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Metasurface-Based Wideband MIMO Antenna for 5G Millimeter-Wave Systems

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ABSTRACT This paper presents a metasurface based multiple-input multiple-output (MIMO) antenna with a wideband operation for millimeter-wave 5G communication systems. The antenna system consists of four elements placed with a 90 degree shift in order to achieve a compact MIMO system while a 2 × 2 non-uniform metasurface (total four elements) is placed at the back of the MIMO configuration to improve the radiation characteristics of it. The overall size of the MIMO antenna is 24 × 24 mm^2 while the operational bandwidth of the proposed antenna system ranges from 23.5-29.4 GHz. The peak gain achieved by the proposed MIMO antenna is almost 7dB which is further improved up to 10.44 dB by employing a 2 × 2 metasurface. The total efficiency is also observed more than 80% across the operating band. Apart from this, the MIMO performance metrics such as envelope correlation coefficient (ECC), diversity gain (DG), and channel capacity loss (CCL) are analyzed which demonstrate good characteristics. All the simulations of the proposed design are carried out in computer simulation technology (CST) software, and measured results reveal good agreement with the simulated one which make it a potential contender for the upcoming 5G communication systems.

INDEX TERMS CCL, CST, ECC, 5G, millimeter-wave, MIMO, metasurface.

I. INTRODUCTION

In the coming years, the requirement of more capacity may be increased by 1000 times due to the tremendous growth in the annual data traffic i.e., 40-70 %. To accomplish this continuous growing demand, the upcoming generation i.e., 5G is considered as a potential candidate which would be able to provide a throughput in multi giga-bits per second [1]–[3]. The engineers and academic researchers have been forced to utilize the less occupied portion of the millimeter-wave (mm-wave) portion of the spectrum due to the limited capacity and bandwidth constraints at the sub-6 GHz band [4], [5]. The advantages of this 5G technology are not only limited to addressing growing demand of higher data rates or to ensure the reliable transmission and reception of date for ascending devices being connected to the network but also aimed to fortify the competences of the emerging technologies, as virtual reality, smart cities, and Internet of Vehicles [6].

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On the other hand, path loss and atmospheric attenuations being a signal degradation factors also rise at the mm-wave spectrum [7]. As in the modelling of any communication network, the role of frequency band allocation is important and that is why, most of the telecom regulatory bodies and industry all over the world are doing great efforts to regularize the communication networks of 5G. Till now, the current worldwide allocation of a mm-wave spectrum analysis shows that mostly, 26/28 GHz frequency band is being considered by most of the regions for the 5G communication [1], [7]. And to successfully deploy the communication networks, the role of antennas cannot be ignored. Therefore, the antenna designing must be considered carefully to realize a communication at the mm-wave frequencies. It is expected that 5G systems will utilize several antennas at the user and base station terminals. Similarly, for the 5G mm-wave communication, MIMO and arrays are the key enablers [4]. In recent times, lot of antenna designs have been reported for the communication at the potential mm-wave bands [8]–[39]. To address the atmospheric attenuations issue at the mm-wave band, antenna arrays have been reported, numerously to offer a high gain which in turns strengthen a signal [8]–[17]. Although, gain is increased by accommodating multiple antenna elements, but sometimes these types of structures are highly suffered by losses across the power dividers and apart from this, the profile of the antenna also increases by increasing several elements in an array structure. Thus, antennas with a low profile and high gain feature are of great importance. Several antennas with a high gain characteristic and maintaining a low profile have also been investigated which include lens coupled antennas, metamaterial based antennas and fabry-perot cavity antennas [18]–[25]. Although, these antennas achieve high gain and low profile, but the capacity was same as that of single antenna because of single port usage. For this, MIMO antennas are of great significance due to their usage of multi-ports which is helpful to provide high data rates, good capacity and across that a reliable communication link. Several antennas with a MIMO characteristic have been reported in literature [26]–[32], but the gain achieved by them was comparatively low.

Recently, lot of research has been done on metamaterials due to their electromagnetic properties do not present in the natural materials [33]–[35]. Few mm-wave antennas utilizing a metamaterials concept, specifically focusing on gain improvement have been reported in [29], [36]–[39]. In [36], a bow-tie shaped antenna for the mm-wave band holding a MIMO configuration is presented. Three pairs of metamaterial arrays are utilized which improves the gain of the antenna by 7.4 dB over the operating bandwidth of 24.25-27.5 GHz. While the overall size is noted to be 30. 5 × 30 mm^2. Similarly, a EBG based MIMO antenna is reported in [37]. The EBG structure incorporation gives enhancement in gain by 1.9 dB while 6 dB peak gain is achieved. The proposed antenna yields a maximum bandwidth of 1 GHz while the size of the antenna after employing EBG surface becomes 27. 5 × 27.5 mm^2. Likewise, in [38], a DRA with four port MIMO antenna is proposed for the mm-wave band. For the gain enhancement purpose, a metamaterial surface is used on the top of DRA surface which gives a maximum gain of 7 dB for the desired operating band (26.71-28.91 GHz). The overall size of the reported antenna is 20 × 40 mm^2. In [39], a metasurface based reflector is placed at the back of a two port MIMO configuration which improves the gain and a peak gain of 11.5 dB is attained. Although, a good peak gain is observed but the size of the reported antenna is 31. 7 × 53 mm^2 which is quite large. In [29], antenna covering the operational bandwidth from 29.7-31.5 GHz is proposed. The total size of the reported antenna is 48 × 21 mm^2 after adopting two port MIMO configuration while a peak gain of 8.6 dB is observed. The size of the reported antenna is quite large as when it will be extended to four port MIMO configuration from two port; so, the size will be increased more, and operational bandwidth achieved is also less.

TABLE 1. Summary of the dimensions of a proposed antenna element.

Parameter	Value (mm)	Parameter	Value (mm)
Aw	10.0	fl	5.6
ccw	0.8	fw	0.7
icw	1.1	gl	5.0
icl	1.4	gcl	1.5
cw	1.9	gcw	1.5
Al	12.0	cl	1.0

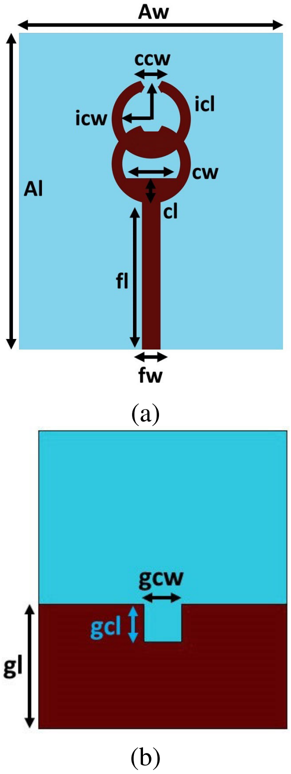
Thus, considering the above limitations in the reported designs, this paper presents a high gain, wideband antenna with a compact four port MIMO configuration for the mm-wave 5G communication systems. A 2×2 metasurface is employed below the proposed MIMO antenna to improve the gain and it is worthy to mention that the gain of the proposed MIMO antenna improves and a peak gain results in 10.44 dB. Furthermore, the proposed metasurface based antenna covers a bandwidth from 23.3-28.8 GHz (measured) with a total efficiency of more than 80% over the operating band.

II. DESIGN PROCEDURE FOR THE PROPOSED ANTENNA

In this section, the geometry of an antenna element and four-port MIMO antenna system is presented. Also, the MIMO antenna integration with the proposed metasurface is discussed. Furthermore, the design evaluations steps of the proposed antenna element are analyzed. All the simulations of the proposed design are performed in computer simulation technology (CST) software.

A. SINGLE ELEMENT DESIGN

Fig. 1 shows the geometry of an antenna element which is used later for the proposed MIMO configuration. The Rogers RT-5880 substrate with a total volume of 12 × 10 × 0.254 mm^3 is used to back the radiating element. The copper material is used for the radiating element with a very stable conductivity of 5.8 × 10^7 S/m. A truncated ground plane is used to back the substrate, in order to achieve



(a)

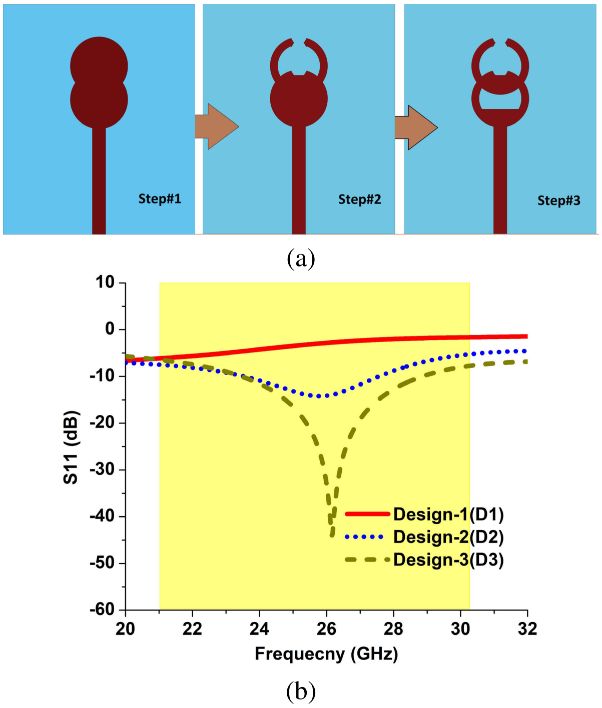
(b)

FIGURE 1. Geometry of the proposed antenna element (a) front view (b) back view.

a good performance in terms of optimum gain, return loss and efficiency etc. The various dimensions of the proposed antenna element are listed in Table 1.

The radiating patch (step 1) shown in Fig. 2(a) is the combination of two circular shaped structures and its S-parameter is shown in Fig. 2(b). The initial geometry gives a response over the desired frequency range with a non-satisfactory impedance bandwidth based on −10 dB criteria. While in case of step 2, when slot is inserted in the radiating structure, so it gives the improvement in the impedance bandwidth and finally another slot insertion (step 3) in the lower end of the radiating structure makes the proposed design to operate with an impedance bandwidth ranging from 23.413-28.91 GHz with a magnitude of return loss more than −40 dB. Thus, the geometry of the antenna element obtained in step 3 is used ahead for the further process.

The role of the ground trimming is also important to analyze as it was quite helpful to achieve the desired magnitude return loss. Thus, in Fig. 3, the effect of the ground plane length variation on the return loss is presented. The variation in the length of a ground plane from 12 mm to 5 mm helps to improve the return loss with the several modifications as well in the radiating structure (Fig. 2(a)). While finally the mini-slot insertion in the mid of the ground plane having length of 1.5 mm following the modifications in the radiation structure gives a return loss of satisfactory impedance bandwidth. Moreover, during the optimization process, the antenna front and back are step by step modified to achieve good-bandwidth with a satisfactory impedance matching. As usually, ground cuts are helpful to achieve a wideband operation, with a slight variations in the radiating portion can give a good-operating band with a better impedance matching. Thus, both the variations given in Fig. 2 and 3 have significant role, combine to achieve a good operation for single element to extend it further to different configurations.



(a)

(b)

FIGURE 2. Steps for the progress towards obtaining (a) antenna element final structure with an analysis of (b) return loss.

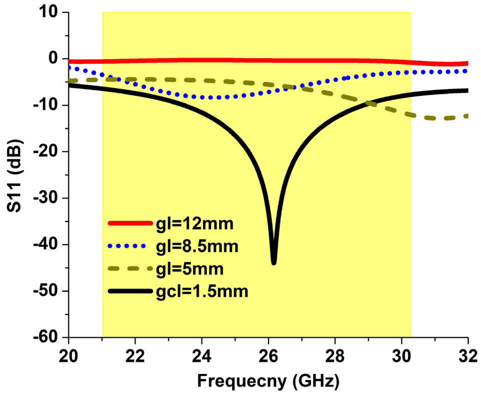
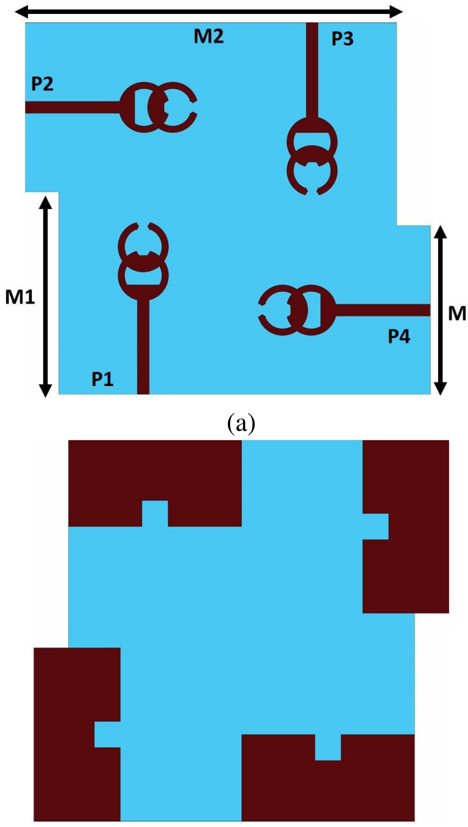


FIGURE 3. Return loss analysis with varying ground plane length.

B. MIMO ANTENNA SYSTEM

The antenna element structure finalized in the previous section is further headed towards the multi-port configuration such that each element is positioned in a manner to



(a)

(b)

FIGURE 4. Proposed MIMO antenna layout (a) front (b) back.

TABLE 2. Summary of the proposed MIMO antenna system dimensions.

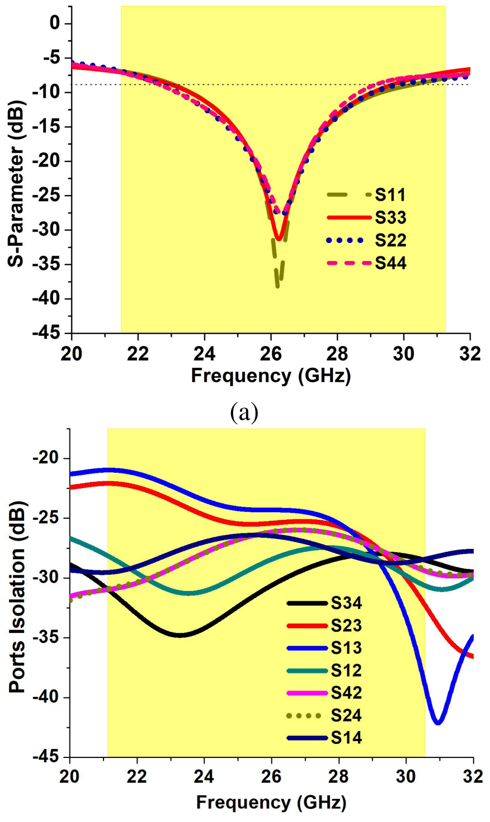
Parameter	Value (mm)	Parameter	Value (mm)
M1	12.0	M3	10.0
M2	22.0	–	–

achieve a good isolation and compact assembly as depicted in Fig. 4(a). Moreover, the single element is rotated in four rotations such that the central operating frequency of the MIMO antenna and single element be close to each other with a negligible deviation. The ground plane as obtained for the antenna element is adopted in the multi-port configuration for each element of it, correspondingly as shown in Fig. 4(b). The total length and width of the proposed MIMO structure is 22mm × 24mm.

Fig. 5(a) depicts the S-parameters for the multi-port antenna presented. It can be seen that all the elements give resonance nearly across the same frequency band i.e., 26 GHz with a good dip of return loss. While the isolation is observed in Fig. 5(b) which is noticed to be more than −20 dB within the operating band and maximum isolation of −35 dB is achieved.

C. UNIT CELL DESIGNING

Fig. 6 shows the geometry of the proposed unit cell with a 2 × 2 metasurface that is used ahead to improve the performance of the proposed MIMO antenna system. The unit cells are assembled in such a manner that each cell should cover at least the first lower inner cut of the radiating element of the proposed MIMO antenna, respectively to have a good improvement in the performance of it instead of using large number of unit cells within the same substrate limit. Furthermore, the unit cell is rotated as like the antenna element to have multiple-element configuration on a single printed circuit board (PCB) which results in a different PCB size due to the difference between the single element size of antenna MIMO and 2 × 2 metasurface configuration. The reflection phase and the transmission coefficient response of the unit cell is observed to check whether the stop band and in-phase reflection feature is achieved. Fig. 7 clearly depicts



(a)

(b)

FIGURE 5. MIMO antenna system (a) S-parameters (b) isolation.

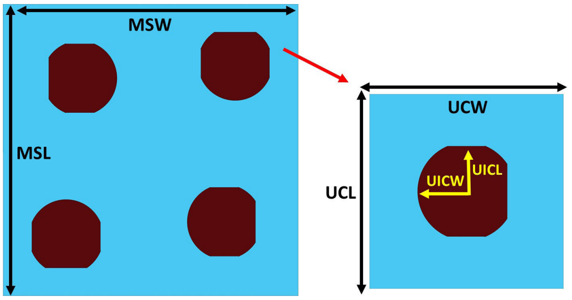


FIGURE 6. Proposed metasurface view with a unit cell.

TABLE 3. Summary of the proposed metasurface and unit cell dimensions.

Parameter	Value (mm)	Parameter	Value (mm)
MSL	20.6	UCW	10.3
MSW	20.3	UCL	10.3
UICW	2.4	UICL	2.6

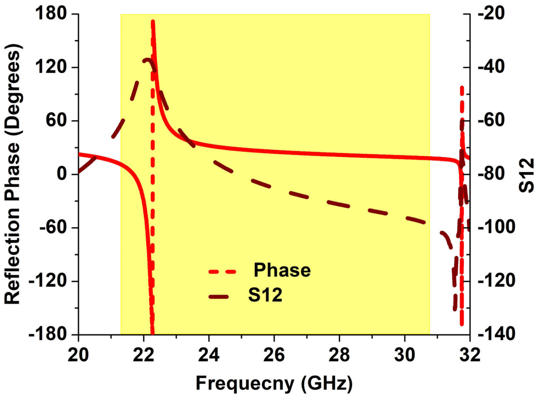
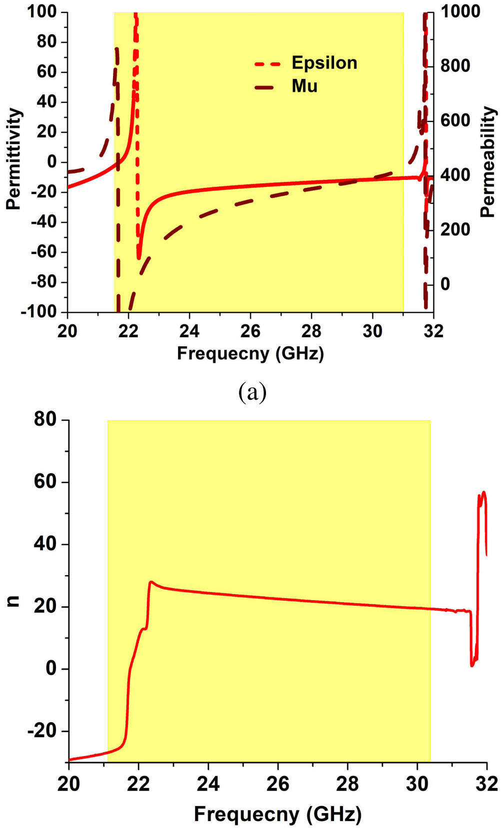


FIGURE 7. Reflection phase and transmission coefficient analysis for a unit cell.



(a)

(b)

FIGURE 8. Proposed unit cell (a) permittivity, permeability and (b) refractive index response.

that at the desired band of interest, both features are attained. While in Fig. 8, the permittivity, permeability, and refractive index response is observed which are extracted by using the S-parameter retrieval method [40]. It can be seen that the permittivity value is negative while the permeability value is positive at the central frequency of 26 GHz. The overall refractive index is thus, highly positive i.e., more than 20.

In Fig. 9, the surface current distribution is observed such that the current in the opposite direction flows specifically withing the patch of the unit cell which depicts that a good stop band feature is achieved by the proposed metasurface at the desired frequency band.

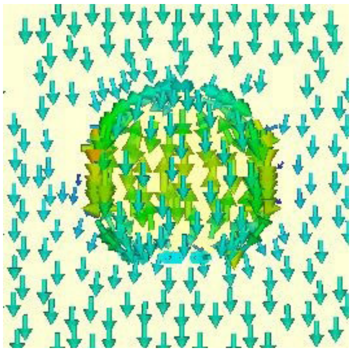


FIGURE 9. Proposed unit cell surface current distribution.

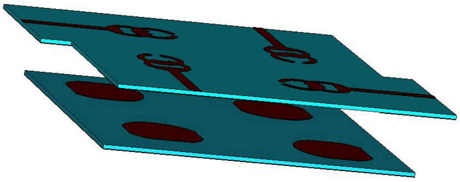


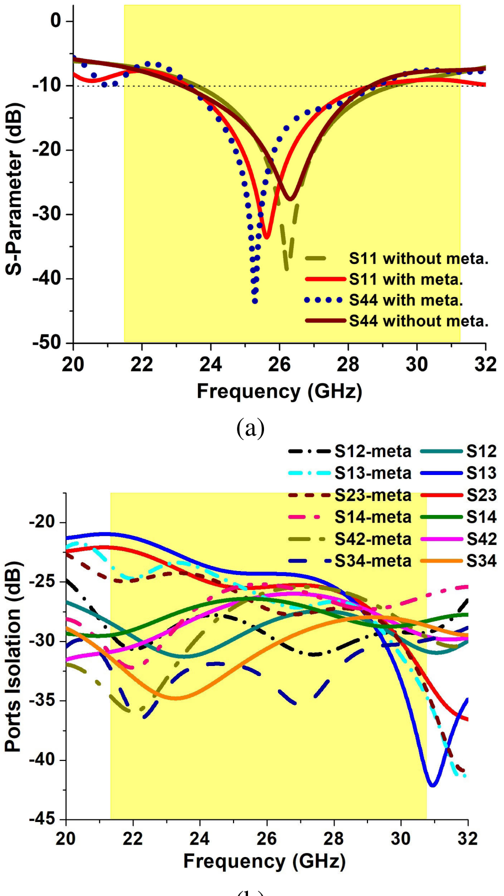
FIGURE 10. Proposed metasurface based antenna with a multi-port configuration.

D. METASURFACE BASED ANTENNA SYSTEM

Fig. 10 shows the geometry of the proposed metasurface based antenna. The gap of 3.75 mm is set between the antenna with a multi-port configuration and the proposed metasurface. Maintaining a 3.75 mm air gap, the metasurface based antenna and before employing a metasurface, the S-parameters are compared in Fig. 11. Overall a good resemblance is observed in the return loss and isolation results of antenna with a multi-port configuration with and without metasurface. While in Fig. 12, the gain comparison is observed and found that without the use of metasurface, the multiport antenna gives a peak gain of near 7 dB within the operating band while after employing a metasurface the gain rises by near 10.42 dB.

III. EXPERIMENTAL RESULTS

In Fig. 13, the fabricated model of the multi-port antenna and its combination with the metasurface is demonstrated. A specific spacer has been used to maintain a desired gap between the two substrate layer such that coherence with simulated results should be achieved as much possible. Rogers 5880 with a thickness of 0.254 mm is used to paste the



(a)

(b)

FIGURE 11. S-parameters comparison (a) return loss (b) isolation.

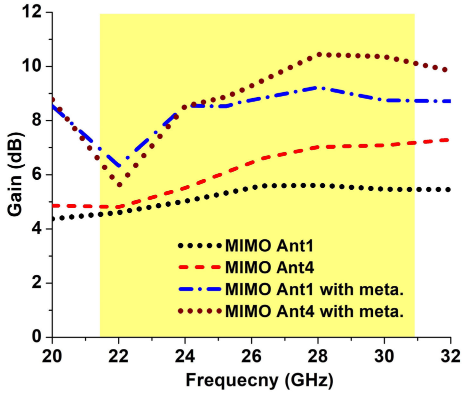
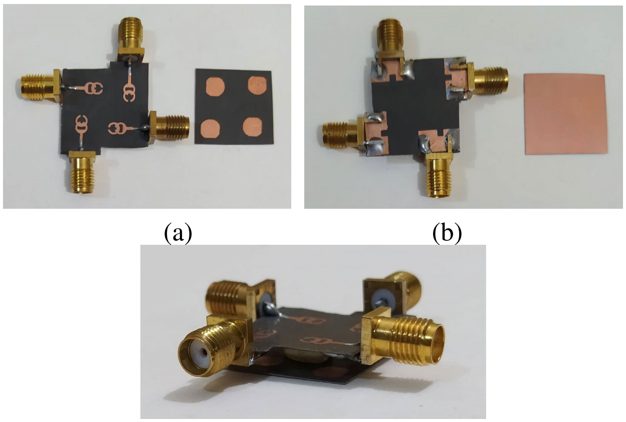


FIGURE 12. Gain comparison of the proposed antenna with and without metasurface.

conductive layers. The measured S-parameters, radiation patterns and multi-port antenna performance metrics are also analyzed in this section.

A. S-PARAMETERS

The reflection coefficient in terms of simulation and measurement is compared in Fig. 14. The simulated bandwidth based on −10 dB criteria is observed to be 23.3 to 28.8 GHz while the measured one follows it quite likely with minor disobey due to the fabrication tolerances and errors in the calibration during measurements. The isolation analysis is presented in Fig. 15 which shown that the peak value i.e., measured one is −32.5 dB within the operating band while the minimum is noticed to be more than −22.5 dB.



(a)

(b)

(c)

FIGURE 13. Proposed metasurface based antenna with multi-port configuration fabricated model in different scenarios (a) front (b) back (c) two layers assembly combined.

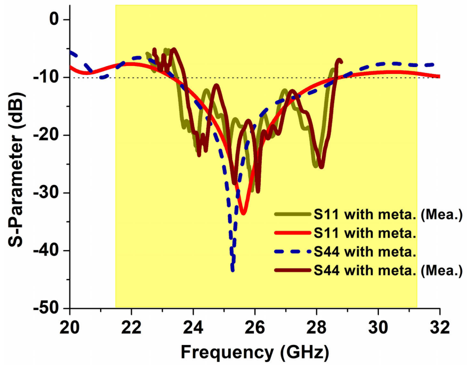


FIGURE 14. Simulated and measured reflection coefficients for the multi-port antenna with and without metasurface.

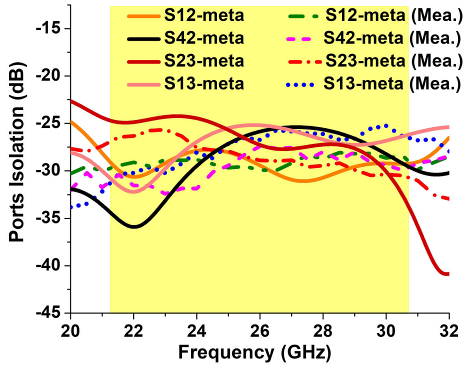
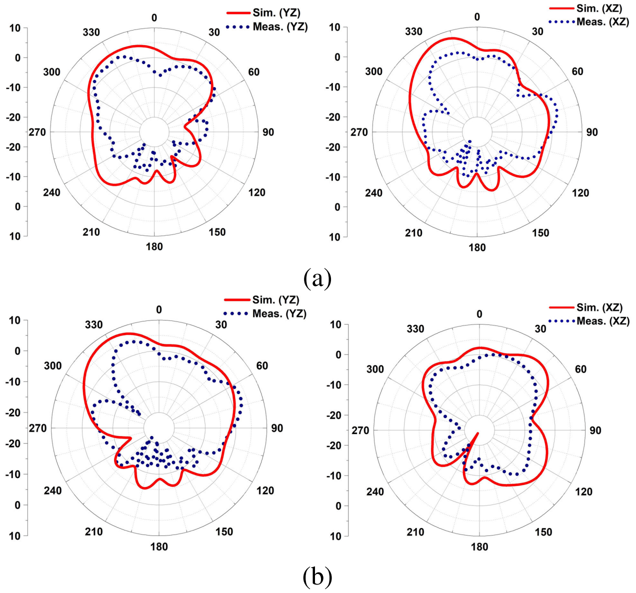


FIGURE 15. Simulated and measured isolations for the multi-port antenna with and without metasurface.



(a)

(b)

FIGURE 16. Measured and simulated polar radiation patterns (a) port-1 (b) port-4.

TABLE 4. Gain observed at few sample frequencies.

Frequency (GHz)	Value (dB)	Sim.	Frequency (GHz)	Value (dB)	Mea.
24.0 (P1)	8.55		24.0 (P1)	8.25	
26.0 (P1)	8.75		26.0 (P1)	8.5	
28.0 (P1)	9.22		28.0 (P1)	8.9	
24.0 (P4)	8.53		24.0 (P4)	8.24	
26.0 (P4)	9.29		26.0 (P4)	8.95	
28.0 (P4)	10.44		28.0 (P4)	10.21	

B. 2D RADIATION PATTERNS (FAR-FIELD)

The polar radiation patterns (gain) are depicted in Fig. 16 such that a comparison is made between the simulated and measured obtained results in the XZ and YZ planes, correspondingly, at the 26 GHz frequency band. A quite good resemblance is obtained between the simulated and measured results while minor disobey is due to the fabrication tolerances and errors in the calibration during measurements. The peak total efficiency of 92% is attained while for the entire operating band the value of more than 80% is achieved. In Table 4, the gain measured at few frequency samples is compared with the simulated one.

C. MIMO PERFORMANCE METRICS

To evaluate further the performance of the proposed meta based multi-port antenna, several performance metrics are demonstrated in this section. As to check the correlation level among the antenna elements within the multi-port assembly after employing a metasurface, Envelope Correlation Coefficient (ECC), Diversity Gain (DG) and Channel Capacity Loss (CCL) are analyzed. In Fig. 17, the EEC is notices to be below the standard value i.e., <0.5 and has been computer using the far-field calculation method given in [41]. Likewise, the DG is found quite closed to the standard value of 10 as shown in Fig. 18 while the CCL is presented in Fig. 19 which is below 0.5 bits/s/Hz within the operating band which means that capacity loss will be minimum which arises due to the correlation in the multi-port antenna or MIMO links. All these performance metrics depicts the high potentials of the proposed design for the 5G millimeter-wave communication systems.

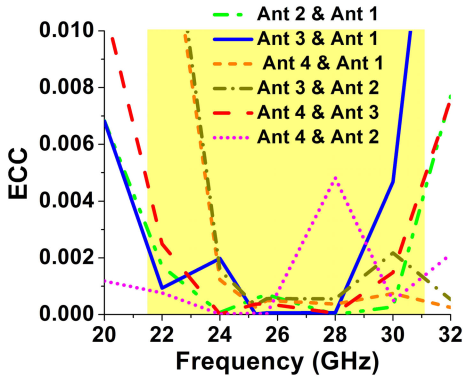


FIGURE 17. ECC for multi-port antenna based on metamaterial surface.

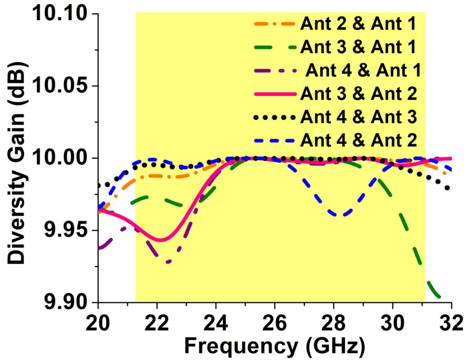


FIGURE 18. DG for multi-port antenna based on metamaterial surface.

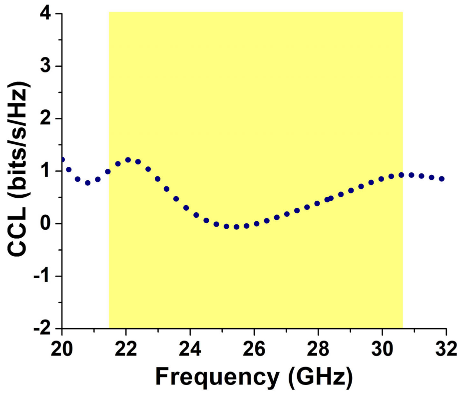


FIGURE 19. CCL for multi-port antenna based on metamaterial surface.

IV. CONCLUSION

In this paper, a metasurface based multiple-input multiple-output (MIMO) antenna with a wideband operation for millimeter-wave 5G communication systems is presented. The antenna system consists of four elements placed with a 90 degree shift in order to achieve a compact MIMO system while a 2 × 2 non-uniform metasurface (total four elements) is placed at the back of the MIMO configuration to improve the radiation characteristics of it. The proposed metasurface based antenna covers a bandwidth from 23.3-28.8 GHz with a total efficiency of more than 80% over the operating band. While a peak gain achieved by the proposed MIMO antenna is almost 7dB which is further improved up to 10.44 dB by employing a 2 × 2 metasurface. Apart from this, the MIMO performance metrics such as envelope correlation coefficient (ECC), diversity gain (DG), and channel capacity loss (CCL) are analyzed which demonstrate good characteristics. The measured results reveal good agreement with the simulated one which make it a potential contender for the upcoming 5G communication systems.

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