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Intelligent Metasurface Layer for Direct Antenna Amplitude Modulation Scheme

Marwah Haleem Jwair[1], Taha A. Elwi[2]*, Mohammad Alibakhshikenari[3]*, Bal. S. Virdee[4], Hayder Almizan[5], Zaid A. Abdul Hassain[6], Syed Mansoor Ali[7], Lida Kouhalvandi[8], Patrizia Livreri[9], Nurhan Türker Tokan[10], Giovanni Pau[11], Chan Hwang See[12], and Ernesto Limiti[13]

[1]Department of Information and Communication Engineering, College of information engineering, Al-Nahrain University, Baghdad, Iraq
[2]International Applied and Theoretical Research Center (IATRC), Baghdad Quarter, Iraq
[3]Department of Signal Theory and Communications, Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain
[4]Center for Communications Technology, London Metropolitan University, London N7 8DB, United Kingdom
[5]Department of Electronics and Communication, College of Engineering, Kufa University, Najaf, Iraq
[6]Electrical Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
[7]Department of Physics and Astronomy, College of Science, P.O. BOX 2455, King Saud University, Riyadh 11451, Saudi Arabia
[8]Department of Electrical and Electronics Engineering, Dogus University, Istanbul 34775, Turkey
[9]Department of Engineering, University of Palermo, viale delle Scienze BLDG 9, Palermo, IT 90128, Sicily, Italy
[10]Department of Electronics and Communications Engineering, Yildiz Technical University, Esenler, Istanbul 34220, Turkey
[11]Faculty of Engineering and Architecture, Kore University of Enna, 94100 Enna, Italy
[12]School of Engineering and the Built Environment, Edinburgh Napier University, 10 Colinton Rd., Edinburgh, EH10 5DT, U.K. (e-mail: c.see@napier.ac.uk)
[13]Electronic Engineering Department, University of Rome "Tor Vergata", Via del Politecnico 1, 00133 Rome, Italy

*Corresponding Authors: tahaelwi82@almamonuc.edu.iq, mohammad.alibakhshikenari@uc3m.es, and giovanni.pau@unikore.it

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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 25×25×7.3 cm^3.

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

1. 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

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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]-[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].

2. 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:

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

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]

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

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.

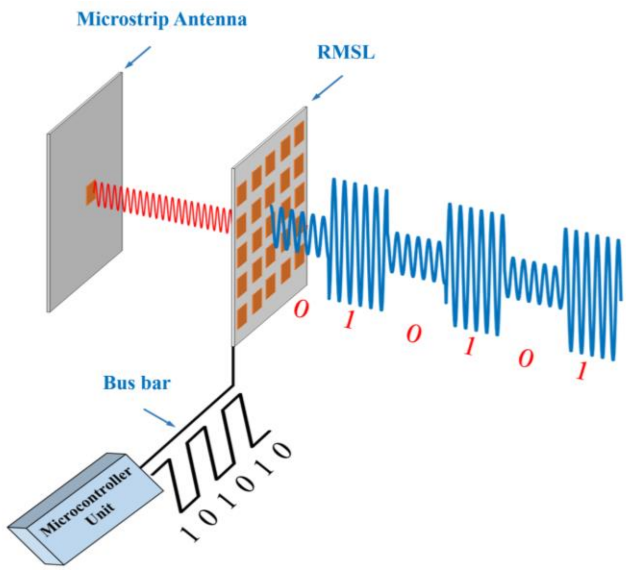

Fig. 1. System schematic of the proposed ASK modulator.

3. 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]:

$$W = \frac{c}{2f_o}\sqrt{\frac{2}{\varepsilon_r + 1}} \qquad (3)$$

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

Where

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

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).

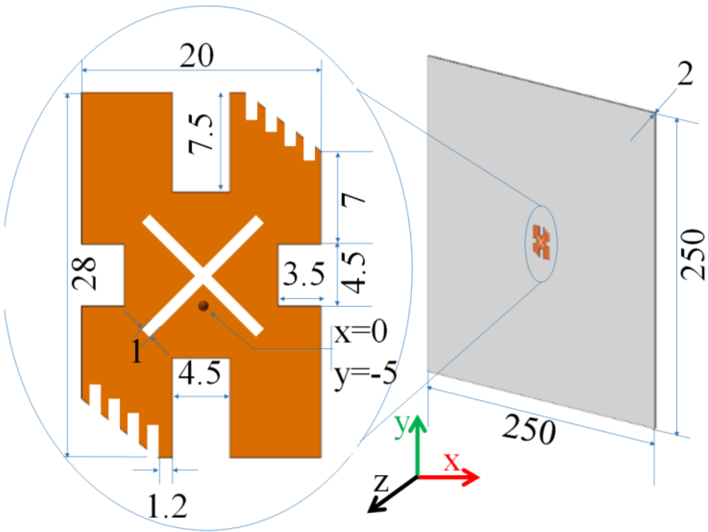

Fig. 2. Microstrip antenna patch details in millimeter scale.

4. 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].

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).

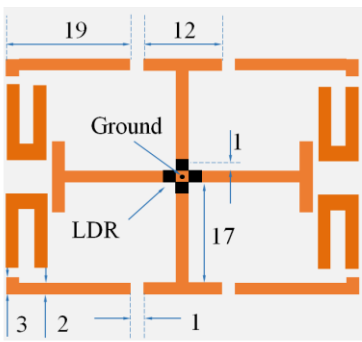

Fig. 3 Metasurface unit cell structure in millimeter scale.

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^o. This phenomenon declares that imaginary part of the impedance to vanish, and it confirms that the result 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.

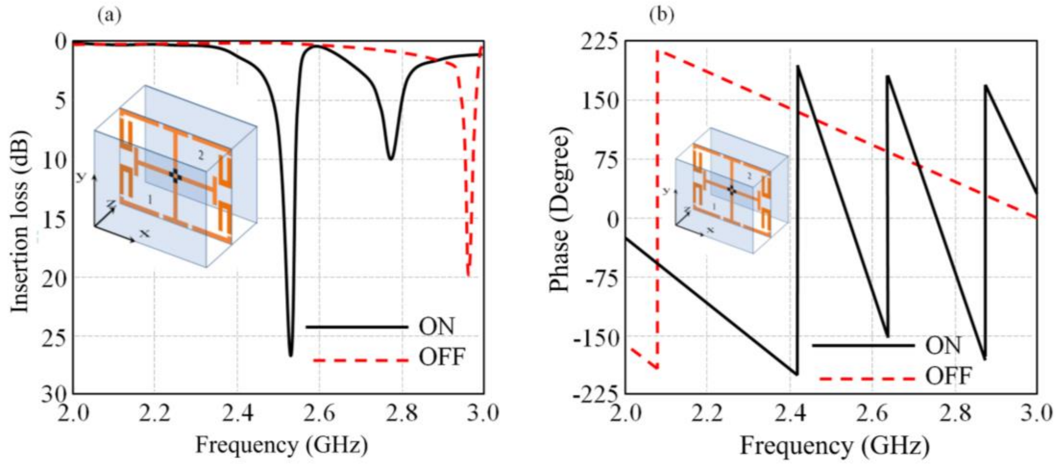

Fig. 4. Unit cell performance characterization, **(a)** S_{21} magnitude spectra, and **(c)** S_{21} phase response.

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]:

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

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

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

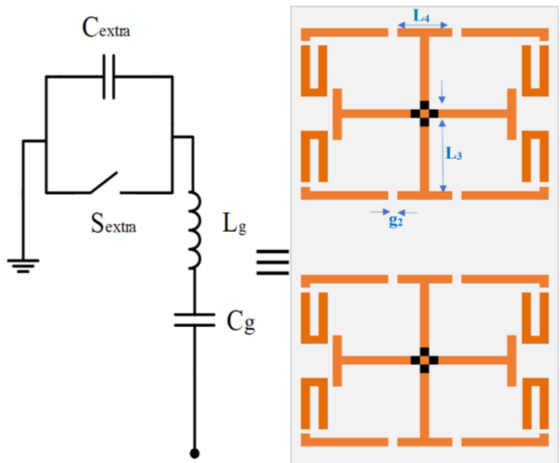

Fig. 5. The equivalent circuit of the proposed RMSL.

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 $L_h = 2\mathrm{L}_3 + \mathrm{L}_4$ and $L_v = 2\mathrm{L}_3 + g_2$. 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]:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{\mathrm{C_g} + \mathrm{C_{extra}}}{\mathrm{C_g C_{extra} L_g}}} \qquad (7)$$

For the ON state, the calculated equivalent circuit parameters are as follows: $\mathrm{C_g} = 0.1953$ pF, $\mathrm{L_g} = 21.241$ nH and $f_r = 2.47$ GHz. For the OFF state, $\mathrm{C_{extra}}$ appears in series with $\mathrm{C_g}$ which results in reducing the value of equivalent capacitance and shift-up the resonance frequency. A small capacitance value of $\mathrm{C_{extra}}$ is expected by considering the physical gap. In fact, $\mathrm{C_{extra}}$ has a value of 0.08 pF 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).

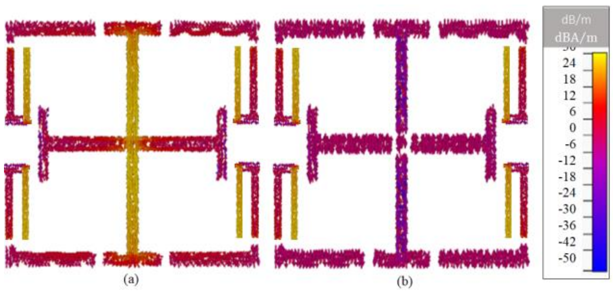

Fig. 6. Surface current distributions of the proposed unit cell; **(a)** status-ON; **(b)** status-OFF.

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 (~λ/2) [31].

A perspective view of the proposed antenna and RMSL structure is shown in Fig. 7.

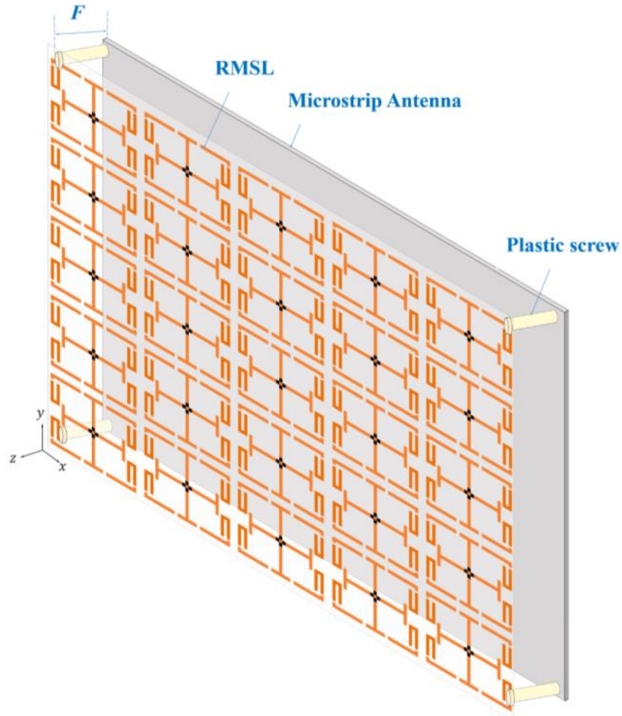

Fig. 7. The proposed RMSL structure.

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 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].

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

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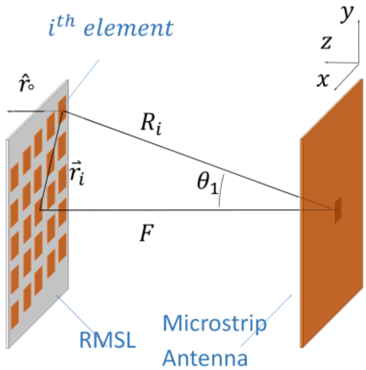

Fig. 8. Ray-tracing based phase difference.

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.

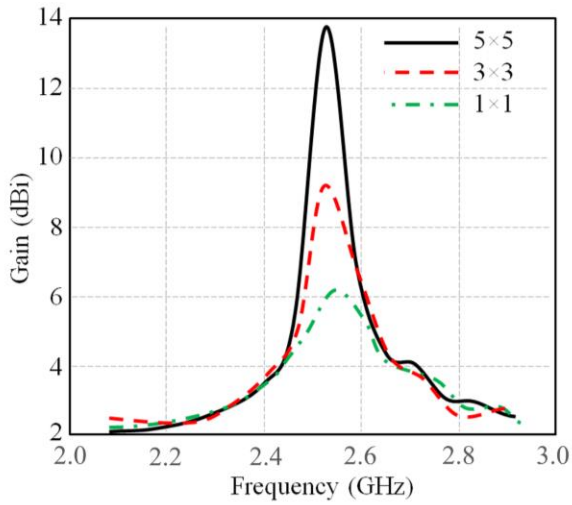

Fig. 9. A parametric study for the proposed system performance.

5. 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.

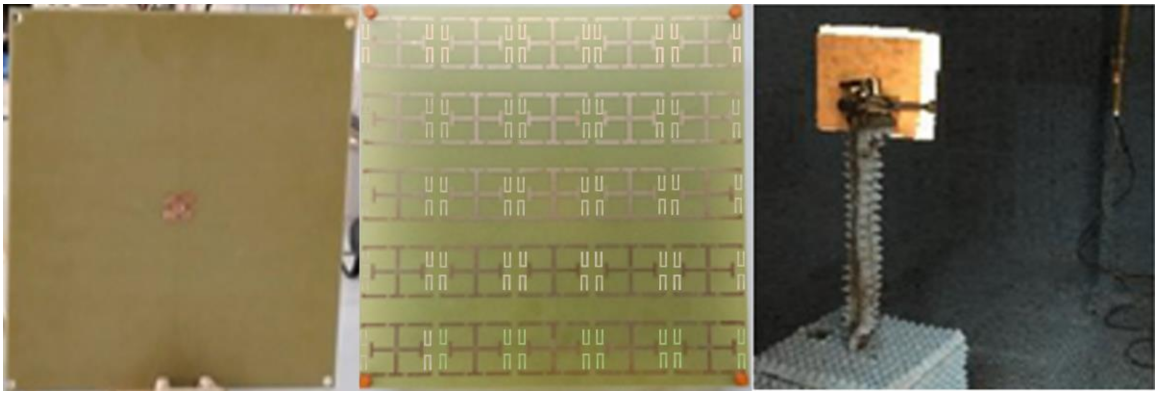

Fig. 10. The fabricated prototypes and measurement setup. From left to right: Fabricated microstrip antenna, top view of the RMSL, and antenna measurement setup inside the RF anechoic chamber.

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 136º 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

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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 113º. 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 26º.

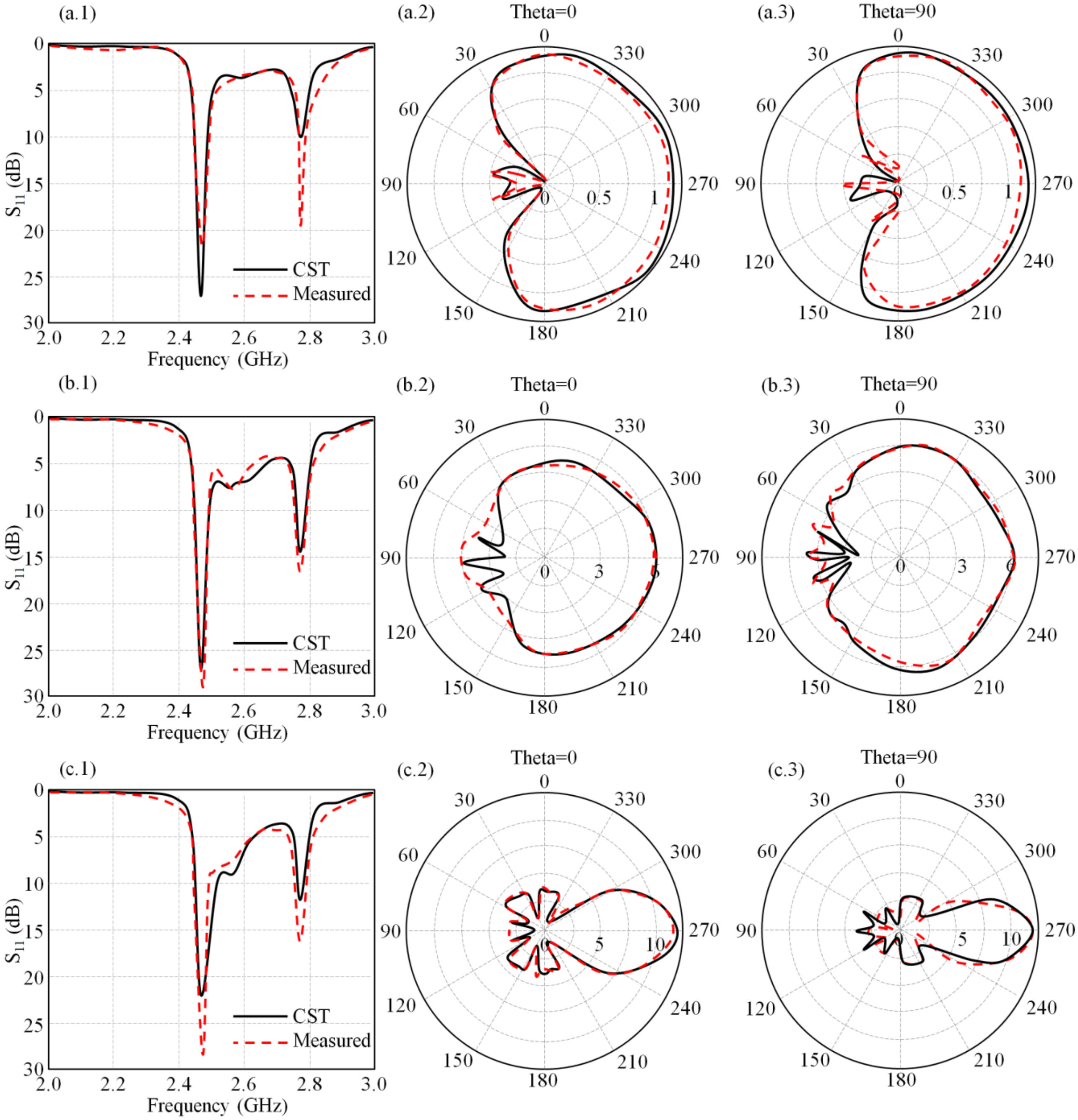


Fig. 11. Measured and simulated results of the proposed antennas, **(a.1)** S_{11} spectra of the antenna without RMSL, **(a.2),** and **(a.3)** radiation pattern of the antenna without the RMSL at $\varphi = 0^{\circ}$ and $\varphi = 90^{\circ}$, respectively, **(b.1)** S_{11} spectra of the antenna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

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 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 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.

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

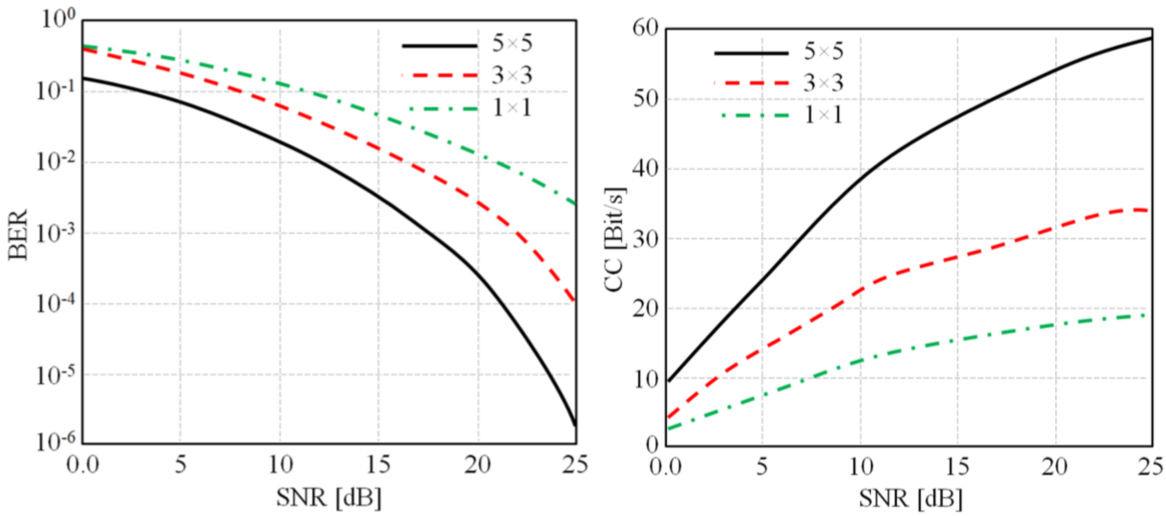
Previous antenna research has essentially paid attention to improving the antenna gain. The performance of the proposed antenna is compared with other published works in Table 2. It is evident from the table that the proposed antenna exhibits exceptional gain improvement resulting from the use of the 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.

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

6. 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.



(a) (b)

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

7. Conclusions

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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Taha A. Elwi received his B.Sc. in Electrical Engineering Department (2003) (Highest Graduation Award), Postgraduate M.Sc. in Laser and Optoelectronics Engineering Department (2005) (Highest Graduation Award) from Nahrain University Baghdad, Iraq. From April 2005 to August 2007, he was working with Huawei Technologies Company, Baghdad, Iraq. On January, 2008, he joined the University of Arkansas at Little Rock and he obtained his Ph.D. in December 2011 from the system engineering and science. His research areas include wearable and implantable antennas for biomedical wireless systems, smart antennas, WiFi deployment, electromagnetic wave scattering by complex objects, design, modeling and testing of metamaterial structures for microwave applications, design and analysis of microstrip antennas for mobile radio systems, precipitation effects on terrestrial and satellite frequency re-use communication systems, effects of the complex media on electromagnetic propagation and GPS. The nano-scale structures in the entire electromagnetic spectrum are a part of his research interest.

Mohammad Alibakhshikenari (Member, IEEE) was born in Mazandaran, Iran, in February 1988. He received the Ph.D. degree (Hons.) with European Label in electronics engineering from the University of Rome ‘‘Tor Vergata’’, Italy, in February 2020. From May 2018 to December 2018 he was a Ph.D. Visiting Researcher at the Chalmers University of Technology, Gothenburg, Sweden. His training during this Ph.D. research visit included a research stage in the Swedish Company Gap Waves AB in Gothenburg as well. Since July 2021 he is with the Department of Signal Theory and Communications, Universidad Carlos III de Madrid (uc3m), Spain, as a Principal Investigator of the CONEX (CONnecting EXcellence)-Plus Talent Training Program and Marie Skłodowska-Curie Actions. He was also a Lecturer of the electromagnetic fields and electromagnetic laboratory with the Department of Signal Theory and Communications for academic year 2021–2022 and he received the “Teaching Excellent Acknowledgement” Certificate for the course of electromagnetic fields from Vice-Rector of studies of uc3m. From December 2022 to May 2023 he spent three industrial and academic research visits in (i) SARAS Technology Ltd Company in Leeds, England; (ii) Edinburgh Napier University in Edinburgh, Scotland; and (iii) University of Bradford in West Yorkshire, England which were defined by CONEX-Plus Talent Training Program and Marie Skłodowska-Curie Actions as his secondment research visit plans. His research interests include electromagnetic systems, antennas and wave-propagations, metamaterials and metasurfaces, sensors, synthetic aperture radars (SAR), 5G and beyond wireless communications, multiple input multiple output (MIMO) systems, RFID tag antennas, substrate integrated waveguides (SIWs), impedance matching circuits, microwave components, millimeter-waves and terahertz integrated circuits, gap waveguide technology, beamforming matrix, and reconfigurable intelligent surfaces (RIS), which led to achieve more than 4200 citations and H-index above 41 reported by Scopus, Google Scholar, and ResearchGate. He was a recipient of the (i) three years Principal Investigator research grant funded by Universidad Carlos III de Madrid and the European Union’s Horizon 2020 Research and Innovation Program under the Marie Skłodowska-Curie Grant started in July 2021, (ii) two years postdoctoral research grant funded by the University of Rome ‘‘Tor Vergata’’ started in November 2019, (iii) three years Ph.D. Scholarship funded by the University of Rome ‘‘Tor Vergata’’ started in November 2016, and (iv) two Young Engineer Awards of the 47th and 48th European Microwave Conference were held in Nuremberg, Germany, in 2017, and in Madrid, Spain, in 2018, respectively. In April 2020 his research article entitled ‘‘High-Gain Metasurface in Polyimide On-Chip Antenna Based on CRLH-TL for Sub Terahertz Integrated Circuits’’ published in Scientific Reports was awarded as the Best Month Paper at the University of Bradford, West Yorkshire, England. He is serving as an Associate Editor for (i) *Radio Science*, and (ii) *IET Journal of Engineering*. He also acts as a referee in several highly reputed journals and international conferences.

Bal S. Virdee (SM’08) received the B.Sc. and MPhil degrees in Communications-Engineering from the University of Leeds-UK and his Ph.D. in Electronic-Engineering from the University of London-UK. He has worked in industry for various companies including Philips (UK) as an R&D-engineer and at Teledyne Defence & Space (Shipley, UK) as a future products design engineer in RF/microwave communication systems. He has taught at several academic institutions in the UK before joining London Metropolitan University where he is a Senior Professor of Communications Technology in the School of Computing & Digital Media, and Director of the Center for Communications Technology. His research, in collaboration with industry and academia, is in microwave/millimeter-wave/terahertz wireless communications encompassing mobile-phones to satellite-technology. Prof. Virdee has chaired numerous technical sessions at IEEE international conferences and published numerous research papers. He is Chair and Executive Member of the Institution of Engineering and Technology (IET) Technical and Professional Network Committee on RF/Microwave-Technology. He is a Fellow of IET, a Chartered Engineer and a Senior-Member of IEEE. He is also a Senior Fellow of the Higher Education Academy.

Zaid Abedul Hassain was born in Baghdad (Iraq), in 1979. He received the B.Eng. degree in electrical engineering from University of Mustansiriyah, Baghdad, in 2000, and the master’s degree in engineering science in 2002. He is currently a professor and the director of the antenna and microwave, department of Electrical Engineering, University of Mustansiriyah.

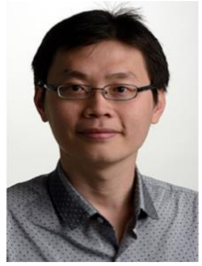
Syed Mansoor Ali received his PhD in Physics in 2014 from the Islmia University of Bahawalpur, Pakistan. Since September 2012 to date, he is working as a researcher in the department of Physics and Astronomy, College of Science, King Saud University, Riyadh Saudi Arabia. His research specialization in materials science includes radiation interaction with nanomaterials for radiation and energy conversion/storage applications. Besides that, the various heterostructure junction fabrication and simulation for application of perovskite solar cell, supercapacitor and radiation sensor/detector are the main focus of his research concern.

Lida Kouhalvandi, IEEE Senior Member and PhD (with honor), joined the Department of Electrical and Electronics Engineering at Dogus University as an Assistant Professor in October 2021 and she took possession of Associate Professor degree in February 2023. She received her PhD in Electronics Engineering in 2021 from the Istanbul Technical University, Istanbul, Turkey. She received her MSc in Electronics Engineering in 2015 from the Istanbul Technical University, Istanbul, Turkey, and her BSc in Electronics Engineering in 2011 from the Azad University of Tabriz, Tabriz, Iran. In recognition of her research, she received the Doctoral Fellowship at Department of Electronics and Telecommunications, Politecnico di Torino, Turin, Italy from 2019 to 2020 and also, she joined to Politecnico di Torino, Turin, Italy as a Research Fellowship from February 2021 up to July 2021 and also from May 2022 up to May 2023. Dr. Kouhalvandi’s research interests as a radio frequency and analog engineer are power amplifier, antenna, analog designs, and implantable medical devices. She also has experience in computer-aided designs and optimization algorithms through machine learning. she received 'Best Presentation Award' from EExPolytech-2021: Electrical Engineering and Photonics conference in 2021. Additionally, her PhD thesis accepted for the presentation at PhD Forum of the 2021 IEEE/ACM Design Automation Conference (DAC 2021) in San Francisco, USA. From the 30th IEEE conference on signal processing and communications applications, she received another 'Best Paper Award' in 2022. She received the 2022 Mojgan Daneshmand Grant from the IEEE Antennas and Propagation Society (AP-S), organized by the IEEE AP-S Young Professionals. Additionally, her PhD thesis was awarded by Istanbul Technical University as the 'Outstanding PhD Thesis' and also from Turkish Electronics Industrialists Association (TESID) as the 'Best Innovation and Creativity PhD Thesis' in 2022.

Patrizia Livreri, (M'90) PhD, is a Professor with the Department of Engineering, University of Palermo, and a Visiting Professor with the San Diego State University. She received her "Laurea degree" in Electronics Engineering with honors in 1986 and her Ph.D. in Electronics and Communications Engineering in 1992, both from the University of Palermo, Italy. From 1993 to 1994, she was a researcher at CNR. Since 1995, she has been serving as the scientific director for the "Microwave Instruments and Measurements Lab" of the Engineering Department at the University of Palermo. In 2020, she also joined the CNIT National Laboratory for Radar and Surveillance Systems RaSS in Pisa. Her research interests are in microwave and millimeter vacuum high power (TWT, Klystron) and solid-state power amplifiers for radar applications; high power microwave source (virtual cathode oscillator, magnetically insulated transmission line oscillator); microwave and optical antennas, radar, and microwave quantum radar. She is the principal investigator of the "Microwave Quantum Radar" project, funded by the Ministry of Defense in 2021. She is the supervisor of many funded project and the author of more than 200 published papers.

Nurhan Türker Tokan received her B.Sc. degree in Electronics and Communications Engineering from Kocaeli University in 2002 and her M.Sc. and Ph.D. degree in Communication Engineering from Yildiz Technical University (YTU), Istanbul, Turkey, in 2004 and 2009, respectively. From May 2003 to May 2009, she worked as a research assistant in the Electromagnetic Fields and Microwave Technique Section of the Electronics and Comm. Eng. Dept. of YTU, Istanbul, Turkey. Between May2 009 and April 2015, she worked as an assistant professor and between April 2015 and August 2021, she worked as an associate professor in the Electronics and Comm. Eng. Dept. of YTU. Since August 2020, she has been working as a professor at the same department. From October 2011 to October 2012, she was Postdoctoral researcher in the EEMCS Department of Delft University of Technology, Delft, Netherlands. From October 2012 to May 2013, she was a Postdoctoral Fellow supported by European Science Foundation at the Institute of Electronics and Telecommunications (IETR), University of Rennes1, Rennes, France. She is the author or coauthor of more than 50 papers published in peer-reviewed international journals and conference proceedings. Her current research interests are analysis and design of antennas with emphasis on dielectric lens antennas and wideband antennas, microwave circuits and intelligent systems.

Giovanni Pau is an Associate Professor at the Faculty of Engineering and Architecture, Kore University of Enna, Italy. Prof. Pau received his Bachelor's degree in Telematic Engineering from the University of Catania, Italy, and both his Master's degree (cum Laude) in Telematic Engineering and Ph.D. from Kore University of Enna, Italy. Prof. Pau is the author/co-author of more than 80 refereed articles published in journals and conference proceedings. He is a Member of the IEEE (Italy Section) and has been involved in several international conferences as a session Co-Chair and Technical Program Committee member. Prof. Pau serves/served as a leading Guest Editor in special issues of several international journals and is an Editorial Board member as Associate Editor of several journals, such as IEEE Access, Wireless Networks (Springer), EURASIP Journal on Wireless Communications and Networking (Springer), Wireless Communications and Mobile Computing (Hindawi), Sensors (MDPI), and Future Internet (MDPI), to name a few. His research interests include Wireless Sensor Networks, Fuzzy Logic Controllers, Intelligent Transportation Systems, Internet of Things, Smart Homes, and Network Security.



Chan Hwang See (M'14, SM'15) received a first-class B.Eng. Honours degree in Electronic, Telecommunication and Computer Engineering and a Ph.D. degree from the University of Bradford, UK in 2002 and 2007, respectively. He is an associate Professor in School of Computing, Engineering and the Built Environment, Edinburgh Napier University, UK. Previously, he was Head of Electrical Engineering and Mathematics. Prior to this, he was a Senior Lecturer (Programme Leader) in Electrical & Electronic Engineering, School of Engineering, University of Bolton, UK. Before this, he was a Senior Research Fellow in the Antennas and Applied Electromagnetics Research Group within the University of Bradford. His research interests cover wireless sensor network system design, computational electromagnetism, antennas, microwave circuits, Wireless Power Transfer and acoustic sensor design. He has published over 130 peer-reviewed journal articles in these research areas. He is a co-author for one book and three book chapters. He was a recipient of two Young Scientist Awards from the International Union of Radio Science (URSI) and Asia-Pacific Radio Science Conference (AP-RASC) in 2008 and 2010, respectively. He was awarded a certificate of excellence for his successful Knowledge Transfer Partnership (KTP) with Yorkshire Water on the design and implementation of a wireless sensor system for sewerage infrastructure monitoring in 2009. Dr. See is a Chartered Engineer, Fellow of the Institution of Engineering and Technology. He is also a Fellow of the Higher Education Academy, a full member of the EPSRC Review College, an Associate Editor for IEEE Access and an Editor for Journal of Electronics and Electrical Engineering, Scientific Reports, PeerJ Computer Science, PLOS One and Wireless Power Transfer Journals.

Ernesto Limiti (S'87–M'92–SM'17) is a full professor of Electronics in the Engineering Faculty of the University of Roma Tor Vergata since 2002, after being research and teaching assistant (since 1991) and associate professor (since 1998) in the same University. Ernesto Limiti represents University of Roma Tor Vergata in the governing body of the MECSA (Microwave Engineering Center for Space Applications), an inter-universitary center among several Italian Universities. He has been elected to represent the Industrial Engineering sector in the Academic Senate of the University for the period 2007-2010 and 2010-2013. Ernesto Limiti is actually the president of the Consortium "Advanced research and Engineering for Space", ARES, formed between the University and two companies. Further, he is actually the president of the Laurea and Laurea Magistrale degrees in Electronic Engineering of the University of Roma Tor Vergata. The research activity of Ernesto Limiti is focused on three main lines, all of them belonging to the microwave and millimetre-wave electronics research area. The first one is related to characterisation and modelling for active and passive microwave and millimetre-wave devices. Regarding active devices, the research line is oriented to the small-signal, noise and large signal modelling. Regarding passive devices, equivalent-circuit models have been developed for interacting discontinuities in microstrip, for typical MMIC passive components (MIM capacitors) and to waveguide/coplanar waveguide transitions analysis and design. For active devices, new methodologies have been developed for the noise characterisation and the subsequent modelling, and equivalent-circuit modelling strategies have been implemented both for small and large-signal operating regimes for GaAs, GaN, SiC, Si, InP MESFET/HEMT devices. The second line is related to design methodologies and characterisation methods for low noise circuits. The main focus is on cryogenic amplifiers and devices. Collaborations are currently ongoing with the major radioastronomy institutes all around Europe within the frame of FP6 and FP7 programmes (RadioNet). Finally, the third line is in the analysis methods for nonlinear microwave circuits. In this line, novel analysis methods (Spectral Balance) are developed, together with the stability analysis of the solutions making use of traditional (harmonic balance) approaches. The above research lines have produced more than 250 publications on refereed international journals and presentations

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within international conferences. Ernesto Limiti acts as a referee of international journals of the microwave and millimetre wave electronics sector and is in the steering committee of international conferences and workshops. He is actively involved in research activities with many research groups, both European and Italian, and he is in tight collaborations with high-tech italian (Selex - SI, Thales Alenia Space, Rheinmetall, Elettronica S.p.A., Space Engineering …) and foreign (OMMIC, Siemens, UMS, …) companies. He contributed, as a researcher and/or as unit responsible, to several National (PRIN MIUR, Madess CNR, Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, RadioNet FP6 and FP7 …) projects. Regarding teaching activities, Ernesto Limiti teaches, over his istitutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, "Elettronica per lo Spazio" within the Master Course in Sistemi Avanzati di Comunicazione e Navigazione Satellitare. He is a member of the committee of the PhD program in Telecommunications and Microelectronics at the University of Roma Tor Vergata, tutoring an average of four PhD candidates per year.