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RESEARCH ARTICLE

Intelligent Metasurface Layer for Direct Antenna Amplitude Modulation Scheme

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ABSTRACT This paper proposes a transmitter system based on direct antenna amplitude-shift keying modulation for point-to-point microwave link. The proposed system is formed from a conventional microstrip antenna and a novel reconfigurable metasurface layer (RMSL). The proposed RMSL has two states: OFF (or Logic-0) and ON (or Logic-1) where each switching scenario provides a certain gain level. This is achieved through controlling the proposed RMSL switching configuration to control the amplitude of the transmitted signal. Results show that such a system can modulate electromagnetic signals directly by varying the antenna's gain from about 2 dBi for Logic-0 to 13.8 dBi for Logic-1. An analytical model-based ray-tracing technique is invoked to explain the operation of the proposed antenna system. To demonstrate the operation of the proposed system, both the antenna and the RMSL structures were fabricated, assembled and tested. Measurements show good agreement with the theoretical model and numerical simulations obtained using CST Microwave Studio software package. The overall system has dimensions of $25 \times 25 \times 7.3$ cm^3.

INDEX TERMS ASK modulation, direct antenna modulation, microstrip antenna, reconfigurable metasurface.

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I. INTRODUCTION

Amplitude-shift keying (ASK) is a digital modulation scheme that was invented for modern wireless communication networks where the amplitude of the carrier wave is varied in accordance with the baseband data source [1]. In any wireless communication system, the carrier wave, which is a sinusoidal signal of a high frequency corresponding to the radio frequency (RF) channel of interest, is modulated with the baseband data prior to transmission. The digital signal is upconverted using a mixer, which is a nonlinear device. The output of the mixer needs to be filtered to remove intermodulation artifacts generated in the modulation process and the resulting signal is amplified with a power amplifier (PA) before transmission [1]. Unfortunately, high peak-to-average-power ratio of the baseband signals can cause the PA, which is a nonlinear device to generate spuria responses that can interfere with other wireless systems. To eliminate this issue a relative new technique has been developed and is referred to as direct antenna modulation (DAM) [2]. This modulation scheme uses the baseband data to control the radiation properties of an antenna to generate a modulated signal.

Various approaches of DAM have been presented in literature [3], [4], [5], [6]. Many researchers achieved ASK-DAM by controlling the antenna input impedance. In [7] it is shown that although reconfigurable antenna systems could fulfil the requirements for smart communication systems however, they have limitations for application in most types of modulation schemes. The authors in [8] designed a DAM based on array of switchable passive reflectors. Pulse duration modulation was achieved directly with a multiple/input-multiple/output (MIMO) system through timed switching for antennas [9].

In [10] a new feed mechanism is proposed for an electrically small antenna. Using this technique, an arbitrary amplitude-modulated waveform can be transmitted through a high-Q electrically small transient-state antenna. In [11] and [12] a new strategy involving direct transmission of data via programmable coding RMSL is employed to modulate a signal. In [13] it is shown that the use of metasurface structures can be used to enhance the performance of an antenna as well as the electromagnetic wave characteristics. Moreover, it is shown that metasurface can be used to for beam forming applications. In [14], a high gain RMSL-antenna is presented. This antenna was further developed in [15] to realize gain variation by changing the metasurface array dimensions. A reprogrammable hologram was produced based on a one-bit metasurface for imaging applications in [16]. In [17] microwave imaging is proposed based on 2-bit programmable metasurface for a single sensor at a single frequency. Scattering diffusion is improved in [18] using an active metasurface at THz frequencies. The authors of [19] presented dual band metasurface operating at microwave frequencies. In [20], a digital coding transmissive RMSL is proposed that produces multiple beams. In [21] and [22], a multifunctional coding RMSL has been suggested as a means of producing dual-circularly polarized beams.

In this paper, the design of an ASK-modulator based on patch antenna-RMSL is presented for point-to-point microwave link. The proposed ASK-modulator technique addresses the nonlinearity issue with power amplifiers and reduces the complexity and expense of the transmitter. The proposed system can be used in many wireless communication applications including near-field [8], fixed point-to-point microwave link, Radar [23], remote sensing [24], DAM [25] and medical applications [26].

II. SYSTEM OPERATION

The proposed system basically consists of two components, i.e., a microstrip antenna having a gain of about 1 dBi gain (G_t), and a RMSL consisting of 5 × 5 unit cells. The unit cells are controlled by a group of light-dependent resistors (LDR). The RMSL is used to enhance the gain of the microstrip antenna, which is controlled by the activation status of the LDR. If the LDR devices are OFF, the microstrip antenna gain is about 2 dBi, however when LDR devices are ON, the microstrip antenna gain is enhanced to about 13.8 dBi. The resultant gain achieved is thus:

$$G_t = \begin{cases} 2 & \text{dBi status : OFF} \\ 13.8 & \text{dBi status : ON} \end{cases} \tag{1}$$

The gain improvement in the ON state results by the improvement of the impedance matching of the metasurface layer and the increase in the effective aperture area of the antenna. In [27] it's shown how metasurface can change the radiation phase of a patch antenna to an in-phase profile such that the antenna radiates like a planar wave thus enhancing the antenna's performance.

The received power (P_r) at the proposed antenna for a fixed point-to-point microwave link is given by Friis transmission equation [28]

$$P_r = P_t + G_r + 20\log\left(\frac{\lambda}{4\pi R}\right) + \begin{cases} 2 & \text{dBi status : OFF} \\ 13.8 & \text{dBi status : ON} \end{cases} \tag{2}$$

where P_t is the transmitted power (dB), G_r is the receiver gain (dBi), λ is the wavelength (m) and R is the distance between the transmitter and the receiver (m). Equation (2) clearly shows that using the proposed RMSL, the transmitted power can be boosted according to the activation status of the LDR devices. If the RMSL is managed via a data source via a microcontroller, the transmitted power will represent the data. Fig. 1 illustrates the proposed system as an ASK-modulator.

III. ANTENNA DESIGN

The proposed antenna is based on the design of a standard microstrip patch antenna where the width (W) and the length (L) can be determined from the following expressions [28]:

$$W = \frac{c}{2f_o}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{3}$$

$$L = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} - 0.824h\left[\frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}\right] \tag{4}$$

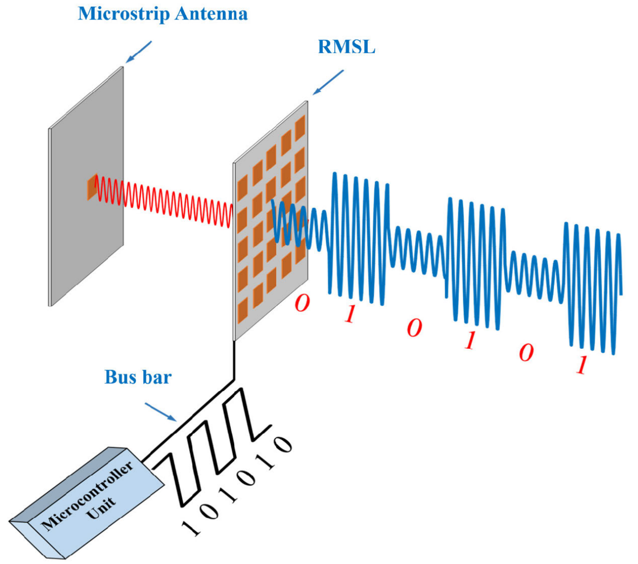

FIGURE 1. System schematic of the proposed ASK modulator.

where

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} - \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\frac{h}{W}}}\right] \tag{5}$$

Fig. 2 shows the design of the proposed microstrip antenna at 2.45 GHz, where the patch antenna is directly fed through a coaxial probe of a 50 Ω SMA port. The patch geometry is based on a truncated rectangular structure that was inspired by [29]; however, the patch edges have been etched to create corrugated slots. The purpose for this is to reduce unwanted surface effects that can compromise the antenna's impedance matching characteristics. It should be noted that the slots have been known to affect the symmetry of the radiation pattern [15]. The FR4 material with $\varepsilon_r = 4.3$, $\tan\delta = 0.025$, and thickness of 2 mm was chosen to implement the antenna. The corresponding dimensions of the slot in terms of wavelength are as follows: 7.5 mm = $0.061\lambda_o$, 3.5 mm = $0.028\lambda_o$, 4.5 mm = $0.036\lambda_o$, and 1.2 mm = $0.0098\lambda_o$ where λ_o is the center frequency. The rectangular grove has a width of $0.008\lambda_o$, larger side length of $0.01\lambda_o$ and shorter side length of $0.01\lambda_o$. These values were obtained through optimization using CST Microwave Studio (MWS).

IV. RMSL DESIGN

The unit cell, which is shown in Fig. 3, is constructed from microstrip-lines, cross with T-shaped ends also commonly referred to a crutch cross, and U-shaped resonant structures. The motion of the electrical current over the structure is controlled by the four LDR devices which eliminate the limitations of the traditional patches [30]. The LDR devices provide a mechanism to control the antenna gain in both the azimuth and zenith planes. The dimensions of the unit cell are approximately $\lambda/2$ at the operating frequency according to the criterion given in [31].

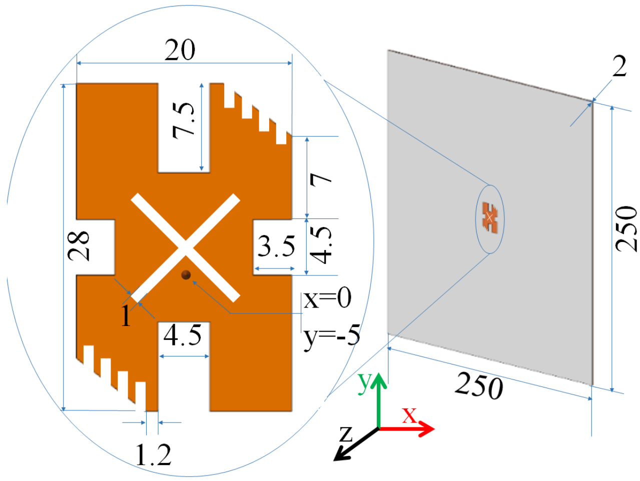

FIGURE 2. Microstrip antenna patch details in millimeter scale.

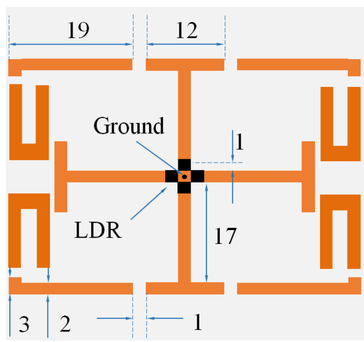

FIGURE 3. Metasurface unit cell structure in millimeter scale.

Electromagnetic characterization of the proposed unit cell was investigated numerically using CST MWS in [32]. To evaluate the constitutive characteristics of the unit cell, it was located at the center of a virtual waveguide, as illustrated in Fig. 4. The top and bottom sides (perpendicular to the y-axis) of the boundary conditions are chosen as Perfect-Magnetic-Conductors (PMC), while the left and right sides are chosen as Perfect-Electric-Conductors (PEC) (perpendicular to x-axis).

According to Fig. 4, two ports along the z-axis are used to stimulate the TEM mode. The magnitude fluctuation of S_{21} for the ON and OFF situations is depicted in Fig. 4(a). It is important to note that the resonant frequency at Logic-1 was required to be at 2.56 GHz for the given design specifications, however in the case of Logic-0, the frequency resonance is eliminated from the frequency of interest. As a result, only Logic-1 can achieve the maximum power transfer at 2.45 GHz, and Logic-0 results in no power transmission.

The corresponding phase variation of the forward transmission coefficient (S_{21}) is plotted in Fig. 4(b) for both ON and OFF states. For the ON case, the matching impedance occurs at the resonant frequency of 2.56 GHz where the phase is 0°. This phenomenon declares that imaginary part of the impedance to vanish, and it confirms that the result

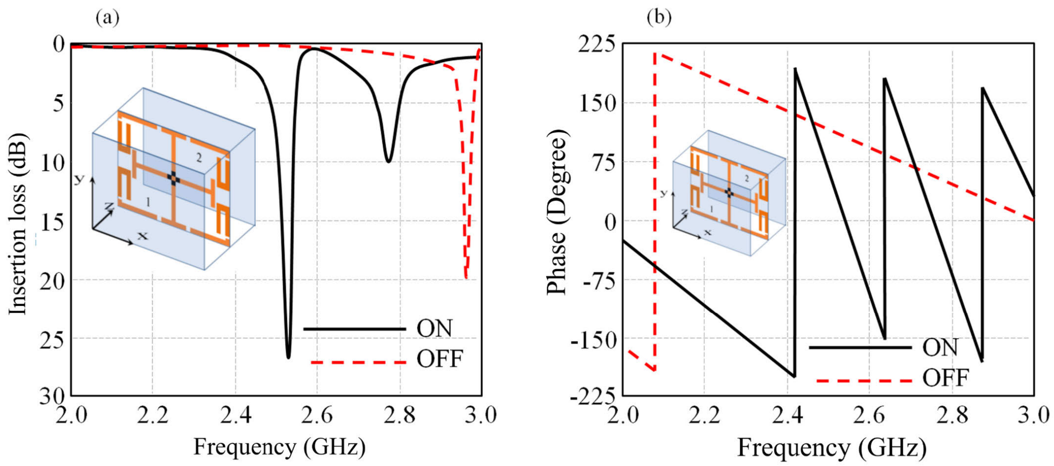

FIGURE 4. Unit cell performance characterization, (a) S_{21} magnitude spectra, and (c) S_{21} phase response.

of maximum-power-transfer can be obtained at Logic-1 [10]. The ON and OFF states of the LDR determine the sections of the metasurface unit cell structure, shown in Fig. 5, that are connected. In the ON state, the LDR makes the unit cell appear bigger and the corresponding frequency drops, however the vice versa applies when the LDR is in the OFF state.

The transmission-line model in [30] and [33] has been modified to manage the proposed RMSL design. The modifications comprise addition of an extra-capacitance (C_{extra}) parallel with the switch (S_{extra}), as shown in Fig. 5. When the LDR of the reconfigurable metasurface unit cell is in the OFF state, four new capacitances appear due to the gaps in the reconfigurable metasurface unit cell structure. Therefore, C_{extra} in Fig. 5 represents the equivalent capacitance of the four capacitances. S_{extra} represents the four LDR devices. By switching the unit cell to the OFF state, the frequency resonance must vanish from the frequency band of interest. On the other hand, in the ON state, the four LDR devices leads to eliminate the four gaps. In this case, the proposed RMSL provides a well-defined frequency response at 2.56 GHz.

Based on the unit cell's geometrical dimensions, the following equations can be used to calculate the lumped circuit components [33]:

$$C_g \approx \frac{2\epsilon_\circ \epsilon_{reff} L}{\pi}\left(\frac{L_h}{L}\right)\ln\left[\frac{1}{sin\left(\frac{\pi g}{2L}\right)}\right] \tag{6a}$$

$$L_g \approx \frac{\mu_\circ L}{2\pi}\left(\frac{L_v}{L}\right)\ln\left[\frac{1}{sin\left(\frac{\pi L_2}{2L}\right)}\right] \tag{6b}$$

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left\{\left[1 + 12\left(\frac{h}{w}\right)\right]^{-0.5} + \left[1 - \left(\frac{w}{h}\right)\right]^2\right\} \tag{6c}$$

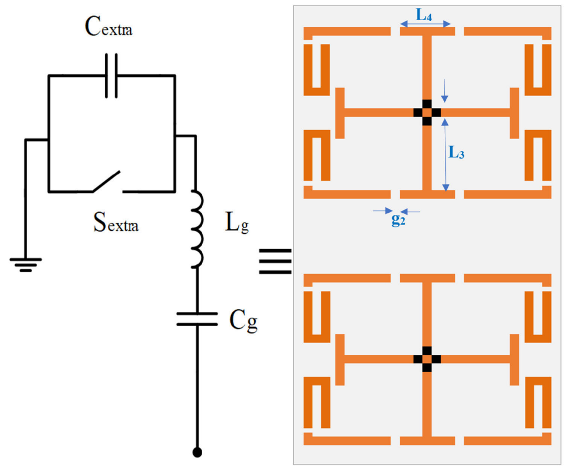

FIGURE 5. The equivalent circuit of the proposed RMSL.

where L_g is the total inductance of the metasurface layer, and C_g is the total capacitance of the metasurface layer, which is mostly due to the fringing capacitance. The substrate thickness and microstrip-line width are represented by h and w. The gap between the two neighboring unit cell's and between the center and edges, respectively, are represented by L and g. Lengths $L_h = 2L_3 + L_4$ and $L_v = 2L_3 + g_2$. For a very thin metasurface substrate, ϵ_{reff} can be assumed to equate to unity from equation (6c). From the equivalent circuit model given in Fig. 5, the resonance frequency f_r can be obtained using the following expression [33]:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{C_g + C_{extra}}{C_g C_{extra} L_g}} \tag{7}$$

For the ON state, the calculated equivalent circuit parameters are as follows: $C_g = 0.1953$pF, $L_g = 21.241$nH and $f_r = 2.47$ GHz. For the OFF state, C_{extra} appears in series with C_g which results in reducing the value of equivalent

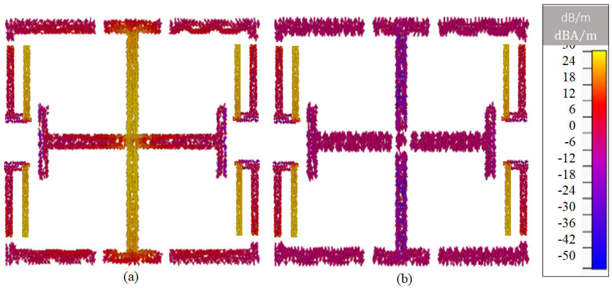

FIGURE 6. Surface current distributions of the proposed unit cell; (a) status-ON; (b) status-OFF.

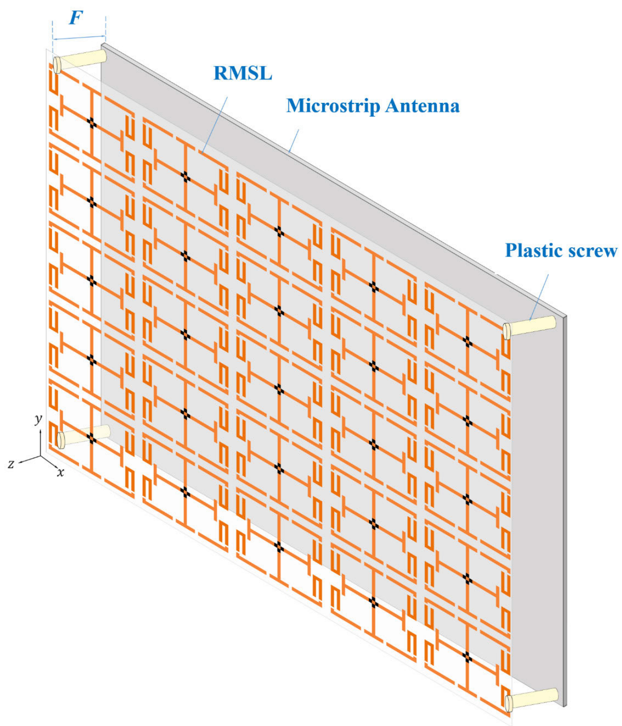

FIGURE 7. The proposed RMSL structure.

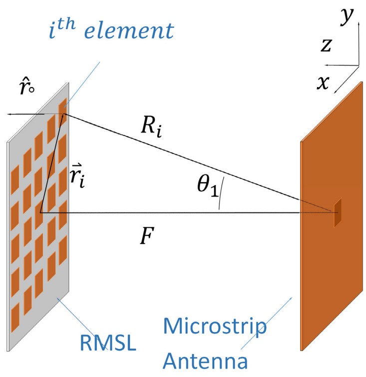

FIGURE 8. Ray-tracing based phase difference.

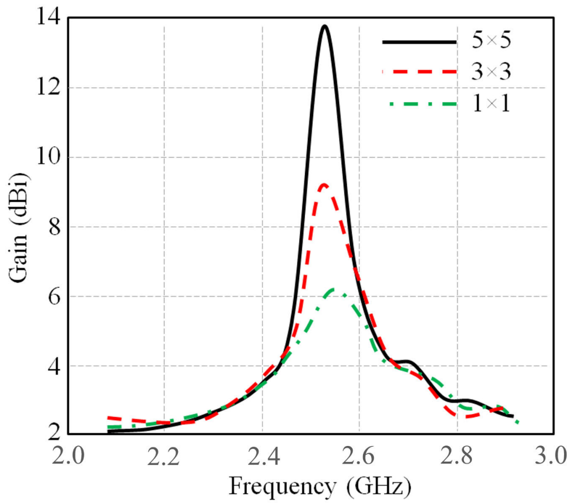

FIGURE 9. A parametric study for the proposed system performance.

capacitance and shift-up the resonance frequency. A small capacitance value of C_{extra} is expected by considering the physical gap. In fact, C_{extra} has a value of 0.08pF and as a result, the resonance frequency f_r shifts up in frequency to 4.4 GHz.

The surface current distributions over the proposed metasurface unit cell structure in the ON and OFF LDR states are shown in Fig. 6. The surface current over the antenna structure is due to the flow of electrical charge over the antenna structure. The non-uniform distribution of surface current is due to the changing electromagnetic field impinging on the antenna and the interaction between the adjacent metasurface unit cells. Nevertheless, in the case of ON state, the surface current distribution reaches a maximum magnitude of 29 dBA/m, as shown in Fig. 6(a), at a resonance frequency of 2.45 GHz. In the OFF state, the surface current distribution is observed to be around 0 dBA/m, as shown in Fig. 6(b).

The proposed RMSL is based on an array of 5 × 5 unit cells distributed uniformly. The RMSL that is constructed from the proposed unit cell is mounted on a FR4 substrate ($\varepsilon_r = 4.3, \tan\delta = 0.025$) with a thickness of 1 mm. The dimensions of the individual unit cell are 50 × 50 mm^2 where outer physical dimensions of the conductor region are 45 × 36 mm^2 and the space between the conductors of neighbor unit cells are 10 mm and 14 mm along x- and y-axes, respectively. To ensure minimum coupling between the unit cells, the periodicity of the unit cell was adjusted to 50 mm ($\sim\lambda/2$) [31]. A perspective view of the proposed antenna and RMSL structure is shown in Fig. 7.

One of the key points in the design of the RMSL was the determination of focal length (F) under ON and OFF LDR states. While optimal gain may be obtained when the distance between the RMSL and the antenna is set to achieve the paraxial rays, proper focal length selection is essential. The unit cell in the ON and OFF scenarios has a distinct focal length. We achieved the greatest increase in antenna gain when RMSL was placed at the focus point. When the RMSL

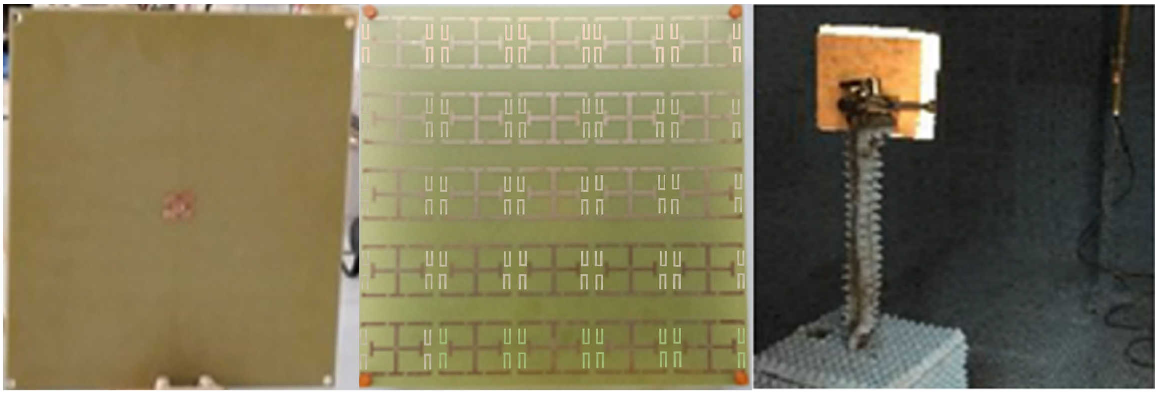

FIGURE 10. The fabricated prototypes and measurement setup. From left to right: Fabricated microstrip antenna, top view of the RMSL, and antenna measurement setup inside the RF anechoic chamber.

was switched to the OFF state, the focal length changes to a different value and the antenna gain drops. The gap between the RMSL and antenna was held constant in this study.

In this work, two methods are introduced to find the value of the focal point. The first approach uses ray-tracing analysis, which was motivated by optical theory in [34]. The authors performed the necessary computations while imagining the metasurface layer as a lens mounted antenna to investigate the basic workings of the layer. The RMSL's dimensions were kept the same as the ground plane of the microstrip antenna to reduce the side-lobe levels. Moreover, the phase difference between the central unit cell and the diagonal unit cell on the metasurface layer were made to be $(2n+1)\pi$ rad (n is an integer). This condition is necessary to guarantee the maximum possible deconstructive interference of the radiated electromagnetic waves from the layer's unit cells at the rim. From the illustrated in Fig. 8 it can be shown that the phase difference is given by [35].

$$k\left[R_i - \left(\vec{r}_i.\hat{r}_\circ\right)\right] = \psi_i - \psi_\circ \tag{8}$$

where k is the propagation constant in free space. The distance from the center of the patch antenna to the center of the i^{th} element is represented by R_i, and $\vec{r}_i$ is the position vector of the i^{th} element. The direction vector of the main beam is $\hat{r}_\circ$. To meet this condition, the term $\psi_i - \psi_\circ$ must be adjusted to be 3π rad. The other clue at the broadside direction is that both $\vec{r}_i$ and $\hat{r}_\circ$ are almost perpendicular, which means that the dot product between $\vec{r}_i$ and $\hat{r}_\circ$ is null. Therefore, the value of R_i is found to be 153 mm, $\theta_1 = 67.6^\circ$. RMSL is mounted at a focal point (F) distance of 70 mm.

Based on CST MWS simulations, the second approach is determined by the focal length. To achieve the greatest gain increase, CST MWS is used to investigate the ideal metasurface placement, array size, and orientation of the microstrip patch antenna. By changing the reconfigurable metasurface array configuration size from 1 × 1, 3 × 3, and 5 × 5, the antenna gain is found to change significantly as shown in Fig. 9.

V. MEASUREMENTS AND VALIDATION

The antenna and RMSL were constructed and installed, as shown in Fig. 10, following the determination of the ideal system design parameters. Chemical etching using PCB technology is used to create the antenna and RMSL. Four plastic screws, each measuring 70 mm in length, are used to install the RMSL. It is important to note that LDR are not soldered while making RMSL. Instead, two distinct layers are constructed to show the ON and OFF states. A common measuring system is used to assess the antenna performance in terms of S_{11} spectra and radiation patterns. Coaxial cables, an Agilent PNA 8720 series vector network analyzer, and an 82357A USB to GPIB interface that is linked to an external computer make up the measurement setup. As shown in Fig. 10, the antenna is mounted on a rotating holder which is located inside an RF anechoic chamber.

The simulated and measured S_{11} variation as the function of frequency and the antenna radiation pattern at $\varphi = 0^\circ$ and $\varphi = 90^\circ$ planes are shown in Fig.11. Fig. 11(a) shows S_{11} of the antenna without RMSL. It is observed from this figure that the antenna radiation pattern covers a wide 3-dB beamwidth of 136° with a gain of about 1 dBi at 2.45 GHz. The spectra of S_{11} for the antenna with RMSL in the OFF state is shown in Fig. 11(b) together with radiation patterns at perpendicular planes. The antenna resonates frequency at 2.45 GHz with a gain of about 2 dBi and exhibits a 3-dB beamwidth of 113°. The final set of measurements is presented in Fig. 11(c) for the antenna with RMSL in the ON state. It is found from this figure that the antenna exhibits a gain of about 13.8 dBi at 2.45 GHz. In this case, the antenna's 3-dB beamwidth is significantly reduced to 26°.

Total efficiency of the antennas was investigated in this study. The total efficiency of the antenna was 20% when RMSL is not employed. However, by assembling the RMSL on the microstrip antenna, the total efficiency improved to 28% in the OFF state but in the ON state the efficiency significantly increased to 45%. The reason for the improvement in total efficiency in the ON state is because the reactive part of the RMSL at its resonance frequency, i.e., operating

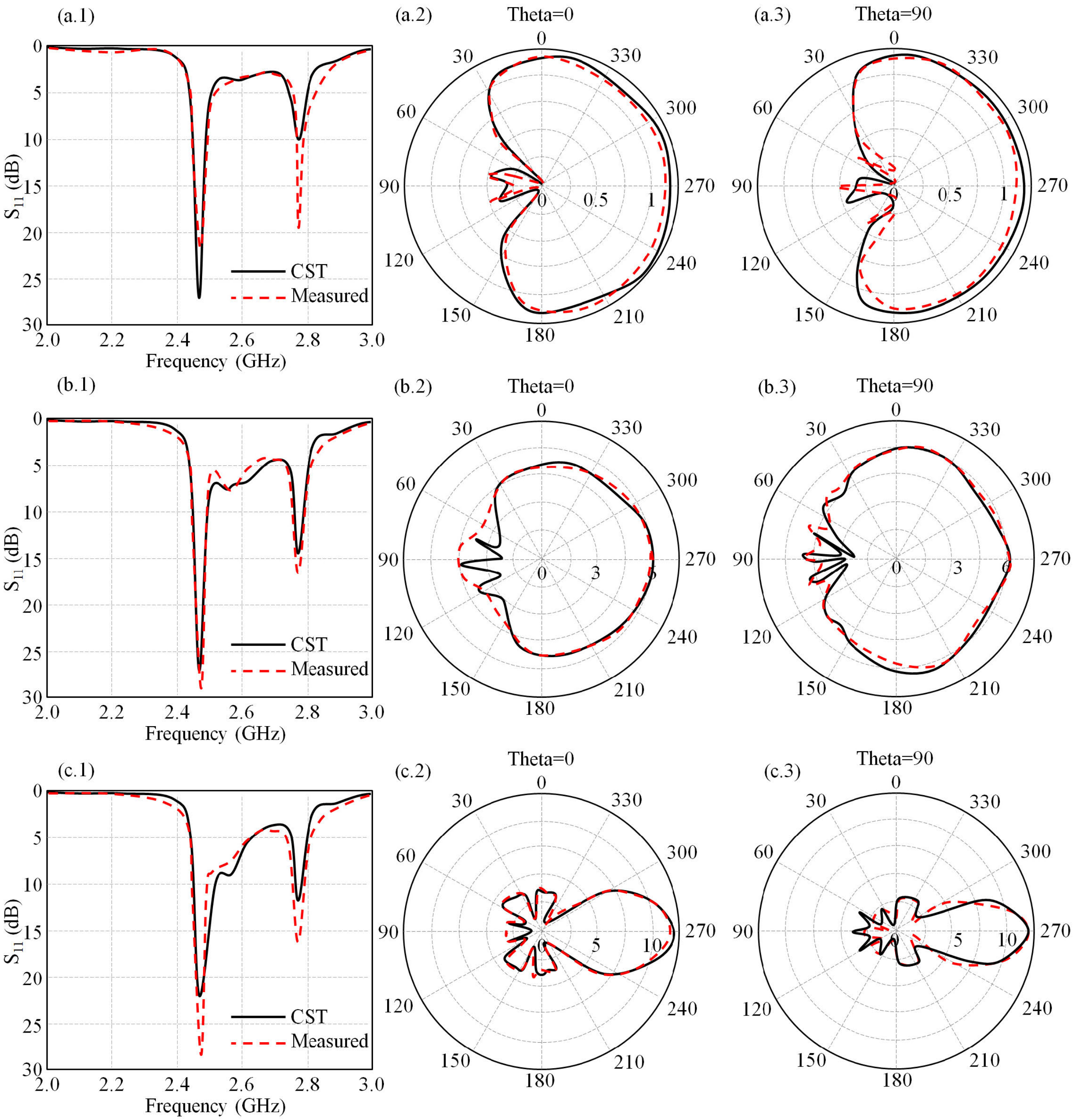

FIGURE 11. Measured and simulated results of the proposed antennas, (a.1) S_{11} spectra of the antenna without RMSL, (a.2), and (a.3) radiation pattern of the antenna without the RMSL at $\varphi = 0^{\circ}$ and $\varphi = 90^{\circ}$, respectively, (b.1) S_{11} spectra of the antenna with RMSL in the OFF state, (b.2), and (b.3) radiation pattern of the antenna with RMSL in the OFF state at $\varphi = 0^{\circ}$ and $\varphi = 90^{\circ}$, respectively, (c.1)S_{11} spectra of the antenna with RMSL in the ON state, (c.2), and (c.3) radiation pattern of the antenna with RMSL in the ON state at $\varphi = 0^{\circ}$ and $\varphi = 90^{\circ}$, respectively.

frequency, is negated. Hence, optimum power is transferred through the RMSL.

RMSL does not have the same symmetry along x and y-planes. Thus, to observe the effects of RMSL placement on the antenna performance, RMSL is rotated 90° with respect to the microstrip antenna on $x-y$ plane around its center. The antenna parameters are listed in Table 1 for non-rotated and 90°-rotated cases. When the RMSL is rotated 90°, the antenna gain obtained is 2.6 dBi and 10 dBi for the OFF and ON states, respectively. The difference in the gain between the ON and OFF states is 7.4 dB. An optimum gain of 9 dB was obtained at 0° orientation. Therefore, 0° orientation was chosen as the optimal case. The simulated antenna gain was 11.8 dB. The discrepancy between the measured and simulated results is

TABLE 1. Effects of RMSL rotation on the antenna performance.

At orientation = 0°						
status	f_r (GHz)	S_{11} (dB)	Gain (dBi)	F/B (dB)	Total efficiency (%)	Radiation efficiency (%)
OFF	2.45	-24	2	7.5	28	29
ON	2.45	-21	13.8	5.2	44	45
At orientation = 90°						
status	f_r (GHz)	S_{11} (dB)	Gain (dBi)	F/B (dB)	Total efficiency (%)	Radiation efficiency (%)
OFF	2.45	-25	2.3	7.4	28	29
ON	2.45	-20	13.6	6.5	39	39

TABLE 2. Comparison of the proposed work with other published results.

Reference	f_r (GHz)	Substrate	Size (mm^2)	Number of layers	Gain enhancement (G) (dB)
[15]	2.45	FR4	240 × 240	2 layers	5.1
[35]	2.65	Taconic	360 × 360	2 layers (Octagon)	7.8
[36]	5.8	FR4	50 × 50	1 layer	1.2
[37]	11.38	Polymer	50 × 50	1 layer	7.9
[38]	5.2	FR4	50 × 50	1 Layer	4.5
[39]	2.65	Taconic	360 × 360	2 layers (circular)	6.0
proposed work	2.45	FR4	250 × 250	1 layer	9.0

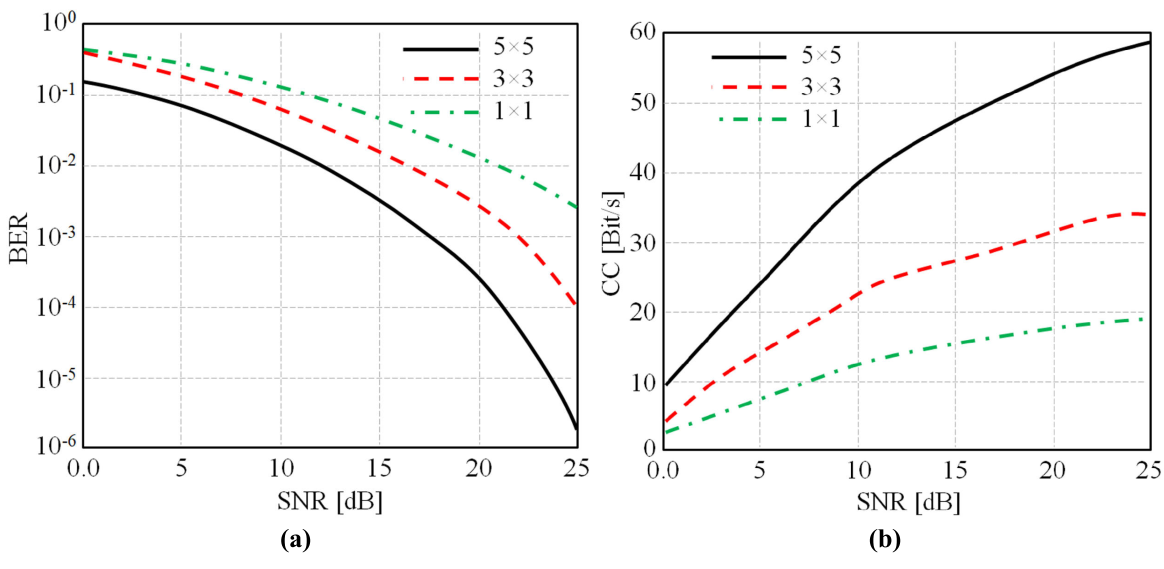

FIGURE 12. Channel performance: (a) BER for 12 bits/s/Hz, and (b) CC evaluations.

attributed to manufacturing tolerance and the inaccuracy of the simulation models. Front-to-back ratio (F/B) change is insignificant by the orientation of the RMSL.

Previous antenna research has essentially paid attention to improving the antenna gain. The performance of the proposed antenna is compared with other published works in Table 2. It is evident from the table that the proposed antenna exhibits exceptional gain improvement resulting from the use of the reconfigurable RMSL. In this work, the application intended for the proposed antenna is for controlling the antenna gain required direct antenna modulation schemes. According to authors' knowledge, the proposed work is the first of its kind on intelligent metasurface layer for amplitude modulation technology.

VI. CHANNEL PERFORMANCE RESULTS

In this section, the proposed antenna system is evaluated in terms of bit error rate (BER) and channel capacity (CC). ASK schema was applied to the antenna directly by reconfiguring the RMSL. This was achieved by switching the status of the LDR devices. The BER performance was determined at various signal-to-noise ratios (SNR) and in the ON/OFF

LDR scenarios. In the MATLAB computation Additive white Gaussian noise (AWGN) was considered. The maximum BER is placed at 100 and the maximum number of bits is taken as 1×10^7. The BER behavior as a function of S/N and RMSL array size is shown in Fig. 12(a). The performance of the proposed antenna system in terms of CC as a function of S/N and RMSL array size is shown in Fig. 12(b). It was discovered that significant variation in CC could occur with changing the switching scenarios at the frequency band of interest.

VII. CONCLUSION

Proposed here is an ASK transmitter system based on microstrip antenna and RMSL for point-to-point microwave link. When the RMSL is turned on (Logic-1), the proposed antenna system offers a gain of 13.8 dBi. However, when the RMSL is turned off (Logic-0), the gain only reaches 2 dBi in relation to cycles of the modulation period. Digital coding can regulate the transmitted electromagnetic power from the proposed antenna system by electrically switching each unit cell in the RMSL. The operating principle is explained using an analogous circuit model and optical ray-tracing analysis. By changing the metasurface layer, the antenna gain can be controlled. The antenna system was practically evaluated. The measured findings show excellent agreement with the numerical predictions. Rotating the RMSL in relation to the microstrip antenna around its center allowed one to see how the positioning of the RMSL affects the antenna's performance. It was discovered that the radiation pattern and gain could be significantly altered by 90° rotation of the metasurface layer with respect to the patch antenna's normal axis. It was discovered that when the RMSL is switched to the OFF state, the surface current over the structure is reduced and vice-versa in the ON state. The phase variation of the forward transmission coefficient shows impedance matching at the resonant frequency at the ON state. In this case, the phase is zero and the imaginary part of the impedance is negligible. As a result, maximum power transfer is obtained at Logic-1. Finally, the efficiency of the antenna system was found to be significantly enhanced by switching the RMSL to the ON state. This was because the reactive component of the antenna is negated at its resonance frequency. As a future work, the proposed RMSL structure needs to be analyzed using different modulation processes. Also, investigation needs to be conducted to realize beam splitting for space division multiple access applications.

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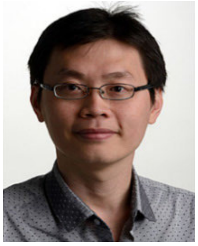

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