigned to B_0, B_1, B_2, B_3.

B_0	B_1	B_2	B_3
0	0	0	0
	⋮		
1	1	1	1

- Three bits are added called parity bits. Even parity (0) is an even number of 1s and odd parity (1) is an odd number of 1s. Using logic elements called Exclusive-OR gates (XOR), parity bits are generated as follows; [21]

  Parity bit 0, $P_0 = B_0 + B_1 + B_3$

  Parity bit 1, $P_1 = B_0 + B_2 + B_3$

  Parity bit 2, $P_2 = B_1 + B_2 + B_3$

Reference in [21] provides an electronic analogy of the XOR technique.

- Using the three parity bits, 7-bit block is formed as B_0, B_1, B_2, B_3 , P_0, P_1, P_2 and then encoded.
- After decoding, the 7-bit code word can be re-arranged as follows using XOR technique;

$$P_0 + B_0 + B_1 + B_3 = 0$$
$$P_1 + B_0 + B_2 + B_3 = 0$$
$$P_2 + B_1 + B_2 + B_3 = 0$$

- To check the if the above equations are true, the detectors' logic generate an error 3-bit syndrome using the 7-bit code word, again using XOR and the syndrome bits are;

$$S_0 = P_0 + B_0 + B_1 + B_3$$
$$S_1 = P_1 + B_0 + B_2 + B_3$$
$$S_3 = P_2 + B_1 + B_2 + B_3$$

- Finally, if all the bits in the syndrome are zero, the data has been decoded accurately. If one of the bit in the original 4-bit data is received in error, then the syndrome values can be used to identify and correct the error as follows;

S_0	S_1	S_2	**Verdict**	**Reason**
0	0	0	No errors	All 0s
1	1	0	B_0 is inverted	B_0 is common in S_0 and S_1 and value is 1
1	0	1	B_1 is inverted	B_1 is common in S_0 and S_2 and value is 1
0	1	1	B_2 is inverted	B_2 is common in S_2 and S_3 and value is 1
1	1	1	B_3 is inverted	B_0 is common in S_0 ,S_1 and S_2 and value is 1

5.3 Barcode Capacity

In any storage device, the capacity is crucial as this aids the user to understand how much data can be stored in that device. The same principle applies in this barcode system, where the table below provide the capacity of the symbol.

Table 5.7: Barcode Capacity

Security	**Symbol Size (incl. both layer)**	**Barcode Capacity**		
		Numeric	**Characters**	**Data Bits**
None	160 modules	79	39.5	316
Check Character	160 modules	73	35.5	142
Error Correction	160 modules	45	22.5	180

5.4 Summary

This chapter describes how data is stored and read successfully from the barcode system. A definition of data is given along with some examples and its importance in the barcode system. The gratings used as the barcode are used to represent/store data. Incident light projected on the gratings is collected back by detectors after the diffraction has taken place. A set of five different gratings with different features are used per layer. Each grating diffracts a unique spectrum of light. The barcode is made of 80 modules per layer of the same size. The set of gratings are used to fill the modules and offers five sets of data per layer, resulting into 2 bits per module. This feature allows data to be represented into the form of gratings and into the modules of the barcode. An algorithm is defined to help decode the signal output from the detectors.

The next phase explains the range of data that are defined and chosen for the symbol. The range of data is summarised into character sets. Two sets are chosen and they are Numeric and Extended ASCII. Four gratings allow 8 bits of data that is used to represent the Extended ASCII character set. For numeric, two gratings allowing 4 bits are used. Each character are represented using 4 gratings and each numeric using 2 gratings. 4 sets of gratings are used for the data offering eight 2-bits codeword and the fifth one is used as finder path. For top layer, the fifth set is used to start reading symbol and the fifth set for the second layer is used to stop reading the symbol.

The final phase is data security used to ensure data is read accurately and successfully. Two levels of security are given and they are check characters and error correction. Check characters offers the ability to check for errors whilst error correction allows both detection and correction or the data error. The technique and implementation check character is given in details. For error correction, an explanation is given rather than an example. This will be considered in the next chapter. Data capacity is also defined in three sets. First set of values are without any security, second set is with check characters and the last set is with error correction. For each sets, capacity is defined into bits, characters and numeric per symbol.

Chapter 6

Laser Light Source

This chapter offers an alternative light source to LED. Laser is considered to be more advantageous than LED when it comes down to collimated beam of light, beam spot size and light intensity. In this project, it is very beneficial to have these three mentioned characteristics from the source light, specially the collimated beam which is a requirement for gratings' diffractions. While a lot of tweaking is required to try and achieve some of the three characteristics from LED, others such as collimated beams will not be possible due to the way light is generated from a LED diode. The following sections introduce an introduction to lasers and provide the design of the alternate Laser light source along with some challenges that will need to be considered. White laser light is not available from the market yet as it is still being researched. However, a brief strategy of how white laser can be achieved will be explained. The laser spot might not be of desired size where in some cases a bigger beam spot will be required to cover a the size of one module in the barcode. To achieve this, a beam expander is designed and explained.

6.1 Fundamentals

Light Amplification by Stimulated Emission of Radiation (LASER) is an optical component which uses electrical or optical energy to excite atoms or molecules which then convert energy into light. A laser consists of two main elements: [92]

1. An amplifying or gain medium (solid, a liquid or a gas) composed of atoms, molecules, ions or electrons. The latter's energy levels are used to increase the power of a light wave during its propagation and this physical principle involved is referred to stimulated emission.
2. A pumping system used to excite the amplifying medium. This creates the conditions for light amplification by supplying the necessary energy. There are different kinds of pumping system: optical (the sun, flash lamps, continuous arc lamps or tungsten-filament lamps, diode or other lasers), electrical (gas discharge tubes, electric current in semi-conductors) or even chemical.
3. An optical cavity or resonator to maintain the gain of the system and help overcome light losses.

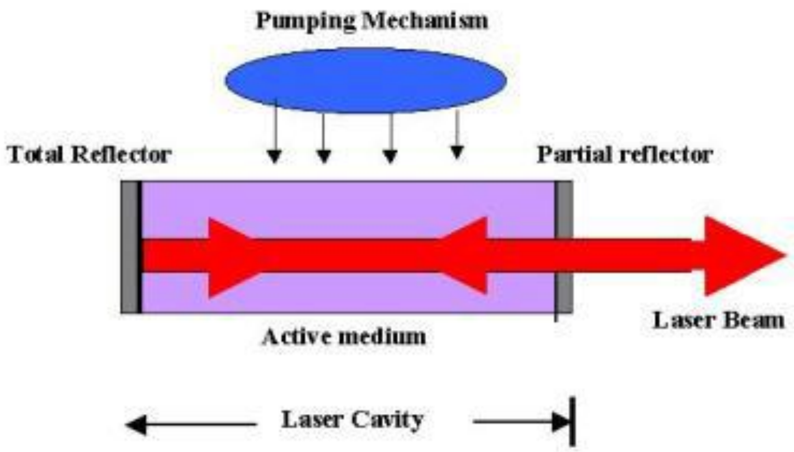


Fig 6.1 Simple Laser System [93]

The principle behind the laser is like this. Suppose we can produce a large number of atoms all in excited states. If one of the atoms emitted spontaneously, then the emitted photon would stimulate other atoms to emit. These emitted photons would, in turn, stimulate further emission. The result would be an intense burst of coherent radiation. [93]

6.1.1 Elements

The elements of a laser are;

1. **Beam Size :** This refers to the diameter of the beam which is measured at the exit face of the laser housing as shown below.

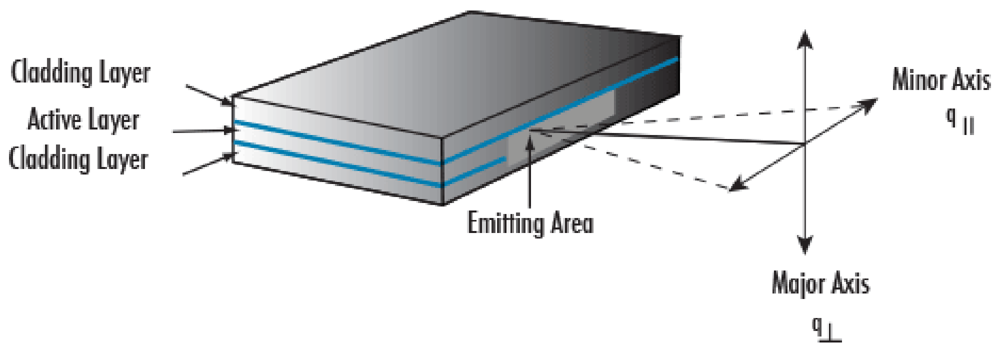


Fig 6.2 Laser Beam Size [94]

2. **Beam Divergence :** This specification defines how much beam spreads out over distance. It is defined by the full angle.

3. **Fan Angle :** It is the angle produced by an accessory line or pattern generators as shown in figure 6.3.

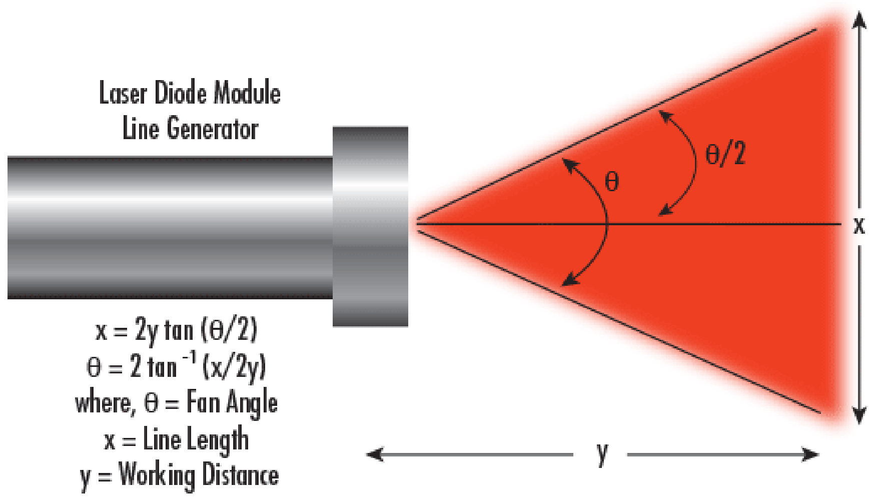


Fig 6.3 Laser Diode [94]

4. **Output Power :** It is the maximum power measured after the laser beam exits the laser housing and it is rated after passing through (but not before) any optics. Values are typically within +/-10%. The light intensity has a Gaussian profile which means that it is highest at the centre of the beam and dissipates outwards.

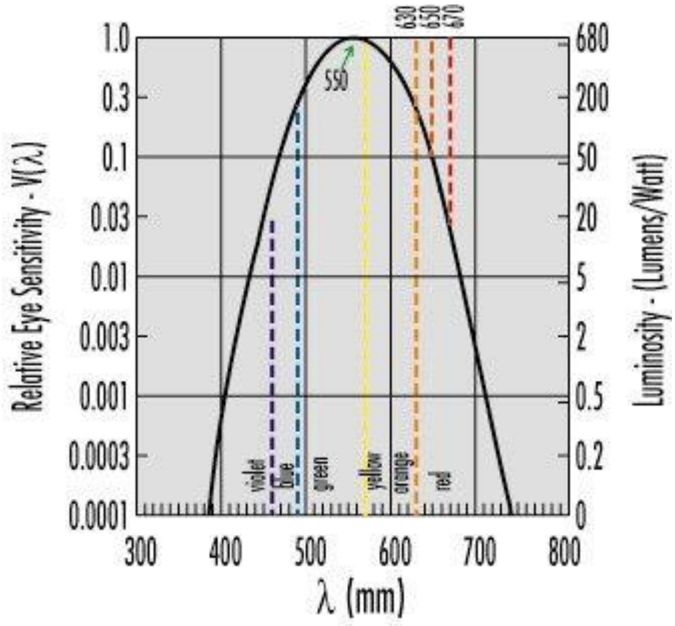


Fig 6.4 Laser Output Power [94]

5. **Class :** This is the warning required on all laser products also known as CDRH (Center for Devices and Radiological Health). The classifications relate to the maximum amount of laser radiation emitted from the laser at a specific wavelength.

6. **Detectability/Visibility :** The visibility if the laser spot depends on the SNR. Higher SNR means the laser spot is more detectable. Filtering can be used to increase the SNR. The responsibility of a detector relies on the choice of the wavelength.

7. **Lifetime :** Lifetime of lasers can be easily extended by running the power supply at lowest voltage. Operating at high or near maximum voltages requires heat sinks. Temperature can be maintained at low to extend lifetime of the laers. Diode modules typically have a lifetime of 10,000 to 20,000 hours and the diode components have a lifetime of 100,000 hours.

6.1.2 Types of Lasers

Since the invention of laser in the 1950's up to now, various types of lasers have been invented to fit various applications (research, medical, industrial or commercial) and to improve efficiency. Lasers are defined and described by the kind of lasing medium they used and below is a list of the types of lasers that exist; [95]

Gas lasers [95]

These lasers contain a mixture of helium and neon. This mixture is packed up into a glass tube which acts as an active medium. The pressure inside the tube is maintained at 1 torr for helium and .1 torr for neon. The length of the glass tube is approx from .25m to 1m. Its diameter is nearly 1cm. Two electrodes present in the tube are connected to a high voltage d.c. source. This circuit results in the generation of the discharge inside the tube. Further this discharge works like a pump. Two parallel mirrors are placed in front of each other. Both mirrors are present inside the tube. Only mirror M1 shows the complete reflection. The mirror M2 shows partial reflection.

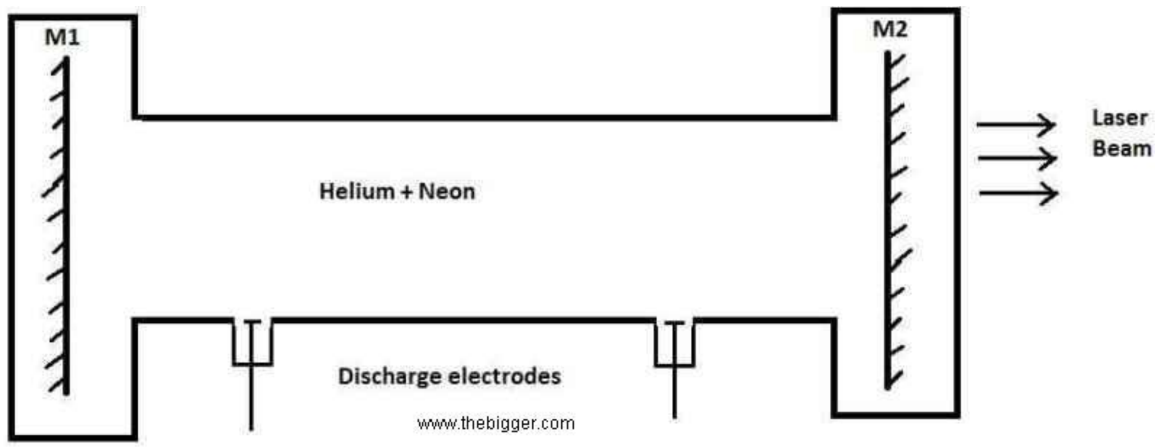


Fig 6.5 Gas Laser [95]

When we pass the electric current through the tube, a continuous light wave will start flowing inside the tube with constant frequency. It is also known as coherent light waves. It will come out from the side of mirror M2.

Solid Lasers [95]

In this a ruby like crystal is used which acts as an active medium. It is basically cylindrical in shape. This crystal is surrounded by a xenon flash lamp T. This flash lamp is of helical shape. In this arrangement this lamp acts as a pumping arrangement. Both the ends E1 and E2 of the crystal are properly polished. Similar to the gas lasers, the surface M1 will do the complete reflection but on the other hand M2 will reflect partially. Whenever we will pass the current through the arrangement a laser beam of red color having large intensity will come out.

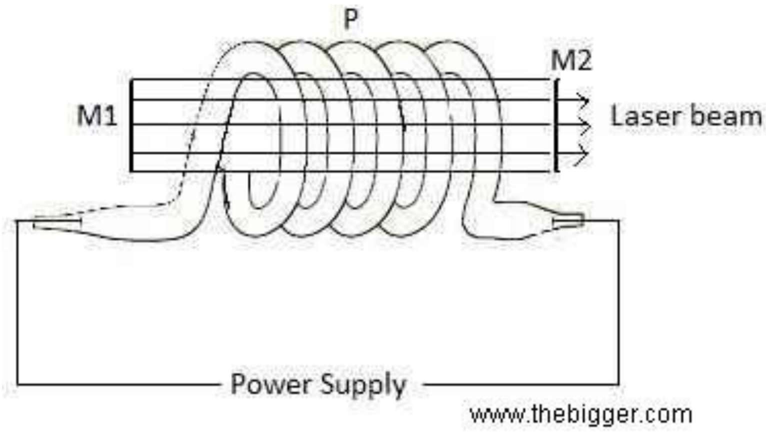


Fig 6.6 Solid State Laser [95]

Liquid Lasers

In liquids, most of the excited states decay so rapidly due to collisions with surrounding atoms or molecules that it first difficult to accumulate enough population in an upper laser level and to achieve significant gain. Fluorescent dyes are the best liquid media for lasers; their excited energy levels are populated either by flash lamps or by lasers. They are tuneable over a broad range of wavelengths

Semi conductor Lasers

Semi conductor lasers, sometimes called diode lasers, are not solid-state lasers. In these lasers junction diodes are used. The doping of p-n junction diode is done. Both the acceptors and donors are doped. These are known as ILD (Injection Laser Diodes). Whenever the current is passed then the light modulation from the ILD can be seen. This is used in various electronic equipments. These electronic devices are generally very small and use low power. They may be built into larger arrays, e.g., the writing source in some laser printers or compact disk players. This laser is the chosen one for the light source design due to its characteristics and this is explained in the next section.

6.1.3 Semiconductor Laser [97]

Semiconductor lasers are very powerful, small lasers and create precise beam of light as any other lasers. The lasers can be seen in DVD players, barcode scanners, or laser printers. The idea of using this type of laser is due to its cheaper prices, much smaller size and the power output is adequate for the barcode system. These lasers are readily and easily available from the market and come in different output power rate that can suit any or this application. Semiconductor lasers uses the same principle as LED but are tweaked to produce more power of light. As in LED, p-type (rich in holes, negatively charged atoms) and n-type (electrons) are put together to create the p-n junction diode. In semiconductor laser, a different medium, an alloy of aluminium and gallium arsenide, other than silicon is used. When the electrons that are injected from the n-type into the diode, they combine with the holes and photons are produced due to excess energy. The photons interact with more incoming electrons helping to produce more photons and so on in a kind of self-perpetuating process called resonance. This repeated conversion of incoming electrons into the outgoing photons is the same as the process of stimulated emission that normally occurs in a conventional gas-based laser.[97]

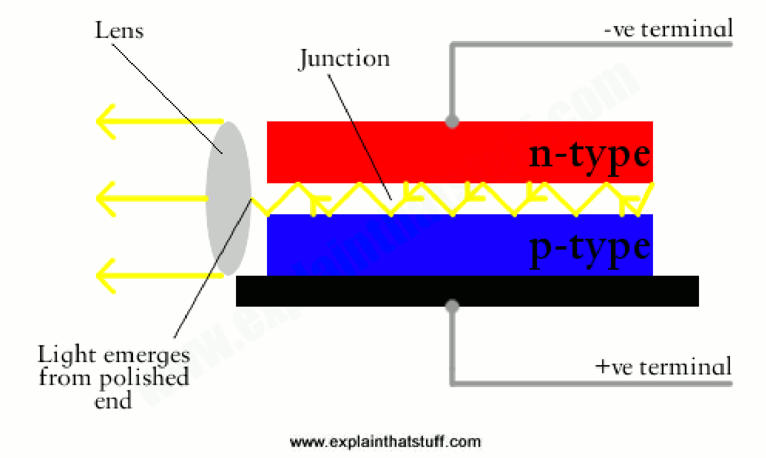


Fig 6.7 Semiconductor Laser [97]

As in conventional laser, the concentrated beam of light s produced by pumping light emitted from atoms repeatedly between two mirrors. In a semiconductor laser, this technique is replicated when the photons bounce back and forth in the microscopic junction between the n-type and p-type known as a Fabry-Perot resonant cavity. The amplified laser light emerges from the polished end gap in a beam parallel to the junction as shown in figure 6.7.

6.2 White Laser

The laser source design is very simple and consists of three main components; the Micro-Electro-Mechanical Systems (mems) mirror which rotates to direct the beam over the barcode, the beam expander which expands the beam to the desired size of one module and the laser diodes which are set-up to achieve white light. The mems mirror is easily available from the market and do not require further design or invention. The other two components are explained further in the following sections. When the research started, White laser was not yet discovered but was being researched. Back from 2015, White laser was introduced [89] but however is still not available in the market. The idea of achieving white laser is through the use of wavelength-multiplexed technique. Three main lasers; Red, Blue and Green are used. Optical beam splitters are used to redirect the laser wavelengths into a parallel beam, hence merging them together to get the white light. Below is a set-up of the Laser diodes to generate the white led beam.

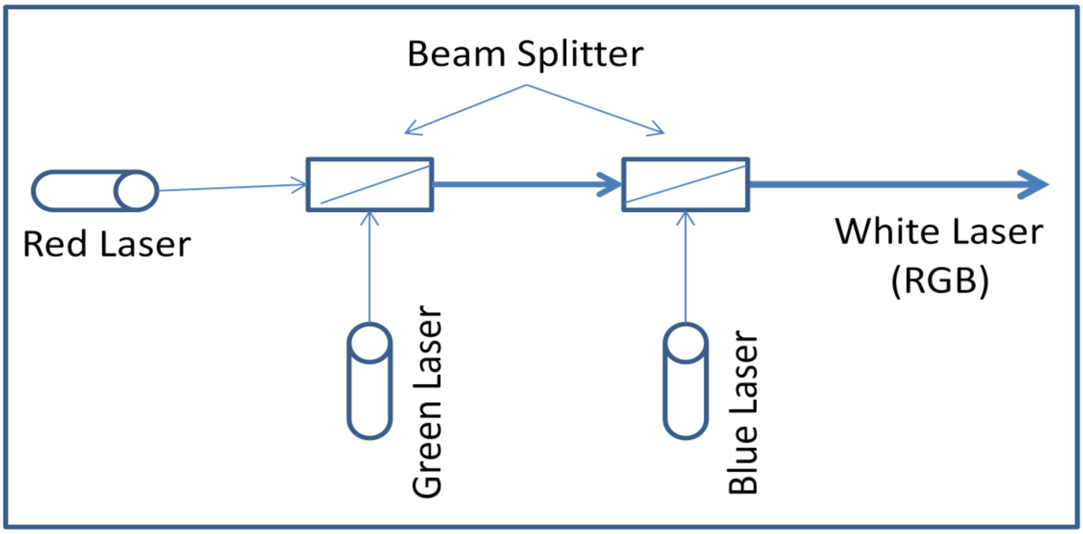


Fig 6.8: White Laser

The technique in use is wavelength-division multiplexed. Three primary colours required to generate white light are obtained from red (approx 630nm), blue (approx 425nm) and green (approx 515nm) lasers. The first beam splitter is used to direct the laser lights from the red and green lasers towards the second splitter. The latter combines the lasers' beam with the blue one laser into one single parallel beam which eventually merges to white. The graph on the following page illustrates the wavelengths of the three lasers at their highest intensity.

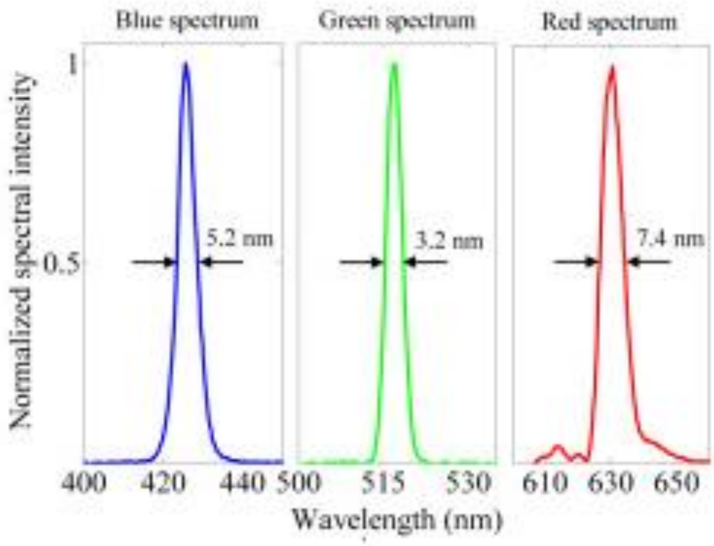


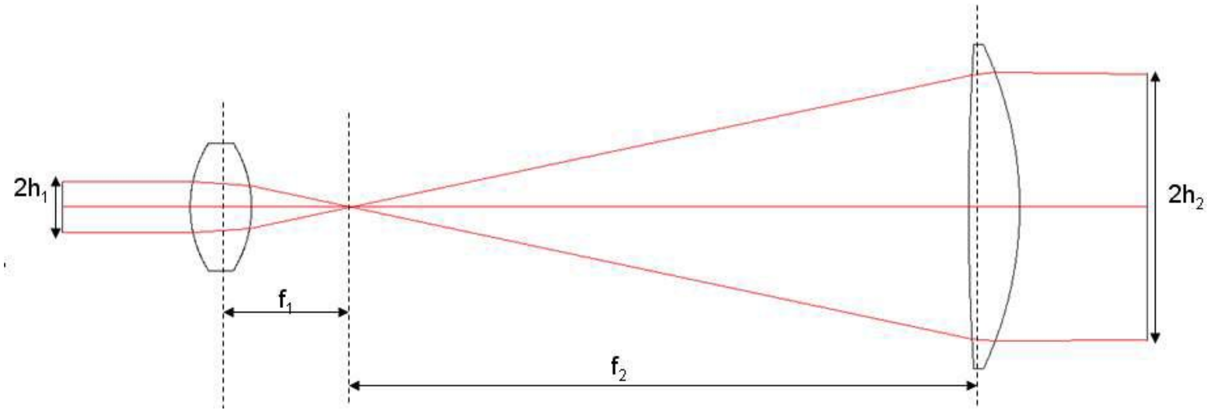
Fig 6.9: RGB Wavelength [90]

6.2.1 Beam Expander

The use of a beam expander is very common in most lasers' applications in optics. Very often, like in this project, the desired beam spot size is different from the beam size from different lasers in use. To eliminate this problem and achieve the correct laser beam size, a beam expansion or reduction is used. A beam expander will be used in this project as the desire beam spot of diameter 5mm is bigger than the laser beam from the lasers to be used. For every applications and requirements, a unique beam expander is required to be built. This means that for a specific laser choice, a unique beam expander will need to be designed to magnify the original beam size to the desired output beam required. For this reason, the principle of designing the beam expander will be explained along with some samples. This guide will be followed to design the final beam expander once the right and final lasers have been chosen in later chapters. Please note that for every laser in use in the barcode system, a unique beam expander will be needed.

Different types of beam expanders exist [91] while a basic one will be used in this project. A basic one consists of two lenses with positive focal lengths; one small lens with diameter which should be a bit bigger than the input beam and one bigger lens with diameter which will be slightly bigger than the desired exit beam size. It is recommended to use a lens that a little bigger than the input beam where for instance if the input beam is

10mm, the lens diameter should be of minimum 12mm [91]. Around 80% of a lens is always useable [91]. Below is a model of a basic beam expander.



$$M = \frac{f2}{f1} = \frac{R2}{R1} = \frac{h2}{h1}$$

Fig 6.10 Beam Expander [91]

M = the magnification of the beam expander

$\mathbf{f_2}$ = effective focal length of exit lens

$\mathbf{f_1}$ = effective focal length of entry lens

$\mathbf{R_2}$ = radius of curvature of exit lens

$\mathbf{R_1}$ = radius of curvature of entry lens

$\mathbf{h_2}$ = radius of exit spot (image height)

$\mathbf{h_1}$ = radius of entry spot (object height)

The distance between the two lenses is the sum of f_1 and f_2.

Considering a laser with 1.59mm beam spot, to achieve around 5mm beam spot;

- A magnification value of 3.15 is required
- The input lens diameter will be of minimum 2mm with 2mm focal length
- The output lens diameter will be of minimum 6.3mm with focal length 6.3mm

Some samples of a basic beam expander known as Keplerian Beam Expander from [91] which uses the same technique shown above is given below. This can be used as a guide to customise the beam expander for use in unique applications.

Table 6.1: Keplerian Beam Expander Samples

M (approx)	**Lens 1**	**Diameter (mm)**	**Focal Length (mm)**	**Lens 2**	**Diameter (mm)**	**Focal Length (mm)**	**Max Input Beam Diameter (mm)**
2x	KBX022	12.7	12.7	KPX076	25.4	25.4	10
3x	KBX028	12.7	25.4	KPX181	50.8	75.6	10
4x	KBX028	12.7	25.4	KPX187	50.8	100	10
6x	KBX028	12.7	25.4	KPX226	76.2	150	10

6.3 Challenges

Despite having achieved the minimum requirement for the light source, there are still more challenges that the barcode system faces when it comes to the full symbol scan. Ideally, the mems mirror in the light source component helps to direct the laser spot over the barcode symbol to cover and illuminate all the modules one at a time. The beam expander helps to increase the initial laser spot to the desired 5mm diameter that will cover the surface of one module. The problem of the laser beam occurs when the mems mirror moves the laser spot from and to each end of the barcode and this is shown below. As seen in the following figure, the laser spot is of stretches more than its original sizes when it reaches the modules of the barcode symbol. The beam spot is of diameter 5mm when it is perpendicular to the light source mems mirror. As soon as the mirror rotates, the angles changes and this forces the laser beam to stretch further than the desired 5mm diameter due to the law of reflection.

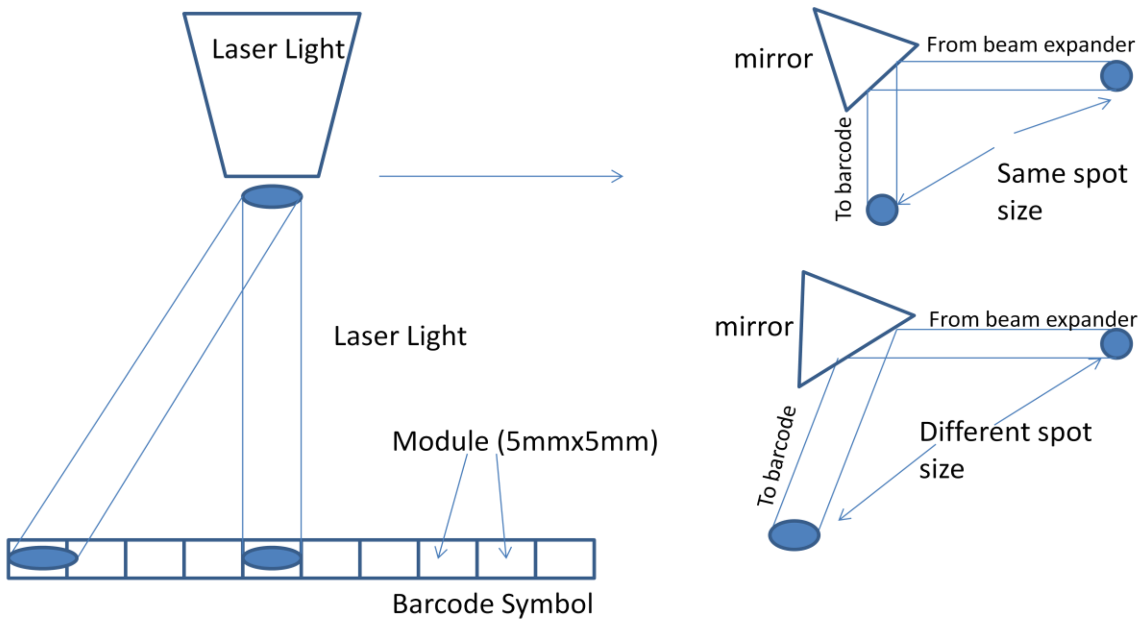
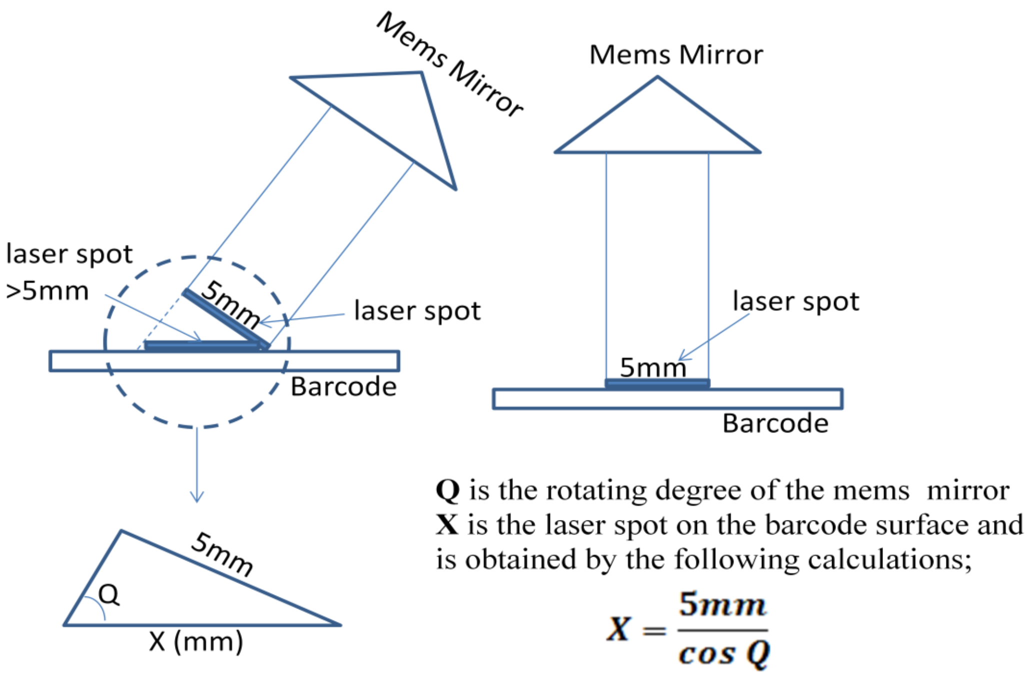


Fig 6.11 Laser Light Source Challenge

The challenge occurs at the barcode surface itself. Below are some detailed pictures which help to have a better understanding of why this occurs.



Q is the rotating degree of the mems mirror
X is the laser spot on the barcode surface and is obtained by the following calculations;

$$X = \frac{5mm}{\cos Q}$$

Fig 6.12 Laser spot Stretch

As clearly seen above, when the mirror rotates, the degree of rotation affects the size of the laser spot when it reaches the barcode surface. Two proposals are given below and evaluated. However, this phenomenon will be dealt with in future work. The higher the rotation angle, the longer the laser spot is stretched.

The first proposal is to have a smaller laser spot than the size of the module. This will help eliminate the second challenge mentioned above. When rotation occurs at maximum, then the size of the laser spot stretches to a maximum length that matches the module size. However, this practise is still not favourable as the barcode design minimum requirements do not allow any light spot smaller than the barcode module. The simple reason is because each module needs to be illuminated on its own at each time intervals and any light spot bigger or smaller will result in illuminating two modules or parts of 2 modules at the same time.

The second proposal is to move the laser and beam expander along with the mems mirror. This setup is very complicated and requires further research. It will help eliminate the first challenge explained above. Moving all the components within the light source will still not eliminate the second issue. However, the stretch can be controlled if the angle of rotation is kept at minimum (around 3 degrees). The only way this can be achieved is by keeping the light source furthest possible from the barcode symbol. The distances along with rotations are explained in chapter 3 and 4. Stretch of around 0.1mm can be neglected if achieved.

The best solution is to have the entire light source moving over the barcode symbol. The idea is to stop using the mems mirror. The beam expander directs the light towards the barcode modules directly. The entire light source moves over each of the barcode modules illuminating them each at one time covering the 2D surface. This however requires intensive optical development for the entire light source to move and will therefore be considered in future works.

6.4 Summary

This chapter designs an alternative light source which is laser. LED has been the primary light source choice. Due to some complicated set-up required for LED to achieve the minimum requirements of the project, laser has been chosen as an alternative source of light to be tested. The components in the laser light design are explained. White laser is still being research. A proposal of how white Laser can be achieved from RGB (Red, Green, and Blue laser diodes) is given. A beam expander is used to increase the laser spot to the desired size of 5mm. Challenges are discovered in the laser light source and explained. Some proposals are given to eliminate any of these limitations in order to achieve 100% efficiency.

Chapter 7

Experimental Work

This chapter sets out to partially test the barcode system designed. Due to the unavailability of the desired simulation software LightTools, the new barcode model could not be tested. However, using some components that are available from the market, part of the system can be designed and tested in the University Laboratory using the specifications set out in chapter 4. The goal here is to prove and show that the main components of the system designed will deliver the basic requirements of the barcode system. This achievement will mean that the entire system will be a success if put in production. This chapter illustrate each test carried out in sequence along with a summary of the observations. Below is a list of the components that are used in the experiments;

- LED diode (Luminous Flux of 1550-2402 lumens)
- Helium-Neon Laser (5mW, max output at 632nm)
- Convex lens (Diameter of 50mm with focal length of 5cm)
- Si PIN Photodiode (spectral response: 320nm to 1100nm)
- Hameg Triple Power Supply HM 8040
- Digital Multimeter HM8011-3
- Rulers and free hold stands

The technical data sheets for the Laser, LED and Photodiode are found in Appendix C.

7.1 Practical Work

Experiment 1 –Light Source

This experiment uses a LED diode, a convex lens and a mirror to simulate the light source required to illuminate the barcode symbol. The goal here is to obtain a led spot of at least 5mm over a distance of at least 50cm which meets the design requirements. A tube (made of carton) is placed in front of the led diode to direct the light towards the desired target. A convex lens is used to achieve the led spot required to illuminate a 5mm grating module of the barcode symbol. The mirror is used to replicate the functions of a MEMs mirror which would illuminate all the modules in the barcode each at a time. The figures below illustrate the experiment followed by the results obtained and observed.

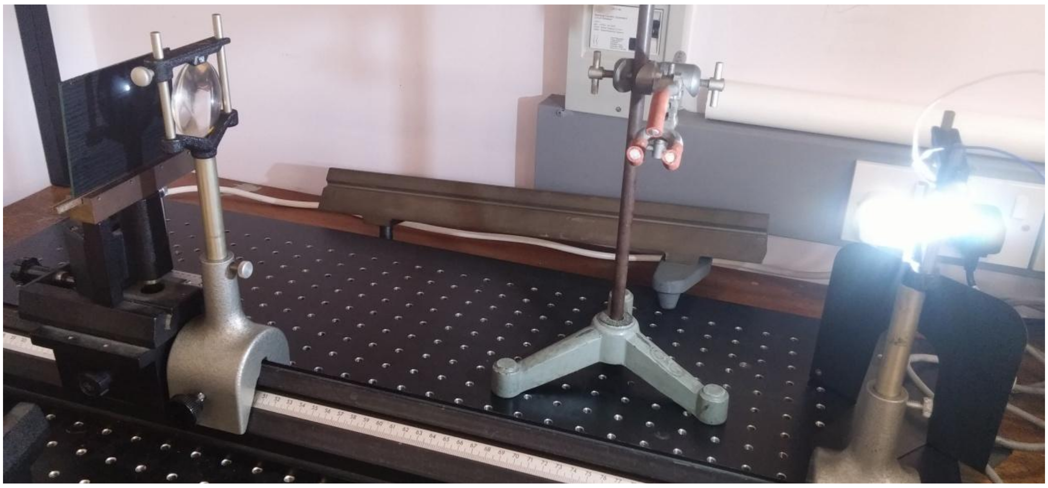


Fig 7.1(a) LED Source Light

Fig 7.1(b) LED Spot

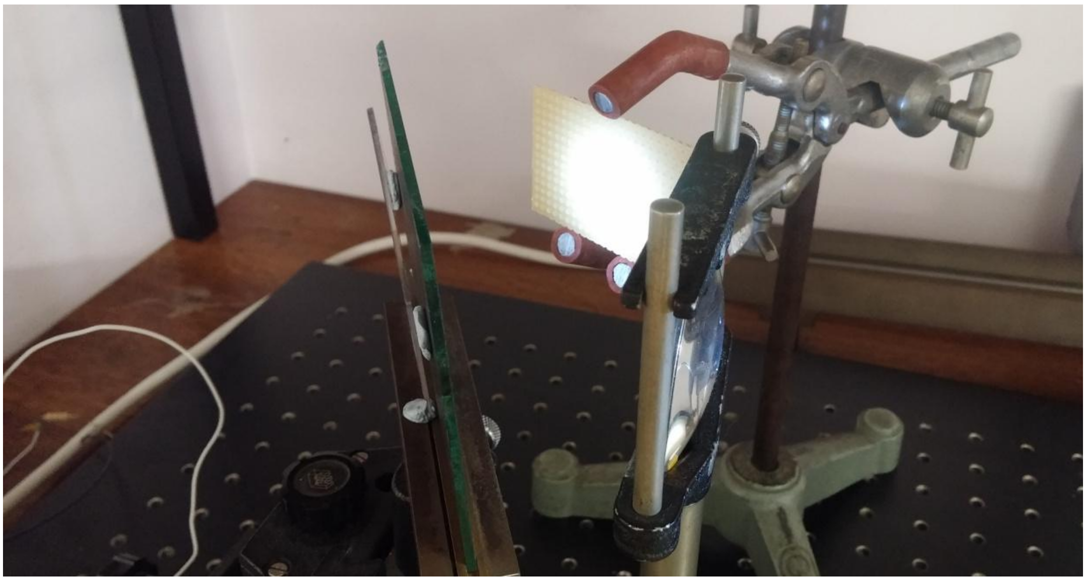


Fig 7.1(c) LED Spot Reflection

Observation

- Figure (a) shows that with the help of a convex lens, it possible to converge the light to a small spot. The tube made of carton prevents loss of light by diffusing all the light towards the lens.
- Figure (b) shows the proof that a small LED spot of at least 5mm is achievable.
- Figure (c) shows the effects of the LED spot light when it is reflected off a mirror. The spot light of 5mm widens and becomes bigger as the screen is moved further away.

Experiment 2 – Alternative Source Light

As shown in the first step the further the barcode/ projection screen is placed from the source light, the wider the light spreads which fails to achieve the minimum required light spot of 5mm by 5mm. To prevent this phenomenon, an alternative light source is the best option. Since the start of the research, white laser did not exist until recently. The first white laser has been designed and tested at the Arizona State University in July 2015[89]. Despite the fact that white laser conductor is unavailable for practical work, red laser, which is assumed to have the same laser intensity as the white laser, will instead be used in this experiment. Pictures below show the experiment where a Laser Diode is used with a mirror that will replicate the MEMs mirror.

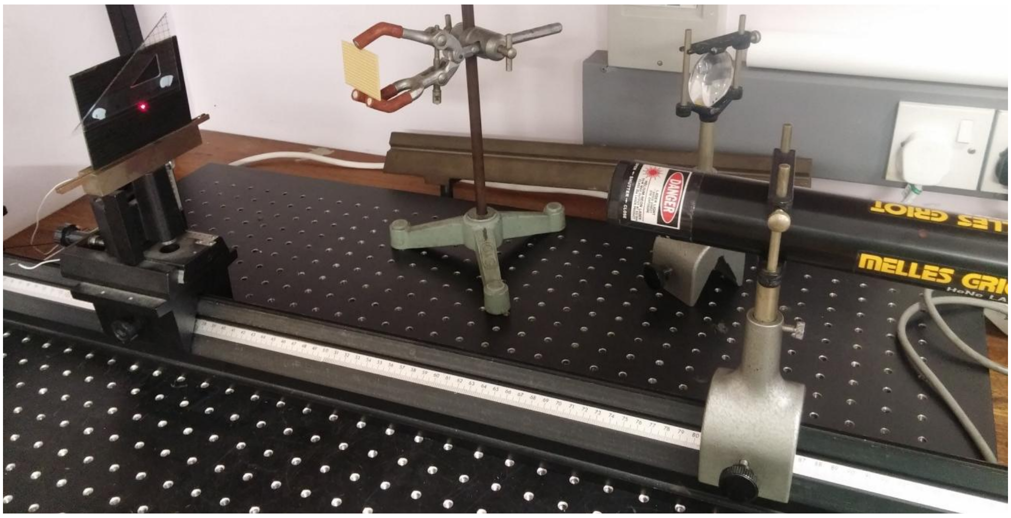


Fig 7.2(a) Laser Source

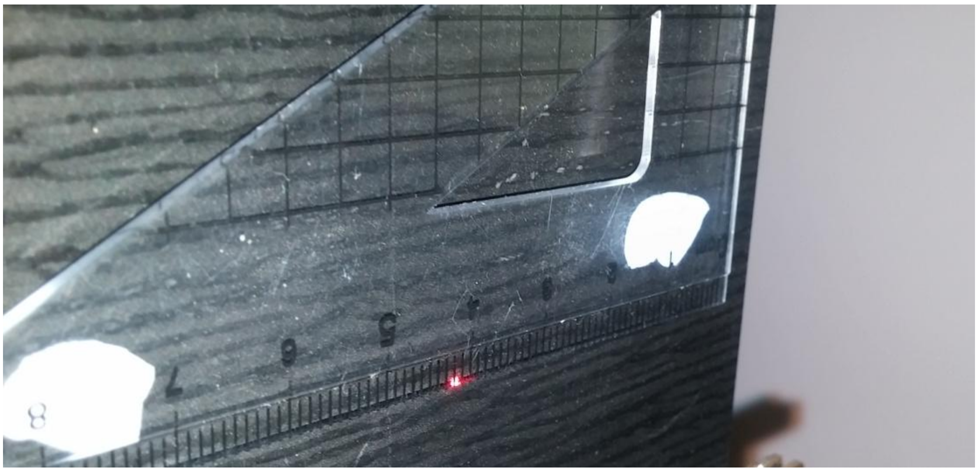


Fig 7.2(b) Laser Spot

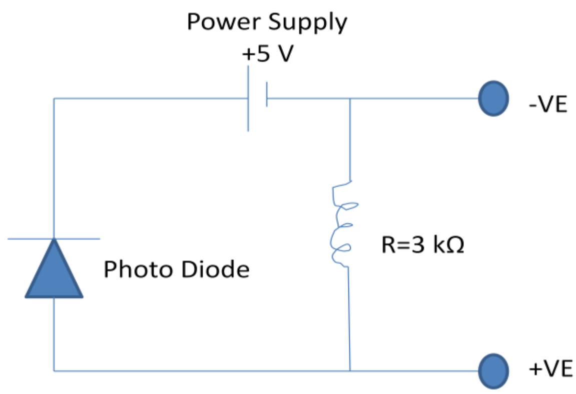
Fig 7.2(c) Laser Spot Reflection

Observation

- Figure (a) displays the setup of the Laser light, mirror and the screen (barcode symbol). The screen is placed 50cm from the mirror which will be the light source as mentioned in the chapter 4.
- Figure (b) shows that the projected laser spot is at least 5mm as required. Compared to LED light, the laser beam will stay the same over very long distances, as shown in picture.
- Figure (c) shows that the laser spot is less than 5mm and to achieve the desired spot diameter, the beam expander mentioned in earlier chapters will be used final applications.

Experiment 3 – Light Detector

This experiment puts a Silicon Photodiode under test to observe and understand how the designed detectors will behave within the barcode system design. A 5V power supply and a resistance of 3kohms are used to connect the photodiode to the multimeter as shown in figure 6.5. Below are some figures with different tests and resulting current followed by a summary of the observations.



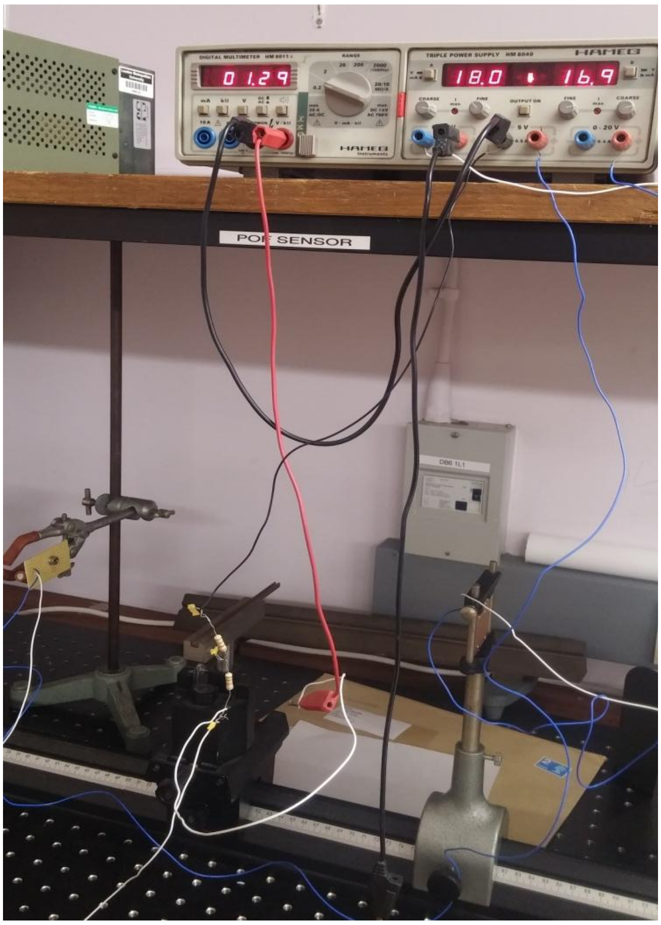


Fig 7.3 SI Photodiode Connection Circuit

Fig 7.4(a) SI Photodiode Calibration 1

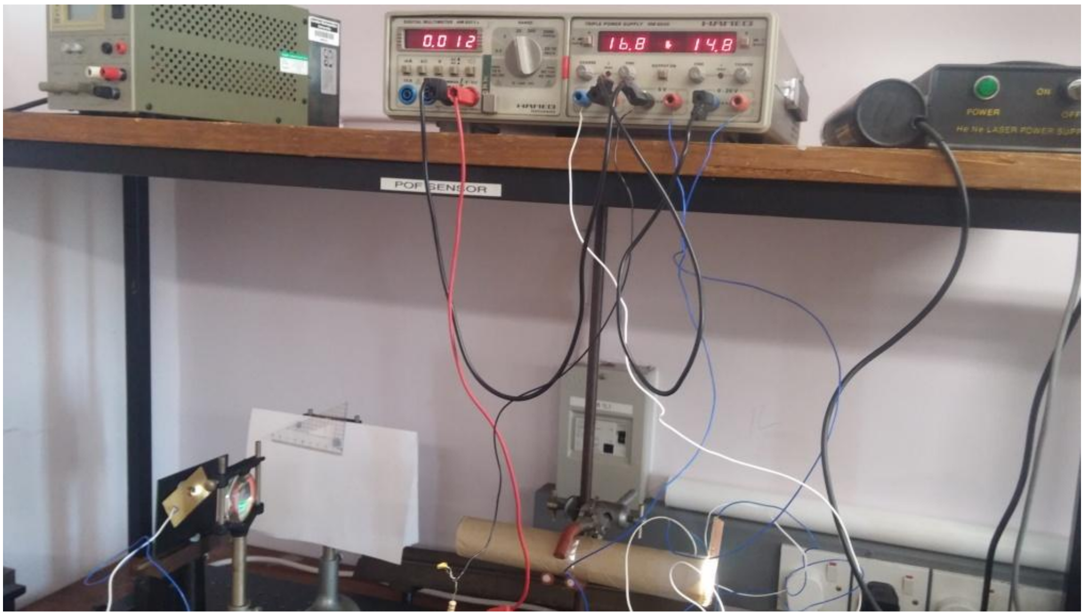


Fig 7.4(b) SI Photodiode Calibration 2

Observation

- The reading 1.3mV in figure 7.3 is the noise in the system under normal day-light conditions. The noise reading is around 0.1mV under dark conditions.
- Figure 7.4(a) show the reading obtained when the Laser light is projected onto the detector. The result is around 2.5 V. Signal-to-Noise under normal day-light is 20 log (signal/noise) = 65.7dB and 88dB under dark conditions.

- Figure 7.4(b) show the reading obtained when the LED spot light is projected on to the detector. The result is around 12 mV. SNR under normal day-light is 20 log (signal/noise) = 19.3dB and 41.6dB under dark conditions.
- The reading obtained from the photodiode depends not only on the wavelength of the light but also the intensity of it. The higher intense the light, a higher voltage is obtained and vice-versa.
- Below is a table which summarises the reading obtained when the photodiode is used to detect and read the light spectrum diffracted from the gratings. Both LED and Laser are used in this experiment.

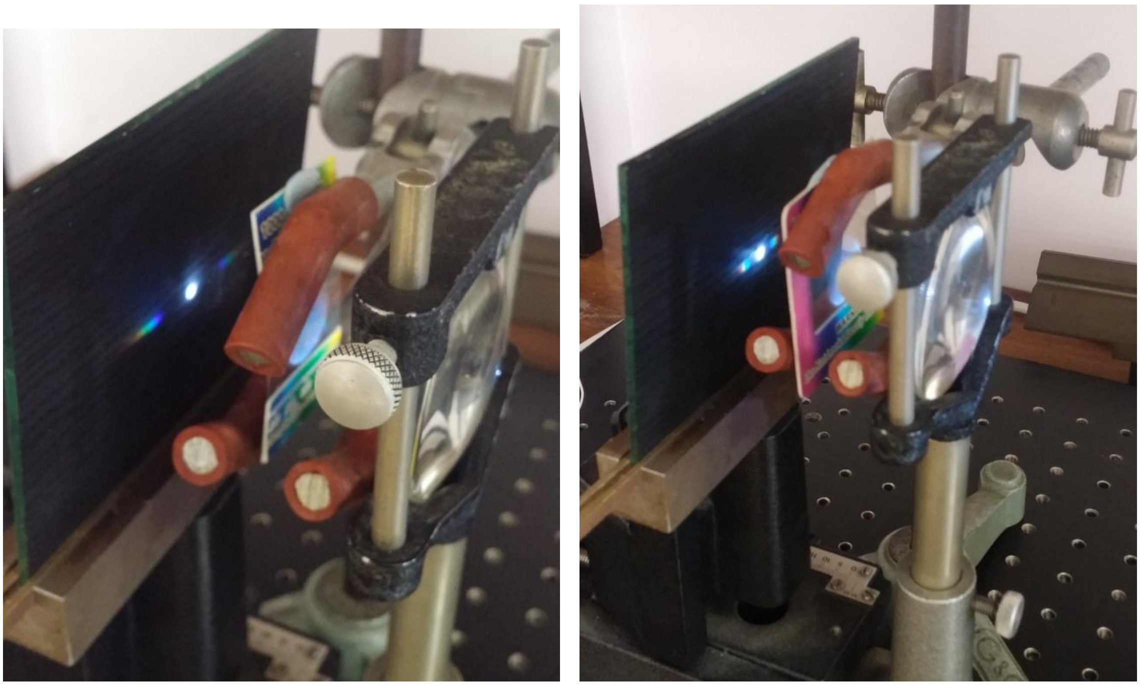
Table 7.1: Photodiode Readings

Light Source	**Distance from Detector**	**Grating**	**Reading (V)**	**SNR (dB) Day-light**	**SNR (dB) Dark**
LED	40cm	None	0.12	19.3	41.6
LASER	50cm	None	2.5	65.7	88

- The readings obtained above in the table clearly show that the reading obtained from the photodiode heavily depends on the intensity of the light. Light intensity decreases after each diffraction.
- Laser light maintain higher light intensity over a very long distance as compared to LED which drops the light density very rapidly over a short distance.

Experiment 4 – Barcode Symbol

The second main component is the barcode itself which is composed of diffraction grating. The experiment is carried out to find how gratings behave under the light source specified for the barcode system. The purpose is to prove the theory and formulae of gratings used in the design chapter. The first light source used to help illuminate the grating is LED followed by the alternative proposed Laser light. Two different set of gratings with specifications of 500 and 100 lines per mm each are tested.



(i) 500 lines/mm (ii) 1000 lines/mm

Fig 7.5(a) Diffraction Grating (LED)

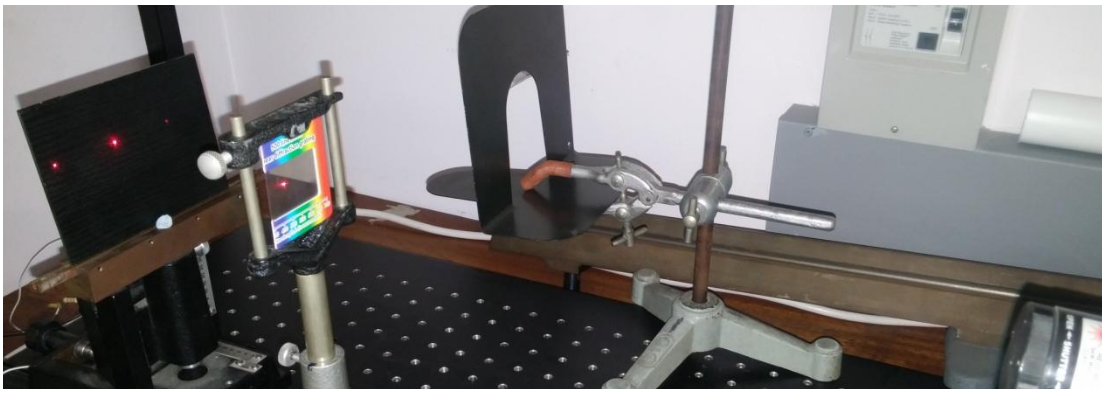


Fig 7.5(b) 500 l/mm Diffraction Grating (Laser)

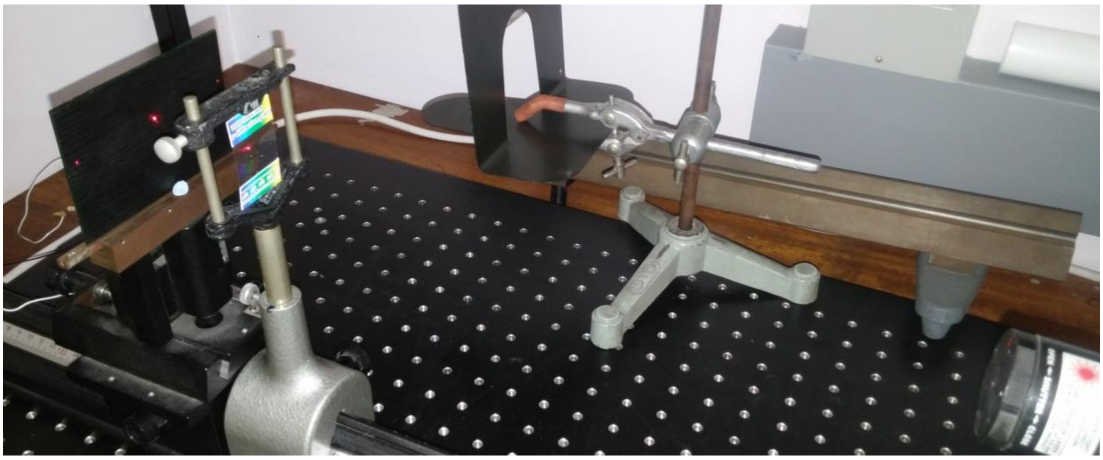


Fig 7.5(c) 1000 l/mm Diffraction Grating (Laser)

Observation

The first two pictures show experiments using LED as source light while and the last two pictures shows experiments using Laser source light. Other observations are as follows;

- The experiment clearly demonstrates that using a grating and a source light, makes it possible to obtain a spectrum of visible light with a variety of wavelength.
- Figure 7.5(a)(i) and 7.5(b) show the diffracted visible light spectrum from a 500 line per mm grating.
- Figure 7.5(a)(ii) and 7.5(c) show the diffracted visible light spectrum from a 1000 line per mm grating.
- Both gratings diffract light in different ways proving that the number of lines in a grating influence the way light diffraction occurs. This means that it is possible to

obtain desired range of wavelength by using different gratings with specific lines per mm.

- Table below show the readings obtained using the photodiode with SNR under day-light conditions.

Table 7.2: One-layer Grating Readings

Laser	**M=0**	**M=1**	**M=-1**
500 l/m	1.26V	0.115V	0.120V
SNR(dB)	59.7	38.9	39.3
1000 l/m	2.0V	0.023V	0.026V
SNR(dB)	63.7	25	26
LED	**M=0**	**M=1**	**M=-1**
500 l/m	0.69V	0.05 – 0.11V	0.05 – 0.11V
SNR(dB)	76.8	34-60.8	34-60.8
1000 l/m	1.82V	0.02 – 0.025V	0,01 – 0.015V
SNR(dB)	85.2	46-48	40-43.5

Experiment 5 – Alternate way to achieve desired wavelengths' diffraction

Experiment 3 shows that using specific gratings with specific lines per mm allows to obtain the desired spectrum of visible light. This experiment tests an alternative way to try and achieve desired light wavelength. The technique used is simply to alter the incident light angle by tilting the grating.

Fig 7.6(a) Incident Light Angle (LED)

Fig 7.6(b) Incident Light Angle (Laser)

Observation

- Normally, with the incident angle of 0 degree, there will be two diffractions in the first order (m=-1 and m=1). By tilting the grating, the incident angle is changed which then diffract different sets of light wavelengths. The experiment has been done using both LED (shown in first picture) and Laser (shown in second picture) to observe the different ways the light are diffracted.
- As seen in both pictures some wavelengths are missing on one side compared to the other. This happens because when the incident angle is changed (tilting the grating axis), then the diffracted wavelengths of visible light also changes. Based on diffraction grating theory, some wavelengths will not be diffracted whilst the diffraction angles of some orders will change also. Diffraction formula explained in chapter 3 gives further details.
- Table below shows some reading taken for the diffraction orders with daylight SNR.

Table 7.3: Tilted Grating Readings

Laser	**M=0**	**SNR(dB)**	**M=1**	**SNR(dB)**	**M=-1**	**SNR(dB)**
500 l/m	1.92V	85.7	0.142V	63	0.189V	65.5
1000 l/m	2.3V	87.2	0.048V	53.6	0V	0
LED	**M=0**	**SNR(dB)**	**M=1**	**SNR(dB)**	**M=-1**	**SNR(dB)**
500 l/m	1.43V	60.8	0.095V	37.3	0.15V	41.2
1000 l/m	0.93V	57.1	0.008V	15.8	0.35V	48.6

Experiment 6 – Projected Screen / Detector

The original positioning of the top layer detector was specified to be 4.5cm to the left and 1.5cm to the top of the grating. This experiment replicates the specifications along with the grating tilted 4 degrees to test if the proposed position of the detectors will be able to capture the light diffraction. The detectors have been replaced by a white paper which acts as a screen to make it visible.

Fig 7.7(a) First Layer Projection Screen (LED)

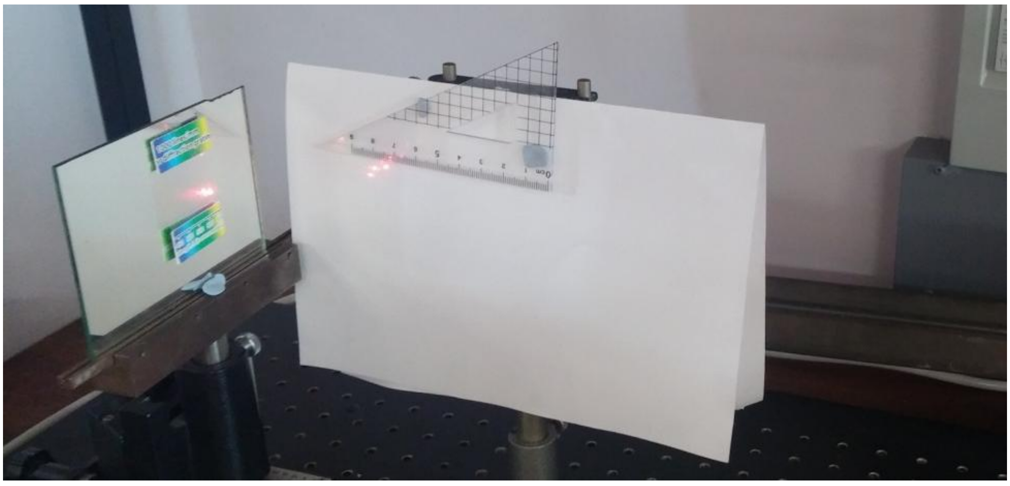


Fig 7.7(b) First Layer Projection Screen (Laser)

Observation

- The white paper is used as the projection screen and is positioned as specified for the top layer detector. The light diffraction can be seen projected on the paper screen for both the LED and Laser light sources in the figure 7.7 for both the LED and Laser light sources.

Experiment 7 – Dual Layer

The first part of this experiment is carried out to understand how two gratings will react and diffract light. The second part of the experiment is done to understand how the reflection of dual grating diffraction will occur. Two gratings with different specifications (500 lines/mm and 1000 lines/mm) are used and figures 7.8 (a) and (b) illustrate the diffractions of each of them. Figures 7.8 illustrate the first part of the experiment followed by the observation and figure 7.9 shows the second part.

Fig 7.8(a) Dual Layer (LED)

Fig 7.8(b) Dual Layer (Laser)

Observation

LED source light is used in the figure (a) and laser source light is used in figure (b).

- The incident light is diffracted through the first layer, and then the diffracted light (including all m orders) is diffracted again through the second grating resulting in dual-diffraction phenomena.
- The resulting diffraction on the screen shows that;
    1. The incident light is diffracted from the first layer (first grating) resulting in different m orders and m=0 order.
    2. Then the diffracted light from the first layer along with the m=0 order (incident light) are all diffracted again through the second layer (second grating). The resulted diffraction observed on the screen at the back is the result which can be seen as a combination of the diffractions seen individually for each grating.
- The following table on next page summarises the results captured using the photo diode.

Table 7.4: Dual-Grating Readings

Laser		M=0	M=1	M=-1	M=2	M=-2
1st Layer	**2nd Layer**					
500 l/mm	1000 l/mm	1.51V	0.112V	0.1V	0.04V	0.042V
1000 l/mm	500 l/mm	1.55V	0.115V	0.096V	0.041V	0.031V

LED		M=0	M=1	M=-1	M=2	M=-2
1st Layer	**2nd Layer**					
500 l/mm	1000 l/mm	0.65V	0.045V	0.06V	0.02V	0.02V
1000 l/mm	500 l/mm	0.60V	0.05V	0.05V	0.017V	0.02V

The second part of the experiment is to understand how the second layer diffraction will reach the second detector. The first layer is semi-reflective where the reflection is simple. Two gratings are used with a mirror at the back to reflect the diffractions towards a screen acting as one of the detectors. Only laser has been chosen for this experiment as the diffraction is clearer to observe and understand. Below is the picture of the experiment followed by the observations.

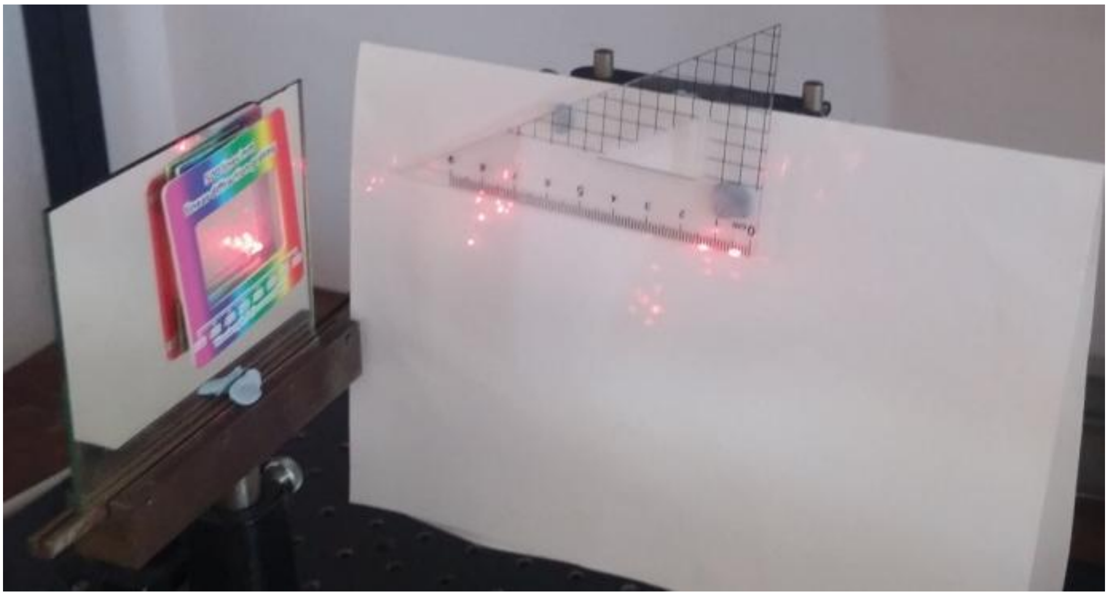


Fig 7.9 Dual Layer Diffractions

Observation

- The diffraction through the two layers occurs as explained in the first part above.
- When the diffraction is reflected towards the detector, it goes through the gratings again. This forces the diffracted spectrum to diffract again.
- This is observed in figure 6.9 where few dots of the red laser light are seen in a single area. These dots are the results of the incident light being diffracted more than two times.

Experiment 8 – Alternative Barcode Layers' alignment

A different setup of the barcode layers mentioned in chapter 4 (refer to Figure 4.9) is tested in this experiment. The purpose of this test is to prove that using the setup in Figure 4.9 will force two grating module to diffract light at the same time. Laser light is preferred to be used as source light as it is clearer to observe the behaviour of the diffractions.

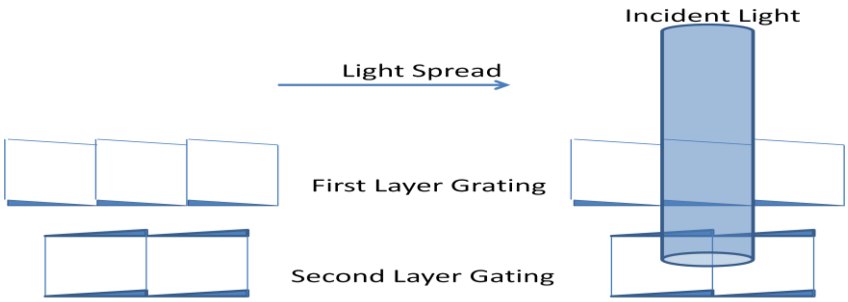


Fig 7.10(a) Alternate Layer Alignment Diagram

(i) (ii)

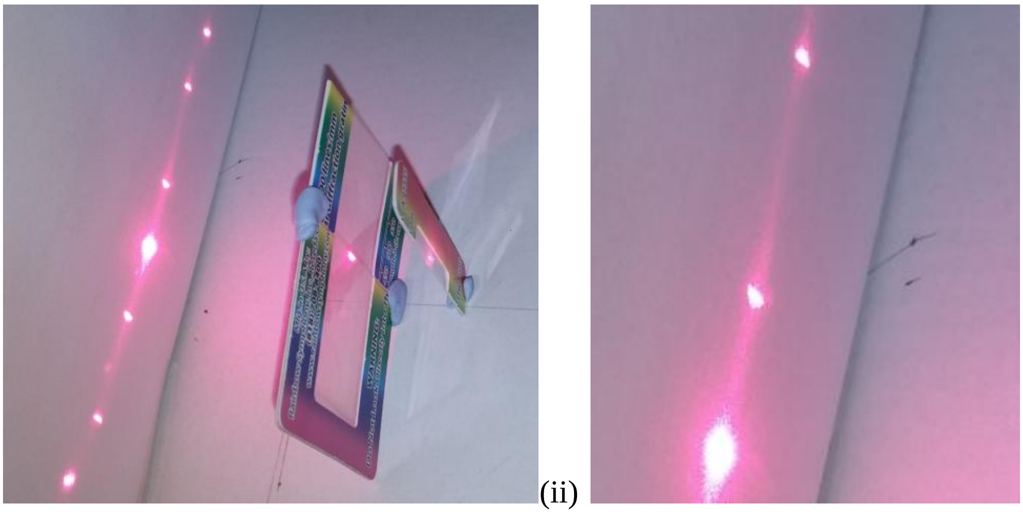


Fig 7.10(b) Alternate Layer Alignment Experiment

Observation

- Figure (a) is the drawing from chapter 4 to explain the grating layers' setup. Figure (b)(i) shows the diffraction results and figure 7.10(b)(ii) is a close look at one of the diffraction order.
- The laser spots observed are all different diffraction orders from the more than one grating at one time.
- The resulted diffraction in figure 7.10(b)(ii) shows that half of the laser's spot is diffracted though the left grating and the other half laser spot is diffracted through the other spot.
- This simply means that this setup doesn't meet the minimum requirement of the barcode system where only one grating is required to be illuminated at one time.

Experiment 9 – Use of gratings with coloured films

The Barcode System designed uses two sets of different gratings with different specifications for each layer to diffract different sets of wavelength spectrum. This experiment proposes and tests an alternative way to get different sets of visible light wavelength. The technique is to use grating with a specific wavelength and this is shown below in the pictures.

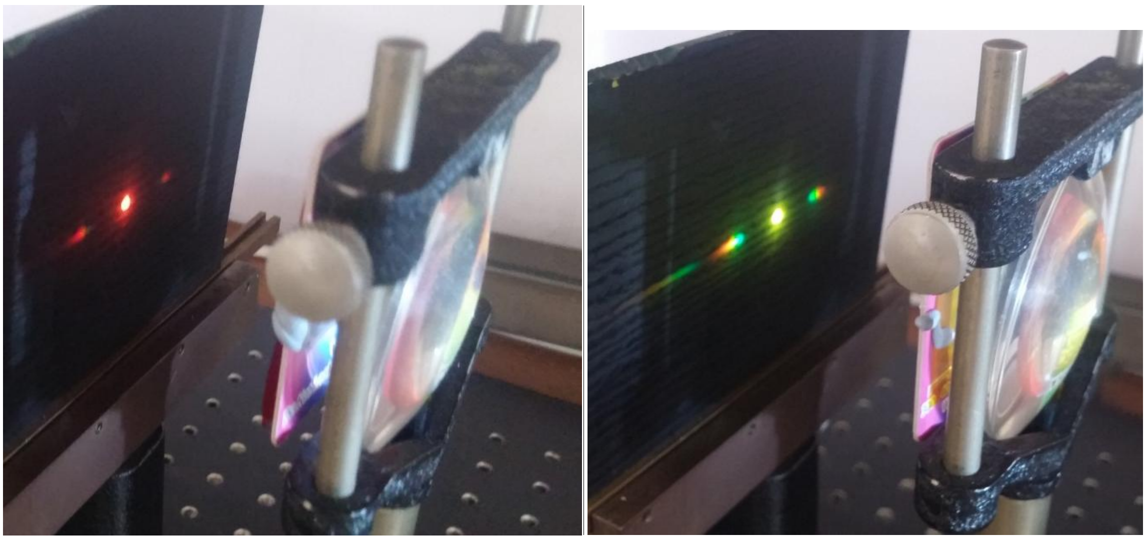


Fig 7.11(a) Diffraction using Coloured Gratings (LED)

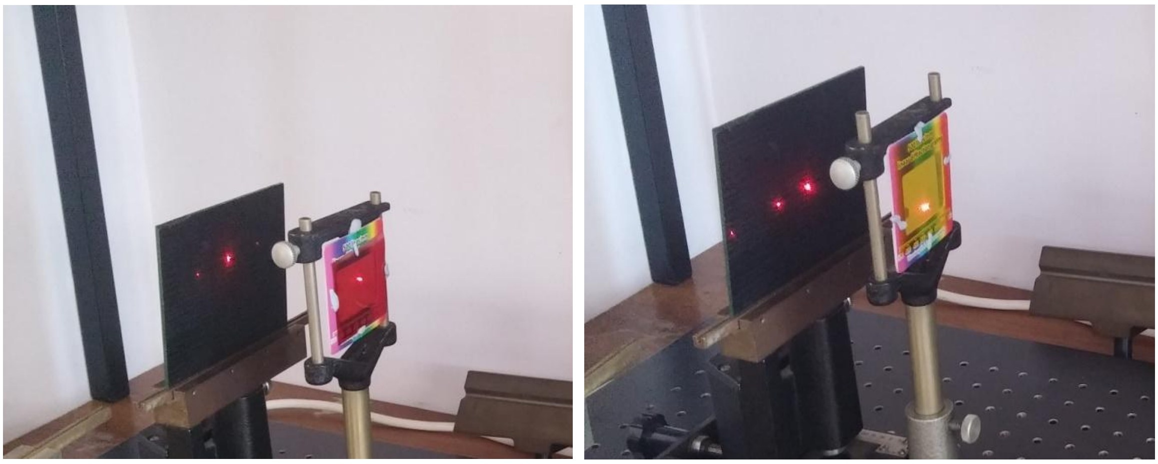


Fig 7.11(b) Diffraction using Coloured Gratings (Laser)

Observation

- Red and yellow are used to change the wavelength incoming incident light as seen in figure 7.11(b). Figure 7.11(a) shows diffraction using LED source light and figure 7.11(b) shows diffraction from a Laser.
- In figure 7.11(a), it is clearly observed that the incident light is filtered through the coloured film placed on the grating and the diffraction of the m order is the wavelength represented by the coloured film.
- This idea of using a coloured film on the same grating works great for white incident light. This technique has been adopted by other researches (HCCB) and will not be considered in this project.
- Below is a table of readings captured by the photo diode.

Table 7.5: Coloured film on 500 l/mm Grating Readings

Laser	**M=0**	**SNR(dB)**	**M=1**	**SNR(dB)**	**M=-1**	**SNR(dB)**
Red	1.35V	60.3	0.041V	30	0.043V	30.4
Yellow	1.5V	61.2	0.13V	40	0.17V	42.3
LED	**M=0**	**SNR(dB)**	**M=1**	**SNR(dB)**	**M=-1**	**SNR(dB)**
Red	0.51V	42.3	0.032V	50.1	0.010V	40
Yellow	0.65V	76.3	0.10V	60	0.061V	55.7

Experiment 10 – Alternative Grating Alignment

This experiment proposes a different setup of the gratings for one of the layers. Diffractions from gratings occur on two sides; the left and the right side with positive and negative m diffraction orders. Figure 7.12 (a) illustrates the new proposal which uses each grating on each layer to diffract light in four sides in total. The idea came whilst other experiments were being done.

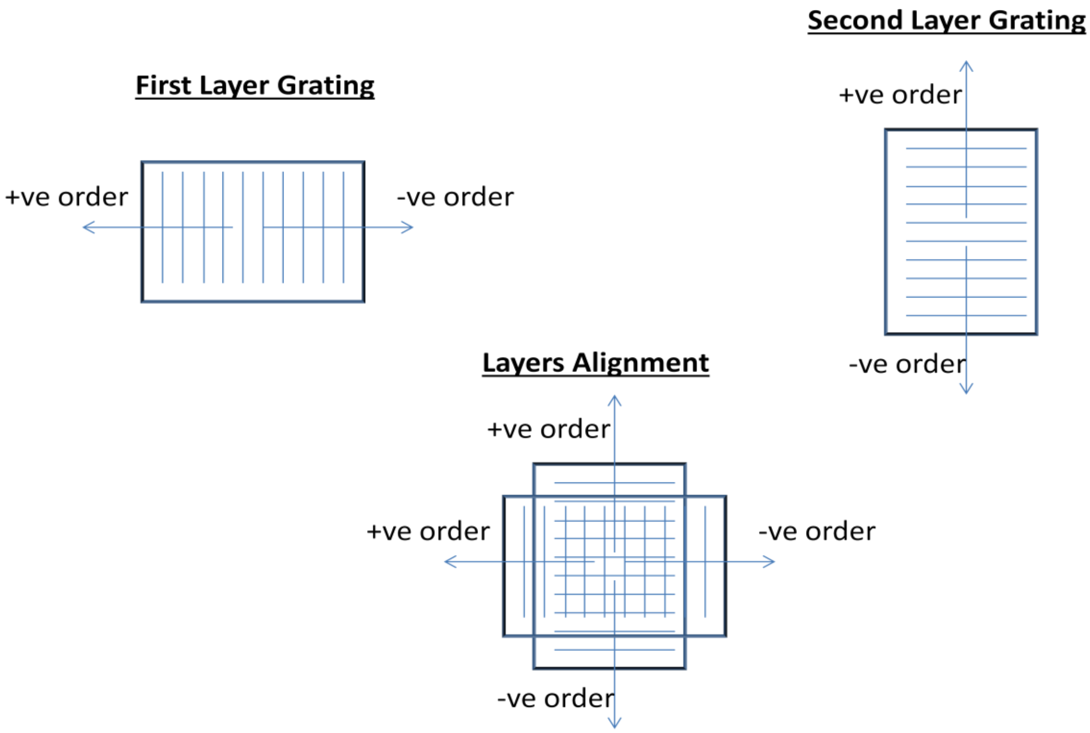
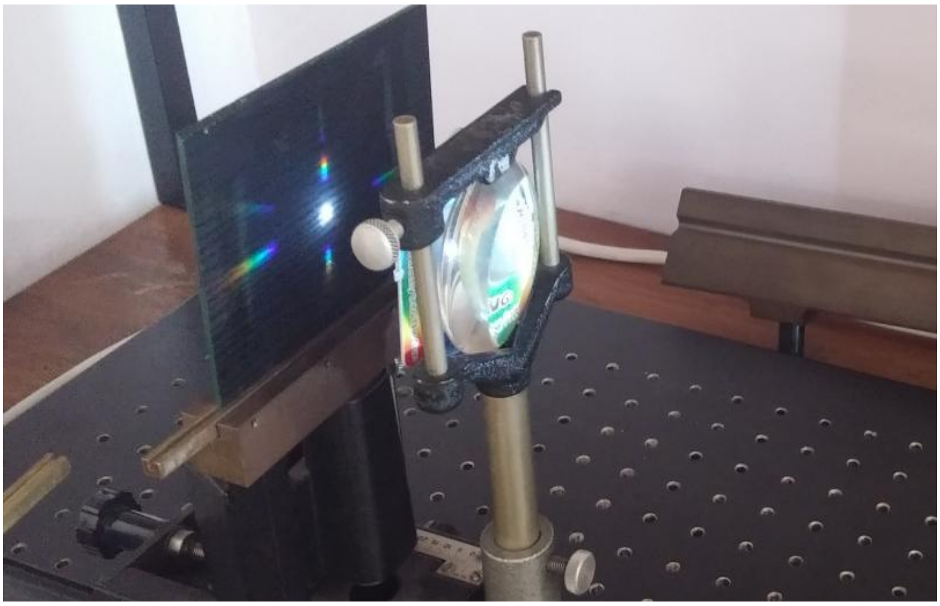


Fig 7.12(a) Alternate Grating Alignment Diagram



- **Fig 7.12(b)** Alternate Grating Alignment Experiment (LED)

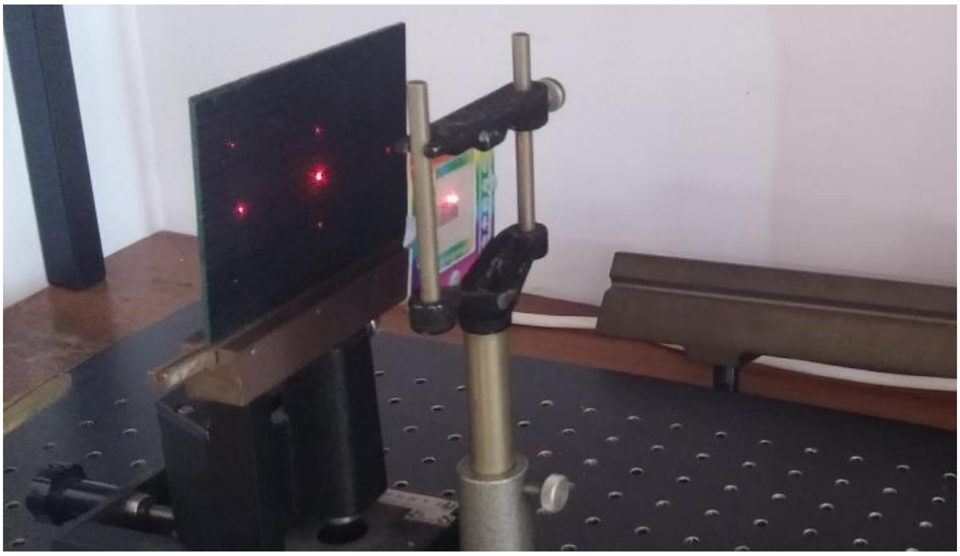


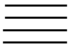
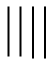
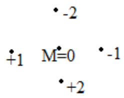
Fig 7.12(c) Alternate Grating Alignment Experiment (Laser)

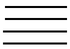
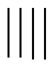
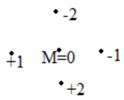
Observation

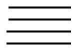
- Figure 7.12 (b) and (c) show the experiment of the new grating alignment.
- As observed, the first grating is diffracted on the left and right hand side while the second layer is diffracted on the top and bottom.
- There is more diffraction in the corners which is the results of the first layer diffracted orders being diffracted again through the second layer as explained in experiment 7.

- However, this set-up will not work in the current barcode system as the detectors alignment would need to be different. The last experiment is a proposal of a new alignment designs that will incorporate this new grating alignment if preferred. SNR is not included but can however be easily calculated using the 20 log (Signal / Noise) formula.

Table 7.6: Alternate Dual-Grating Readings

Laser		**M=0**	**M=1**	**M=-1**	**M=2**	**M=-2**
						
500 l/mm	1000 l/mm	1.75V	0.035V	0.04V	0.087V	0.078V
1000 l/mm	500 l/mm	1.67V	0.11V	0.096V	0.007V	0.06V

LED		**M=0**	**M=1**	**M=-1**	**M=2**	**M=-2**
						
500 l/mm	1000 l/mm	0.42V	0.015V	0.018V	0.06V	0.085V
1000 l/mm	500 l/mm	0.68V	0.067V	0.053V	0.018V	0.018V

P.S: M=2 and M=-2 refers to the first refraction order of the first grating 

7.2 Summary

This chapter involves practical work carried to test some components' designs in the barcode system as well as to observe how each component designed will work under the specified specifications. All the experiments have been done in stepwise; starting with the light source, the gratings, the dual layers, and the finally the entire barcode design. Most of the experiments have been done using both laser and LED source light. Alternative techniques of some components or specifications have also been proposed and experimented to aid tune the barcode system to deliver better results. The practical starts with the source light where a 5mm LED spot was unable to achieve over a distance of at least 50cm. Alternative light source which is white laser has been proposed to solve the problem and tested. The next experiment involves the grating itself which shows how a grating diffracts light and how the spectrum of light can be limited to a certain range of wavelengths. Two different gratings with different lines per mm have been used to simulate the dual layer. However, the spacing between the layers mentioned in the barcode design has not been tested. Most of the testing involved the first layer rather than the second layer. This is due to the complication to actually simulate the second layer along with spacing. An alternative way of positioning the barcode layers that was proposed in the design chapter was experimented which proved that the set-up would illuminate two diffraction gratings at one time. The positioning of the detector for the top layer is simulated using a white paper screen to prove the theory used in the design section to position the detectors. Instead of using five different gratings per layer, an alternative way which involves covering coloured films on top of the same gratings has been experimented. The practical has showed that using two layers of semi-reflective and reflective gratings will diffract the incident light more than 2 times which is unwanted. To prevent this phenomenon, an alternative way of positioning the gratings of each layer has been experimented. The next chapter analyses and evaluates the designs of each component and the practical results obtained from the experiments. The final barcode design is then given which will aim to answer the research questions.

Chapter 8

Analysis and Evaluation

Following the initial design of the barcode system and experimental works with the components, this chapter prepares a critical analysis report of each of the phases and provide an evaluation for each of the components and the final design. The purpose of this chapter is to argue and explain every fact collected, designs proposed, experiments carried out in the laboratory and alternative solutions mentioned in the previous chapters. The goal is to combine all the results obtained in the research and to come up with a final evaluation that will try and answer the research questions. The chapter starts with the light source where the design recommendations, the experimental works and alternative proposals are analysed and explained in details followed by an evaluation. The next analysis is the barcode symbol itself. The dual layered technique tested and the alternative layer setups provided are evaluated. The third component which is the detector is analysed using the results obtained during the practical works and evaluated. The security features and storage capabilities are briefly analysed and an evaluation is provided which determine the best choice. Finally the entire design of the system with reference to the positioning of each component is analysed. The alternative system design mentioned in previous chapter is compared with the original one designed and an evaluation is carried out to determine the best one that will aid answer the research questions.

8.1 Light Source

As in any optical barcode system, the primary resource is the light which will illuminate the barcode symbol. The purpose of a light source is to illuminate the barcode while the resultant light diffracted off the barcode symbol is collected by a detector to be read and decoded. The initial proposal for the light source in this research was LED followed later by Laser during the practical in the laboratory.

8.1.1 Analysis

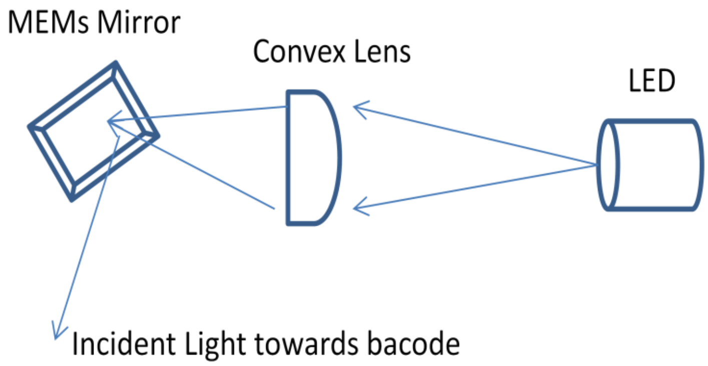


Fig 8.1 Light Source Analysis

The choice for the LED light source was because of the use of diffraction grating for the barcode symbol design. Laser lights are monochromatic and do not exist in white. White Led is easily obtainable which meet the requirements of the barcode system. The simple design of the light source (fig 8.1) was done to deliver a small led spot light which will illuminate a small area of the barcode symbol at one time. The minimum requirement for the light spot is 5mm but the smaller the better. LED light propagation does not allow a 5mm spot to be achieved and hence, other optical components are chosen such as convex lens and mirrors in the design to meet the light source objective. Once the 5mm led spot is achieved, a MEMs mirror is used reflect the led spot of 5mm to illuminate the 2-D barcode surface from left to right and top to bottom. The other requirement of the light source is to be able to illuminate the barcode over a distance of at least 50cm to meet the barcode design objectives. The distance 50cm is derived in order to have minimum change in the incident angles for all the modules of the symbol. Any change in incident angles has an impact on the diffracted spectrum in terms of both direction and wavelengths. The design was put under practical tests in the laboratory except for the MEMs mirror which was not available. The first experiment in chapter 7 shows the observations. The LED spot of 5mm was easily achievable using a convex lens over a short distance. However, using a mirror to project the light over the barcode proved that the light spot widens over increasing distances. This phenomenon is shown below.

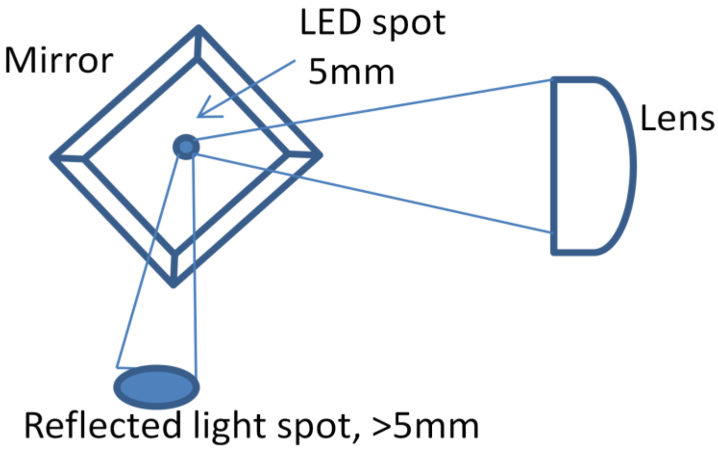


Fig 8.2 LED Light Spot Phenomenon

The second downfall is that the luminous flux of the LED decreases over an increasing distance. As observed, the light intensity is primarily diminished by the convex lens and over a further distance of around 50cm, the LED spot fades out completely. On the other hand, whilst experiments were being done, white laser was just invented and tested [89]. Due to white laser being unavailable for purchase to test in the barcode system, red laser which is assumed to generate the same laser spot and intensity was tested. The red laser was chosen as an alternative light source and the latter delivered the requirements of the barcode design which consist of a minimum of 5mm laser spot and a maintained intensity over a distance of more than 50cm. The red laser light as well as the LED light was both used in all the experiments. Using laser, a spot light of less than 5mm is obtained. The red laser shows how the intensity of the white laser would generate and the led light shows how the visible light wave-length would be diffracted using the white laser.

8.1.2 Evaluation

The two main specifications needed from a successful light source are firstly a minimum of 5mm light spot and a maintained intensity over a distance of at least 50cm. LED light source has been tested using convex lens and mirrors but unfortunately failed to deliver the required specifications. For this reason, LED light source will not be chosen for the barcode system. Instead, white laser which has recently been invented is the preferred choice. This choice makes the light source simpler to design than LED. Red laser which is assumed to generate the same intensity and laser spot of a white laser has proved and meet the specifications required and hence, white laser is the right ad best source light in the new barcode system. Using laser light, a spot light of < 5mm is obtained. This characteristic allows the grating modules of the barcode symbol to be designed smaller and hence increase the storage capacity by allowing more modules using the same size of barcode symbol. The figure illustrated the new simpler source light design.

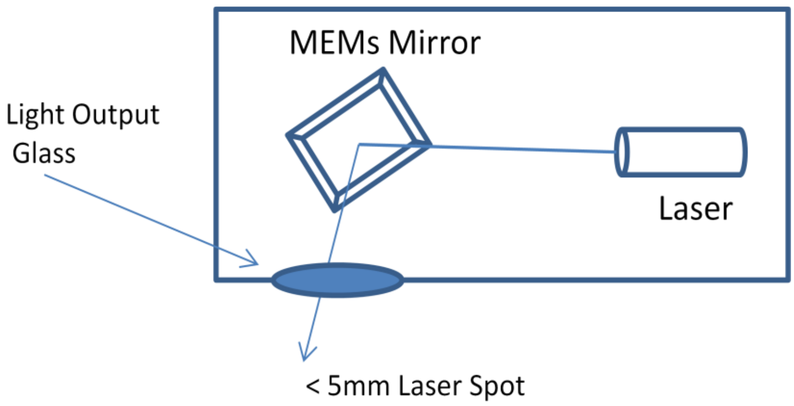


Fig 8.3 White Laser Light Source

8.2 Barcode Symbol

The first requirement of the barcode symbol is to store or represent data using the technique wavelength-multiplexed. The second requirement for the barcode symbol is higher data storage than existing barcode symbols. This section focuses more on the wavelength-multiplexed technique whilst the data storage is analysed in sub section 8.5.

8.2.1 Analysis

The barcode symbol is composed of two 2-D layers of diffraction gratings. The diffraction gratings diffract incident light into a spectrum of visible wavelength which is then read by a detector. The layers of the barcode symbol are segmented into small modules of 5mm by 5mm which is illuminated each at one time by the laser light source. The technique is using segmented small modules allows high data storage. The top layer sits exactly on the second layer with a thin separator in between that allows light to pass through with minimum or no diffraction. The mounts of each layer are tilted slightly to direct the diffracted light to the detectors place on the two sides of the barcode. The top layer grating of the barcode is semi-reflective and directs the light diffraction to the top left positioned detector. The bottom layer is reflective and sends the diffraction to the right top positioned detector.

Two non-reflective diffraction gratings with different specifications (500l/mm and 1000l/mm) have been bought off from the market to experiment the design in the laboratory. Tests with one grating which acts as the first layer have proved successful. Two diffracted visible light spectrum achieved from the two gratings prove that gratings can be used as barcodes. Using a mirror for the one layer, the diffraction was directed to a screen paper which was positioned to imitate the photodiode detector as specified in the design chapter. The same tests were done using a second layer by placing the first grating (first layer) on top of the other grating (second layer). Using a mirror the diffraction was reflected to a paper screen to observe the light diffraction. The outcome showed that the incident light was diffracted more than 2 times and this does not meet the specification of the barcode symbol requirements. As observed, every time the light passes through the grating, it is diffracted as shown in figure 8.4. However, each diffraction order will have different intensity resulting in a set of readings where photo detectors can be used to capture these readings. This is not favourable as in theory it is ideal to have a set of unique readings when it comes down to data storage. There are no gaps between the gratings' layers as any gap will result in the wider diffraction angles.

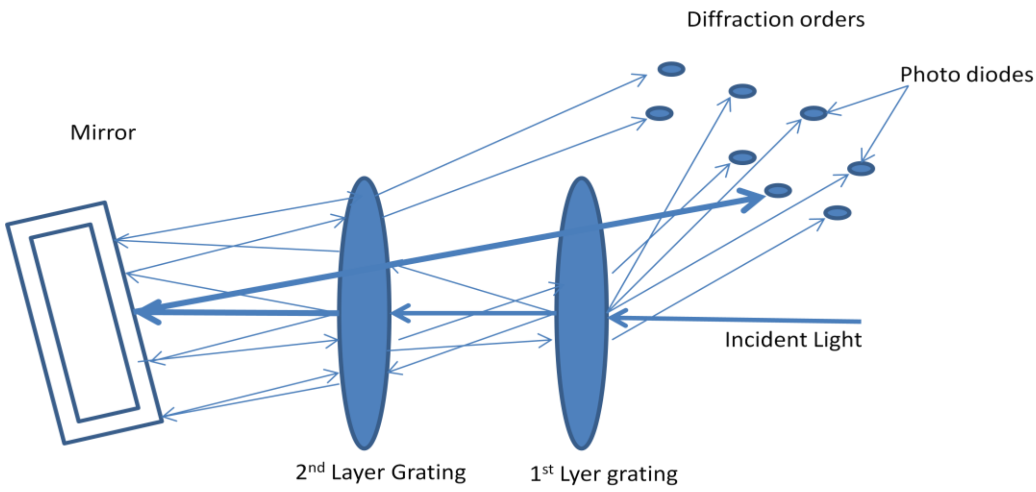


Fig 8.4 2-Layers Diffraction

An alternative method is proposed where the detectors are placed under the gratings. This set-up requires no more usage of any reflective gratings but instead only transmissive ones. The resultant diffraction is shown below.

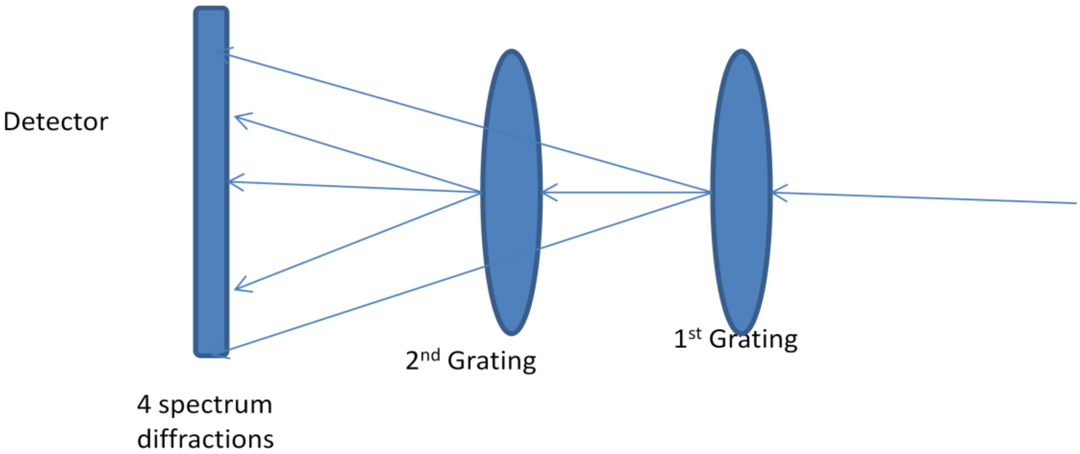


Fig 8.5 Alternative 2-Layers Diffraction

Table 8.1 below shows the number of diffractions when several layers are used. This finding can be used in further research work where the technique might help increase data storage.

Table 8.1: Layers vs. Diffraction Orders

Layers	1	2	3	4	N
Diffraction Orders	3	5	7	9	2n+1

Diffraction from the first grating and second grating both reach the detector placed on the bottom of the barcode symbol. Readings from the photo diode used during the experiments have proved that this technique stops the multiple unwanted light diffractions experienced when using the reflective gratings. This set-up of 2 layers has a downfall where two module gratings (one from each layer) are diffracting light to the same location. This makes it hard to position two detectors to individually capture the two diffractions. The solution to this is to alter the axis of the second grating. This new set up (Fig 8.6) was tested and it allows one grating to diffract light in two sides (left and right) and the other grating to diffract light in two other directions (top and bottom). This is shown below in figure 8.6.

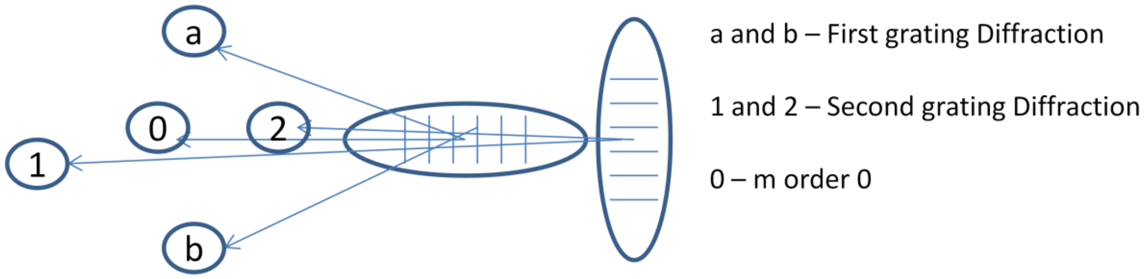


Fig 8.6 Two-Layer Axis Design

8.2.2 Evaluation

The main technique which answers the first question of the thesis is wavelength-multiplexed. The Laser light source uses the multiplexing technique to merge the RGB lasers to achieve white LED. When the white led hits the gratings in the barcode, the light is diffracted into a spectrum of visible light wavelengths. The second specification of the barcode design is dual-layer. This has proved to be successful only if the detectors are placed under the barcode symbol. Using the initial design mentioned in chapter 3, where the two detectors are placed on top of each sides of the barcode, will not incorporate the two layered barcode but instead will work for only one layer. However, the newer design of using two transmissive gratings illuminates two grating modules at one time where all the diffractions reach the same detector. This prevents the detector to identify the layers. To overcome this short outcome, the grating axis of one of the layers has been changed perpendicular to the other layer as shown in figure 7.5. Gratings normally diffract light in the negative and positive orders which are on the left and right hand side. Rotation one of the gratings can easily allow the diffractions of both gratings to project in four sides (left/right for one grating and top/bottom for the second grating). Hence, using these tweaks, the final choice is to move the detectors to incorporate the dual layer barcode and alter the gratings of the one layer perpendicular to the other one to allow diffractions from each layer to reach one detector. The use of LED source light makes this new design more advantageous too as the intensity of lasers compared to LED is much stronger. Lasers are coherent and can easily deliver the required laser spot over longer distances than LED. Using lasers makes the application more practical as less optical components are required to achieve the required light spot compared to LED.

8.3 Photo Diode Detectors

The importance of detectors in the barcode system is to capture the resultant diffracted spectrum of visible light wavelengths from the barcode symbol. The captured light is then used to decode the information saved or represented by the barcode symbol. This sub-section analyses how the photo diode specified for the detectors react to LED and Laser light.

8.3.1 Analysis

The design of the detectors is very simple and consists of arrays of photo diodes arranged in two dimensions as shown in chapter 4. The final design of the barcode system requires the detectors to be placed below the barcode symbol. This simply means that the new dimensions required would be much smaller than the ones in the first design proposed in the design chapter. An idea is given in figure 8.9 but this will however need to be tested in further work. The specified photo diode mentioned for the detectors' design was not available for testing. Instead one which has a smaller detecting surface but which performs almost like the one specified has been put under some testing. The experiments done for the photo diode were mainly to understand how they would behave under different light sources and also how the readings would vary from different gratings. Table 8.1 shows the readings obtained without any gratings based on a distance of around 50cm. Table 7.2 captures the readings obtained for both LED and Laser light when one layer grating is used. For each experiment, a tabular form of reading is produced. The reading for the laser spot is easily as the diffractions consist of only one red spot. For the

LED light source, the reading in the middle of the spectrum has been used. Figure 8.7 below shows an example of the light being captured by the photodiode.

Fig 8.7 LED Diffraction Spectrum Capture

Whilst doing the practical, it has been observed that the reading of the diffracted light changes as the light fades. This explains the theory behind light intensity. The further the light detector is placed, the lower the reading will be. The intensity of LED light decreases as distance increases where as for laser light, the intensity remains the same. However, only when gratings are used, then the intensity of laser light decreases as well. For each experiment the photodiode had to be moved to capture different readings of diffracted spectrums (2 orders) and this made the calibration irrelevant for the experiments. The light sources were fixed at the same position for all the experiments to ensure the readings can be compared with each other and against the original table 7.1. The photodiode was maintained at a distance of around 1cm from the gratings. Section 8.4 analyses the readings in further details. Another aspect that influenced the readings taken was the positions of the diffraction with relative to the 0 order. The 2nd order diffractions outputs much lower voltage than the first order of diffraction. Figure 8.8 sets an example.

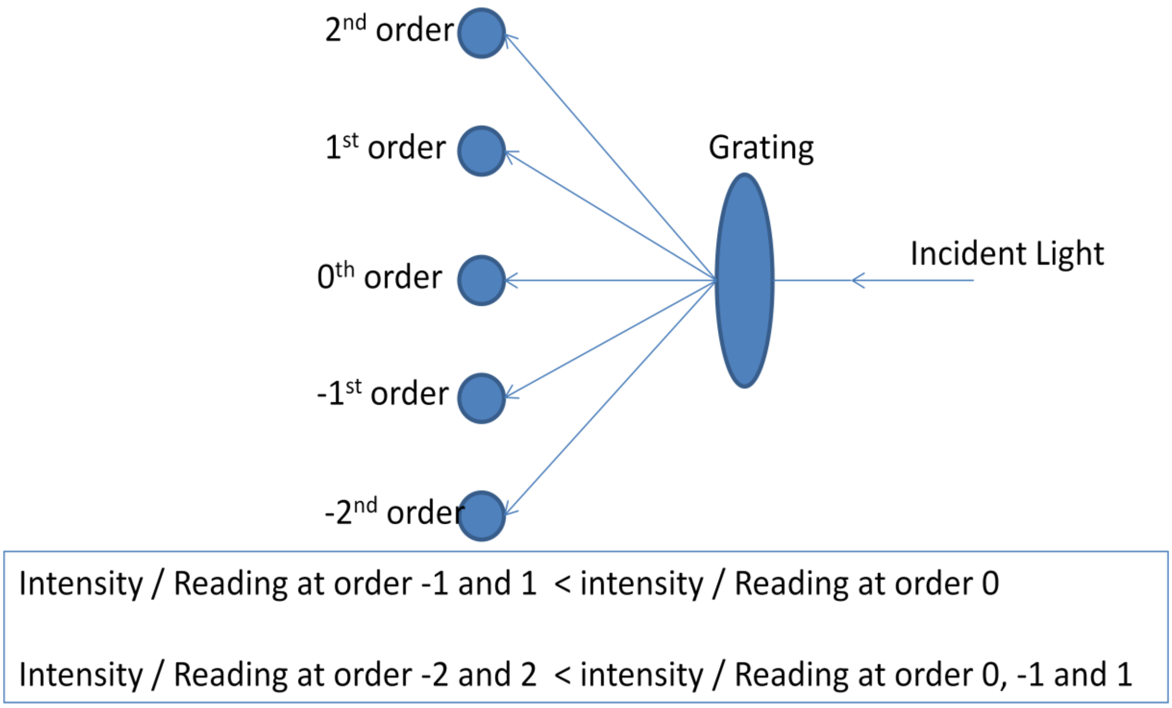


Fig 8.8 Light Intensity vs Diffraction Orders

8.3.2 Evaluation

The benefit of using multiple arrays of diodes in 2 dimensional is that it maximises the chances of capturing the maximum or entire spectrum of diffracted light wavelength. Using arrays of photo diodes in the design makes it ideal to build any size and any design of detectors. Despite the fact the calibration was not completed during for the practical, it is imperative that for every single applications the barcode system is designed for, the photo diode in use has to be calibrated with the light source. As observed in the experiments, the readings differ each time the light intensity differs. The intensity will normally change in any application due to external light (from the sun or light bulbs) or when the detector is moved further away from the light source (Intensity of light (lumens) $\propto 1/d^2$). White LED is the preferred source light as white light is split into visible light spectrum as it passes through the diffraction grating used in the barcode. The principle of intensity has enabled the use of any coloured lasers possible as well. This technique will however not be used in this project but will be reference for further research and explained in more details in the last chapter. As mentioned in 8.2, the detectors would be best placed under the barcode symbol. This change simplifies the design of the second-layer detector as a smaller size with less photo diodes will suffice. This will require two small detectors, one for each layer as shown below in the Final Design.

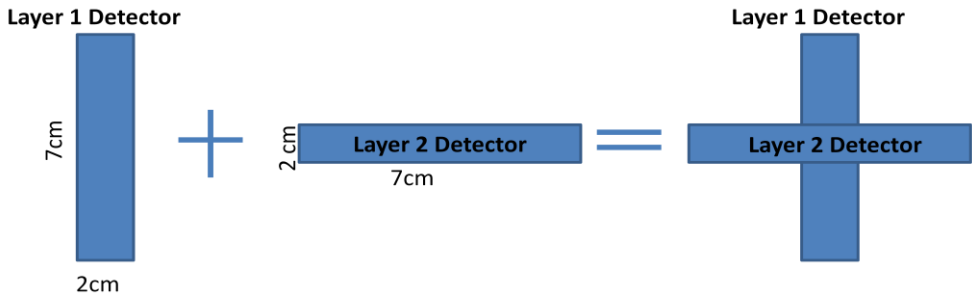


Fig 8.9 Final Detector Design

8.4 Barcode Storage

The main goal of building the barcode system is to be able to store and represent data. This section analyses the proposed design along with the new better recommended solutions proposed. The success of data storage is dependent on the reading captured by the photo detectors.

8.4.1 Analysis

The concept is very simple where a set of 5 different gratings, with different lines per mm, were chosen for each layers which would diffract unique set of wavelengths' spectrum. The technique adapted is to represent a set of bits using the different unique gratings which diffracts unique sets of wavelengths spectrums. For each layer, 4 gratings result in each representing 2 bits (00, 01, 10, and 11) and the 5th one is used for finder path or end of barcode. Each module represents 2 bits of data. A character set is defined to aid convert the bits into ASCII characters and this is represented in appendix C.

Two gratings (500 l/mm and 1000 l/mm) were used to test the how the barcode layers would diffract light. Tables of reading are given in chapter 6 to show the readings. Using one layer diffract the incident light as predicted in the design chapter. Whilst using two layers, it was observed that the light gets diffracted more than two times. Using a semi reflective first layer and a reflective second layer gratings, the resultant diffraction from the second layer is observed as being diffracted a minimum of three times. The same experiment was done using the new proposed design and position of the detectors. The detectors were placed under the gratings and each of the layers were tested individually and both together. Using a single layer, the diffraction resulted as expected but with two layers, the first diffraction order would reach the same detector and thus making it difficult to distinguish the readings from the layers. To solve this issue, as shown in figure 8.6 and 8.9, the grating for layer two were placed perpendicular to the first layer gratings. Using this setup, the readings obtained showed that the incident light is first diffracted through the first layer grating and then diffracted again through the second layer grating. As mentioned in 8.3, each time a light travels through a grating, the intensity decreases. The readings obtained for the two layers were lower than the readings for a single layer. All experiments only relates to the first diffraction order which include the 1^{st} positive and negative orders.

Alternate ways of achieving unique sets of diffraction spectrums have been tried and experimented. The first one consists of tilting the grating to achieve a different set of wavelengths. The idea behind it is to change the angle of incidence using the same grating. Each module is designed to have the same diffraction gratings but with different mounts placed at different angles. Changes in incidence angle prevent some light wavelength from being diffracted and thus a number of unique wavelengths' spectrums can be achieved using one single type of grating. The second alternative way of achieving unique wavelength spectrums is to use gratings along with a coloured film. The idea is to change the incident white light into different spectral width using different film colour wavelength placed on the grating. The practical shows the observation where each film colour used resulted in a different spectral width and readings. This is an alternative way to achieve unique gratings instead of using 5 different gratings (lines per mm). However, this technique is adopted in HCCB (see chapter 2) and therefore will not be considered.

8.4.2 Evaluation

The technique used to represent the data, where the unique sets of diffracted wavelengths' spectrums are assigned a unique set of bits, is the right choice for the barcode system. Using the proposed design of 5 sets of gratings per module, high data storage is unachievable. However, the technique works and proves that using diffraction grating as a barcode is possible. The initial barcode design can represent the full ASCII set as shown in appendix C. Unfortunately, having a reflective second layer proved to be unsuccessful as the resultant spectrum of light is diffracted at least 3 times. The chosen solution is to place the detectors below the barcode symbol.

The alternate ways of achieving unique sets of wavelengths will not be considered to improve the barcode design. The first technique which involves altering the incident angle will need each of the modules mounting to be unique constructed with unique angles. Having modules of 5mm by 5mm and with a possibility of smaller ones in the future makes it impossible to adapt the technique of changing the mounts for each module. The second alternative is to use coloured films on top of the gratings. This idea is perfect but unfortunately not for this research. The objective is to avoid using techniques already in use and the colour technique is already being used by Microsoft in their latest barcode system (refer to chapter 2). Hence, both techniques will not be used in the barcode design.

Another phenomenon observed is that the source light is diffracted through the first layer and then the both the diffracted light and the incident light (m order =0) is diffracted again. Along with the diffractions, the light intensity is also decreased resulting in lower readings. If the same first layer grating is used along various second layer gratings, the expected first layer reading will vary for each of the unique second layer grating used. This simply means that decoding the first layer is impossible due to unwanted diffractions with the two layers. Thus, using each layer to represent data is not achievable.

As a solution, the data will be stored in one layer. But the second layer will be used to create more unique diffracted spectrum of wavelengths. If one first layer module contains 500 l/gratings, then the second layer module under it can contain 6 different types of unique gratings which will diffract 6 different sets of light wavelengths' spectrum. Using 16 sets of gratings for each layer (500-1900 l/mm) will offer a range of 256 unique set of spectrums. This simply means that 169 unique options per module can save a minimum of 8 bits per module. A symbol of 100 modules will be able to save 8 bytes which is much more than the first design barcode symbol in chapter 3. This technique of saving the data answers the question of high data storage. It also allows the use of more than two layers which can increase the number of unique set of gratings per module, thus increasing the data capacity. Table 8.2 gives an estimate of the data storage using 2 layers and more than 2.

Table 8.2: Data storage Estimate

Layers	Number of unique gratings per layers	Data estimate per module	Data estimate for symbol of 80 modules
1	16	4 bits	40 bytes
2	16	8 bits	80 bytes
3	16	12 bits	120 bytes
4	16	16 bits	160 bytes

Each time the incident light is diffracted, the intensity decreases. Use of several layers will help get different diffracted light intensities and this technique can be used to store data. The reading captured by the photodiode is more dependent on the light intensity rather than the visible light wavelengths. For instance, the same colour (red wavelength) observed in different experiments resulted in different readings. During the experimental works, it has been observed that the photodiode can detect and differentiate different light intensities. For LED, the reading is much lower compared to lasers due to different light intensity. Each time the incident light is diffracted through a grating, the density is changed along with its density resulting in a new reading detected by the photodiode.

The security chosen for the barcode system is check character. This technique is very simple and need small data storage. The other technique error correction requires more storage and this will only be recommended for use in high security applications.

8.5 Barcode System Design

The barcode system design brings together all the components which are light detectors, barcode symbol, and light sources. The design specifies the positioning of each component with relative to each other to allow maximum efficiency of the system and minimise any disturbance. The original proposed design that has been tested is analysed followed by a better design based on experimental findings.

8.5.1 Analysis

The design is very simple with the light source positioned at least 50 cm above the barcode symbol to minimise the incident angle of the modules on the ends and two detectors positioned above on each side of the barcode symbol. The light source initially proposed was white LED and the barcode symbol designed was two layered with first layer semi-reflective and second layer reflective gratings. Each of the components have been analysed and evaluated individually in the sections above. Some tests have been done to the alternate designs and they have proved to deliver better results than the original designs initially proposed in chapter 3. Alternate designs aided to show that detectors placed under the barcode are better than placed on top of the barcodes. Using two transmissive layers of gratings are more efficient than using one semi-reflective and one fully reflective layer. Use of laser instead of led offers stronger light intensity over longer distances. 5mm laser spot is only achievable using lasers along with a beam expansion instead of led over a maximum distance of 50cm as proved in the experimental work.

8.5.2 Evaluation

The original proposed design has some deficiencies. Using LED failed to deliver the light spot required. The two-layered barcode with semi-reflective and reflective layers did not meet the required diffraction spectrums needed and specified for the barcode system. However, the idea of using grating in barcode symbol is a success and the SI photodiode detectors also were the right choice. To meet the required specifications of the barcode system, few changes were made to some components as well as their designs. To incorporate all of them together, a new proposed barcode system design is given below in figure 8.10. In the new design, the grating of each layer in the barcode is aligned in different positions to allow diffractions in four sides. The light source stays on top of the barcode symbol and the light illumination technique is the same. Using a MEMs mirror each grating module will be illuminated. Non-reflective gratings are used instead which allow the diffraction to occur below the barcode symbol. The detectors are placed below the barcode symbol to capture the diffracted light. The two detectors are place under the barcode symbol in a cross positions to capture the diffracted spectrums from both layers.

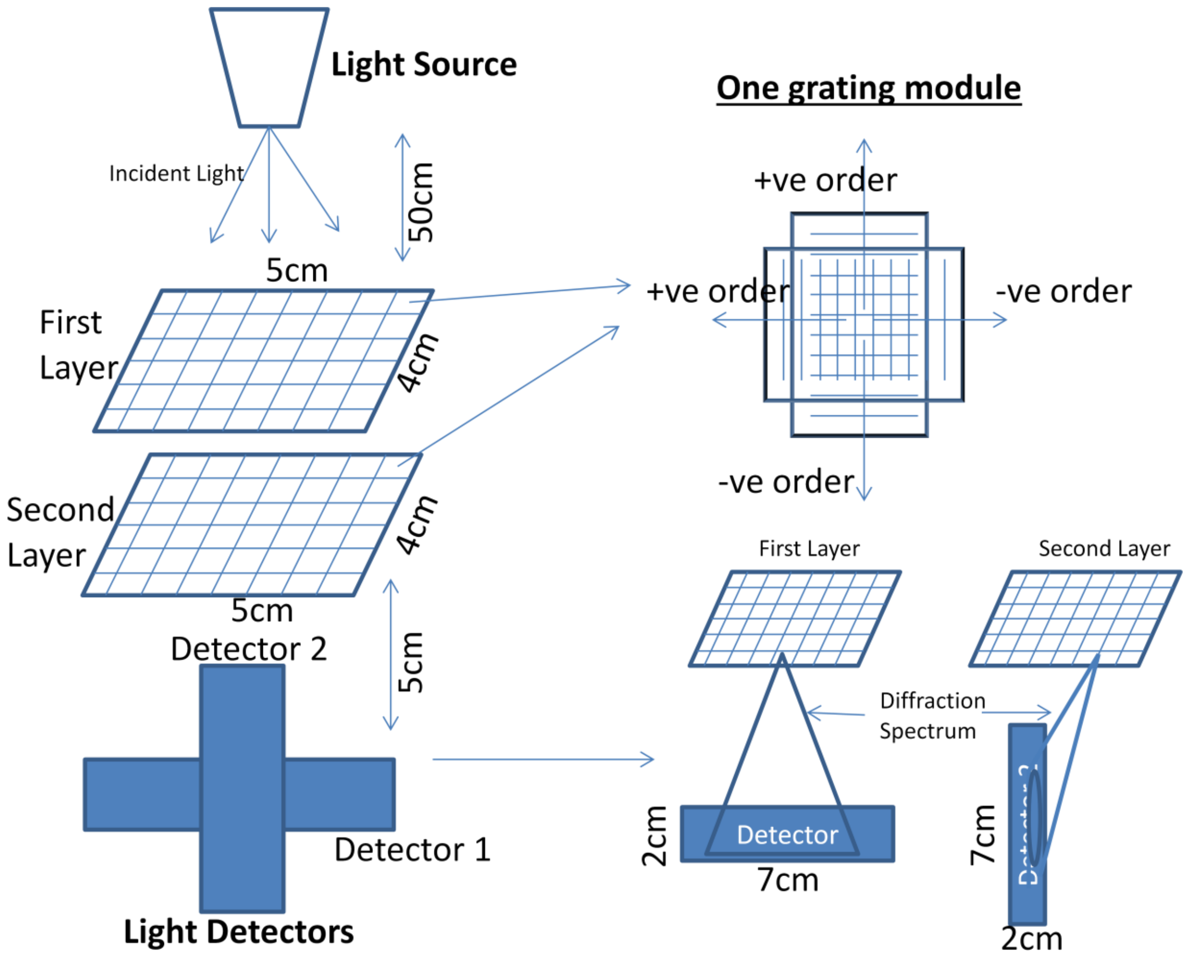
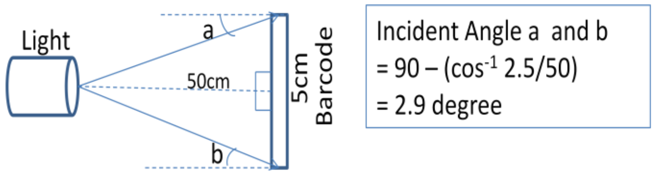


Fig 8.10 Final Barcode Design

Each component design have been modified and given in the sections above. As a brief, the light source will be white Laser but use of any laser light has also been recommended for testing in future works. The mounting design of the barcode symbol is defined according to the positioning of the laser while the incident angle for the entire barcode is kept between 0 and 5 degrees. The necessity to keep the incident angle between 0 and 2 degrees is due to the fact that having several incident angles for the same grating will result in different diffraction intensities. This will not be ideal specification to have unique gratings. The detectors will be designed much smaller and both will be of the same sizes as they will be placed closer to the barcode symbol. The light source and detectors can be positioned closer to the barcode symbol with all the possibilities to be calculated in further works. Use of layers will offer smaller laser spots than 5mm and this will increase the number of grating modules with smaller sizes. The same basics and techniques used in chapter 3 will be repeated to achieve and test the new alternative barcode system design proposed.

8.5.3 Final Barcode Design Operation

1. The light source is white laser light and the design is explained in chapter 6. The distance between the light source and the barcode system is 50cm to minimise the incident angle. Below shows the incident angle ranges from -2.9 to 2.9 degree. [refer to chapter 2]



2. The barcode mounting is flat and there are no elevated modules. This is because the detector is place closer to the barcode symbol underneath and the gratings for both layers are transmissive and diversion of diffraction is not required. There are no spacing between the layers and the alignments are shown above in figure 8.10. Experiment 10 (chapter 7) shows how the alignment works. Each layer diffracts light in opposite alignments allowing each of the layers to be identified (refer to picture figure 7.12).

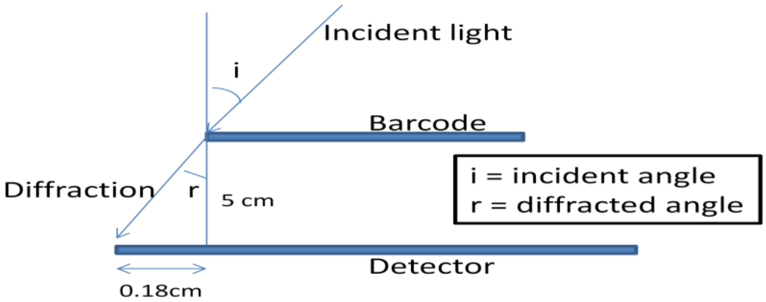
3. The detectors are placed under the barcode symbol to pick up the diffractions from the gratings. As experimented in the lab and shown in chapter 7, the readings taken from table 7.6 are as follows for the laser;

Laser		**M=0**	**M=1**	**M=-1**	**M=2**	**M=-2**
			-2 +1 M=0 -1 +2			
500 l/mm	1000 l/mm	1.75V	0.035V	0.04V	0.087V	0.078V
1000 l/mm	500 l/mm	1.67V	0.11V	0.096V	0.007V	0.06V

P.S: M=2 and M=-2 refers to the first refraction order of the first grating

The left side is the first layer and right side is the second layer along with the alignment shown using the lines. This shows that reading for each of the layers can be separated.

4. The size of the detector depends on its position with relative to the symbol. Based of the diffractions, the following calculations that were used in the first proposed barcode design in chapter 3 helps to define and understand the size of the detectors. Using 500 l/mm grating, the diffractions are as follows;



For wavelength of 300nm and incident angle of up to 3 degrees, the diffracted angle is 2 degrees for the first order and this is achieved using the principle of diffraction. Again, for wavelength of 900nm and incident angle of up to 3 degrees, the diffracted angle is about 0.5 degrees for the first order and this is achieved using the principle of diffraction. For a diffraction of 2 degree, a distance of 5cm for the detector from the barcode, the maximum length of the detector on one side should be 0.18cm longer. The defined lengths of the detectors are 7 cm long positioned 1cm longer on each side of the 5cm barcode symbol. Please refer to chapter 3 for further explanation about the formulae and the trigonometry used.

5. The electric signals captured by the detectors for the layers are shown in volts. These readings are digital and can be easily converted to binary digits that will be fed in as input data for the software that will help decode the data. Data storage as explained in chapter 5 requires unique sets of gratings. Using different sets of gratings in the first and second layer, a range of unique reading can be obtained. This unique set of gratings can be referred to different sets of binary set of digits which can then represent characters in different data sets that can be defined. Please refer to chapter 5 to gain an understanding on how data sets can be created and used.

6. The number of chosen gratings for each layer will be experimented together with each grating used in each layer at one time to obtain the set of unique electrical signals detected by the detectors along with the SNR value. Then these signals will be fed to the software that will be designed for this barcode application. Higher number of unique grating used will mean higher data storage capacity as shown in table 8.2. The

software will use the digital signals detected by the detector in volts to match them against a list of readings in its database. The readings in the database are obtained after testing all the gratings for the barcode symbol in the laboratory. Each reading will have a upper and lower threshold value to adopt the SNR in the system. The reading in the software database for each unique set of grating will not be a single value but a small range, which is 0.025V to 0.027V. Each of these readings in the database will relate to a set of binary digits. After reading the symbol, the list of binary digits obtained from the software database will be matched to a separate database where the characters and data sets are stored.

7. To summarise the light from the laser will illuminate each module from both layers at one time. These modules will have 2 gratings which will diffract into different alignments. The detectors below the barcode capture the light diffracted and generate an electrical signal for each diffraction orders from both. These signals are sent to the software which will then match these signals to its database and generate a list of binary code that is eventually matched with the data set database to output the stored or relevant characters.

8.5.4 Production Cost

This section gives an overview and a guide of the production cost of each of the components. The prices mentioned below are obtained from different sources on the internet from several sources (Maplin, Rapidonline, Richardson gratings, etc) and the labour costs are assumptions. The costs mentioned are mostly assumptions.

8.5.4.1 Light Source

The main component in the light source is the laser diode. With the choice of semi-conductor lasers over the different types (refer to chapter 6), the prices are much lower and affordable. These lasers are also easily widely available and can range from £2 to £10 each depending on the power output. The choice is heavily dependent on the application where its environment needs to be considered. The beam expander is a combination of lenses which are normally ranged between £5 to £15. Mems mirrors are normally around £3-£5 each. The wires and housing accessories of the light source range around £4. The labour to build the component might be around £20 per hour and it should roughly take about 1hr to build one.

8.5.4.2 Barcode Symbol

The main component is the gratings. Gratings are quite expensive and costs around $59 each for each module (Richardson gratings). Gratings are normally used in fibre optics applications and are considered to be a very high precision component. If this barcode system is to be a success production, it is assumed that the price of gratings will drop massively as there will be higher demand and more competitions from different markets. The labour cost is assumed to be £20 per hour and it should take about 1-2hrs to create one barcode symbol.

8.5.4.3 Barcode Detector

The main electronic component is the photodiode. The price ranges from £10 to £15 each. Based on the sizes of the detectors, up to a maximum of 4 per detector should be ideal. The housing and wires should typically cost about £4. The labour cost is assumed to be £20 per hour and it should take about 1hr to build one detector.

8.5.4.4 Software

The software needed will be a generic one that uses and interprets the signals from the detectors as its input data and output the information in binary digits. Different applications will have different databases which can be implemented in the software to decode the signals from the detector and the output binary digits. Study in software engineering has progressed massively until now and this has helped the work acquire a number of experienced programmers. To design the software for this barcode system, it is assumed that the costs for the generic software may range from £100 to £200.

8.6 Summary

This chapter analyses the proposed barcode design along with all the components, the experimental work, alternative proposals and then evaluates the best possible solutions and designs that will make the final barcode design more efficient. The analysis starts with the source light where the final selection is White Laser. White laser delivers a smaller spot light than the required 5mm. Hence, a beam expansion has been designed to enlarge the beam spot to 5mm. The barcode symbol is analysed along with the proposed alternative designs. The final verdict is that the initial two-layered reflective barcode was unable to provide the required results in the laboratory tests. Instead, the new proposed design has been chosen as a replacement solution where both layers contain transmissive gratings and the second layer axis is positioned perpendicular to the first layer. The third analysis is the SI photodiode detectors which detect visible light wavelengths (refer to appendix A). The new barcode system requires the detectors to be moved in a new position which is below the barcode symbol. This new position means that the detector can be place closer to the barcode symbol and relatively smaller to the original specified size. During experimental work, light intensity has been seen as one of the characteristics of the light diffractions that could help in data storage. The proof is shown whilst taking readings for LED and laser where the readings in volts vary massively due to the light intensities. The initial dual layer set-up with detectors on top of each sides of the barcode symbol allows small data storage and no room for improvements. The reason is simply because only a limited set of 5 unique gratings were defined for each layers while adding any more unique layers would require bigger detectors and add further complications. However, with the use of light intensities, more than 5 unique gratings per layer can be chosen. Light intensity differ for each grating and adding two layers increase the number of unique set of gratings. This technique meets the requirement of the project to deliver high data storage. The data security chosen is check characters. The signal-to-noise ratio for the barcode system was calculated in dark conditions and day-light conditions. However, for all the experimental work, only SNR for day-light conditions were considered. SNR values captured will be beneficial in future works when data storage will be researched further. Finally the entire design was analysed and the new proposed design was chosen as an alternative to deliver the required specifications needed for the new Dual-Layered and Wavelength-Multiplexed Optical Barcode for High Data Storage.

Chapter 9

Conclusion

This thesis sets out to design and develop a novel optical barcode system which is dual-layered and embeds a wavelength-multiplexed technique. Barcodes are most commonly known as series of black lines known as one dimension used to unique identify a product in Retail Industry. During the recent year, various developments of barcodes have seen the invention of two dimensional and coloured barcodes. The need of more data storage is increasing. Whilst the 1D barcodes has limitations in terms of data storage, 2D and coloured have increased the data storage which has seen their uses in Advertising Industries. All these barcode systems are optical requiring an optical reader while the barcode itself are printed lines or colours on white paper. The purpose of this project was to find an alternative way to design a barcode system rather than paper and one which can be dual-layer to increase the data storage. The questions of the research are as follows;

1. Is it possible to use diffraction grating as a barcode rather than paper?
2. Is it possible to create and design a barcode with two or several layers of gratings?
3. Is it possible to design a higher data storage barcode system than the existing ones?

Diffraction gratings diffract white light in a spectrum of visible light wavelength, thus introducing the technique of wavelength-multiplexing to be used in the new barcode design. The design concept introduced consists of three main components; the light source which illuminates the barcode symbol, the barcode symbol itself composed of two layers and diffraction grating modules, and the detectors made of SI photo diodes to capture the diffracted wavelength spectrums.

9.1 Conclusion

The thesis started with the Introduction chapter where the entire research work is planned. It was vital to break down the research questions and the proposed title of the thesis so that the aims and objectives could be defined. The main benefit of defining the objectives was to offer guidelines for the research work. Without this technique, there would be a possibility of researching outside the area of the title. The introduction chapter was essential for readers as it provides them with a flow of what the thesis sets out to achieve and how the completed research work was done. Research questions explained why the research in this area is important and what contributions it would bring to knowledge. A review of all the chapters gives the reader an idea of what each of them sets out to research and achieve.

Background reading was used to gather as much data possible on Barcodes. Before starting the research work, it was important to understand in depth the existing barcode systems along with their usage in current market. 1D, 2D and coloured barcode systems were researched and explained in details with different types of symbols. The data coding and the security features for each of the symbols were individually researched and explained. It was very important to find out if any other researchers are or have already done the same type of thesis of research work that could answer the research questions of the thesis. Any related work found would simply prove that this thesis would be a duplicate and would not bring any new contributions to research. Chapter 2 delivered this objective of identifying related researches and analyses them. Various dual-layered coloured barcode were claimed to have been developed but however, none of them uses the techniques mentioned in the thesis title which is diffraction grating and wavelength-multiplexed. The existing barcode with more than one layer are physically one layer with the use of multiple colours (one per layer) mixed together. Microsoft latest barcode invention uses single layer barcode with colours which proved to be one of the highest data storage systems. In all researches found, the word dual-layer was being referred to mixture of colours. However this research uses two layers of grating in the barcode symbol and this technique was never researched in the past. Wavelength-multiplexed technique also was not researched before in any barcode system. Hence, the study of previous related researches allowed the continuity of the thesis.

The findings in the background research from chapter 2 helped to initially design the new barcode system. The main components that are required in an optical barcode system are Light source, Barcode symbol and detectors. The idea was to use white light to illuminate the gratings in the barcode as only white light can be diffracted into a spectrum of visible light. Choice of light source was LED as lasers at this time of research were all monochromatic. LED spread light and a spot light of around 5mm diameter was needed to illuminate each barcode module. The barcode symbol was designed to have two layers, with the first layer to use semi-reflective gratings to direct the light to one side and the second layer to use reflective gratings to reflect light to the other side. The barcode mountings were modified to be able to direct the diffractions to both sides. Each layer of the barcode was split into small modules to allow high data storage. Two detectors made were needed to capture the diffractions of the layers and each side. Mathematical formulae were used to position all the components together so that the led light can reach the barcode and the diffracted light can reach each detector for each layer. Specifications for each component along with their position with relation to each other were defined and given. The design was simply to have the light source on top of the barcode symbol and two detectors on each side and above the barcode symbol.

The design chapter defined the specifications for the entire system along with their positioning. The design was needed to be simulated to test before building the final designs of the components. LightTools simulation software was proposed to test the design of the barcode. Unfortunately the software was not available from the supplier due to their license policy. Chapter 4 used real components available from the current market to actually simulate each component with relation to the specifications from chapter 3. The only way to prove that the barcode system can successfully work is to actually build it. For each component, optical parts available from retailers have been referenced and used to complete the final design of each component. LED spread light but using convex lens, required 5mm spot light was able to be achieved. The barcode layers' mountings were defined with relation to the light and detector positioning. Polycarbonate was chosen to fill the gaps between the two layers as this material has a low diffraction index and easily malleable. This was important as all diffractions needed to reach the detector. Any loss of light would be a failure in reading data from the barcode. The size of the each detector was defined with relation to the diffracted spectrum of light as diffractions for each layer were different. Both the detectors were designed with different sizes. SI photo diodes were chosen to be used in the detectors because of the capability to capture the entire visible light wavelengths. The simulation chapter used the specifications from chapter 3 to create the final designs of all the components using real optical parts. The difference between the two chapters is that chapter 3 used mathematical calculations and formulae to create the design whilst chapter 4 used real parts that match the specifications from chapter 3 to create the components.

After having designed the barcode system, the next phase of the project was to integrate the data storage capability. This is explained in depth along with data security in chapter 5. Data are represented using 0s and 1s in any storage device. The key findings were to be able to define sets of unique diffraction gratings. This was necessary as each of the unique gratings was used to represent 0s or 1s. The higher the number of unique gratings, the longer number of bits each of them can represent. The entire symbol was broken into small modules where each of the modules in each layer would represent a set of bits (0s or 1s). The total number of modules was defined as 80 per layer and 160 for entire symbol. When the diffraction spectrums are read by the detectors, it was crucial to decode the readings in order to identify the diffraction grating read along with the data. To help achieving this, a pseudo code was defined which would help a software decode the reading. Data sets were created to match the characters and numbers to the gratings. This was important to define the number of modules needed to represent one character from the sets. Data capacity was defined to understand the limit of data in bits the symbol can represent. Data security is crucial in computing to help protect and recover data. Two types of security were chosen to be used and they are check characters and error correction. Check characters is the simpler and preferred one as it uses less data storage. Error correction is preferred in applications requiring higher security and aids to recover lost bits. This chapter explains the technique to store and read data in the barcode system. This also proved that data can be represented or stored using diffraction gratings. Chapter 6 offered an alternative light source which is a laser. This chapter explains the design of the laser light source and the technique proposed to achieve alternate white light. The challenges were also identified and mitigations were proposed.

After having designed the entire barcode system in theory, it was imperative to build and test the prototype. The simulation software was unavailable and thus, parts of the system were tested in the laboratory to understand and see the behaviour of the system. Real optical parts matching the specifications from chapter 4 were purchased and the components' positioning in the lab was matched with the specifications from chapter 3. This was important to understand and prove that the theory and calculations derived would work. The experiments showed some flaws in the original design. The use of white LED did not deliver the required spot light and the reflective layers proved to generate more diffraction orders than expected. These resulted in having the detector moved underneath the barcode and the gratings were changed to transmissive ones rather than reflective. Other alternate techniques were tested such as coloured gratings (using filters), layers arrangement and gratings alignments. The only alternate technique implemented was the grating alignments for each layer. This change allowed the diffractions from each layer to be in different axis where two detectors were chosen to capture them. All the experiments carried out gave results that helped to improve the system. The final barcode design concept was defined using the results from the experiments.

It was important to analyse all the results obtained from the experiments along with the theory from previous chapters from previous chapters. Chapter 8 analysed and evaluated all the findings in the research to come up with the final design in theory. The barcode symbol was analysed and the mounting design was changed to deliver incident angle of 0-1 degrees. The spacing between the layers was removed to achieve narrower diffraction spectrums. Laser light was chosen rather than LED to achieve the spot light required. Intensity was analysed and the use of any laser light was proved to be possible. Smaller detectors were designed for the system after they were moved under the barcode symbol. The most important analysis was the data storage where the use of each layer to hold separate set of data was a failure. This was simply because every time the light went through a grating, it was diffracted and thus making hard to recover the data from each layer individually. Instead the first layer and second layer used both together would easily increase the number of unique set of diffraction gratings. One layer with 16 unique gratings would have 16 unique readings. Two layers with 16 unique set of gratings would have 256 unique readings. This technique allowed representing 1 byte in one module using both layers. The number of modules would only be the first layer and not second one. This technique extended the possibility of using more than two layers which can increase the number of bits per module (refer to table 8.2).

9.2 Recommendations

- It is recommended that laser is used instead of LED for the light source as LED has lower intensity and it is not possible to achieve a minimum of required 5mm spot light from LED.

- It is recommended to use Silicon Photo diodes in the detectors as they can detect the desired spectrum visible light wavelength.

- It is recommended to use a symbol size of 5cm by 5cm. The bigger the symbol, the bigger the detector has to be and the higher the source light has to be from the symbol to match the requirements of the design.

- It is recommended to have the detectors closer to the barcode as the further it is place, the bigger it should be. (Refer to chapter 3)

- It is recommended to calibrate the laser light with the detectors used for open-air environment or screen environment. Each application will have different specifications and light diffraction will differ as well as light intensity.

- It is recommended to use the system in darker surroundings or environments where there is no direct sunlight. This will reduce noises in the light detection.

9.3 Future Work

Despite that the new barcode system answers the questions of the thesis; the system can further be developed. During the experimental phase of the project, various different techniques that could offer alternative ways to answer the questions of the thesis were identified. These techniques are summarised below and need further research to prove if they can be used to improve the efficiency or storage of the barcode system. Applications where the system can be used in the future are proposed.

9.3.1 Further Testing

The components have been tested to prove that they work while some components were unavailable for testing. The white laser will need to be experimented in the future work. The final recommendations for the data storage were to use both layers together to generate a number of unique sets of gratings. The gratings with different lines per mm will need to be tested in each layer individually and in both layers together to define the maximum possibility of unique sets that can be created. Based on this value, the new character sets will need to be created using the technique from chapter 5.

9.3.2 Reflective Gratings

Reflective gratings were initially proposed to be used but later found not to match he specifications of the barcode system. To facilitate the data storage capacity, transmissive gratings were chosen where lesser diffractions per module in the barcode symbol made it easier to read the desired data that was represented. While doing experimental work, the reflective gratings were tested using a mirror and as observed in chapter 7, there are a number of diffractions that are obtained. The further research involved would be to investigate each of the readings from two reflective gratings. Figure 8.4 demonstrates an idea of where the photodiode could be placed to capture the readings. At this point different diffractions are obtained resulting in different electric signals that can be captured. The main reason the number of diffractions are not favourable in this thesis is simply because they cannot be uniquely identified. However, this might be further research using appropriate software that can differentiate the different sets of electric signals and translate them into data storage.

9.3.3 Use of more than two Layers

The research work uses two layers of gratings to generate a set of unique grating sets. The second layer adds to increase the data storage for the barcode. Using more than 2 layers has the possibility to increase the data storage further. Each time the incident light is diffracted, the intensity decreases and each time the incident light travels through a grating layer, 2 more diffraction orders are generated as shown in table 8.1. This phenomenon can be investigated and experimented further so that the extra diffractions can be used to store more data.

9.3.4 Use of multi-Lasers

The experimental work was done using red laser and white LED. Both of them helped to choose white laser as the final choice for the light source. In chapter 8, any laser light was recommended to be used in the barcode system after the experiments proved that intensity could be the main factor which can be used for data storage. This has raised the opportunity to investigate and test different laser colours as each of them generate different light intensities as experimented in the laboratory. Using more than one laser with the same sets of gratings in sequence will help increase the storage capacity. This might be considered as future research which will help achieve high data storage.

9.3.5 Software

Software is the tool that helps to decode the readings captured by the photo detectors. A simple pseudo code was given in chapter 5 which helped readers gain an understanding of how the data will be decoded. However, the software was not designed. Further work will be to design the software that will work with the barcode system to store and retrieve data for users. The software will include;

- the database that holds the character set,
- the encoder that will encode and generate the gratings for each module and layer,
- the decoder that compares the readings with the database and generates the desired output,
- the security features.

9.4 Applications

Chapter 1 proposed some ideas where the new barcode system would be ideal to be used in the future. After having designed the entire system, the final concept made it easier to define some further applications where the barcode system would be used. Firstly, the data that will be stored in a specific barcode symbol with gratings in both layers will be permanent and will not be able to be modified once created. The barcode symbol will need to be transmissive which means it simply cannot be placed on top of a hard surface such as products in supermarkets. The only best option left for now is to use the barcode symbol in bank cards, personal identity cards, passports or in car keys' tag.

- In bank cards, the barcode symbol will hold data for the client along with the credentials such as PIN number. This application will demand low storage capacity where a small symbol of lower number or modules will be ideal.
- In Personal Identity card, the symbol can be used to hold personal details such as name, address, medical records and criminal records. Every time a data is changed, a new symbol can easily be created.
- In car keys' tag, the symbol can be used to hold data about the owner along with all the standard specifications, the service history, the engine and chassis number. Amy changes that are made will require a new symbol to be created.

The mentioned data to be stored within the applications above are just ideas. Further research is required to acquire a wider understanding of the information that can be stored as the barcode can hold higher capacity of data. Below are some pictures of how the symbol can be used in these applications.

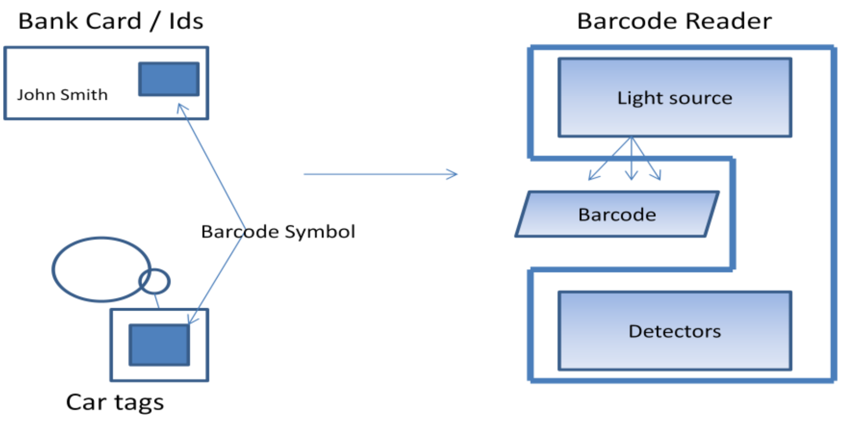


Fig 9.1 Barcode System Future Application Concept

Appendix A- Component Specification

<u>LED Component CBT-90 [76]</u>

Overview:

Designed for high performance applications, the White Unencapsulated High Brightness LED product line is a breakthrough for illumination systems that require maximum lumens/mm2 at the source. Due to its low profile window and direct chip-to-air emission the White High Brightness product line has been optimized for coupling to proximity optics and optical light engines, thereby maximizing optical throughput while maintaining long life and high reliability. With exceptionally high thermal conductivity packaging technology, Luminus' Unencapsulated High Brightness LEDs enable users to drive the devices at high input power to maximize lumen output while ensuring long life and high reliability. Customers can select from chip-on-board solutions for optimal thermal conductivity, or surface mount solutions to accommodate volume production needs. Typical applications include entertainment wash lighting, fiber coupled medical lighting and automotive forward lighting.

Features:

• High surface brightness - over 275 lm/mm2 (CBT-90)

• Extremely high optical output

• High thermal conductivity package

• Lumen maintenance greater than 70% after 60,000 hours

• Patented & exclusive Photonic Lattice technology for high efficiency and uniform emission

• Available in 6500K - 5700K CCT per ANSI C78-377-2008

• Mercury-free, RoHS compliant

Product Performance at nominal current

Package Dimensions	10mm x 11mm	**Colour**	6500K
Input Power	30 W	**Colour Temperature**	Cool White
Typical Voltage	3.6 V	**CRI**	73
Nominal Current	9.0 A	**Typical Flux (nominal current)**	1600lm
Max. Current	13.5 A	**Typical Flux (max current)**	2250lm

MEMs Mirror [80]

OVERVIEW

The sercalo MEMS 3D mirrors are used for precise optical beam steering. The micromirror is designed to minimize effects such as drift, hysteresis and temperature dependent performance. The angle is set using electrostatic actuation.

FEATURES	APPLICATIONS
• Low drift	• Optical Beam Steering
• 2 independent axis	• Reconfigurable Add-Drop Multiplexer
• Continuous tilting	• Vibration control in free space optics
• Single mirror	• Optical Processor
• 2.0 x 2.5 mm2 mirror	
• High fill factor	

ORDERING INFORMATION

TM	-	2520	X75	Y45	N

Surface finish
- = Alu
AU = Gold

Mirror Size
2520 = 2.5 x 2.0 mm^2

Angle *X (inner)*
X75>= ±7.5°
(mechanical @ 60V)

Angle Y *(outer)*
Y45 >= ±4.5°
(mechanical @ 60V)

Window
N = no window
G = glass without coating
AR 15 = anti reflective coating @ 1550nm

TYPICAL SPECIFICATIONS

	Unit	Min	Typ	Max
Max. Actuation Voltage	V		60	70
Surface Finish	-		Al or Au	
Reflectivity (900-2000 nm)	%		95	
Mirror Size – X	µm	2500		
Mirror Size – Y	µm	2000		
Mirror Radius of Curvature	m	1.0		
Tilt Angle – X (Mechanical) @ 60 V	°		±7.5	
Tilt Angle – Y (Mechanical) @ 60 V	°		±4.5	
Resonant Frequency - X	Hz		100	
Resonant Frequency - Y	Hz		145	
Package		TO5		
ESD	Unprotected = VERY SENSITIVE Overvoltage above 70 V can permanently damage the device.			

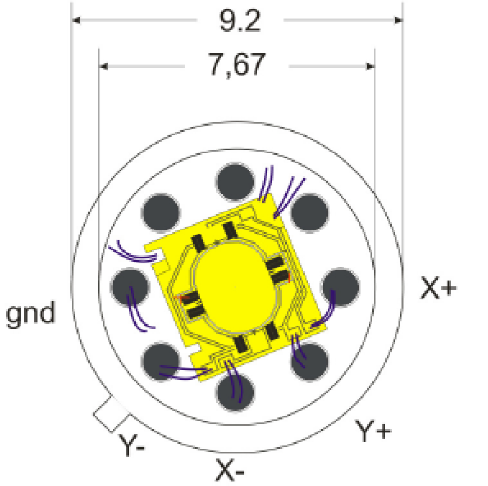


Figure 1: Pin layout of a Ø2.0 mm micro-mirror chip on TO5 socket

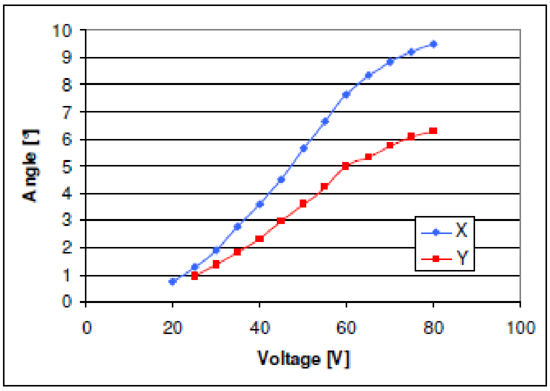


Figure 2: Typical tilt angle vs. applied voltage

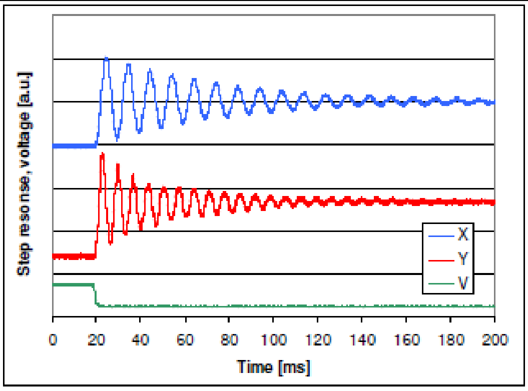
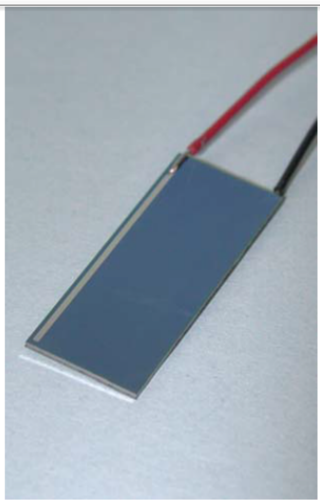
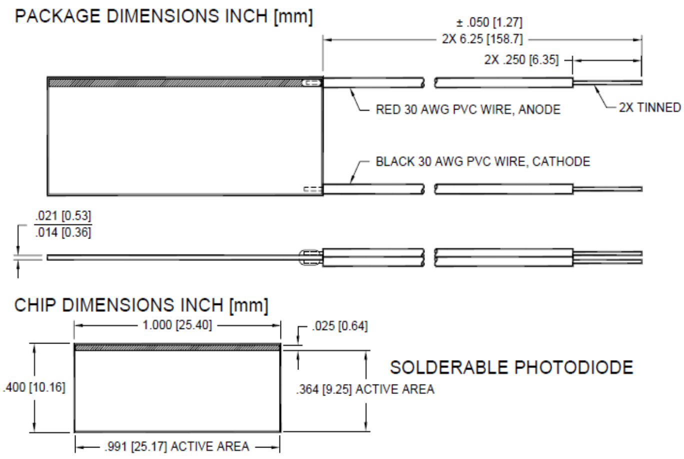


Figure 3: Typical step response

Silicon Photodiode PDB-C615-2 [84]





FEATURES

- Red enhanced
- Photoconductive
- High quantum efficiency

DESCRIPTION

The **PDB-C615-2** is a silicon red enhanced solderable photodiode designed for low capacitance and high speed for photoconductive applications.

APPLICATIONS

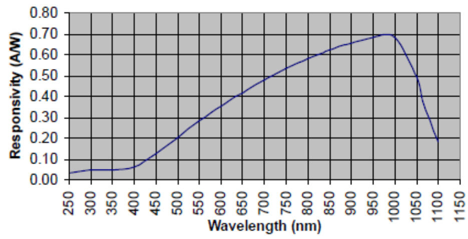
- Optical encoder
- Position sensor
- Industrial controls
- Instrumentation

ABSOLUTE MAXIMUM RATING (TA)= 23°C UNLESS OTHERWISE NOTED

SYMBOL	PARAMETER	MIN	MAX	UNITS
V_{BR}	Reverse Voltage		75	V
T_{STG}	Storage Temperature	-40	+125	°C
T_O	Operating Temperature	-40	+100	°C
T_S	Soldering Temperature*		+224	°C

* 1/16 inch from case for 3 seconds max.

SPECTRAL RESPONSE



ELECTRO-OPTICAL CHARACTERISTICS RATING (TA)= 23°C UNLESS OTHERWISE NOTED

SYMBOL	CHARACTERISTIC	TEST CONDITIONS	MIN	TYP	MAX	UNITS
I_{SC}	Short Circuit Current	H = 100 fc, 2850 K	2.5	2.8		mA
I_D	Dark Current	V_R = 5 V		350	700	nA
R_{SH}	Shunt Resistance	V_R = 10 mV	0.1	0.25		MΩ
C_J	Junction Capacitance	V_R = 5 V, *f* = 1 MHz		775		pF
λrange	Spectral Application Range	Spot Scan	350		1100	nm
V_{BR}	Breakdown Voltage	I = 10 μA	25	50		V
NEP	Noise Equivalent Power	V_R = 0V @ λ = Peak		$3x10^{-12}$		W/ √ Hz
t_r	Response Time	RL = 1KΩ, V_R = 5V		150		nS

**Response time of 10% to 90% is specified at 660nm wavelength light.

Information in this technical datasheet is believed to be correct and reliable. However, no responsibility is assumed for possible inaccuracies or omission. Specifications are subject to change without notice.

LTC1856 - 8-Channel, ±10V Input 16-Bit, 100ksps ADC Converter with Shutdown [84]

Description

The LTC1854/LTC1855/LTC1856 are 8-channel, low power, 12-/14-/16-bit, 100ksps, analog-to-digital converters (ADCs). These ADCs operate from a single 5V supply and the 8-channel multiplexer can be programmed for single-ended inputs, pairs of differential inputs, or combinations of both. In addition, all channels are fault protected to ±30V. A fault condition on any channel will not affect the conversion result of the selected channel.

An onboard precision reference minimizes external components. Power dissipation is 40mW at 100ksps and lower in two power shutdown modes (27.5mW in Nap mode and 40mW in Sleep mode.) DC specifications include ±3LSB INL for the LTC1856, ±1.5LSB INL for the LTC1855 and ±1LSB for the LTC1854.

The internal clock is trimmed for 5ms maximum conversion time and the sampling rate is guaranteed at 100ksps. A separate convert start input and data ready signal (BUSY) ease connections to FIFOs, DSPs and microprocessors.

Applications

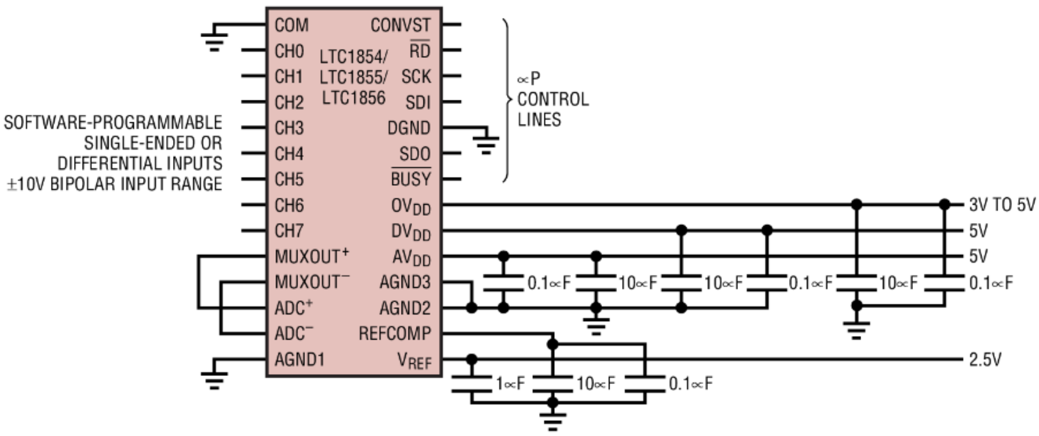
- Industrial Process Control
- Multiplexed Data Acquisition Systems
- High Speed Data Acquisition for PCs
- Digital Signal Processing

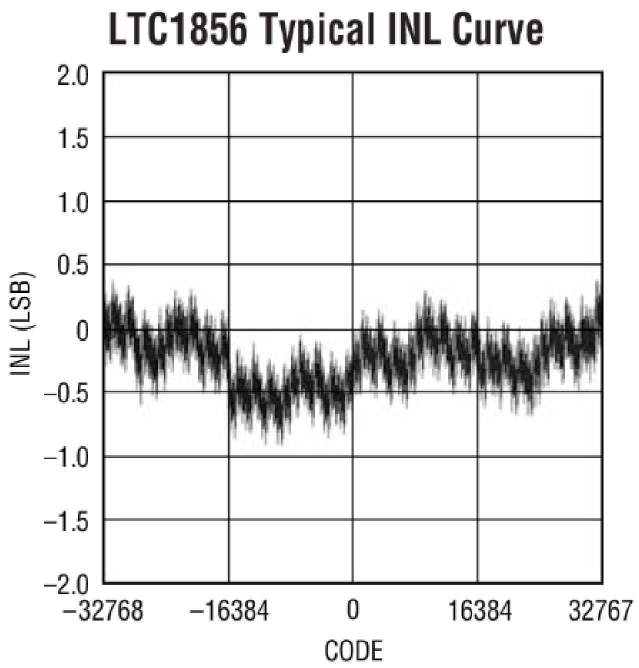
Features

- Single 5V Supply
- Sample Rate: 100ksps
- 8-Channel Multiplexer with ±30V Protection
- ±10V Bipolar Input Range
  Single Ended or Differential
- ±3LSB INL for the LTC1856,
  ±1.5LSB INL for the LTC1855,
  ±1LSB INL for the LTC1854
- Power Dissipation: 40mW (Typ)
- SPI/MICROWIRETM Compatible Serial I/O
- Power Shutdown: Nap and Sleep
- SINAD: 87dB (LTC1856)
- Operates with Internal or External Reference
- Internal Synchronized Clock
- 28-Pin SSOP Package

Typical Application

100kHz, 12-Bit/14-/16-Bit Sampling ADC




LTC1856 Typical INL Curve
2.0
1.5
1.0
0.5
0
−0.5
−1.0
−1.5
−2.0
INL (LSB)
−32768
−16384
0
16384
32767
CODE

Appendix B- Character Set Table

ASCII Character Set [87]

Char	Hexa-decimal	Control Action	Top Layer Gratings	Bottom Layer Grating
NUL	00	NULl character	T-A,T-A, T-A,T-A	B-A,B-A, B-A,B-A
SOH	01	Start Of Heading	T-A,T-A, T-A,T-B	B-A,B-A, B-A,B-B
STX	02	Start of TeXt	T-A,T-A, T-A,T-C	B-A,B-A, B-A,B-C
ETX	03	End of TeXt	T-A,T-A, T-A,T-D	B-A,B-A, B-A,B-D
EOT	04	End Of Transmission	T-A,T-A, T-B,T-A	B-A,B-A, B-B,B-A
ENQ	05	ENQuiry	T-A,T-A, T-B,T-B	B-A,B-A, B-B,B-B
ACK	06	ACKnowledge	T-A,T-A, T-B,T-C	B-A,B-A, B-B,B-C
BEL	07	BELl, rings terminal bell	T-A,T-A, T-B,T-D	B-A,B-A, B-B,B-D
BS	08	BackSpace (non-destructive)	T-A,T-A, T-C,T-A	B-A,B-A, B-C,B-A
HT	09	Horizontal Tab (move to next tab position)	T-A,T-A, T-C,T-B	B-A,B-A, B-C,B-B
LF	0a	Line Feed	T-A,T-A, T-C,T-C	B-A,B-A, B-C,B-C
VT	0b	Vertical Tab	T-A,T-A, T-B,T-D	B-A,B-A, B-B,B-D
FF	0c	Form Feed	T-A,T-A, T-D,T-A	B-A,B-A, B-D,B-A
CR	0d	Carriage Return	T-A,T-A, T-D,T-B	B-A,B-A, B-D,B-B
SO	0e	Shift Out	T-A,T-A, T-D,T-C	B-A,B-A, B-D,B-C
SI	0f	Shift In	T-A,T-A, T-D,T-D	B-A,B-A, B-D,B-D
DLE	10	Data Link Escape	T-A,T-B ,T-A,T-A	B-A,B-B ,B-A,B-A,
DC1	11	Device Control 1, normally XON	T-A,T-B, T-A,T-B	B-A,B-B, B-A,B-B
DC2	12	Device Control 2	T-A,T-B, T-A,T-C	B-A,B-B, B-A,B-C
DC3	13	Device Control 3, normally XOFF	T-A,T-B, T-A,T-D	B-A,B-B, B-A,B-D
DC4	14	Device Control 4	T-A,T-B, T-B,T-A	B-A,B-B, B-B,B-A
NAK	15	Negative AcKnowledge	T-A,T-B, T-B,T-B	B-A,B-B, B-B,B-B
SYN	16	SYNchronous idle	T-A,T-B, T-B,T-C	B-A,B-B, B-B,B-C
ETB	17	End Transmission Block	T-A,T-B, T-B,T-D	B-A,B-B, B-B,B-D
CAN	18	CANcel line	T-A,T-B, T-C,T-A	B-A,B-B, B-C,B-A
EM	19	End of Medium	T-A,T-B, T-C,T-B	B-A,B-B, B-C,B-B
SUB	1a	SUBstitute	T-A,T-B, T-C,T-C	B-A,B-B, B-C,B-C
ESC	1b	ESCape	T-A,T-B, T-B,T-D	B-A,B-B, B-B,B-D
FS	1c	File Separator	T-A,T-B, T-D,T-A	B-A,B-B, B-D,B-A
GS	1d	Group Separator	T-A,T-B, T-D,T-B	B-A,B-B, B-D,B-B
RS	1e	Record Separator	T-A,T-B, T-D,T-C	B-A,B-B, B-D,B-C
US	1f	Unit Separator	T-A,T-B, T-D,T-D	B-A,B-B, B-D,B-D
SP	20	Space	T-A,T-C ,T-A,T-A	B-A,B-C ,B-A,B-A
!	21	Exclamation mark	T-A,T-C ,T-A,T-B	B-A,B-C ,B-A,B-B
"	22	Quotation mark (" in HTML)	T-A,T-C, T-A,T-C	B-A,B-C, B-A,B-C
#	23	Cross hatch (number sign)	T-A,T-C, T-A,T-D	B-A,B-C, B-A,B-D
$	24	Dollar sign	T-A,T-C, T-B,T-A	B-A,B-C, B-B,B-A
%	25	Percent sign	T-A,T-C, T-B,T-B	B-A,B-C, B-B,B-B
&	26	Ampersand	T-A,T-C, T-B,T-C	B-A,B-C, B-B,B-C
`	27	Closing single quote (apostrophe)	T-A,T-C, T-B,T-D	B-A,B-C, B-B,B-D
(	28	Opening parentheses	T-A,T-C, T-C,T-A	B-A,B-C, B-C,B-A
)	29	Closing parentheses	T-A,T-C, T-C,T-B	B-A,B-C, B-C,B-B
*	2a	Asterisk (star, multiply)	T-A,T-C, T-C,T-C	B-A,B-C, B-C,B-C

+	2b	Plus	T-A,T-C, T-B,T-D	B-A,B-C, B-B,B-D
,	2c	Comma	T-A,T-C, T-D,T-A	B-A,B-C, B-D,B-A
-	2d	Hyphen, dash, minus	T-A,T-C, T-D,T-B	B-A,B-C, B-D,B-B
.	2e	Period	T-A,T-C, T-D,T-C	B-A,B-C, B-D,B-C
/	2f	Slash (forward or divide)	T-A,T-C, T-D,T-D	B-A,B-C, B-D,B-D
0	30	Zero	T-A,T-D ,T-A,T-A	B-A,B-D ,B-A,B-A
1	31	One	T-A,T-D ,T-A,T-B	B-A,B-D ,B-A,B-B
2	32	Two	T-A,T-D ,T-A,T-C	B-A,B-D ,B-A,B-C
3	33	Three	T-A,T-D, T-A,T-D	B-A,B-D, B-A,B-D
4	34	Four	T-A,T-D, T-B,T-A	B-A,B-D, B-B,B-A
5	35	Five	T-A,T-D, T-B,T-B	B-A,B-D, B-B,B-B
6	36	Six	T-A,T-D, T-B,T-C	B-A,B-D, B-B,B-C
7	37	Seven	T-A,T-D, T-B,T-D	B-A,B-D, B-B,B-D
8	38	Eight	T-A,T-D, T-C,T-A	B-A,B-D, B-C,B-A
9	39	Nine	T-A,T-D, T-C,T-B	B-A,B-D, B-C,B-B
:	3a	Colon	T-A,T-D, T-C,T-C	B-A,B-D, B-C,B-C
;	3b	Semicolon	T-A,T-D, T-B,T-D	B-A,B-D, B-B,B-D
<	3c	Less than sign (< in HTML)	T-A,T-D, T-D,T-A	B-A,B-D, B-D,B-A
=	3d	Equals sign	T-A,T-D, T-D,T-B	B-A,B-D, B-D,B-B
>	3e	Greater than sign (> in HTML)	T-A,T-D, T-D,T-C	B-A,B-D, B-D,B-C
?	3f	Question mark	T-A,T-D, T-D,T-D	B-A,B-D, B-D,B-D
@	40	At-sign	T-B,T-A ,T-A,T-A	B-B,B-A ,B-A,B-A
A	41	Upper case A	T-B,T-A ,T-A,T-B	B-B,B-A ,B-A,B-B
B	42	Upper case B	T-B,T-A ,T-A,T-C	B-B,B-A ,B-A,B-C
C	43	Upper case C	T-B,T-A ,T-A,T-D	B-B,B-A ,B-A,B-D
D	44	Upper case D	T-B,T-A, T-B,T-A	B-B,B-A ,B-B,B-A
E	45	Upper case E	T-B,T-A, T-B,T-B	B-B,B-A, B-B,B-B
F	46	Upper case F	T-B,T-A, T-B,T-C	B-B,B-A, B-B,B-C
G	47	Upper case G	T-B,T-A, T-B,T-D	B-B,B-A, B-B,B-D
H	48	Upper case H	T-B,T-A, T-C,T-A	B-B,B-A, B-C,B-A
I	49	Upper case I	T-B,T-A, T-C,T-B	B-B,B-A, B-C,B-B
J	4a	Upper case J	T-B,T-A, T-C,T-C	B-B,B-A, B-C,B-C
K	4b	Upper case K	T-B,T-A, T-B,T-D	B-B,B-A, B-B,B-D
L	4c	Upper case L	T-B,T-A, T-D,T-A	B-B,B-A, B-D,B-A
M	4d	Upper case M	T-B,T-A, T-D,T-B	B-B,B-A, B-D,B-B
N	4e	Upper case N	T-B,T-A, T-D,T-C	B-B,B-A, B-D,B-C
O	4f	Upper case O	T-B,T-A, T-D,T-D	B-B,B-A, B-D,B-D
P	50	Upper case P	T-B,T-B ,T-A,T-A	B-B,B-B ,B-A,B-A
Q	51	Upper case Q	T-B,T-B ,T-A,T-B	B-B,B-B ,B-A,B-B
R	52	Upper case R	T-B,T-B ,T-A,T-C	B-B,B-B ,B-A,B-C
S	53	Upper case S	T-B,T-B ,T-A,T-D	B-B,B-B ,B-A,B-D
T	54	Upper case T	T-B,T-B ,T-B,T-A	B-B,B-B ,B-B,B-A
U	55	Upper case U	T-B,T-B, T-B,T-B	B-B,B-B, B-B,B-B
V	56	Upper case V	T-B,T-B, T-B,T-C	B-B,B-B, B-B,B-C
W	57	Upper case W	T-B,T-B, T-B,T-D	B-B,B-B, B-B,B-D
X	58	Upper case X	T-B,T-B, T-C,T-A	B-B,B-B, B-C,B-A
Y	59	Upper case Y	T-B,T-B, T-C,T-B	B-B,B-B, B-C,B-B
Z	5a	Upper case Z	T-B,T-B, T-C,T-C	B-B,B-B, B-C,B-C
[	5b	Opening square bracket	T-B,T-B, T-B,T-D	B-B,B-B, B-B,B-D
\	5c	Backslash (Reverse slant)	T-B,T-B, T-D,T-A	B-B,B-B, B-D,B-A
]	5d	Closing square bracket	T-B,T-B, T-D,T-B	B-B,B-B, B-D,B-B
^	5e	Caret (Circumflex)	T-B,T-B, T-D,T-C	B-B,B-B, B-D,B-C
_	5f	Underscore	T-B,T-B, T-D,T-D	B-B,B-B, B-D,B-D
`	60	Opening single quote	T-B,T-C ,T-A,T-A	B-B,B-C ,B-A,B-A
a	61	Lower case a	T-B,T-C ,T-A,T-B	B-B,B-C ,B-A,B-B
b	62	Lower case b	T-B,T-C ,T-A,T-C	B-B,B-C ,B-A,B-C

c	63	Lower case c	T-B,T-C ,T-A,T-D	B-B,B-C ,B-A,B-D
d	64	Lower case d	T-B,T-C ,T-B,T-A	B-B,B-C ,B-B,B-A
e	65	Lower case e	T-B,T-C ,T-B,T-B	B-B,B-C ,B-B,B-B
f	66	Lower case f	T-B,T-C, T-B,T-C	B-B,B-C, B-B,B-C
g	67	Lower case g	T-B,T-C, T-B,T-D	B-B,B-C, B-B,B-D
h	68	Lower case h	T-B,T-C, T-C,T-A	B-B,B-C, B-C,B-A
i	69	Lower case i	T-B,T-C, T-C,T-B	B-B,B-C, B-C,B-B
j	6a	Lower case j	T-B,T-C, T-C,T-C	B-B,B-C, B-C,B-C
k	6b	Lower case k	T-B,T-C, T-B,T-D	B-B,B-C, B-B,B-D
l	6c	Lower case l	T-B,T-C, T-D,T-A	B-B,B-C, B-D,B-A
m	6d	Lower case m	T-B,T-C, T-D,T-B	B-B,B-C, B-D,B-B
n	6e	Lower case n	T-B,T-C, T-D,T-C	B-B,B-C, B-D,B-C
o	6f	Lower case o	T-B,T-C, T-D,T-D	B-B,B-C, B-D,B-D
p	70	Lower case p	T-B,T-D, T-A,T-A	B-B,B-D ,B-A,B-A
q	71	Lower case q	T-B,T-D, T-A,T-B	B-B,B-D ,B-A,B-B
r	72	Lower case r	T-B,T-D ,T-A,T-C	B-B,B-D ,B-A,B-C
s	73	Lower case s	T-B,T-D ,T-A,T-D	B-B,B-D ,B-A,B-D
t	74	Lower case t	T-B,T-D ,T-B,T-A	B-B,B-D ,B-B,B-A
u	75	Lower case u	T-B,T-D ,T-B,T-B	B-B,B-D ,B-B,B-B
v	76	Lower case v	T-B,T-D ,T-B,T-C	B-B,B-D ,B-B,B-C
w	77	Lower case w	T-B,T-D, T-B,T-D	B-B,B-D, B-B,B-D
x	78	Lower case x	T-B,T-D, T-C,T-A	B-B,B-D, B-C,B-A
y	79	Lower case y	T-B,T-D, T-C,T-B	B-B,B-D, B-C,B-B
z	7a	Lower case z	T-B,T-D, T-C,T-C	B-B,B-D, B-C,B-C
{	7b	Opening curly brace	T-B,T-D, T-B,T-D	B-B,B-D, B-B,B-D
|	7c	Vertical line	T-B,T-D, T-D,T-A	B-B,B-D, B-D,B-A
}	7d	Closing curly brace	T-B,T-D, T-D,T-B	B-B,B-D, B-D,B-B
~	7e	Tilde (approximate)	T-B,T-D, T-D,T-C	B-B,B-D, B-D,B-C
DEL	7f	Delete (rubout), cross-hatch box	T-B,T-D, T-D,T-D	B-B,B-D, B-D,B-D

Extended ASCII Character Set [88]

Char	Hexa-decimal	Control Action	Top Layer Gratings	Bottom Layer Grating
€	80	Euro sign	T-C,T-A ,T-A,T-A	B-C,B-A ,B-A,B-A
	81		T-C,T-A ,T-A,T-B	B-C,B-A ,B-A,B-B
‚	82	Single low-9 quotation mark	T-C,T-A ,T-A,T-C	B-C,B-A ,B-A,B-C
ƒ	83	Latin small letter f with hook	T-C,T-A, T-A,T-D	B-C,B-A ,B-A,B-D
„	84	Double low-9 quotation mark	T-C,T-A ,T-B,T-A	B-C,B-A ,B-B,B-A
…	85	Horizontal ellipsis	T-C,T-A ,T-B,T-B	B-C,B-A ,B-B,B-B
†	86	Dagger	T-C,T-A ,T-B,T-C	B-C,B-A ,B-B,B-C
‡	87	Double dagger	T-C,T-A ,T-B,T-D	B-C,B-A ,B-B,B-D
ˆ	88	Modifier letter circumflex accent	T-C,T-A ,T-C,T-A	B-C,B-A ,B-C,B-A
‰	89	Per mille sign	T-C,T-A ,T-C,T-B	B-C,B-A ,B-C,B-B
Š	8A	Latin capital letter S with caron	T-C,T-A ,T-C,T-C	B-C,B-A ,B-C,B-C
‹	8B	Single left-pointing angle quotation	T-C,T-A ,T-B,T-D	B-C,B-A ,B-B,B-D
Œ	8C	Latin capital ligature OE	T-C,T-A ,T-D,T-A	B-C,B-A ,B-D,B-A
	8D		T-C,T-A ,T-D,T-B	B-C,B-A ,B-D,B-B
Ž	8E	Latin captial letter Z with caron	T-C,T-A ,T-D,T-C	B-C,B-A ,B-D,B-C
	8F		T-C,T-A ,T-D,T-D	B-C,B-A ,B-D,B-D
	90		T-C,T-B ,T-A,T-A	B-C,B-B ,B-A,B-A
‘	91	Left single quotation mark	T-C,T-B ,T-A,T-B	B-C,B-B ,B-A,B-B
’	92	Right single quotation mark	T-C,T-B ,T-A,T-C	B-C,B-B ,B-A,B-C
“	93	Left double quotation mark	T-C,T-B ,T-A,T-D	B-C,B-B ,B-A,B-D
”	94	Right double quotation mark	T-C,T-B ,T-B,T-A	B-C,B-B ,B-B,B-A
•	95	Bullet	T-C,T-B ,T-B,T-B	B-C,B-B ,B-B,B-B
–	96	En dash	T-C,T-B ,T-B,T-C	B-C,B-B ,B-B,B-C
—	97	Em dash	T-C,T-B ,T-B,T-D	B-C,B-B ,B-B,B-D
˜	98	Small tilde	T-C,T-B ,T-C,T-A	B-C,B-B ,B-C,B-A
™	99	Trade mark sign	T-C,T-B ,T-C,T-B	B-C,B-B ,B-C,B-B
š	9A	Latin small letter S with caron	T-C,T-B ,T-C,T-C	B-C,B-B ,B-C,B-C
›	9B	Single right-pointing angle quotation mark	T-C,T-B ,T-B,T-D	B-C,B-B ,B-B,B-D
œ	9C	Latin small ligature oe	T-C,T-B ,T-D,T-A	B-C,B-B ,B-D,B-A
	9D		T-C,T-B ,T-D,T-B	B-C,B-B ,B-D,B-B
ž	9E	Latin small letter z with caron	T-C,T-B ,T-D,T-C	B-C,B-B ,B-D,B-C
Ÿ	9F	Latin capital letter Y with diaeresis	T-C,T-B ,T-D,T-D	B-C,B-B, B-D,B-D
	A0	Non-breaking space	T-C,T-C ,T-A,T-A	B-C,B-C ,B-A,B-A
¡	A1	Inverted exclamation	T-C,T-C ,T-A,T-B	B-C,B-C ,B-A,B-B

		mark		
¢	A2	Cent sign	T-C,T-C ,T-A,T-C	B-C,B-C ,B-A,B-C
£	A3	Pound sign	T-C,T-C ,T-A,T-D	B-C,B-C ,B-A,B-D
¤	A4	Currency sign	T-C,T-C ,T-B,T-A	B-C,B-C ,B-B,B-A
¥	A5	Yen sign	T-C,T-C ,T-B,T-B	B-C,B-C ,B-B,B-B
¦	A6	Pipe, Broken vertical bar	T-C,T-C ,T-B,T-C	B-C,B-C ,B-B,B-C
§	A7	Section sign	T-C,T-C ,T-B,T-D	B-C,B-C ,B-B,B-D
¨	A8	Spacing diaeresis – umlaut	T-C,T-C ,T-C,T-A	B-C,B-C ,B-C,B-A
©	A9	Copyright sign	T-C,T-C ,T-C,T-B	B-C,B-C ,B-C,B-B
ª	AA	Feminine ordinal indicator	T-C,T-C ,T-C,T-C	B-C,B-C ,,B-C,B-C
«	AB	Left double angle quotes	T-C,T-C ,T-B,T-D	B-C,B-C ,B-B,B-D
¬	AC	Not sign	T-C,T-C ,T-D,T-A	B-C,B-C ,B-D,B-A
	AD	Soft hyphen	T-C,T-C ,T-D,T-B	B-C,B-C ,B-D,B-B
®	AE	Registered trade mark sign	T-C,T-C ,T-D,T-C	B-C,B-C ,B-D,B-C
¯	AF	Spacing macron - overline	T-C,T-C ,T-D,T-D	B-C,B-C ,B-D,B-D
°	B0	Degree sign	T-B,T-D ,T-A,T-A	B-B,B-D ,B-A,B-A
±	B1	Plus-or-minus sign	T-B,T-D ,T-A,T-B	B-B,B-D ,B-A,B-B
²	B2	Superscript two - squared	T-B,T-D ,T-A,T-C	B-B,B-D ,B-A,B-C
³	B3	Superscript three – cubed	T-B,T-D ,T-A,T-D	B-B,B-D ,B-A,B-D
´	B4	Acute accent - spacing acute	T-B,T-D ,T-B,T-A	B-B,B-D ,B-B,B-A
µ	B5	Micro sign	T-B,T-D ,T-B,T-B	B-B,B-D ,B-B,B-B
¶	B6	Pilcrow sign - paragraph sign	T-B,T-D ,T-B,T-C	B-B,B-D ,B-B,B-C
·	B7	Middle dot - Georgian comma	T-B,T-D ,T-B,T-D	B-B,B-D ,B-B,B-D
¸	B8	Spacing cedilla	T-B,T-D ,T-C,T-A	B-B,B-D ,B-C,B-A
¹	B9	Superscript one	T-B,T-D ,T-C,T-B	B-B,B-D ,B-C,B-B
º	BA	Masculine ordinal indicator	T-B,T-D ,T-C,T-C	B-B,B-D ,B-C,B-C
»	BB	Right double angle quotes	T-B,T-D ,T-B,T-D	B-B,B-D ,B-B,B-D
¼	BC	Fraction one quarter	T-B,T-D ,T-D,T-A	B-B,B-D ,B-D,B-A
½	BD	Fraction one half	T-B,T-D ,T-D,T-B	B-B,B-D ,B-D,B-B
¾	BE	Fraction three quarters	T-B,T-D ,T-D,T-C	B-B,B-D ,B-D,B-C
¿	BF	Inverted question mark	T-B,T-D ,T-D,T-D	B-B,B-D ,B-D,B-D
À	C0	Latin capital letter A with grave	T-D,T-A ,T-A,T-A	B-D,B-A ,B-A,B-A
Á	C1	Latin capital letter A with acute	T-D,T-A ,T-A,T-B	B-D,B-A ,B-A,B-B
Â	C2	Latin capital letter A with circumflex	T-D,T-A ,T-A,T-C	B-D,B-A ,B-A,B-C
Ã	C3	Latin capital letter A with tilde	T-D,T-A ,T-A,T-D	B-D,B-A ,B-A,B-D
Ä	C4	Latin capital letter A with diaeresis	T-D,T-A ,T-B,T-A	B-D,B-A ,B-B,B-A
Å	C5	Latin capital letter A with ring above	T-D,T-A ,T-B,T-B	B-D,B-A ,B-B,B-B
Æ	C6	Latin capital letter AE	T-D,T-A, T-B,T-C	B-D,B-A ,B-B,B-C
Ç	C7	Latin capital letter C with cedilla	T-D,T-A, T-B,T-D	B-D,B-A ,B-B,B-D

È	C8	Latin capital letter E with grave	T-D,T-A ,T-C,T-A	B-D,B-A ,B-C,B-A
É	C9	Latin capital letter E with acute	T-D,T-A ,T-C,T-B	B-D,B-A ,B-C,B-B
Ê	CA	Latin capital letter E with circumflex	T-D,T-A ,T-C,T-C	B-D,B-A ,B-C,B-C
Ë	CB	Latin capital letter E with diaeresis	T-D,T-A ,T-B,T-D	B-D,B-A ,B-B,B-D
Ì	CC	Latin capital letter I with grave	T-D,T-A ,T-D,T-A	B-D,B-A ,B-D,B-A
Í	CD	Latin capital letter I with acute	T-D,T-A ,T-D,T-B	B-D,B-A ,B-D,B-B
Î	CE	Latin capital letter I with circumflex	T-D,T-A ,T-D,T-C	B-D,B-A ,B-D,B-C
Ï	CF	Latin capital letter I with diaeresis	T-D,T-A ,T-D,T-D	B-D,B-A ,B-D,B-D
Ð	D0	Latin capital letter ETH	T-D,T-B ,T-A,T-A	B-D,B-B ,B-A,B-A
Ñ	D1	Latin capital letter N with tilde	T-D,T-B ,T-A,T-B	B-D,B-B ,B-A,B-B
Ò	D2	Latin capital letter O with grave	T-D,T-B ,T-A,T-C	B-D,B-B ,B-A,B-C
Ó	D3	Latin capital letter O with acute	T-D,T-B ,T-A,T-D	B-D,B-B ,B-A,B-D
Ô	D4	Latin capital letter O with circumflex	T-D,T-B ,T-B,T-A	B-D,B-B ,B-B,B-A
Õ	D5	Latin capital letter O with tilde	T-D,T-B ,T-B,T-B	B-D,B-B ,B-B,B-B
Ö	D6	Latin capital letter O with diaeresis	T-D,T-B ,T-B,T-C	B-D,B-B ,B-B,B-C
×	D7	Multiplication sign	T-D,T-B ,T-B,T-D	B-D,B-B ,B-B,B-D
Ø	D8	Latin capital letter O with slash	T-D,T-B ,T-C,T-A	B-D,B-B ,B-C,B-A
Ù	D9	Latin capital letter U with grave	T-D,T-B, T-C,T-B	B-D,B-B ,B-C,B-B
Ú	DA	Latin capital letter U with acute	T-D,T-B ,T-C,T-C	B-D,B-B ,B-C,B-C
Û	DB	Latin capital letter U with circumflex	T-D,T-B ,T-B,T-D	B-D,B-B ,B-B,B-D
Ü	DC	Latin capital letter U with diaeresis	T-D,T-B ,T-D,T-A	B-D,B-B ,B-D,B-A
Ý	DD	Latin capital letter Y with acute	T-D,T-B ,T-D,T-B	B-D,B-B ,B-D,B-B
Þ	DE	Latin capital letter THORN	T T-D,T-B ,T-D,T-C	B-D,B-B ,B-D,B-C
ß	DF	Latin small letter sharp s - ess-zed	T-D,T-B ,T-D,T-D	B-D,B-B ,B-D,B-D
à	E0	Latin small letter a with grave	T-D,T-C ,T-A,T-A	B-D,B-C ,B-A,B-A
á	E1	Latin small letter a with acute	T-D,T-C ,T-A,T-B	B-D,B-C ,B-A,B-B
â	E2	Latin small letter a with circumflex	T-D,T-C ,T-A,T-C	B-D,B-C ,B-A,B-C
ã	E3	Latin small letter a with tilde	T-D,T-C ,T-A,T-D	B-D,B-C ,B-A,B-D

ä	E4	Latin small letter a with diaeresis	T-D,T-C ,T-B,T-A	B-D,B-C ,B-B,B-A
å	E5	Latin small letter a with ring above	T-D,T-C ,T-B,T-B	B-D,B-C ,B-B,B-B
æ	E6	Latin small letter ae	T-D,T-C ,T-B,T-C	B-D,B-C ,B-B,B-C
ç	E7	Latin small letter c with cedilla	T-D,T-C ,T-B,T-D	B-D,B-C ,B-B,B-D
è	E8	Latin small letter e with grave	T-D,T-C ,T-C,T-A	B-D,B-C ,B-C,B-A
é	E9	Latin small letter e with acute	T-D,T-C ,T-C,T-B	B-D,B-C ,B-C,B-B
ê	EA	Latin small letter e with circumflex	T-D,T-C ,T-C,T-C	B-D,B-C ,B-C,B-C
ë	EB	Latin small letter e with diaeresis	T-D,T-C ,T-B,T-D	B-D,B-C ,B-B,B-D
ì	EC	Latin small letter i with grave	T-D,T-C ,T-D,T-A	B-D,B-C ,B-D,B-A
í	ED	Latin small letter i with acute	T-D,T-C ,T-D,T-B	B-D,B-C ,B-D,B-B
î	EE	Latin small letter i with circumflex	T-D,T-C ,T-D,T-C	B-D,B-C ,B-D,B-C
ï	EF	Latin small letter i with diaeresis	T-D,T-C ,T-D,T-D	B-D,B-C ,B-D,B-D
ð	F0	Latin small letter eth	T-D,T-D ,T-A,T-A	B-D,B-D ,B-A,B-A
ñ	F1	Latin small letter n with tilde	T-D,T-D ,T-A,T-B	B-D,B-D ,B-A,B-B
ò	F2	Latin small letter o with grave	T-D,T-D ,T-A,T-C	B-D,B-D ,B-A,B-C
ó	F3	Latin small letter o with acute	T-D,T-D ,T-A,T-D	B-D,B-D ,B-A,B-D
ô	F4	Latin small letter o with circumflex	T-D,T-D ,T-B,T-A	B-D,B-D ,B-B,B-A
Õ	F5	Latin small letter o with tilde	T-D,T-D ,T-B,T-B	B-D,B-D ,B-B,B-B
Ö	F6	Latin small letter o with diaeresis	T-D,T-D ,T-B,T-C	B-D,B-D ,B-B,B-C
÷	F7	Division sign	T-D,T-D, T-B,T-D	B-D,B-D ,B-B,B-D
Ø	F8	Latin small letter o with slash	T-D,T-D ,T-C,T-A	B-D,B-D ,B-C,B-A
Ù	F9	Latin small letter u with grave	T-D,T-D ,T-C,T-B	B-D,B-D ,B-C,B-B
Ú	FA	Latin small letter u with acute	T-D,T-D ,T-C,T-C	B-D,B-D ,B-C,B-C
Û	FB	Latin small letter u with circumflex	T-D,T-D ,T-B,T-D	B-D,B-D ,B-B,B-D
Ü	FC	Latin small letter u with diaeresis	T-D,T-D ,T-D,T-A	B-D,B-D ,B-D,B-A
Ý	FD	Latin small letter y with acute	T-D,T-D ,T-D,T-B	B-D,B-D ,B-D,B-B
Þ	FE	Latin small letter thorn	T-D,T-D ,T-D,T-C	B-D,B-D ,B-D,B-C
Ÿ	FF	Latin small letter y with diaeresis	T-D,T-D ,T-D,T-D	B-D,B-D ,B-D,B-D

P.S: The blank characters are non-printing ones.

Appendix C- Laser Specification

The LHP type laser emits a linearly polarized light.

Specifications :

Type : Red Helium Neon Laser, 1.00mW - 632.8nm

CW Output Power Temp (mW) : 1

Beam diameter 1/e2 (mm) : 0.59

Beam divergence (mrad) : 1.35

Vertical Mode C/2L (MHz) : 687

Operation Current (mA) : 6.5

Laser Classifaction : IIIa

Included :

Melles Griot 05-LHP-111-9

Power Supply : 05-LPM-340

Laser heads with oscillation wavelength of 632.8 nm aluminum cylinder houses laser tube, ballast resistor, electric wiring, and other components.

<u>LED</u> <u>GW5DLC65M04</u> **<u>Specification</u>**

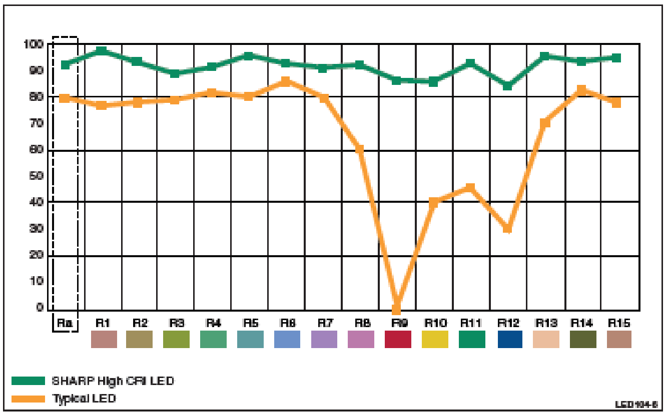
Sharp Zenigata Chip on Board technology leverages a uniform Light Emitting Surface (LES) to make optical design easier, improve light quality, and allow you to create more elegant products. A unique, fully insulating ceramic substrate provides optimal heat dissipation and low color shift, with even lumen output over time. Now, choose from Sharp LEDs ranging from 0.2W – 80W, including Zenigata COB LEDs and Sharp's specialty Double Dome product line. New Mega Zenigata modules deliver up to a 400W equivalent of incandescent light. In addition to big energy savings, these powerful LEDs eliminate the sub-standard design aesthetic and uneven light quality that results from the use of multiple low-power LEDs in a luminaire. Zenigata LEDs deliver high efficacy (high performance modules exceed 100 lm/W) and typical* hot lumen performance is greater than 90%. Each Zenigata product family features a uniform package size and a typical operating life exceeding 50,000 hours.

The Color of Life

Life happens in full spectrum. Lighting products need to be more than just functional and reliable; they must also accurately illuminate the dazzling colors that shape our world, and make objects, people, and places look their absolute best.

Sharp LEDs bring you some of the richest, most true-to-life color rendering available. Products in our Mega Zenigata High CRI line boast color rendering up to 93 CRI, and all Sharp LEDs meet or exceed the ENERGY STAR® minimum requirement of 80 CRI. Still, we recognize that CRI measurement alone is not enough.

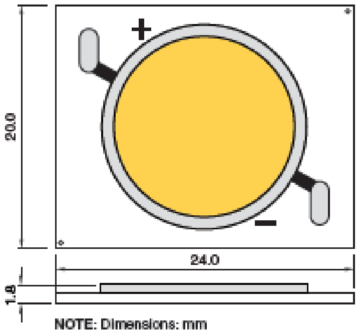
Sharp incorporates a blue LED die with a proprietary mixture of green and red phosphors to go beyond typical CRI measurements (R1 – R8) with powerful performance up to R15. This includes excellent R9 (deep red) rendering. Accurate, deep reds lend a warm, vibrant aesthetic that will help elevate your lighting products from "efficient" to "unforgettable."



The Mega Zenigata COB

The Mega Zenigata COB family provides a powerful, energy-saving LED alternative for incandescent, halogen, and compact fluorescent applications. Use just one LED in a fixture to save space and eliminate the uniformity issues of multiple emitters. Mega Zenigata LEDs deliver high efficacy (high performance modules exceed 100 lm/W) and typically restrict thermal sag to less than 10%.

Sharp's new 50W – 80W Mega Zenigata LEDs provide up to 400W of incandescent equivalent light, and expand the range of luminous flux to more than 6000 lm. The new LEDs maintain the line's compact package dimensions (20 mm × 24 mm) to eliminate unnecessary product redesign.



NOTE: Dimensions: mm
Refer to Specifications for full dimensional information

Type	CRI Ra		Part No.	CCT (K)	Current (mA)	Voltage (V)	Luminous Flux (lm)	Efficacy (lm/W)
	Min.	Typ.						
25W - 40W Normal CRI Rjc = 2.0 K/W	80	82	GW5DLC65M04	6500	1050	38.5	3640	90.0
					700	37	2600	100.4
			GW5DLC50M04	5000	1050	38.5	3640	90.0
					700	37	2600	100.4
			GW5DLC40M04	4000	1050	38.5	3570	88.3
					700	37	2550	98.5
		83	GW5DMC35M04	3500	1050	38.5	3430	84.8
					700	37	2450	94.6
			GW5DMC30M04	3000	1050	38.5	3318	82.1
					700	37	2370	91.5
			GW5DMC27M04	2700	1050	38.5	3220	79.7
					700	37	2300	88.8

Si PIN Photodiode S1223 Specification

For visible to IR, precision photometry

Features

- High sensitivity
- High reliability
- High-speed response
  S1223: fc=30 MHz
  S1223-01: fc=20 MHz
- Low capacitance

Applications

- Optical measurement equipment
- Analytical equipment, etc.

■ General ratings

Parameter	Symbol	S1223	S1223-01	Unit
Window material	-	borosilicate glass		-
Package	-	TO-5		-
Active area size	A	2.4 × 2.8	3.6 × 3.6	mm
Effective active area	-	6.6	13	mm^2

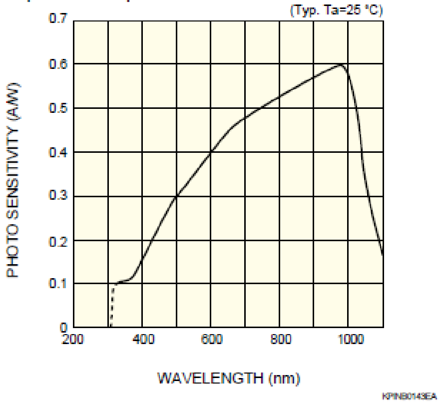
■ Absolute maximum ratings

Parameter	Symbol	S1223	S1223-01	Unit
Reverse voltage	V_R Max.	30		V
Power dissipation	P	100		mW
Operating temperature	Topr	-40 to +100		°C
Storage temperature	Tstg	-55 to +125		°C

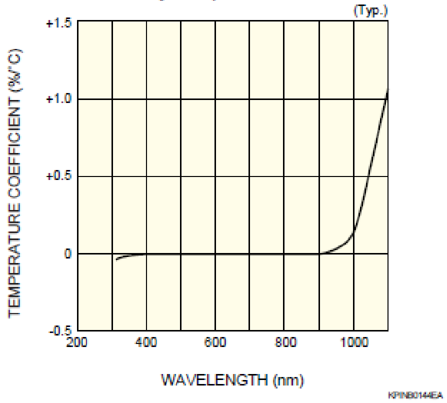
■ Electrical and optical characteristics (Ta=25 °C)

Parameter	Symbol	Condition	S1223			S1223-01			Unit
			Min.	Typ.	Max.	Min.	Typ.	Max.	
Spectral response range	λ		-	320 to 1100	-	-	320 to 1100	-	nm
Peak sensitivity wavelength	λp		-	960	-	-	960	-	nm
Photo sensitivity	S	λ=λp	-	0.6	-	-	0.6	-	A/W
		λ=660 nm	-	0.45	-	-	0.45	-	
		λ=780 nm	-	0.52	-	-	0.52	-	
		λ=830 nm	-	0.54	-	-	0.54	-	
Short circuit current	Isc	100 *lx*	5	6.3	-	10	13	-	µA
Dark current	I_D	V_R=20 V	-	0.1	10	-	0.2	10	nA
Temp. coefficient of I_D	T_{CID}		-	1.15	-	-	1.15	-	times/°C
Cut-off frequency	fc	V_R=20 V, -3 dB	-	30	-	-	20	-	MHz
Terminal capacitance	Ct	V_R=20 V, f=1 MHz	-	10	-	-	20	-	pF
Noise equivalent power	NEP	V_R=20 V, λ=λp	-	9.4×10^{-15}	-	-	1.3×10^{-14}	-	$W/Hz^{1/2}$

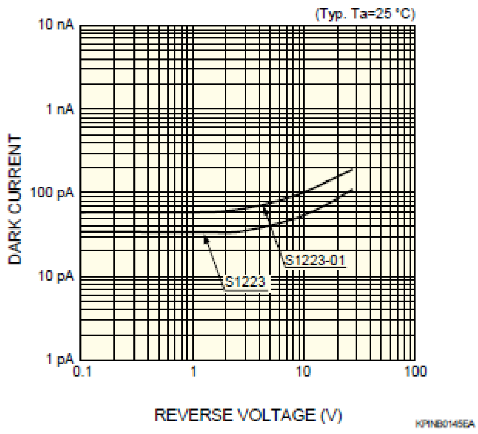
■ Spectral response



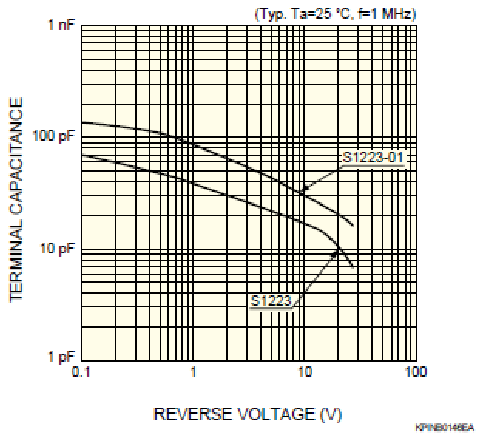
■ Photo sensitivity temperature characteristic



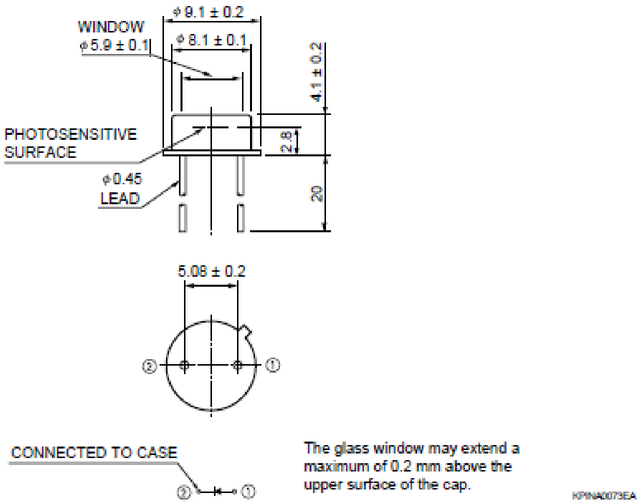
■ Dark current vs. reverse voltage



■ Terminal capacitance vs. reverse voltage



■ Dimensional outline (unit: mm)



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