High Performance Metasurface-Based On-Chip Antenna for Terahertz Integrated Circuits

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***Abstract*— This paper presents a simple prototype of a metasurface-based on-chip antenna operating in 0.3-0.32THz. The proposed structure is constructed from two layers of polyimide-substrates with thickness of 0.1mm that sandwich a middle metallic ground-plane layer of 50-micron thickness. A series of linear slots of varying lengths are etched on the radiation patches of the top-layer to create a metasurface. This is shown to enhance the antenna's effective aperture area that improves its radiation performance without affecting the overall antenna's footprint. To reduce the surface-waves and substrate-losses a meander-line slits has realized inside the ground-plane. The antenna is fed by an open-ended microstrip feedline located on the bottom-layer. The feedline consists of three-branches that are aligned under each radiation patch to achieve the maximum electromagnetic (EM) transfer from bottom-side of the bottom layer to the topside of the top-layer. Coupling of the EM energy from the bottom-layer to the top-layer is via meander-line slits introduced between the two layers. Simulation results show improvement in the antenna's impedance bandwidth, gain and efficiency.**

***Keywords*— On-chip antenna, terahertz (THz) band, metasurface, metamaterial, meander-lines slit, linear slots, polyimide substrate.**

I. Introduction

Wide bandwidth, small form factor, spatial resolution, and high data rate has increased the interest of developing electronic systems in the 0.3-30 THz band [1-5]. Application include biomedical sensors, detection of illicit narcotics, detection of tumors etc. [6]. Besides that, the THz band also finds application in the point-to-point wiresless communications [7-12].

It has been shown that radiation slots that are based on the metasurface properties are sensitive to the polarization orientation of incidence wave due to the gaps in the structure [13, 14]. In addition, radiation efficiency improvement can be achieved in antenna designs that incorporate metasurfaces slots [15, 16].

On-chip antennas can reduce the need for bonding wires that are necessary to connect the antennas constructed on printed circuit boards (PCB) with the integrated circuits (IC). At high frequencies bonding wires are generally not well characterized due to high-loss and impedance mismatch. However, on-chip antennas can overcome this type of debilitating issues. In addition, on-chip antennas eliminate the need of sophisticated packaging technology, often utilized in antenna in a package (AiP) solution. This strategy can radically alleviate the system's manufacturing cost. At the same time, it is possible to realize a compact system without compromising the antenna's characteristics [10-16].

It is well known that microstrip patch antennas possess numerous advantages over conventional bulky antennas in terms of lightweight, compact dimensions, low fabrication cost, and easy circuit integration. These types of antenna find numerous applications such as for example in radio altimeters, satellite communications, remote sensing, biomedical radiators etc. However, these antennas suffer from narrow bandwidth, low gain, and high ohmic losses [17, 18].

In this paper, we present the design of an efficient radiating antenna for on-chip applications that operates over a wide frequency range from 0.3 THz to 0.32 THz. The proposed on-chip antenna is constructed from three layers stacked on top of each other consisting of polyimide-substrate, metallic ground-plane, and polyimide-substrate. The on-chip antenna is excited through a coplanar waveguide (CPW) of open-ended microstrip-line implemented on the lower polyimide substrate. The CPW feedline is split into three branches that are aligned under the three elliptical radiation patches fabricated on the top polyimide-substrate layer. When the CPW port is excited, the electromagnetic (EM) energy is coupled from bottom layer to the top-layer via the meander-line slits in the middle ground-plane. To enhance the antenna's radiation characteristics a series of linear slots of varying length and in parallel configuration are etched in the elliptical radiation patches. The interaction of EM fields between the slots creates characteristics analogous to metasurface that is shown to enhance the antenna's effective aperture without affecting the physical dimensions of the antenna. Simulations results presented show that the proposed on-chip antenna exhibits a wide impedance bandwidth and high radiation efficiency over a specified terahertz frequency range.

II. Proposed Metasurface-Based On-Chip Antenna

A reference on-chip antenna, shown in Fig.1, is constructed from stacking on top of each other three layers comprising polyimide-substrate, metallic ground-plane, and polyimide-substrate. The polyimide-substrate used has a dielectric constant (ε_r) of 3.5, loss tangent (tanδ) of 0.0027, and thickness of 100-microns. Three elliptical patches are realized on the top polyimide layer. Realized on the bottom polyimide layer is an open-circuited microstrip coplanar waveguide feedline. The feedline is split into three branches and each branch of the feedline is aligned exactly under the elliptical patch to achieve maximum power transfer from bottom-layer to the top-layer when the antenna is excited. Sandwiched between top and bottom polyimide-substrates is a metallic ground-plane of 50-micron thickness. Etched in the ground-plane are meander-line slits, as shown in Fig. 1. When the coplanar waveguide port is excited the propagating electromagnetic energy over the microstrip branches is coupled to the elliptical radiators on the top-layer through the meander-line slits in the middle ground-plane. According to transmission-line theory, synchronization needs to be maintained between the patch and the CPW feedline to satisfy the maximum power transfer. Resonant frequency of the patch in TM_{ij} mode and surface impedance can be calculated using well established standard equations found in antenna literature.

The middle ground-plane essentially reduces surface waves and substrate ohmic losses. The meander-line slits embedded in the ground-plane essentially behave like *RLC* resonators. The property of the meander-line slits depends on the plasma resonance frequency of the metal. When the electric field of the signal is directed between the two substrate layers, the surface plasmons get excited and begin to resonate. The band intensity and wavelength of the surface plasmons are dependent on the properties of the particle which includes the shape, structure, metal type, size, and dielectric material.

The simulated reflection-coefficient of the reference on-chip antenna is shown in Fig.2. It shows that this antenna operates over a frequency range of 0.304 THz to 0.308 THz and 0.31 to 0.315 THz for ($S_{11} < -10$dB). Its radiation gain and efficiency plots are shown in Figs. 3 and 4, respectively. The results show that, this antenna has an average radiation gain and efficiency of 1.0 dBi and 25%, respectively, over the specified frequency range.

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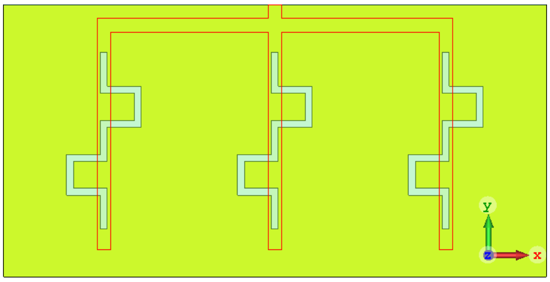

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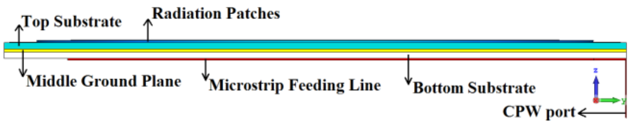

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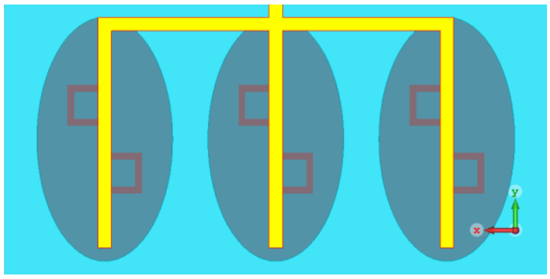

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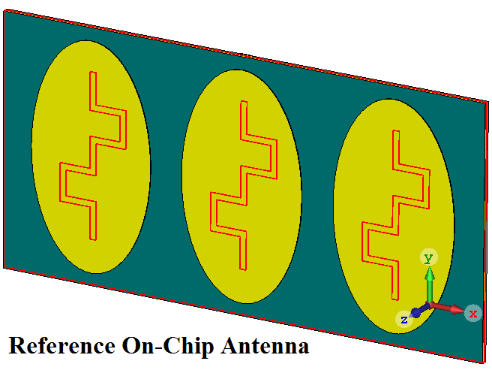


Fig.1. Configuration of the reference on-chip antenna. (a) Top-view, red lines shows the mender-line slits inside the middle ground-plane, (b) middle ground-plane which is sandwiched between the top and bottom layer, red lines shows the microstrip feedline in the bottom layer, (c) side-view representing the stacked layers, and (d) bottom view showing the open-circuited microstrip feedline branches aligned under each patch.

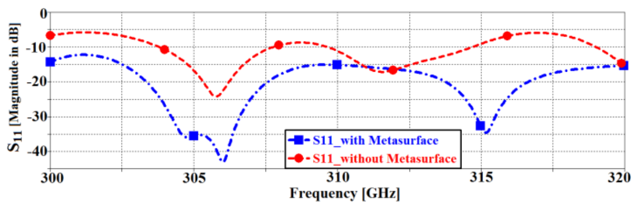


Fig.2. Reflection-coefficients of the reference on-chip antenna (without metasurface) and the proposed on-chip antenna (with metasurface).

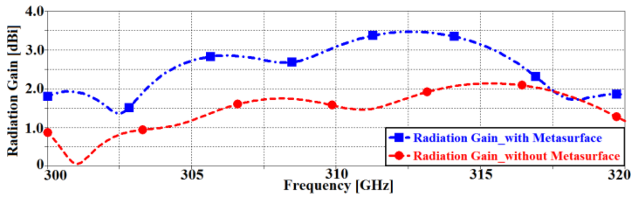


Fig.3. Radiation gain plots of the reference on-chip antenna (without metasurface) and the proposed on-chip antenna (with metasurface).

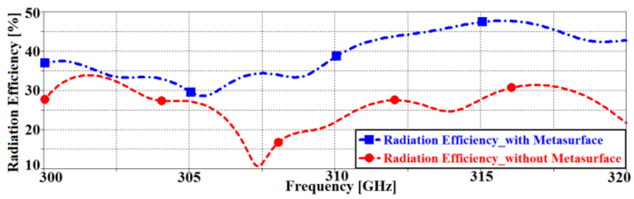
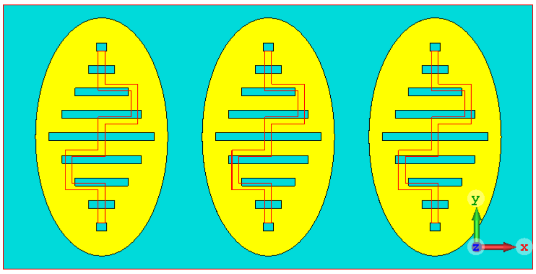
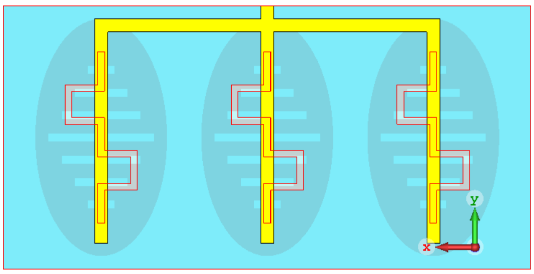


Fig.4. Radiation efficiency plots of the reference on-chip antenna (without metasurface) and the proposed on-chip antenna (with metasurface).

The proposed on-chip antenna with metasurface is shown in Fig.5. A series of linear slots of varying lengths and positioned in a parallel formation are etched on the elliptical patches. Interaction of the electromagnetic energy between the slots essentially creates a metasurface that enhances the effective aperture area of the patch. By optimizing the dimensions of the slots, we can optimize the performance of the antenna in terms of impedance bandwidth, radiation gain, and radiation efficiency, as shown in Figs. 2-4, respectively. These results show improvements in comparison with the reference on-chip antenna, i.e. without metasurface slots. The proposed on-chip antenna with metasurface slots operates over the frequency range of 0.30 THz to 0.32 THz. It is shown that, after creating the metasurface an average improvement of 11dB is achieved in the impedance match. From Figs. 3 and 4, the average radiation gain and efficiency of the proposed on-chip antenna are 2.5 dBi and 40%, respectively, which is an average improvement of 1.5 dB and 15%, then the reference on-chip antenna. The radiation characteristics of both reference and proposed antenna are summarized in Table I. The structural parameters of the proposed antenna are listed in Table II. The results confirm that the proposed on-chip antenna offers advantage of a wider impedance bandwidth, higher gain and efficiency characteristics. The simulations have been carried out in CST™ Microwave Studio.



(a)



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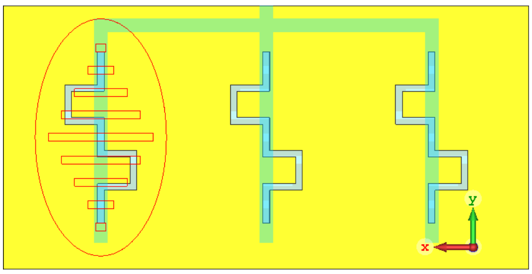

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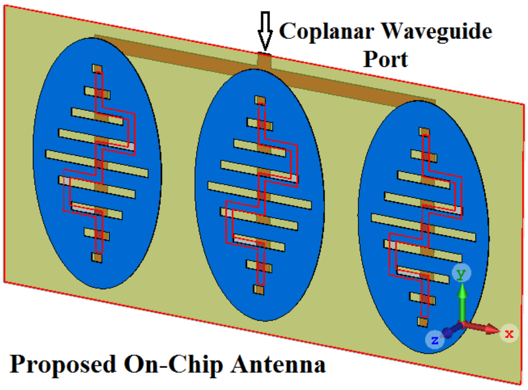

(d)

Fig.5. Layout of the proposed on-chip antenna with metasurface concept. (a) Top-view showing a series of the linear slots, (b) bottom view representing the open-ended microstrip feedline, (c) middle ground-plane layer etched with meander-line slits, red line represents the elliptical patches including the metasurface slots on the top-side, and also shown is the feedline on the bottom side, and (d) isometric view.

TABLE I. RADIATION PROPERTIES

Radiation Gain	
Reference on-chip antenna	***Proposed on-chip antenna***
Max. 2.1dBi @315 GHz	Max. 3.5 dBi @312.5 GHz
Min. 0.0 dBi @301 GHz	Min. 1.4 dBi @302.5 GHz
Average: 1.0 dBi	Average: 2.5 dBi
Average improvement after applying metasurface: 1.5 dBi	

Radiation Efficiency	
Reference on-chip antenna	***Proposed on-chip antenna***
Max. 34% @301.5 GHz	Max. 48% @315 GHz
Min. 10 % @307.5 GHz	Min. 28% @306 GHz
Average: 25%	Average: 40%
Average improvement after applying metasurface: 15%	

TABLE II. STRUCTURAL PARAMETERS (in millimeter)

Length of the polyimide layers	20
Width of the polyimide layers	10
Thickness of the polyimide layers	0.1
Length of the middle ground-plane layer	20
Width of the middle ground-plane layer	10
Thickness of the middle ground-plane layer	0.05
Vertical radius of the elliptical patch	4.5
Horizontal radius of the elliptical patch	2.5
Longest to shortest lengths of the linear slots	4, 3, 2, 1, 0.4
Width of the linear slots	3.0
Space between the linear slots	0.55
Length of the meander-line slits	13.5
Width of the meander-line slits	0.25
Length of each vertical branch of the feedline	8.0
Length of horizontal branch of the feedline	6.3
Width of the feedline	0.5
Space between the feedline branches	6.2
Length and width of feedline junction	0.5, 0.5

III. Conclusion

Feasible study shows that the proposed antenna is viable for on-chip applications operating between 0.30 THz to 0.32 THz. The antenna structure is composed a metallic ground-plane sandwiched between two polyimide substrate layers. Fabricated on the top polyimide layer are three elliptical radiators with embedded dielectric slots of different length to create a metasurface that is established by the interaction of the EM field between the slots. The antenna is excited using a coplanar waveguide feedline implemented in the bottom polyimide-substrate. EM energy is coupled to the radiators via meander-line slits in the ground-plane. Simulation results confirm that the proposed on-chip antenna enhances the impedance bandwidth, gain and radiation efficiency without affecting the form factor of the antenna.

Acknowledgments

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