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

DANIYAL ALI SEHRAI¹, MUHAMMAD ASIF², WAHAB ALI SHAH³, JALAL KHAN⁴,
IBRAR ULLAH⁵, MUHAMMAD IBRAR⁶, SAEEDULLAH JAN⁶,
MOHAMMAD ALIBAKHSHIKENARI⁷, (Member, IEEE),
FRANCISCO FALCONE^{8,9}, (Senior Member, IEEE),
AND ERNESTO LIMITI¹⁰, (Senior Member, IEEE)

¹Department of Electrical Engineering, National University of Computer and Emerging Sciences, Islamabad 44000, Pakistan

²Department of Electrical Engineering, City University of Science and Information Technology, Peshawar 25000, Pakistan

³Department of Electrical Engineering, Namal Institute, Mianwali 42250, Pakistan

⁴Department of Telecommunication Engineering, University of Engineering and Technology, Mardan 23200, Pakistan

⁵Department of Electrical Engineering, University of Engineering and Technology, Bannu Campus, Peshawar 28100, Pakistan

⁶Department of Physics, Islamia College, Peshawar 25000, Pakistan

⁷Department of Signal Theory and Communications, Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain

⁸Electric, Electronic and Communication Engineering Department, Public University of Navarre, 31006 Pamplona, Spain

⁹Institute of Smart Cities, Public University of Navarre, 31006 Pamplona, Spain

¹⁰Electronic Engineering Department, University of Rome "Tor Vergata," 00133 Rome, Italy

Corresponding authors: Muhammad Asif (masife@cusit.edu.pk) and Mohammad Alibakhshikenari (mohammad.alibakhshikenari@uc3m.es)

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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 $24 \times 24 \text{ mm}^2$ 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].

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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 data 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].

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 $30.5 \times 30 \text{ mm}^2$. 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 $27.5 \times 27.5 \text{ mm}^2$. Likewise, in [38],

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

a DRA with four port MIMO antenna is proposed for the mm-wave band. For the gain enhancement purpose, a meta-material 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 $20 \times 40 \text{ mm}^2$. 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 $31.7 \times 53 \text{ mm}^2$ 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 $48 \times 21 \text{ mm}^2$ 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.

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 $12 \times 10 \times 0.254 \text{ mm}^3$ is used to back the radiating element. The copper material is used for the radiating element with a very stable conductivity of $5.8 \times 10^7 \text{ S/m}$. A truncated ground plane is used to back the substrate, in order to achieve

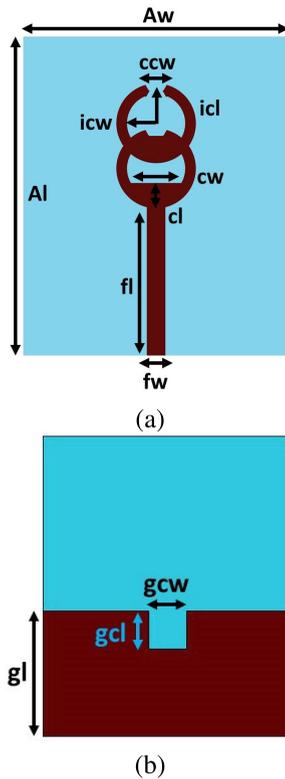


FIGURE 1. Geometry of the proposed antenna element (a) front view (b) back view.

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

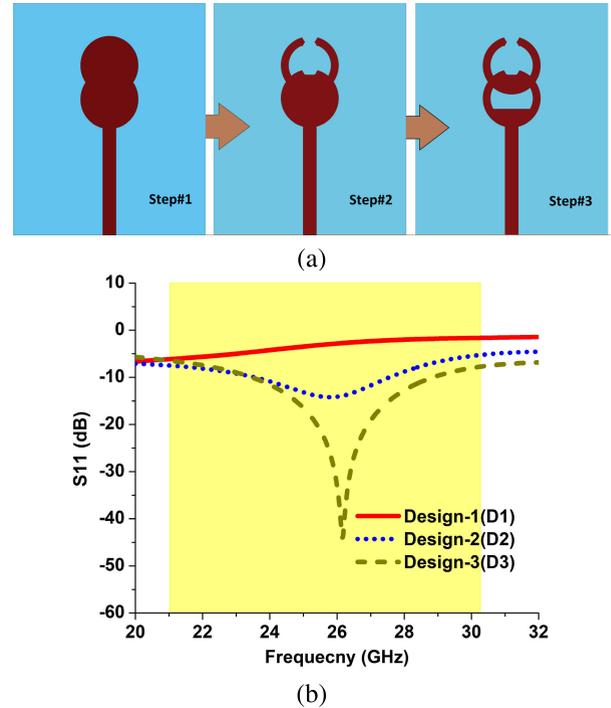


FIGURE 2. Steps for the progress towards obtaining (a) antenna element final structure with an analysis of (b) return loss.

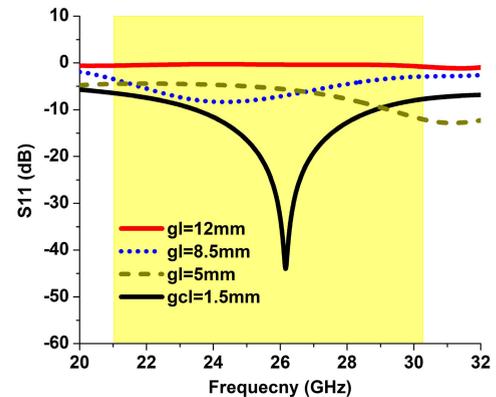


FIGURE 3. Return loss analysis with varying ground plane length.

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.

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

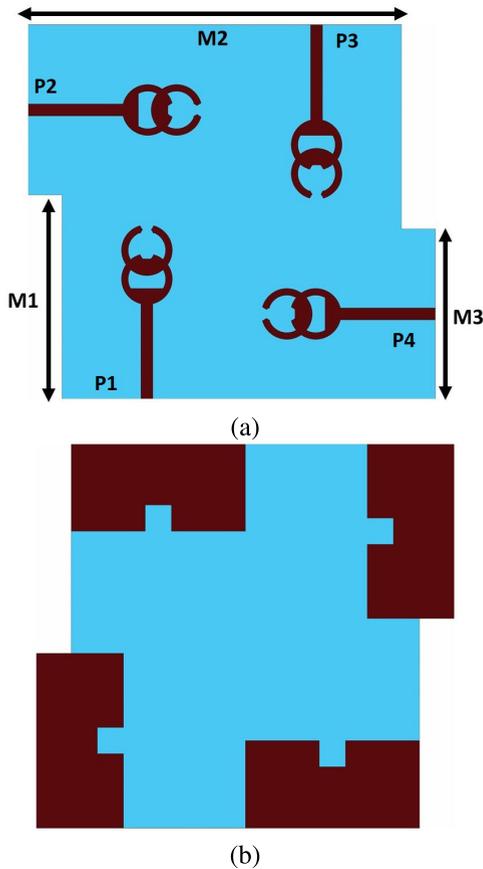


FIGURE 4. Proposed MIMO antenna layout (a) front (b) back.

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

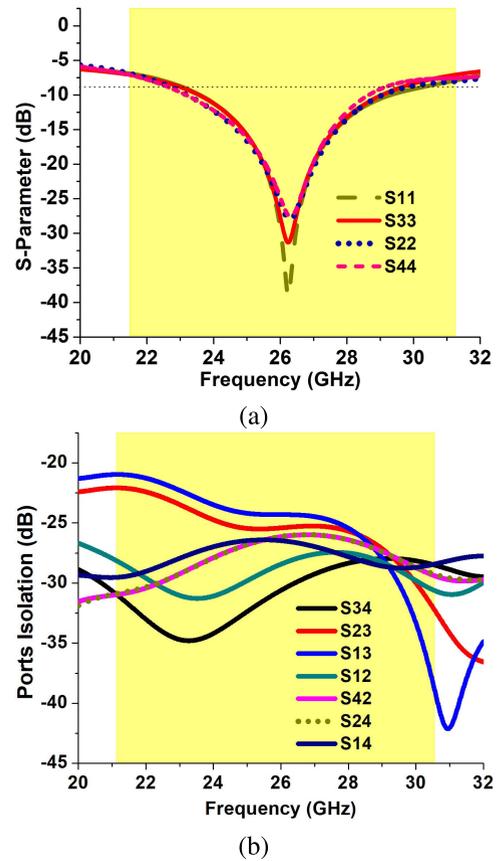


FIGURE 5. MIMO antenna system (a) S-parameters (b) isolation.

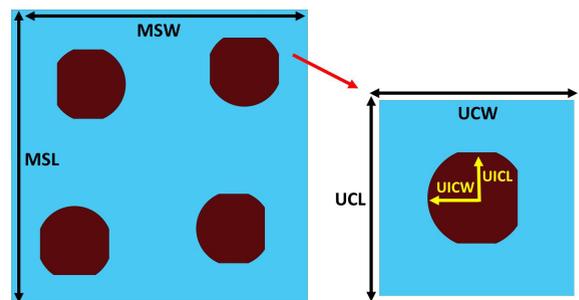


FIGURE 6. Proposed metasurface view with a unit cell.

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

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

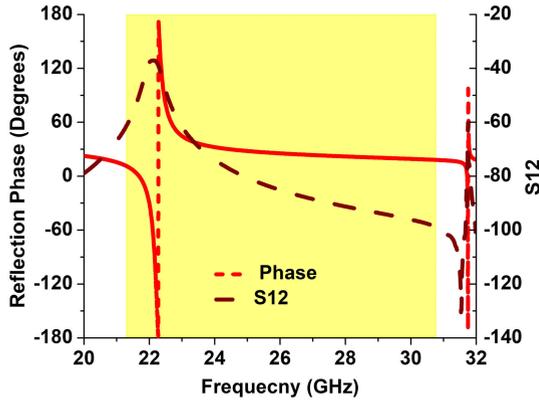
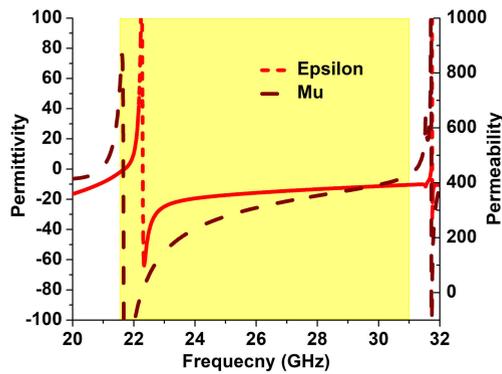
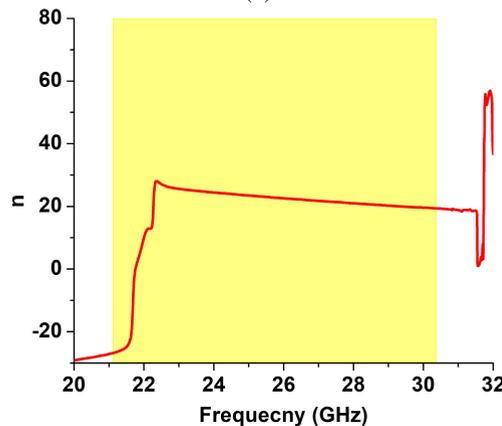


FIGURE 7. Reflection phase and transmission coefficient analysis for a unit cell.



(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

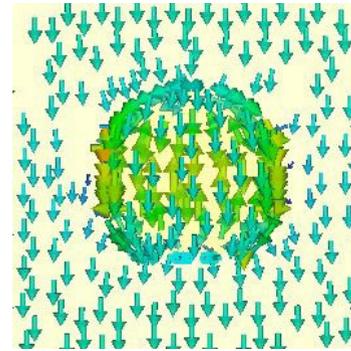


FIGURE 9. Proposed unit cell surface current distribution.

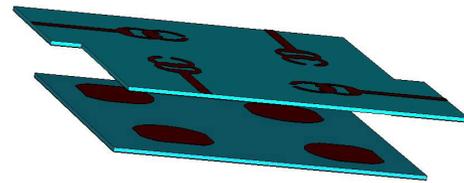


FIGURE 10. Proposed metasurface based antenna with a multi-port configuration.

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 within 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.

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 as possible. Rogers 5880 with a thickness of 0.254 mm is used to paste the

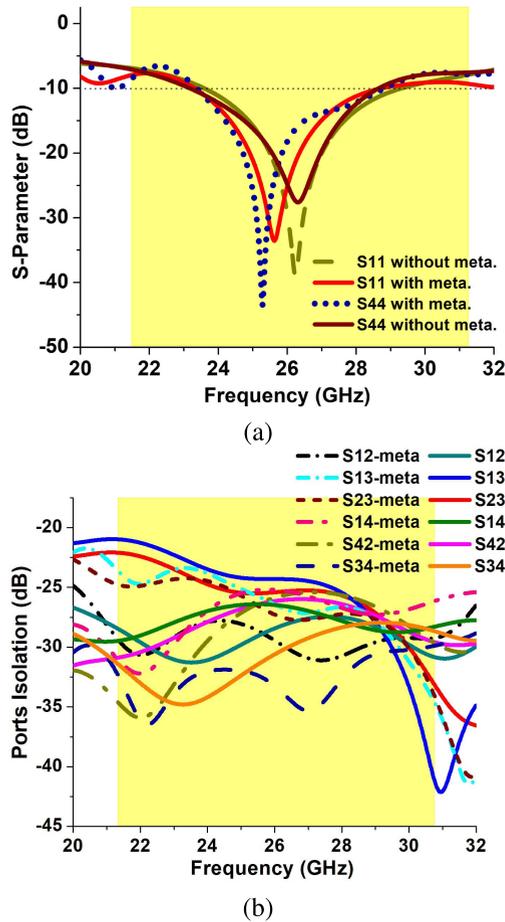


FIGURE 11. S-parameters comparison (a) return loss (b) isolation.

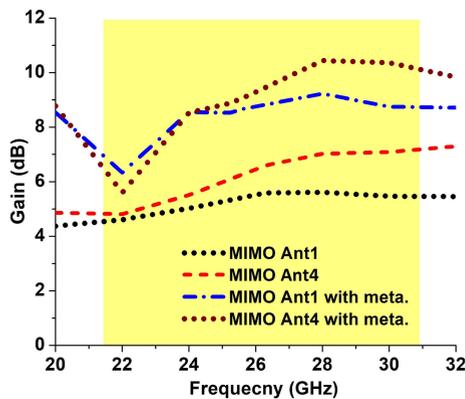


FIGURE 12. Gain comparison of the proposed antenna with and without metasurface.

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

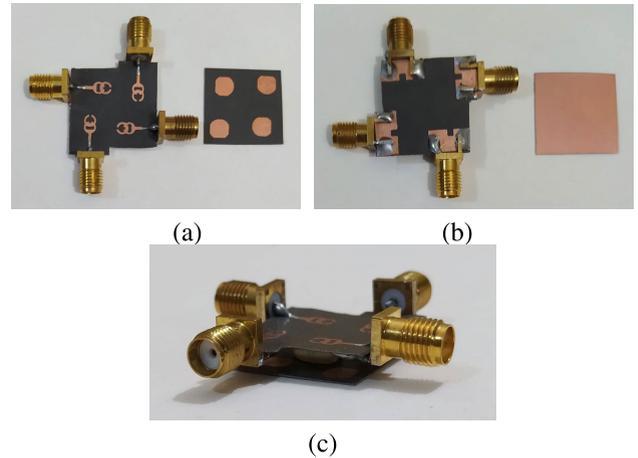


FIGURE 13. Proposed metasurface based antenna with multi-port configuration fabricated model in different scenarios (a) front (b) back (c) two layers assembly combined.

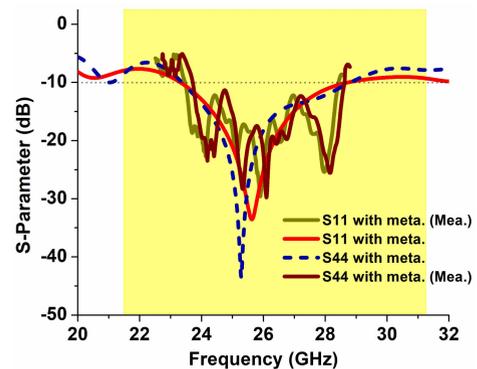


FIGURE 14. Simulated and measured reflection coefficients for the multi-port antenna with and without metasurface.

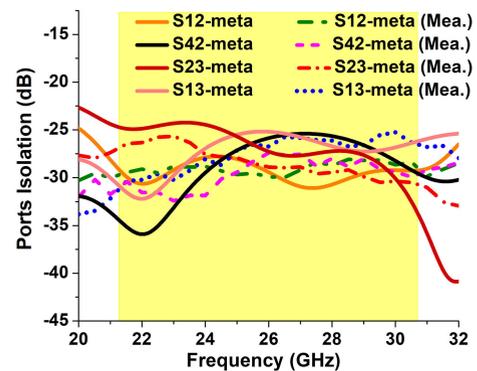


FIGURE 15. Simulated and measured isolations for the multi-port antenna with and without metasurface.

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.

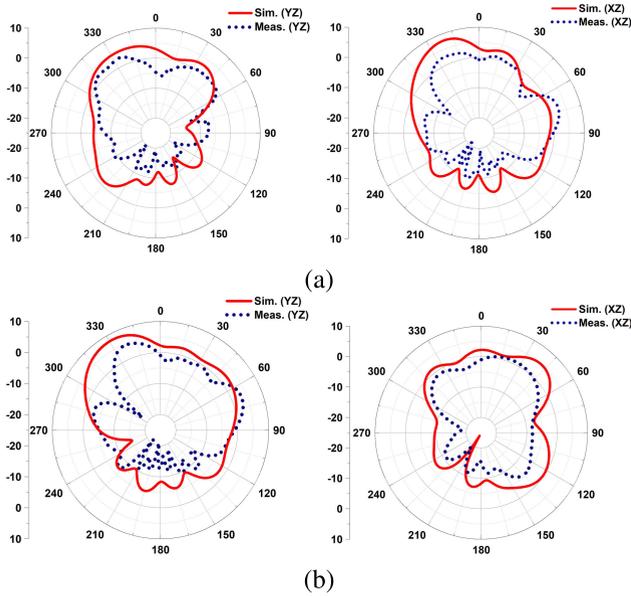


FIGURE 16. Measured and simulated polar radiation patterns (a) port-1 (b) port-4.

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 ECC is noticed to be below the standard value i.e., <0.5 and has been computer

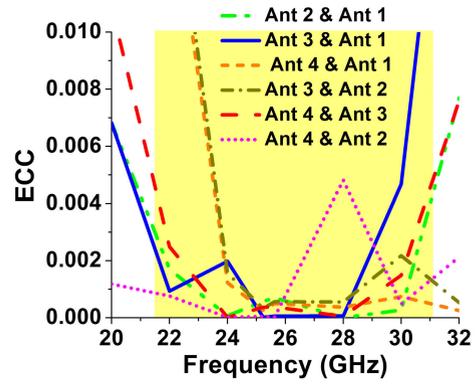


FIGURE 17. ECC for multi-port antenna based on metamaterial surface.

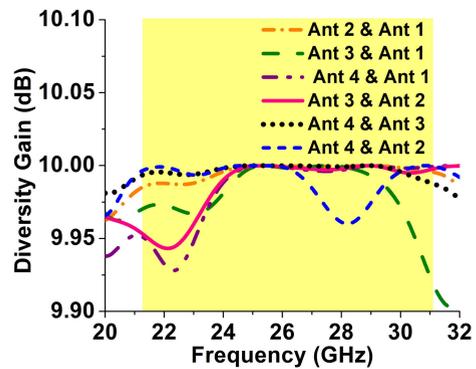


FIGURE 18. DG for multi-port antenna based on metamaterial surface.

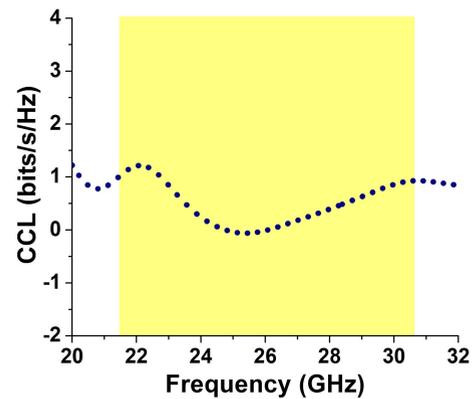


FIGURE 19. CCL for multi-port antenna based on metamaterial surface.

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.

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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DANIYAL ALI SEHRAI was born in Pakistan. He received the B.Sc. degree in telecommunication engineering from the University of Engineering and Technology, Peshawar, Pakistan, in 2018, and the M.Sc. degree in electrical engineering from the City University of Science and Information Technology, Peshawar, in 2021. He is currently working as a Senior Design Engineer with the Department of Electrical Engineering, National University of Computer and Emerging

Sciences, Islamabad, Pakistan. He published more than ten articles in reputed international journals and conferences. His research interests include design and measurement of metasurfaces, metamaterial-based antennas, MIMO antennas, multiband/wideband antennas, RF circuits and sensors, SAR, and Kirigami antennas.



MUHAMMAD ASIF was born in Pakistan. He received the B.S. and M.S. degrees in electrical engineering from the University of Engineering and Technology, Peshawar, Khyber Pakhtunkhwa, Pakistan, and the Ph.D. degree in electrical and electronic engineering from the Institute of Microelectronics Chinese Academy of Sciences, Beijing, China. From 2008 to 2018, he worked as a Lecturer with the Department of Electrical Engineering, CECOS University of IT & Emerging

Sciences, Pakistan. From 2018 to 2019, he worked as an Associate Professor (HoD) with the Department of Electrical Engineering, Qurtuba University of Sciences and IT, Khyber Pakhtunkhwa. He is currently working as an Associate Professor (HoD) with the Department of Electrical Engineering, City University of Sciences and Information Technology, Khyber Pakhtunkhwa. He published more than 30 articles in reputed international journals and conferences. His current research interest includes RF/Microwave devices and circuits, and their applications.



WAHAB ALI SHAH was born in Pakistan, in 1989. He received the bachelor's degree from the CECOS University of IT Emerging Sciences (CEIT), Peshawar, Pakistan, in 2011, the master's degree from Near East University (NEU), Mersin, Turkey, in 2016, and the Ph.D. degree from the School of Electrical and Electronic Engineering, Huazhong University of Science and Technology (HUST), Wuhan, China. Since 2019, he has been an Assistant Professor with the Department of Electrical Engineering, Namal Institute, Mianwali, Pakistan. His current research interests include observation and simulation of the long air-gap discharge in the laboratory, lightning to tall buildings in nature, insulation design of power systems, and high-voltage engineering.



JALAL KHAN was born in Pakistan. He received the B.Sc. degree in electrical engineering from the University of Engineering and Technology (UET), Peshawar, Pakistan, and the M.Sc. degree in personal, mobile and satellite networks from the University of Bradford, U.K. He is currently pursuing the Ph.D. degree in 5G antennas in telecommunication engineering with UET, Peshawar. He is currently an Assistant Professor with the Department of Telecommunication Engineering, University of Engineering and Technology, Mardan, Pakistan. His research interests include 5G antennas, reconfigurable antennas, mobile communications, and signal processing.



IBRAR ULLAH received the B.Sc. and M.S. degrees from the University of Engineering and Technology, Peshawar, Bannu Campus, in 2001 and 2004, respectively, and the Ph.D. degree from the Capital University of Science and Technology (CUST), Islamabad, in 2020. He is currently working as an Assistant Professor with the Department of Electrical Engineering, University of Engineering and Technology, Peshawar, Bannu Campus. His research interests include smart grid, energy optimization, wireless communication, power line communication, and 5G.



MUHAMMAD IBRAR was born in Pakistan. He received the B.Sc. and M.Sc. degrees in physics from the University of Peshawar, Pakistan, and the Ph.D. degree in material physics from the Queen Mary University of London, U.K. He is currently working as an Assistant Professor with the Department of Physics, Islamia College, Peshawar, Pakistan. His current research interests include device fabrication, nanomaterials, carbon nanotubes, and nanowires.



SAIEDULLAH JAN was born in Pakistan. He received the B.Sc. degree from Islamia College, Peshawar, Pakistan, the M.Sc. degree in physics from Gomal University, Pakistan, and the Ph.D. degree in dielectrics for capacitors from the University of Leeds, U.K. He is currently working as an Assistant Professor with the Department of Physics, Islamia College. His current research interests include device fabrication and dielectrics for capacitors.



MOHAMMAD ALIBAKHSHIKENARI (Member, IEEE) was born in Mazandaran, Iran, in February 1988. He received the Ph.D. degree (Hons.) in electronic engineering from the University of Rome “Tor Vergata,” in February 2020. He was a Ph.D. Visiting Researcher with the Chalmers University of Technology, in 2018. His training during the Ph.D. included a research stage in the Swedish company Gap Waves AB. His research interests include antennas and wave-propagations, metamaterials and metasurfaces, synthetic aperture radars (SAR), multiple-input multiple-output (MIMO) systems, substrate integrated waveguides (SIWs), impedance matching circuits, microwave components, millimeter-waves and terahertz integrated circuits, and electromagnetic systems. The above research lines have produced more than 120 publications on international journals, presentations within international conferences, and book chapters with a total number of the citations more than 1900 and H-index of 33. He was a recipient of two Young Engineer Awards of the 47th and 48th European Microwave Conference held in Nuremberg, Germany (2017) and in Madrid, Spain (2018), respectively. 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 in April 2020. He was a recipient of (i) three years research grant funded by the 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 research grant funded by the University of Rome “Tor Vergata” started, in November 2019, and (iii) three years Ph.D. Scholarship funded by the University of Rome “Tor Vergata” started, in November 2016. He is serving as an Associate Editor for *IET Journal of Engineering* and *International Journal of Antennas and Propagation*. He also acts as a referee in several highly reputed journals and international conferences.



FRANCISCO FALCONE (Senior Member, IEEE) received the degree in telecommunication engineering and the Ph.D. degree in communication engineering from the Universidad Publica de Navarra (UPNA), Spain, in 1999 and 2005, respectively. From February 1999 to April 2000, he was the Microwave Commissioning Engineer at Siemens Italtel, deploying microwave access systems. From May 2000 to December 2008, he was a Radio Access Engineer at Telefónica Móviles, performing radio network planning and optimization tasks in mobile network deployment. From February 2003 to May 2009, he was an Assistant Lecturer with the Electrical and Electronic Engineering Department, UPNA. In January 2009, as a Co-Founding Member, he has been the Director of Tafco Metawireless, a spin-off company from UPNA, until May 2009. He became an Associate Professor with the EE Department, in June 2009, and being the Department Head, from January 2012 to July 2018. From January 2018 to May 2018, he was a Visiting Professor with Kuwait College of Science and Technology, Kuwait. He is currently acting as the Head of the ICT Section. He is also affiliated with the Institute for Smart Cities (ISC), UPNA, which hosts around 140 researchers. His research interests include computational electromagnetics applied to the analysis of complex electromagnetic scenarios, with a focus on the analysis, design, and implementation of heterogeneous wireless networks to enable contextaware environments. He has over 500 contributions in indexed international journals, book chapters, and conference contributions. He has been awarded the CST 2003 and CST 2005 Best Paper Award, the Ph.D. Award from the Colegio Oficial de Ingenieros de Telecomunicación (COIT), in 2006, the Doctoral Award UPNA, 2010, 1st Juan Gomez Peñalver Research Award from the Royal Academy of Engineering of Spain, in 2010, the XII Talgo Innovation Award 2012, the IEEE 2014 Best Paper Award, in 2014, the ECSA-3 Best Paper Award, in 2016, and the ECSA-4 Best Paper Award, in 2017.



ERNESTO LIMITI (Senior Member, IEEE) has been a Research and Teaching Assistant, since 1991, an Associate Professor, since 1998, and a Full Professor of electronics with the Engineering Faculty, University of Roma Tor Vergata, since 2002. He represents the University of Roma Tor Vergata in the governing body of the Microwave Engineering Center for Space Applications (MECSA), an inter-university center among several Italian Universities. He has been elected to represent the Industrial Engineering Sector in the Academic Senate of the University, from 2007 to 2010, and from 2010 to 2013. He is actually the President of the Consortium Advanced Research and Engineering for Space (ARES), formed between the University and two companies. He is actually the President of the Laurea and Laurea Magistrale degrees in electronic engineering of the University of Roma Tor Vergata. His research activity is focused on three main lines, all of them belonging to the microwave and millimeter-wave electronics research area. The first one is related to characterization and modeling for active and passive microwave and millimeter-wave devices. Regarding active devices, the research line is oriented to the small-signal, noise and large signal modeling. 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 characterization and the subsequent modeling, and equivalent-circuit modeling strategies have been implemented both for small and large-signal operating regimes for GaAs, GaN, SiC, Si, and InP MESFET/HEMT devices. The second line is related to design methodologies and characterization methods for low noise circuits. The main focus is on cryogenic amplifiers and devices. His collaborations are currently ongoing with the major radio astronomy institutes all around Europe within the frame of FP6 and FP7 programs (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 within international conferences. He acts as a referee of international journals of the microwave and millimeter-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., and Space Engineering) and foreign (OMMIC, Siemens, and UMS) companies. He contributed, as a researcher and/or as unit responsible, to several National (PRIN MIUR, Madess CNR, and Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, and RadioNet FP6 and FP7) projects. Regarding teaching activities, he teaches, over his institutional 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 Ph.D. Program in telecommunications and microelectronics at the University of Roma Tor Vergata, tutoring an average of four Ph.D. candidates per year.

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