Received 14 June 2023, accepted 19 July 2023, date of publication 24 July 2023, date of current version 2 August 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3298568

RESEARCH ARTICLE

A Close Proximity 2-Element MIMO Antenna Using Optically Transparent Wired-Metal Mesh and Polyethylene Terephthalate Material

MUHAMMAD NAWAZ ABBASI[1], (Member, IEEE), ABDUL AZIZ[1], (Member, IEEE), KHALED A. ALJALOUD[2], (Member, IEEE), ABDUL REHMAN CHISHTI[1], (Member, IEEE), YOSEF T. ALADADI[3], AND RIFAQAT HUSSAIN[4], (Senior Member, IEEE)

[1]Faculty of Engineering and Technology, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan
[2]College of Engineering, Muzahimiyah Branch, King Saud University, Riyadh 11451, Saudi Arabia
[3]Department of Electrical Engineering, King Saud University, Riyadh 11421, Saudi Arabia
[4]Antenna and Electromagnetics Research Group, School of Electronic Engineering and Computer Science, Queen Mary University of London, E1 4NS London, U.K.

Corresponding authors: Muhammad Nawaz Abbasi (nawaz.abbasi@iub.edu.pk) and Rifaqat Hussain (rifaqat.hussain@qmul.ac.uk)

The authors would like to acknowledge the support provided by Researchers Supporting Project number (RSP2023R474), King Saud University, Riyadh, Saudi Arabia.

ABSTRACT An optically transparent MIMO antenna with close proximity two-element square patch antenna elements has been presented here to achieve forthcoming requirements of compactness, optical transparency and visual aesthetic for 5G wireless communication and Internet of Things (IoT) applications. A simple, thin optically transparent and more innovative decoupling structure with easier to design closely spaced transparent MIMO antenna configuration is proposed, optimized, and analyzed to achieve higher isolation and diversity gain performance even with close proximity of patch antenna elements. Polyethylene terephthalate (PET) material, a thermoplastic polymer resin of the polyester family, is used as a substrate to achieve optical transparency. The wired metal mesh parameters are considered to achieve the required optical transparency, isolation and radiation performance for the MIMO antenna. The performance of the proposed MIMO antenna is also verified through the fabricated prototype.

INDEX TERMS Proximity elements, MIMO antenna, transparent antenna, polyethylene terephthalate (PET), wired metal mesh.

I. INTRODUCTION

The 5G standard requires the deployment of several smaller base stations and the incorporation of the Internet of Things for realizing its full capabilities and potential. [1]. It will incorporate the use of Multiple-input multiple-output (MIMO) systems, which necessitate the use of multi-antenna designs. A significant hurdle in the implementation of mobile gadgets and base stations for the 5G standard is the wide range of frequency assignments and operational environments. These require a new category of base stations and mobile gadgets, which need to be designed for reliability and ease of integration [1], [2]. The current wireless communication technology will grow significantly with the help of 5G technology because lag-free connections are ensured, and it is possible for millions of connected devices to share data in real-time for activities like preventing traffic accidents or other life-saving operations.

Transparent electronic systems make it possible to achieve a discrete implementation of such systems. A key characteristic of transparent antennas is that these can be integrated seamlessly with transparent objects found in the environment, such as building windows, screens of mobile gadgets, and car windows [3]. So, it will be necessary to upgrade the antennas for modern technology, and as gadgets get smaller and smaller, there is a huge requirement that antennas can support both a larger user capacity and a compact size. Since transparent antennas offer both visual transparency and a suitable

The associate editor coordinating the review of this manuscript and approving it for publication was Binit Lukose.

level of conductance, these can be a good replacement for traditional ones.

An excessive development for the design of transparent antennas has been observed during the last few years [4], [5], [6], [7], [8]. An immense progress has been made in developing hardware technology, including the development of smart windows and augmented reality [9]. Hence, researchers have started focusing on the development of transparent as well as conductive materials, which can be used for wireless transparent applications, including mobile devices, glass windows, glass disguises, display panels, smart glasses and glass walls to meet requirements of increasing demand of wireless connectivity without any significant visual impact. However, transparent antennas may have low efficiency and gain due to the material characteristics of optically transparent conductors and dielectric substrate used in the fabrication of such antennas.

Both transparency and conductivity should be present in the materials needed for transparent gadgets. Transparent conducting oxides are considered a good option due to optical transparency and conductivity. These are largely employed in transparent electronics. Indium tin oxide (ITO), an oxide of varying proportions of Indium and Tin is also widely used as a transparent electrode [10]. However, the use of ITO is limited due to the fact that indium is not only fragile and expensive but also a rare earth metal. Multilayered film (MLF), which consists of Indium zinc thin oxide with a silver coating (IZTO/Ag/IZTO) is considered more flexible and relatively less expensive [7], [8], [11]. However, the performance of such MLF oxides is considered relatively poor as compared to non-transparent antennas. The transparent antennas having MLF ground planes showed poor efficiency in comparison with other types of transparent antennas [11], [12]. The MLF conductivity is considerable. However, increased sheet resistance due to extremely thin film causes poor efficiency. Many transparent antennas that have been investigated to date, use transparent conductive and polyester films coated with silver (AgHT-4 or AgHT-8) as a conducting material and high sheet resistances about 4-8 ohm/sq. Low radiation efficiencies result due to high sheet resistances. For instance, in [6] and [13] the efficiencies of antennas obtained were less than 20%, which rendered them relatively impractical transparent materials for use.

There have been several studies that have explored the transparent dielectric materials' layout, such as quartz or glass, coated with a thin transparent conductive film layer, which can be employed to develop transparent antennas. The performance of such transparent antennas is explored using a variety of conductive films and dielectric substrates [14], [15]. An antenna that consists of a ring-shaped resonator that is fed by a coplanar waveguide had been presented by Hakimi et al. in [16]. The antenna's dimensions were reduced by decreasing the size of the ground plane. The antenna was fabricated using a combination of gold and ITO on a substrate made of glass. To enhance the layer conductivity, the combination of ITO and gold was chosen. The frequency range of this antenna is 2-20 GHz. A transparent compact square patch antenna operates in the frequency band of 2.4 GHz (ISM), as reported by Awalludin et al. [17]. This antenna was fabricated using Aluminum-doped Zinc Oxide on a substrate made of glass. The research also concentrates on enhancing the preceding geometry to achieve better performance of the antenna. According to Song et al. [18], they proposed a Coplanar Waveguide antenna that operates at a frequency of 2.2 GHz. They suggested a technique for enhancing antenna efficiency by incorporating a highly conductive strip in areas where the density of current is relative. As described by Green et. al [15], a sapphire substrate was utilized to fabricate two transparent filters and a transparent antenna, both of which were coated with a Gallium-Zinc Oxide (GZO) conductive film. The antenna operates at a frequency of 2.2 GHz, while the filters function at 23-29 GHz frequency band.

The wired metal mesh type optically transparent antennas are also considered the most suitable option for the last few years. Such transparent antennas have enough conductivity, with suitable transparency and optical characteristics and a rather small fabrication expenditure in contrast to the conventional transparent thin film transparent antennas. In comparison, wired metal mesh transparent electrodes possess high conductivity and low resistance. These two electrical properties increased the possibility of using transparent antennas in patch [19], monopole, and arrayed antenna applications. For electromagnetic (EM) interference shielding, wired metal mesh has been used in [20] and [21], in which research has been done on the effectiveness of infrared light transmission to reduce the risks associated with electromagnetic radiation. Metal mesh technology is also used in military applications to block undesired radiation for infrared windows [21].

There is still limited research on optically transparent MIMO antenna configurations. MIMO antennas can be used for various applications and are also considered more suitable to achieve higher data for different applications like LTE, WI-fi, UWB, X & Ku band and 5G compact devices [22], [23], [24], [25], [26], [27], [28], [29], [30].

Reference [31] describes a transparent multiport monopole coplanar waveguide (CPW) antenna with experimental design evaluation, that is built on Minkowski fractal geometry, and is suitable for frequency band 5G-NR C. This compact MIMO transparent antenna, is manufactured from commonly available transparent materials, ITO films and the substrate is made of glass. The radiation patterns along with the reflection coefficients are used to evaluate the Envelope Correlation Coefficient and diversity gain performance of the proposed MIMO antenna.

There have been several two ports MIMO antenna designs presented in the literature [27], [32], [33], [34], [35], [36]. One of the proposed antennas in [35] is intended for the WLAN band and demonstrates adequate MIMO diversity performance, however, it has not been manufactured yet.

For 5G wireless communication, two elements transparent MIMO antenna employing ITO is presented in [36], however, it has also not been tested, practically. In [28], a micro metal mesh is used to develop a two-element transparent dual-band MIMO antenna that operates in frequency bands of 5.15-5.8 GHz and 2.4-2.48 GHz for Wireless Local Area Network systems. It has 0.05 Ω/sq sheet resistance, which is significantly lower than the 8 Ω/sq achieved by ITO. The antenna performance is evaluated using its S-parameters, however, the diversity gain performance of this MIMO antenna has not been examined.

In [37], the authors examine two different scenarios for simulation and experimental investigation of a two-element MIMO transparent antenna. Devisowjanya Potti et.al presented optically MIMO antenna in [38], which has a high sheet resistance of 10 ohm/sq for conductive layers of antenna printed on the top of the glass substrate. An optically transparent MIMO antenna for 5G has been presented in [39], and ITO film has been used as a conductor. In [40], a four-element wide band optically transparent MIMO antenna is proposed using AgHT-8 transparent conductive sheet and Plexiglas substrate. Arpan Desai et.al presented dual-band optically transparent MIMO antenna in [36] using plexiglass substrate and Silver Tin Oxide as the transparent conducting material. Although, the optically transparent MIMO antennas presented above have relatively good radiation performance, isolation or spectral efficiency, however, larger spacing between MIMO antenna elements has limitations to develop compact MIMO antenna systems in which MIMO antenna elements need to be in close proximity with each other.

MIMO transparent antennas are considered the best solution particularly for indoor applications within a limited space. So, the compact size of a MIMO antenna system is a basic requirement for such applications. However, a compact MIMO antenna system may need to have closely spaced MIMO antenna elements, which may cause strong mutual coupling between closely spaced antenna elements and may affect the performance of the MIMO antenna system negatively [25], [26], [41], [42], [43]. So, there is a need to develop a thin and simple transparent decoupling structure to achieve suitable isolation between closely spaced transparent antenna elements.

In this work, an optically transparent square lattice of the wired metal mesh is used to achieve transparent MIMO antenna for two closely spaced patch antenna elements. Optically transparent polyethylene terephthalate (PET) material is used as a substrate. The proposed transparent metal mesh MIMO antenna is also fabricated using simple printed circuit technology. The closely spaced transparent patch antenna elements are isolated by a novel transparent thin decoupling structure. The transparent MIMO antenna is analyzed and optimized by parametric analysis and surface current distribution analysis of the square lattice for the wired metal mesh and transparent thin decoupling strip structure to reduce the spacing between patch antenna elements with desired transparency, impedance matching, isolation, radiation performance and diversity gain performance.

II. DESIGN AND DEVELOPMENT OF OPTICALLY TRANSPARENT MIMO ANTENNA

To analyze the performance of a wired metal mesh transparent MIMO antenna, a MIMO antenna is selected in which two patch elements are in close proximity and it operates in the 5.74-5.88 GHz frequency band, which is suitable for WLAN applications and 5G applications in sub-6 GHz band. The intention of this study is to explore the feasibility of a 2-element transparent MIMO antenna with closely spaced antenna elements for 5G applications, which may help in the future to develop compact devices with more number of antennas in close proximity without affecting visual aesthetic.

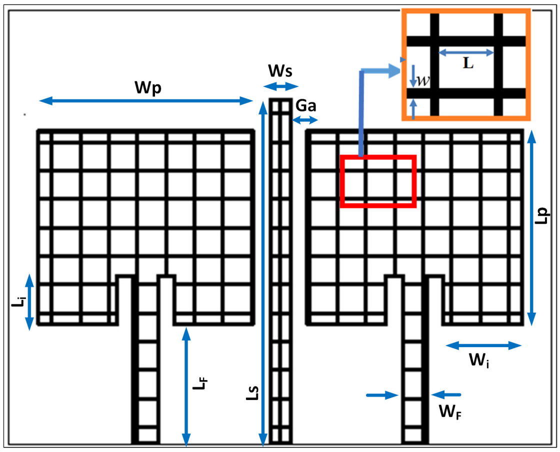


FIGURE 1. The proposed transparent antenna geometry with close proximity patch antenna elements.

The geometry of the proposed antenna is shown in Figure 1. The proposed transparent MIMO antenna consists of two extremely close proximity transparent square patch antenna elements that have very small gaps of 0.1 mm on both sides of the strip and both antennas are separated by 0.9mm spacing. The whole structure of MIMO antenna system is printed on top of PET substrate. The ground of the MIMO antenna system is printed on the bottom of the substrate, and its size is equal to the system substrate without any slot or defect. A low-profile transparent passive decoupling strip of width 0.7mm is used between the patch elements for decoupling. The length of the parasitic strip plays a crucial part in attaining a high level of isolation between the antenna elements. The wired metal mesh with a square lattice is used to achieve optical transparency and 1mm thick optically transparent PET material is used as a substrate. The PET substrate consists of a stack of 10 layers and each layer has a thickness of 0.1 mm and it has a dielectric constant of 3.5.

The size for the square lattice of wired metal mesh ‘L’ and the width of the wires ‘w’ used in the mesh is optimized to achieve about 83% optical transparency. CST Microwave Studio is used to design, analyze and optimize the dimensions

TABLE 1. Geometry parameters of the MIMO antenna.

Parameters	w	L	Wp	Lp	Wf	Lf
Values (mm)	0.2	2	16	16.5	2	7.75
Parameters	Wi	Li	Ws	Ls	Ga	–
Values (mm)	6	3.5	0.7	25.9	0.1	–

of the proposed geometry. The optimized dimensions of the geometry are given in Table 1.

The scattering parameters of the proposed transparent MIMO antenna system are shown in Figure 2. As both the antenna elements are symmetric around the decoupling strip, the S12 curve is overlapped on the S21 curve and in a similar manner S11 and S22 curves are also overlapped. Both the S11 and S22 curves show that the proposed transparent MIMO antenna has good impedance matching at 5.8 GHz and the return loss is well below -10 dB from 5.74 GHz to 5.88 GHz, while the isolation (S21) between the closely spaced transparent elements is greater than 25 dB in the desired frequency band, which shows that the proposed transparent MIMO antenna may have better diversity gain performance as well as good impedance matching.

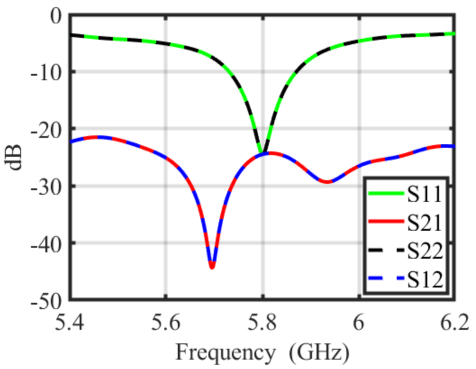
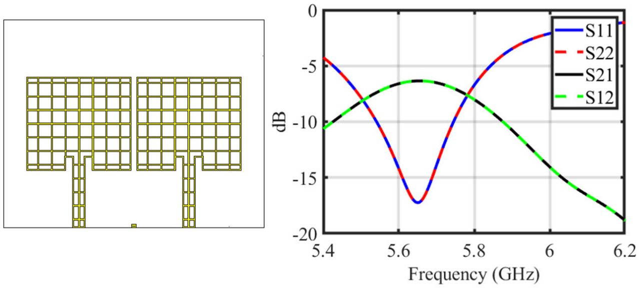


FIGURE 2. Scattering parameters of the proposed transparent MIMO antenna.

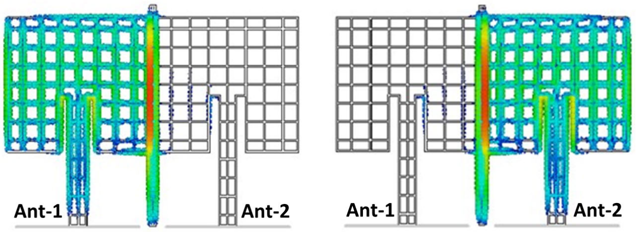
The transparent thin strip has an important role to achieve higher isolation between the patch antenna elements. The length of the passive transparent strip is optimized to achieve higher isolation between the closely spaced patch elements, which causes two out-of-phase currents that cancel the mutual flow of surface current between both the antenna elements. It is also verified by removing the decoupling thin strip between the two antenna elements. In Figure 3, it is observed that the isolation between the closely spaced antenna elements is reduced to -7 dB without proposed decoupling transparent thin strip.

The surface current distribution for the MIMO antenna is also presented in Figure 4. to verify the reason for higher isolation between antenna elements. It can be seen that when antenna-1 is excited then there is almost no surface current coupling observed towards antenna-2 and in a similar manner there is no coupling of surface current to antenna-1 when antenna-2 is excited. This also confirms that the isolation is achieved due to the thin transparent passive decoupling strip between the closely spaced antenna elements.



(a) (b)

FIGURE 3. Transparent MIMO antenna without decoupling strip (a) geometry, (b) scattering parameters.



(a) (b)

FIGURE 4. Surface current distribution at 5.8 GHz (a) antenna-1 excited and antenna-2 is matched to 50 ohm load, (b) antenna-2 excited and antenna-1 is matched to 50 ohm load.

III. RESULTS AND DISCUSSION

A. PARAMETRIC ANALYSIS

The parametric analysis for the proposed transparent MIMO antenna is also presented here to reveal how to optimize square lattice dimensions of the wired metal mesh to achieve better performance with suitable optical transparency for MIMO antenna with closely spaced antenna elements.

The optical transparency (OT) for the wired metal mesh square lattice can be defined as [44]:

$$(O.T) = \left[\frac{L}{w+L}\right]^2 \tag{1}$$

Figure 5 (a), shows the parametric analysis to analyze the effect of the parameters 'w' and 'L' for the square lattice of the wired metal mesh on optical transparency of all the conducting elements including the ground of the MIMO antenna. It can be seen that the optical transparency of the MIMO antenna can be increased by increasing 'L' and decreasing 'w'. The effect of variation in both the dimensions of the square lattice on resonant frequency, return loss and isolation are also analyzed and shown in Figure 5 (b), (c) and (d), respectively, to achieve optimum values for both the dimensions. It can be seen that the resonant frequency decreases minutely with an increase in 'L' and a decrease in 'w', which is due to an increase in the effective electrical length of the

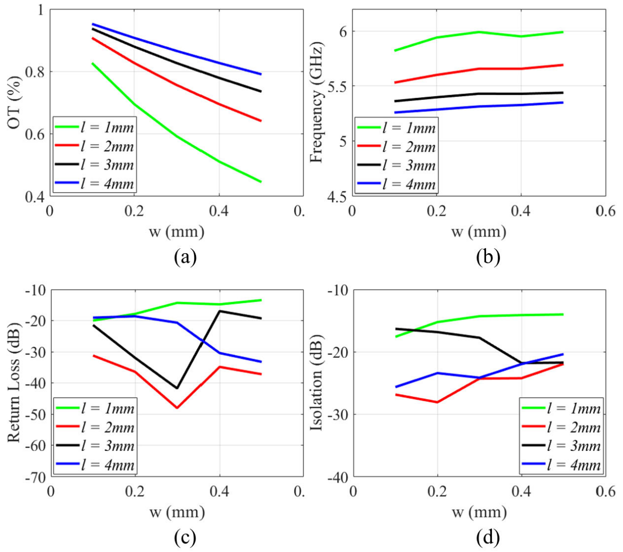
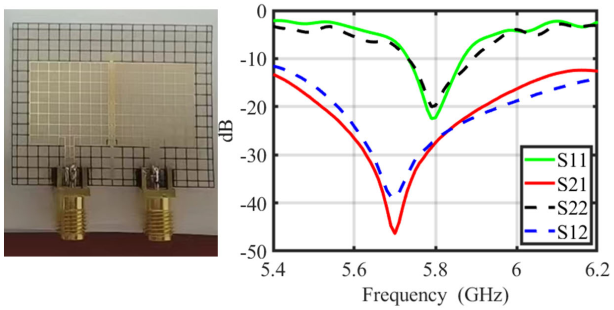


FIGURE 5. Parametric analysis for the proposed transparent MIMO Antenna (a) for optical transparency, (b) for resonance frequency, (c) for return loss, (d) for isolation.

patch antenna element due to the larger size of the square lattice. The return loss for each antenna element varies randomly and the minimum return loss is achieved for L = 2 mm and w = 0.3 mm. The isolation between the patch elements also varies randomly and the maximum Isolation is achieved for L = 2 mm and W = 0.2 mm. Through the above analysis, it is found that L = 2 mm and W = 0.2 mm are the most suitable dimensions for the square lattice to achieve optimum values for optical transparency (83%), return loss (25 dB) and isolation (25 dB) at 5.8 GHz.



(a) (b)

FIGURE 6. (a) Fabricated prototype of the proposed transparent MIMO antenna, (b) measured scattering parameters for the proposed transparent MIMO antenna.

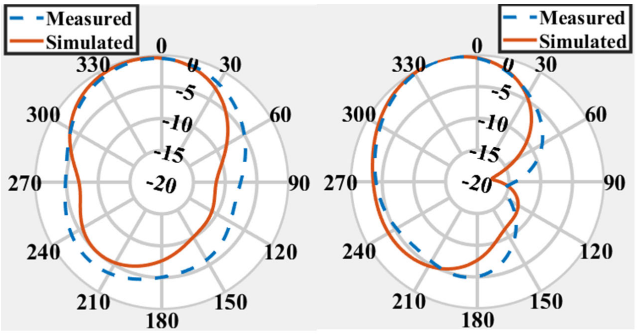
B. PERFORMANCE ANALYSIS

The fabricated prototype of the proposed transparent MIMO antenna shown in Figure 6 (a) is also characterized to verify its simulated performance. The measured scattering parameters for the proposed transparent MIMO antenna are shown in Figure 6(b). It is observed that the measured scattering parameters are almost matched with the simulated ones. A minor shift in resonance frequency and little deviations in transmission coefficient curves have been seen, which may be due to practical tolerance in simulation and measurement environments and imperfect soldering connections of both SMA connectors.

The performance of the proposed transparent MIMO antenna is also analyzed through radiation pattern, Envelope Correlation Coefficient (ECC), Channel Capacity Loss (CCL), Total Active Reflection Coefficient and Mean Effective Gain (MEG).

1) RADIATION PATTERN

The radiation pattern for one of the transparent patch antenna elements at 5.8 GHz is shown in Figure 7.



(a) (b)

FIGURE 7. Radiation pattern of the transparent MIMO antenna at 5.8 GHz (a) E-plane, (b) H-plane.

The transparent antenna element has achieved a gain of 3.55 dBi, radiation efficiency of 65% and total efficiency of 64.5% at 5.8 GHz, while the total efficiency at extreme frequencies of 5.74 GHz and 5.88 GHz is 59% and 63.5%, respectively, which is considered significant performance for a transparent patch antenna element in the desired frequency band. Similar radiation performance is observed for the 2^{nd} closely spaced transparent antenna element.

2) ENVELOPE CORRELATION COEFFICIENT AND DIVERSITY GAIN

The Envelope Correlation Coefficient (ECC) is a measurement of the impact that one antenna element has on another as a result of coupling. This parameter is used to measure the correlation between antenna elements in a MIMO diversity system. When evaluating the diversity performance of the MIMO antennas, the correlation coefficient is a crucial factor.

The ECC performance of the proposed transparent MIMO antenna is calculated in the desired frequency band through far-field radiation pattern technique [43], and it is found to be 0.1198 at 5.8 GHz while its value is 0.134 and 0.1451 at 5.74 and 5.88 GHz, respectively. This ECC value in the required frequency band is below the required minimum value of 0.5 [45].

The diversity gain (DG) is used to express the improvement in combined signal strength of a multiple antenna system over time averaged SNR. It is imperative to state here that the diversity gain, as well as the envelope correlation coefficient, are interrelated. This relation is such that if the correlation coefficient is low, then consequently the diversity gain will be high and vice versa{ [45].

The diversity gain is 9.93 at 5.8 GHz, while it is 9.91 and 9.89 at 5.74 and 5.88 GHz respectively, so the diversity gain is nearly equal to the ideal value of 10 in the desired frequency band, which is also considered good diversity gain performance for the proposed transparent MIMO antenna.

3) TOTAL ACTIVE REFLECTION COEFFICIENT (TARC)

The TARC Characteristic is a measure of the performance of a MIMO antenna. It illustrates the significance of resonance frequency stability even when the phase difference between antenna elements changes. This factor can be computed by taking the square root of the ratio between the available power minus the radiated power and the total available power [45].

The TARC performance of the proposed transparent MIMO antenna is also shown in Figure 8 which is -21 dB at 5.8 GHz.

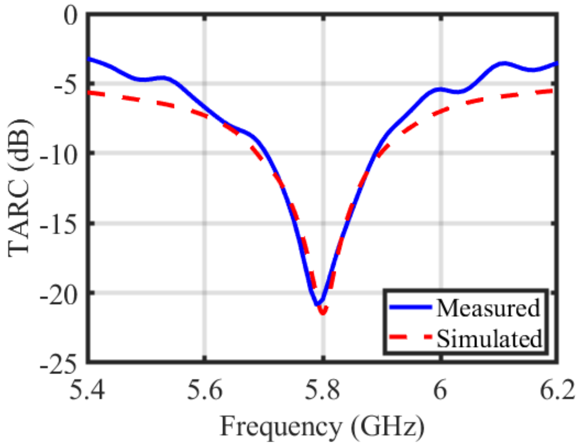


FIGURE 8. Total active reflection coefficient (TARC) for the proposed transparent MIMO antenna.

4) CHANNEL CAPACITY LOSS (CCL)

The CCL parameter is used to find transmission loss in terms of a number of data bits per second per Hertz transmitted through a communication channel. A CCL value less than 0.04 bps/Hz in a MIMO system is desirable for optimal performance [45].

The CCL performance of the proposed transparent MIMO antenna is shown in Figure 9. It can be seen that the CCL value remains less than 0.04 bps/Hz in the desired frequency band.

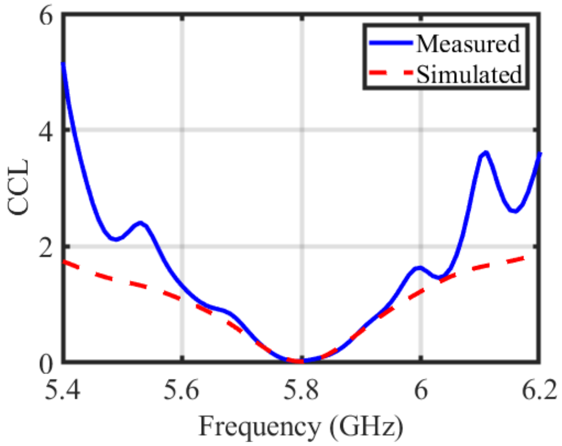


FIGURE 9. Channel Capacity Loss (CCL) performance for the proposed transparent MIMO antenna.

5) MEAN EFFECTIVE GAIN (MEG)

A power imbalance in the diversity elements of the MIMO system can cause diversity loss, which can negatively affect system performance. This imbalance is influenced by the antenna's total efficiency. MEG is a crucial parameter for measuring the performance of a MIMO antenna system, because of its special ability to represent all influences on the antenna's overall efficiency. The multiple antenna system must meet the balanced power requirement in order to provide the best possible diversity performance. It compares the power received by the MIMO antenna at the receiver to the power received by an isotropic antenna in a multipath fading environment [45].

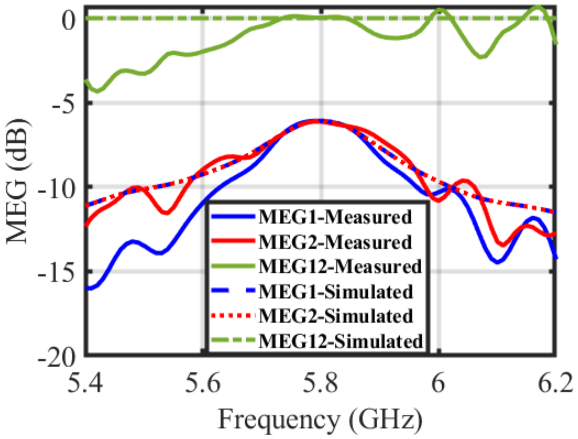


FIGURE 10. Mean Effective Gain (MEG) performance for the proposed transparent MIMO antenna.

The simulated and measured MEG performance for the proposed transparent MIMO antenna is illustrated in Figure 10. It can be seen that the simulated MEG_{12} value remains at 0 dB, while the measured MEG_{12} value is also less than 3 dB in the desired frequency band.

TABLE 2. Comparison with previous recent works.

Ref. No	Freq. Bands (GHz)	Substrate	Conductor	Radiation Eff. (%)	O.T (%)	Peak Gain (dBi)	Isolation (dB)	Element Spacing (mm)
[28]	2.4-2.5, 5.1-5.8	Glass	Micro Metal Mesh	43, 46	40	0.74, 2.30	15, 21	22.4
[36]	2.2-2.5, 3.2-4	Plexi-glass	AgHT-8	86, 88	-	1.98 , 2.95	12, 32	35
[37]	4.6-5	Plexi-glass	AgHT-8	53	45	1.83	10	5
[38]	2.4-11	Glass	ITO & FTO	60	72	2	20	20
[39]	4.8-5, 22.6-28.3	Glass	ITO	-	84	2.3, 3.9	35, 30	90, 130
This-Work	5.7-5.9	PET	Wired Metal Mesh	65	83	3.55	25	0.9

Table 2, compares the performance of the proposed close proximity 2-element optically transparent MIMO antenna with some recent previous works to highlight the importance of the proposed design technique. The results indicate that the proposed transparent thin decoupling strip has helped to achieve comparable isolation and radiation performance even with significantly reduced spacing between antenna elements as compared to spacing demonstrated in previous works. This significant reduction in spacing between antenna elements may help to develop compact and optically transparent MIMO antenna systems for potential future applications of IoT and 5G Communication systems.

IV. CONCLUSION

A transparent MIMO antenna is proposed, which consists of transparent patch elements in close proximity. The wired metal mesh with a square lattice is used to achieve optical transparency and 1mm thick transparent PET material is used as a substrate. A very low-profile decoupling transparent strip is used to achieve more than 25 dB measured isolation in the desired frequency band. The transparent MIMO antenna is optimized and analyzed using parameters of the square lattice wired metal mesh and the length of the thin transparent passive strip between the antenna elements. The proposed MIMO antenna has achieved 83% transparency. The antenna operates at 5.8 GHz and the inset feed technique is used for impedance matching. The transparent MIMO antenna performance is also exhibited through gain, radiation efficiency, total efficiency, envelope correlation coefficient, diversity gain, TARC and mean effective gain. The performance of the proposed transparent MIMO antenna is also verified through measurement of the fabricated prototype, which also confirms the suitability of the proposed transparent MIMO antenna for applications, which need compactness as well as suitable optical transparency and visual aesthetic. The proposed technique may have a key role in the development of future smart wireless transparent gadgets.

V. ACKNOWLEDGMENT

The authors would like to acknowledge the support provided by Researchers Supporting Project number (RSP2023R474), King Saud University, Riyadh, Saudi Arabia.

REFERENCES

[1] L. Wan, Z. Guo, Y. Wu, W. Bi, J. Yuan, M. Elkashlan, and L. Hanzo, "4G5G spectrum sharing: Efficient 5G deployment to serve enhanced mobile broadband and Internet of Things applications," *IEEE Veh. Technol. Mag.*, vol. 13, no. 4, pp. 28–39, Dec. 2018.

[2] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.

[3] J. I. Trujillo-Flores, R. Torrealba-Meléndez, J. M. Muñoz-Pacheco, M. A. Vásquez-Agustín, E. I. Tamariz-Flores, E. Colín-Beltrán, and M. López-López, "CPW-fed transparent antenna for vehicle communications," *Appl. Sci.*, vol. 10, no. 17, p. 6001, Aug. 2020.

[4] Y. Yuan, "Changing the world with virtualaugmented reality technologies," *IEEE Consum. Electron. Mag.*, vol. 6, no. 1, pp. 40–41, Jan. 2017.

[5] T.-J. Ha, "High-performance solution-processed zinc–tin-oxide thin-film transistors employing ferroelectric copolymers fabricated at low temperature for transparent flexible displays," *IEEE Electron Device Lett.*, vol. 37, no. 12, pp. 1586–1589, Dec. 2016.

[6] C. M. Lee, Y. Kim, Y. Kim, I. K. Kim, and C. W. Jung, "A flexible and transparent antenna on a polyamide substrate for laptop computers," *Microw. Opt. Technol. Lett.*, vol. 57, no. 5, pp. 1038–1042, May 2015.

[7] S. Hong, S. H. Kang, Y. Kim, and C. W. Jung, "Transparent and flexible antenna for wearable glasses applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2797–2804, Jul. 2016.

[8] S. Hong, Y. Kim, Y.-B. Jung, and C. W. Jung, "Transparent microstrip line with IZTO/AG/IZTO multilayer electrode," *Microw. Opt. Technol. Lett.*, vol. 59, no. 5, pp. 1161–1164, May 2017.

[9] R. N. Simons and R. Q. Lee, "Feasibility study of optically transparent microstrip patch antenna," in *IEEE Antennas Propag. Soc. Int. Symp., Dig.*, vol. 4, Jul. 1997, pp. 2100–2103.

[10] T. Peter, R. Nilavalan, H. F. AbuTarboush, and S. W. Cheung, "A novel technique and soldering method to improve performance of transparent polymer antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 918–921, 2010.

[11] S. Hong, Y. Kim, and C. Won Jung, "Transparent microstrip patch antennas with multilayer and metal-mesh films," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 772–775, 2017.

[12] S. Hong, Y. Kim, and C. W. Jung, "Transparent UWB antenna with IZTO/Ag/IZTO multilayer electrode film," *Int. J. Antennas Propag.*, vol. 2016, pp. 1–8, Jan. 2016.

[13] Y. Kim, C. Lee, S. Hong, C. W. Jung, and Y. Kim, "Design of transparent multilayer film antenna for wireless communication," *Electron. Lett.*, vol. 51, no. 1, pp. 12–14, Jan. 2015.

[14] Y.-H. Zhang, Z.-X. Mei, H.-L. Liang, and X.-L. Du, "Review of flexible and transparent thin-film transistors based on zinc oxide and related materials," *Chin. Phys. B*, vol. 26, no. 4, Apr. 2017, Art. no. 047307.

[15] R. B. Green, M. Guzman, N. Izyumskaya, B. Ullah, S. Hia, J. Pitchford, R. Timsina, V. Avrutin, U. Ozgur, H. Morkoc, N. Dhar, and E. Topsakal, "Optically transparent antennas and filters: A smart city concept to alleviate infrastructure and network capacity challenges," *IEEE Antennas Propag. Mag.*, vol. 61, no. 3, pp. 37–47, Jun. 2019.

[16] S. Hakimi, S. K. A. Rahim, M. Abedian, S. M. Noghabaei, and M. Khalily, "CPW-fed transparent antenna for extended ultrawideband applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1251–1254, 2014.

[17] M. Awalludin, M. T. Ali, and M. H. Mamat, "Transparent antenna using aluminum doped zinc oxide for wireless application," in *Proc. IEEE Symp. Comput. Appl. Ind. Electron. (ISCAIE)*, Apr. 2015, pp. 33–36.

[18] H. Jae Song, T. Yuan Hsu, D. F. Sievenpiper, H. Pin Hsu, J. Schaffner, and E. Yasan, "A method for improving the efficiency of transparent film antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 753–756, 2008.

[19] G. Clasen and R. Langley, "Meshed patch antennas," *IEEE Trans. Antennas Propag.*, vol. 52, no. 6, pp. 1412–1416, Jun. 2004.

[20] J. Hashiba, T. Kawajiri, R. Shibuya, and H. Ishikuro, "Shield effects of metal plate and mesh in wireless power delivery system," in *Proc. IEEE Int. Symp. Radio-Freq. Integr. Technol. (RFIT)*, Aug. 2015, pp. 235–237.

[21] S. Yan-Jun, C. Hao, W. Song-hang, L. Yan-Bing, and W. Li, "Study on electromagnetic shielding of infrared/visible optical window," *Mod. Appl. Sci.*, vol. 9, no. 13, p. 231, Nov. 2015.

[22] G. Srivastava and A. Mohan, "Compact MIMO slot antenna for UWB applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1057–1060, 2016.

[23] M. N. Hasan, S. Chu, and S. Bashir, "A DGS monopole antenna loaded with U-shape stub for UWB MIMO applications," *Microw. Opt. Technol. Lett.*, vol. 61, no. 9, pp. 2141–2149, Sep. 2019.

[24] D. Manteuffel and R. Martens, "Compact multimode multielement antenna for indoor UWB massive MIMO," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2689–2697, Jul. 2016.

[25] M. Li, Y. Zhang, D. Wu, K. L. Yeung, L. Jiang, and R. Murch, "Decoupling and matching network for dual-band MIMO antennas," *IEEE Trans. Antennas Propag.*, vol. 70, no. 3, pp. 1764–1775, Mar. 2022.

[26] M. Li, Y. Zhang, F. Jiang, D. Wu, K. L. Yeung, L. Jiang, and R. Murch, "Improvement for MIMO systems by increasing antenna isolation and shaping radiation pattern using hybrid network," *IEEE Trans. Ind. Electron.*, vol. 69, no. 12, pp. 13891–13901, Dec. 2022.

[27] Y. Yang, Q. Chu, and C. Mao, "Multiband MIMO antenna for GSM, DCS, and LTE indoor applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1573–1576, 2016.

[28] Q. L. Li, S. W. Cheung, D. Wu, and T. I. Yuk, "Optically transparent dual-band MIMO antenna using micro-metal mesh conductive film for WLAN system," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 920–923, 2017.

[29] H. Li, G. Zhang, J. Xu, J. Ding, and C. Guo, "Aperture-coupling fed high isolation polarization diversity dual-element MIMO antenna system for WLAN application," *Microw. Opt. Technol. Lett.*, vol. 59, no. 5, pp. 1178–1182, May 2017.

[30] H. T. Chattha, "4-port 2-element MIMO antenna for 5G portable applications," *IEEE Access*, vol. 7, pp. 96516–96520, 2019.

[31] F. Lopez-Marcos, R. Torrealba-Melendez, M. A. Vasquez-Agustin, J. M. Muñoz-Pacheco, E. I. Tamariz-Flores, and M. Lopez-Lopez, "A MIMO transparent antenna for FR1-5G communications," *Wireless Pers. Commun.*, vol. 123, no. 4, pp. 3645–3660, Apr. 2022.

[32] A. Moradikordalivand, C. Y. Leow, T. A. Rahman, S. Ebrahimi, and T. H. Chua, "Wideband MIMO antenna system with dual polarization for WiFi and LTE applications," *Int. J. Microw. Wireless Technol.*, vol. 8, no. 3, pp. 643–650, May 2016.

[33] X. You, H. Gao, L. Zhou, and H. Zhao, "Compact dual-element inverted-F MIMO antenna system with enhanced isolation," *Microw. Opt. Technol. Lett.*, vol. 58, no. 2, pp. 363–368, Feb. 2016.

[34] A. Dkiouak, A. Zakriti, and M. E. Ouahabi, "Design of a compact dual-band MIMO antenna with high isolation for WLAN and X-band satellite by using orthogonal polarization," *J. Electromagn. Waves Appl.*, vol. 34, no. 9, pp. 1254–1267, Jun. 2020.

[35] K. K. So, B. J. Chen, C. H. Chan, and K. M. Luk, "Study of MIMO antenna made of transparent conductive ITO films," in *Proc. IEEE Asia–Pacific Microw. Conf. (APMC)*, Dec. 2019, pp. 515–517.

[36] A. Desai, T. Upadhyaya, M. Palandoken, and C. Gocen, "Dual band transparent antenna for wireless MIMO system applications," *Microw. Opt. Technol. Lett.*, vol. 61, no. 7, pp. 1845–1856, Jul. 2019.

[37] A. Desai, M. Palandoken, I. Elfergani, I. Akdag, C. Zebiri, J. Bastos, J. Rodriguez, and R. A. Abd-Alhameed, "Transparent 2-element 5G MIMO antenna for sub-6 GHz applications," *Electronics*, vol. 11, no. 2, p. 251, Jan. 2022.

[38] D. Potti, Y. Tusharika, M. G. N. Alsath, S. Kirubaveni, M. Kanagasabai, R. Sankararajan, S. Narendhiran, and P. B. Bhargav, "A novel optically transparent UWB antenna for automotive MIMO communications," *IEEE Trans. Antennas Propag.*, vol. 69, no. 7, pp. 3821–3828, Jul. 2021.

[39] K. K. So, B.-J. Chen, and C. H. Chan, "Microwave and millimeter-wave MIMO antenna using conductive ITO film," *IEEE Access*, vol. 8, pp. 207024–207033, 2020.

[40] A. Desai, C. D. Bui, J. Patel, T. Upadhyaya, G. Byun, and T. K. Nguyen, "Compact wideband four element optically transparent MIMO antenna for mm-wave 5G applications," *IEEE Access*, vol. 8, pp. 194206–194217, 2020.

[41] K.-L. Wu, C. Wei, X. Mei, and Z.-Y. Zhang, "Array-antenna decoupling surface," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6728–6738, Dec. 2017.

[42] Y. Chang, Q. Liu, X. Tang, G. Du, G. Li, and D. Cheng, "Compact MIMO antenna with high isolation characteristic for UWB portable applications," *Microw. Opt. Technol. Lett.*, vol. 62, no. 3, pp. 1391–1397, Mar. 2020.

[43] M. Li, L. Jiang, and K. L. Yeung, "Novel and efficient parasitic decoupling network for closely coupled antennas," *IEEE Trans. Antennas Propag.*, vol. 67, no. 6, pp. 3574–3585, Jun. 2019.

[44] S. H. Kang and C. W. Jung, "Transparent patch antenna using metal mesh," *IEEE Trans. Antennas Propag.*, vol. 66, no. 4, pp. 2095–2100, Apr. 2018.

[45] P. Pradeep, K. J. Sankar, and P. C. Sekhar, "A compact semi-circular slot MIMO antenna with enhanced isolation for sub-6 GHz 5G WLAN applications," *Wireless Pers. Commun.*, vol. 125, no. 4, pp. 3683–3698, Aug. 2022.

MUHAMMAD NAWAZ ABBASI (Member, IEEE) received the B.E. degree in electronics engineering from the NED University of Engineering and Technology, Karachi, Pakistan, in 1992, and the M.Sc. degree from the University of Engineering and Technology Taxila, Pakistan, in 2003. He is currently pursuing the Ph.D. degree in electrical engineering with The Islamia University of Bahawalpur, Pakistan. He was a Site Engineer with Telecom Foundation, Lahore, Pakistan, from 1993 to 1994. He tendered his services as a Senior Instructor of Electronics with GCT Bahawalpur, Pakistan. He was a Senior Engineer in different departments of Pakistan Telecommunication Company Ltd. (PTCL), from 1996 to 2016. He has been a Faculty Member, since 2016, and he is associated with the Antenna and Microwave Laboratory, The Islamia University of Bahawalpur. His current research interests include multiple input multiple output systems, 5G enabled antenna designs, transparent antennas, and integrated 4G/5G antennas for wireless handsets and access points.

ABDUL AZIZ (Member, IEEE) received the B.S. degree in electrical engineering from Bahauddin Zakariya University, Multan, Pakistan, in 2003, the M.S. degree in telecommunication engineering from the University of Engineering and Technology Peshawar, Peshawar, Pakistan, in 2008, and the Ph.D. degree in electronic engineering from Tsinghua University, Beijing, China, in 2019.

He has been an Associate Professor with The Islamia University of Bahawalpur, since 2009. He has also experience of working in telecom industry, from 2004 to 2009. He is also a HEC approved supervisor and supervising several M.S. and Ph.D. scholars. His research interests include transmissive and reflective metasurfaces, antennas, and applied electromagnetics. He also has several research publications in peer reviewed international conferences and journals.

KHALED A. ALJALOUD (Member, IEEE) received the B.S. degree from King Saud University, Riyadh, Saudi Arabia, in 2009, the M.S. degree from the University of Southern California, Los Angles, USA, in 2013, and the Ph.D. degree from the University College London, London, U.K., in 2018. He is currently with the College of Applied Engineering, King Saud University, as an Assistant Professor. His current research interests include antennas, RF circuits, electromagnetic energy harvesting, embedded systems and deep learning-based embedded systems, and their uses in robotics and aerial vehicles.

ABDUL REHMAN CHISHTI (Member, IEEE) received the B.Sc. degree in electrical engineering (telecommunications) and the M.Sc. degree in electrical engineering from the University of Engineering and Technology (UET) Taxila (CASE), Islamabad, Pakistan, in 2008 and 2013, respectively. He is currently pursuing the Ph.D. degree in electrical engineering, specialization in antenna designing for biomedical applications. His major field of study was control and communication engineering. He was a Lecturer with The Islamia University of Bahawalpur, Pakistan, from 2009 to 2017, where he has been an Assistant Professor with the Department of Information and Communication Engineering, since 2017.

YOSEF T. ALADADI received the B.Sc. degree in electrical communication engineering from Ibb University, Ibb, Yemen, in 2010, and the M.S. and Ph.D. degrees in electric engineering from King Saud University, Riyadh, Saudi Arabia, in 2016 and 2021, respectively. He is currently a Researcher with the Electrical Engineering Department, King Saud University. His research interests include the electromagnetic propagation and electromagnetic characterization of complex materials.

RIFAQAT HUSSAIN (Senior Member, IEEE) received the B.Sc. degree (Hons.) in electrical engineering from the University of Engineering and Technology Peshawar, Pakistan, in 2003, the M.S. degree in systems engineering from PIEAS, Pakistan, in 2005, and the Ph.D. degree in electrical engineering from the King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, in January 2015. His current research interests include re-configurable antennas, 4G/5G integrated antenna designs, CubeSat antenna, the IoT, and 5G-enabled antenna design.

• • •