International Journal of Computer Engineering and Data Science (ISSN: 2737-8543)
Volume 3– Issue 1, January - March 2023

CPW high-isolation UWB transparent MIMO antenna for 5G applications

OMAR OURAHOU [1], HIND ABBAOUI [1], FATIMA EZ-ZAKI[1], Raefat-Jalila El Bakouchi[1,2], HASSAN BELAHRACH [1,3], ABDELILAH GHAMMAZ[1]

[1]*Laboratory of Electrical Systems and Telecommunications, Faculty of Sciences and Technologies, Cadi Ayyad University* Department of physics, *Marrakesh, Morocco*

[2]*Laboratory of Innovation in Management and Engineering for the Enterprise ISGA (The Higher Institute of Engineering and Business), Marrakesh, Morocco*

[3]*Laboratory of Electrical Engineering, Royal School of Aeronautics, Marrakesh, Morocco*

E-mail: ourahoueomare@gmail.com, akb0048ha@gmail.com, fatima.ezzaki@edu.uca.ma , h.belahrach@gmail.com , aghammaz@yahoo.fr

Article history

Received Jun 20, 2023
Revised Jul 06, 2023
Accepted Jul 09, 2023
Published Jul 17, 2023

ABSTRACT

As we edge closer to the integration of printed antennas on the surfaces of buildings and transportation systems, the idea of transparent antennas was highly sought after. In this contribution, a CPW transparent patch antenna with UWB characteristics was first designed and simulated using HFSS software, and then, to enhance the data rate, improve the radio link capacity, and eliminate multipath fading, a MIMO of two elements was made on the basis of the proposed antenna, which is built using a Plexiglas substrate and a silver coated polymer (AGHT-8) for the conducting element. The simulated reflection coefficient displays a fantastic bandwidth of about 21.65GHz. The working band of the band ranges from 22.72 to 44.37 (65.54%) GHz, with a peak gain of more than 3.75 dB and a radiation efficiency of more than 91%. The isolation obtained is less than -32 dB with Diversity Gain is around 10 dB. The value of the envelope correlation coefficient (ECC) is less than 0.015.

Keywords: 5G, Plexiglas, CPW, AGHT-8, Transparent Antenna

I. INTRODUCTION

Compared to the current 4G technology which has reached its saturation point in terms of data support as a result of its restricted bandwidth and the growing number of subscribers[1], the technologies 5G and 6G are coming to offer high speed-data rates and low latency. The spectrum of 5G technology have been divided into two main frequency bands: sub-6 GHz and millimeter wave bands, including frequencies such as, 28, 38, 60, and 70 GHz. 5G millimeter wave offers numerous advantages such as wide bandwidth (up to 400 MHz), increased resolution (better than 4K), low latency (less than 10 ms)[2], and so on, is more suitable, since the sub-6 GHz band is already occupied[1].

5G technology demand numerous base stations and. Transparent antennas enable increased signal strength and data speeds because they can be installed optically transparent antenna can be installed anywhere, such as building windows, car windscreens, smart windows, towers, and trees[3], without causes visual clutter. Using transparent conductive oxides, such as Indium Tin Oxide (ITO), Fluorine-doped Tin Oxide (FTO), and AGHT (silver-coated polyester film), transparent antennas can be created [4]. AGHT is the best transparent conductor for making transparent antennas, it is available commercially in two variants AGHT-4 and AGHT-8 [5]. Numerous rigid substrates have been proposed for transparent antennas, such as Plexiglass, Acryl, Sapphire Glass, and Quartz. Several flexible transparent substrates, including PET, PEN, polyamide, and PI PDMS, have also been proposed for transparent antennas[3].

several countries, such as the USA (27.5–28.35 GHz) and 37–43.5 GHz), China (24.3–27.5 GHz, 37–43.5 GHz), Japan (27.5–28.8 GHz), Sweden (26.5-27.5 GHz), Europe (24.25-27.5 GHz), and Korea (28 GHz), have put forth frequency band proposals for the implementation of 5G millimeter-wave applications[6].

the modern communication system requires a wide band, which can be achieved using Ultra-Wide Band (UWB) technology, which plays a vital role in wireless communication. The UWB technology is very attractive due to its numerous advantages, such as its high data transmission rate, higher data resolution, low spectral power density, and low interference [7]. Nevertheless, UWB technology is predominantly susceptible to degradation caused by multipath fading in cable-free communication[8]. MIMO technology is one solution to eliminate multipath fading[9]. In addition, MIMO technology possesses the ability to significantly enhance the data rate by up to 1000 times using multiplexing techniques and spatial diversity [1].

Various MIMO antennas have been proposed in the literatures, antennas for Wi-Fi, WIMAX ,5G applications has been proposed in [9], and the antenna 4 Port MIMO with high isolation was presented in[10]. In [11] a dual-band four port MIMO array antenna for 5G millimeter wave was built. for sub-6 GHz mm-wave 5G the antenna was designed in [12]. In [13], an antenna waveguide-fed coplanar MIMO for 5G communications has been proposed.

Several transparent antennas are suggested for 5G. A transparent antenna working at 28 GHz is proposed in [4],[5]. In [6], a transparent antenna for 5G communications systems operating in the band 23.92-43.80 GHz is proposed. In [5], a transparent antenna for millimeter wave 5G applications working in the frequency range of 24.100–27.18 GHz and 33–44.13 GHz is proposed.

In[16], a MIMO transparent antenna for sub-6 GHz 5G has been proposed; however, only 0.34 GHz of bandwidth and 1.034 dBi of gain were obtained. [17] presents a MIMO wideband antenna for sub-6 GHz using AGHT-4 as a conductor, however, only 0.53 dBi of maximum gain was achieved. In[18], four-element MIMO wideband antenna for 5G mm-wave applications has been proposed, 3 dBi of gain was achieved.

In this work, a transparent wideband MIMO antenna is presented, a MIMO diversity parameter, such as diversity gain (DG), envelope coefficient correlation (ECC), CCL (channel capacity loss), MEG (mean effective gain), and TARC have been studied using ANSY HFSS software. the proposed antenna is operating in frequency range 22.72-44.37 GHz.

The structure of this paper is as follows: Section 1 presents the simulation results of the reference antenna, which is nontransparent, it is cited in reference [19], the analyze and the simulated results of the single transparent antenna will be presented in section 1, section 3 will present the studied and the simulation results of two-element MIMO antenna.

II. SIMULATION THE REFERENCE ANTENNA

In this section, the non-transparent antenna cited in reference [19] has been simulated using HFSS software. The reference antenna is designed using Rogers as a substrate and Coper as a conductor. Fig.1 depicts its geometry. This antenna is i-shaped and is alimented using a coplanar waveguide, a technique known for its wide band characteristic.

Fig.2 shows the simulation result of the reflection coefficient. From this figure, it is seen that this antenna has an ultra-wide operating band that starts from 26 to 38.8 GHz, with two resonant frequencies, the low resonant is at 29.49 GHz and the higher resonant is at 37.48 GHz. The total gain at frequencies 28 and 38 GHz is displayed in Fig.3. Some of the results obtained by the author of the article [19] have been approximately achieved.

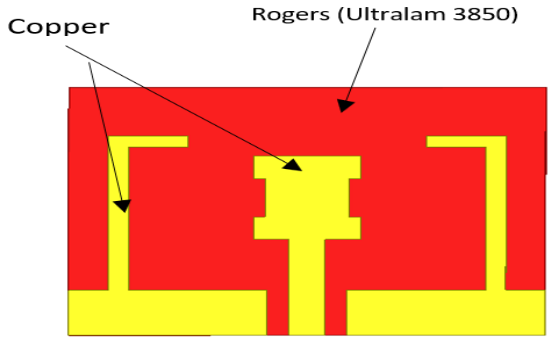


Figure 1. design of the reference antenna

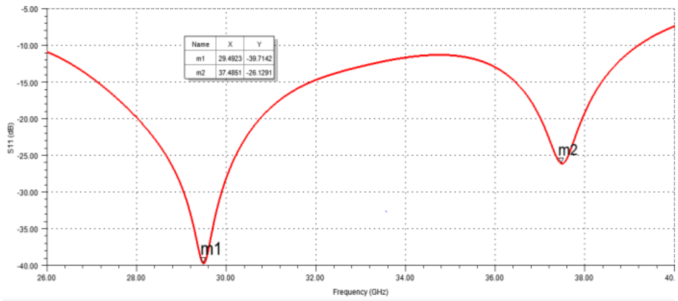


Figure 2. reflection coefficient of the nontransparent antenna

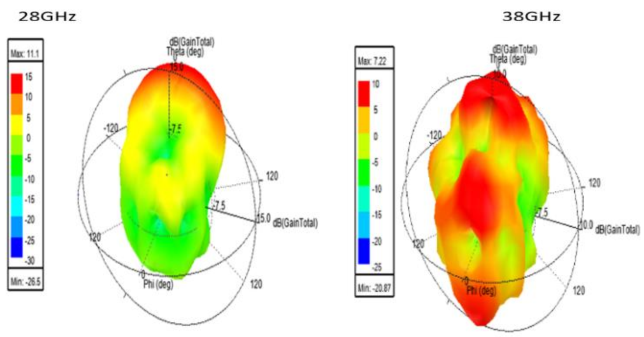


Figure 3. Total gain at frequencies 28 GHz and 38 GHz

III. Proposed Antenna Design and Parameter

The proposed transparent antenna's geometry is depicted in Fig.4. It is constructed on a Plexiglas substrate having a dielectric permittivity of 2.3, a loss tangent of 0.00037 and a thickness of 0.1 mm. The patch and the ground are achieved using AGHT-8, which has a thickness of 0.0175 mm an electric conductivity of 125000 siemens/m. The coplanar waveguide (CPW) of 50 omh is used as a feed the proposed antenna.

The dimensions and resonant frequency were estimated and calculated using the following equations [20] :

$$Wp = \frac{C}{2f_r}\left(\frac{\varepsilon_r + 1}{2}\right)^{-0.5} \quad (1)$$

Where ε_r is the dielectric permittivity of substrate, which equals 3.2 for Plexiglas substrate. Wp is the width of the rectangle patch, C is the velocity of light, h is the thickness of substrate, which equals 0.1 mm in this work, and f_r is the resonant frequency:

$$f_r = \frac{C}{2(\mathrm{L} + \Delta\mathrm{L})\sqrt{\varepsilon_{eff}}} \quad (2)$$

(L) is a length of rectangle patch, and $(\Delta\mathrm{L})$ is an extension in length:

$$L = \frac{C}{2f_r\sqrt{\varepsilon_{eff}}} - 2\Delta\mathrm{L} \quad (3)$$

$(\Delta\mathrm{L})$ is calculated by the following equation:

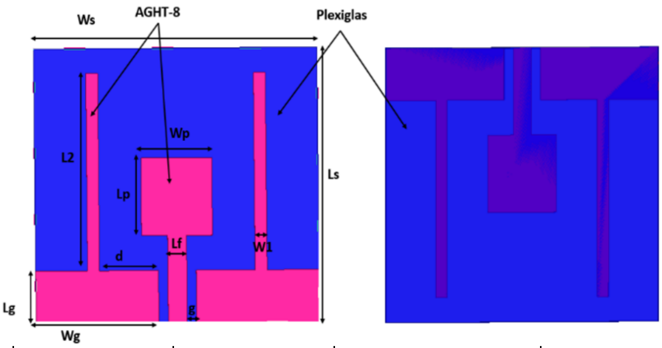
$$\Delta\mathrm{L} = 0.412 * \mathrm{h}\frac{(\varepsilon_{eff} + 3)\left(\left({W_p}/{h}\right) + 0.264\right)}{(\varepsilon_{eff} - 0.528)\left(\left({W_p}/{h}\right) + 0.8\right)} \quad (4)$$

ε_{eff} is effective dielectric constant, which can be calculated by following equation:

$$\varepsilon_{eff} = \left(\frac{\varepsilon_r + 1}{2}\right) + \left(\frac{\varepsilon_r - 1}{2}\right)\left(1 + 12\frac{W_p}{12}\right)^{-0.5} \quad (5)$$

For a 3 mm of W_p (the width of the rectangle patch), the theoretical values of the resonant frequency (f_r), the extension in length (ΔL), the effective dielectric (ε_{eff}), the length of the rectangle patch (L) are equal 38.9 GHz, 2.15, 0.0524 mm, and 2.53 mm, respectively.

The antenna is optimized using ANSYS HFSS. The optimized parameters of the proposed transparent antennae are illustrated in Table. I.



	(mm)		(mm)
Ls	11	Wp	3
Ws	12	L2	7.9
Lp	3.5	W1	0.5
Lf	0.75	g	0.425
Lg	2.1	Wg	5.2
d	3.3	Line's length (Wf)	3.5

Figure 4. Geometry of the proposed antenna (A) top view, (B) bottom view

TABLE I. Parameters of the proposed antenna

IV. Results and Discussion

A. Single element antenna

Using the previous equations, and for a 3 mm of Wp (the width of the patch), the theoretical values of the resonant frequency (f_r), the extension in length (ΔL), the effective dielectric (ε_{eff}), the length of the patch (Lp) are equal to 38.9 GHz, 2.15, 0.0524 mm, and 2.53 mm, respectively. The simulated reflection coefficient for these theoretical values (3 mm of Wp and 2.53 of Lp) shows that the antenna was operated in frequency range of 24-46 GHz, with two resonant frequencies at 30 GHz and 39 GHz (Fig.5 (A)), however, the resonant frequency theoretical is equal to 38.9. After using parameters study the proposed antenna has been optimized, for Lp= 3.5 mm, Wp= 3 mm, and Lg= 2.1 mm.

Fig.6 displays reflection coefficient of the single proposed antenna. It is observed that this antenna is operating in frequency range of 22.94 to 44.71 GHz (S11< -10 dB) with two resonant frequencies 28 and 38.76 GHz. The Ultra-Wide Band (UWB) characteristic have been achieved.

The reflection coefficient (S_{11}) and the voltage standing wave ratio (VSWR) are the main parameters used to define the impedance matching characteristic and the bandwidth. The antenna can only function within a frequency range where the VSWR values remain below 2, as illustrated in Fig.7.

The 2D radiation pattern in terms of E-plan and H-plan is shown in Fig.8. It is observed that all frequencies have bi-directional radiation pattern.

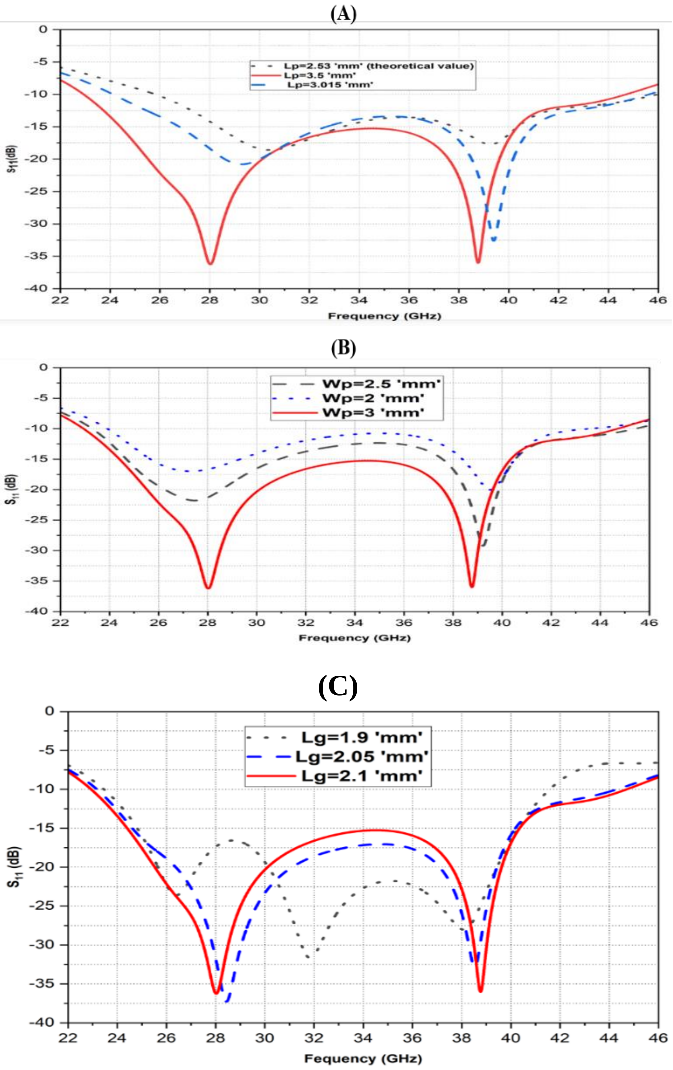


Figure 5. *E*ffect on reflection coefficient due to variation of Lp (A), Wp (B), and Lg (C)

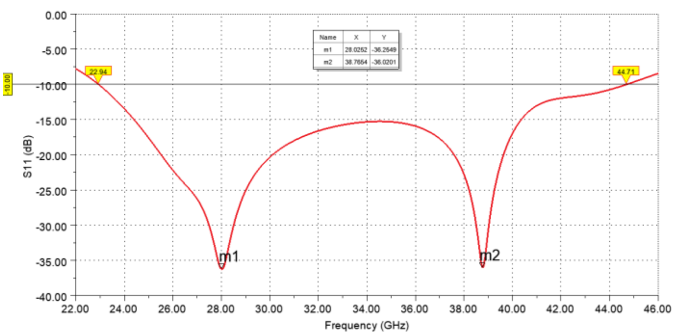


Figure 6. Reflection coefficient of the single proposed antenna

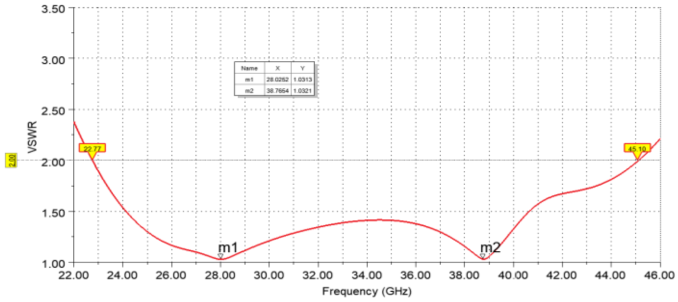


Figure 7. Voltage standing wave ratio (VSWR) values of the proposed antenna

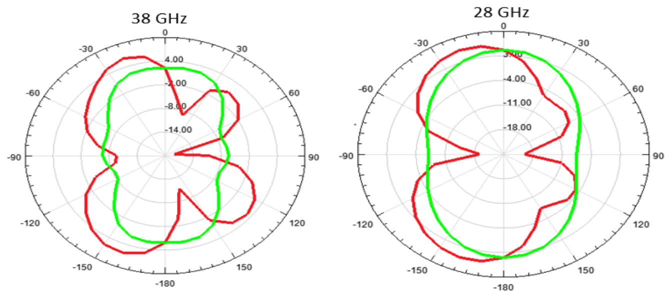


Figure 8. 2D radiation pattern in terms of H-plan (green color) and E-plan (red color) at frequencies 28 and 38 GHz

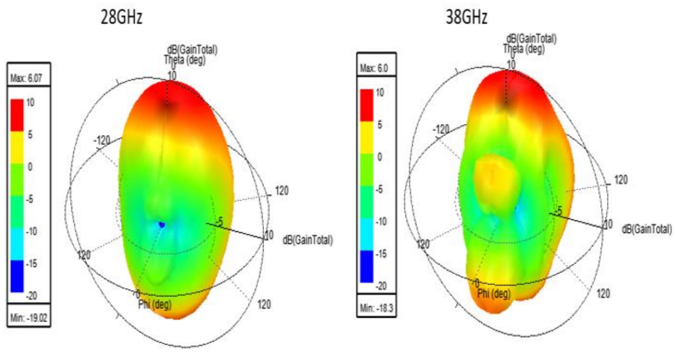


Figure 9. Total gain at frequencies 28 and 38 GHz

Fig.9 shows that the peak gain at the central frequencies 28 and 38 GHz is equal to 6.07 and 6 respectively.

B. Two-element MIMO antenna

After analyzing and studying the single element transparent antenna, which shows promising results in terms of bandwidth, gain, and radiation efficiency, this section will present the simulated results of the transparent two-element MIMO antenna. The obtained results in terms of radiation efficiency, gain, and MIMO diversity are very satisfactory. Fig.10 shows the design of the proposed two-element MIMO antenna.

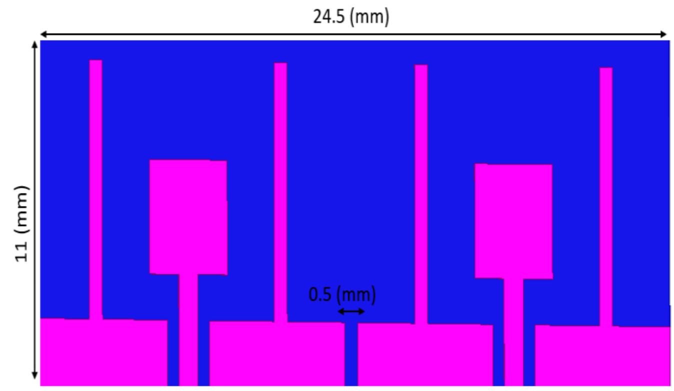


Figure 10. Proposed MIMO antenna design

the S parameters in terms S11, S12, an S22 are revealed in Fig.11. The impedance bandwidth of this MIMO antenna is ranging from 22.77 to 44.37 GHz (64.34%). The resonant frequencies are observed at 28 and 38.8 GHz, having a value of S11=- 34.96 and 42 dB, respectively. The isolation S12 is less than -32 dB , which shows that this MIMO design shows good isolation performance.

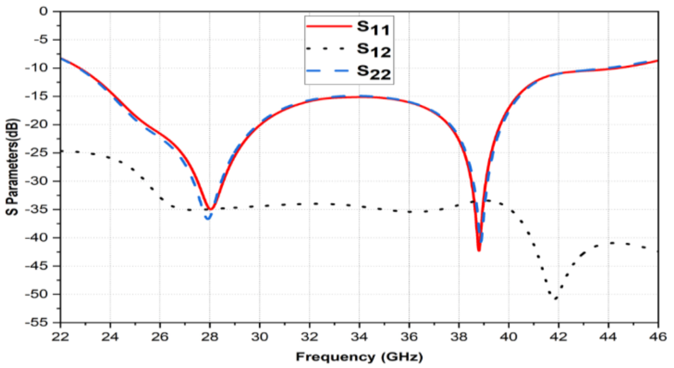
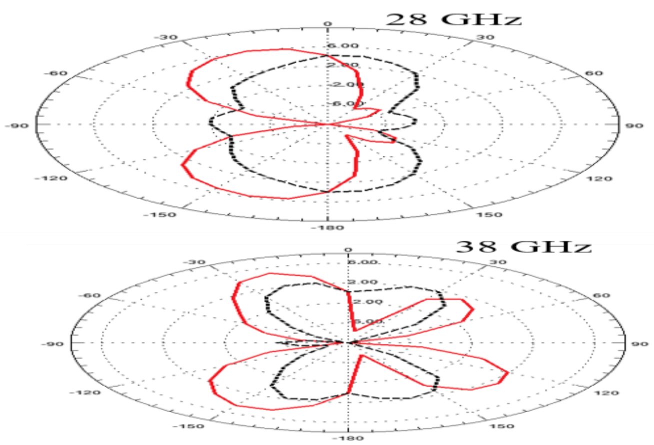


Figure 11. Simulated S parameters of the proposed MIMO antenna



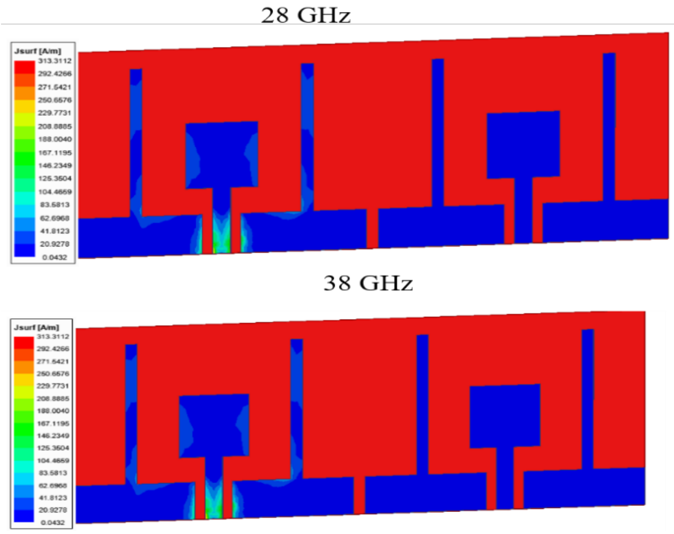


Figure 12. 2D radiation pattern in terms of H-plan (dash) and E-plan (red color) at frequencies 28 and 38 GHz

Figure 13. Current distribution at frequencies 28 GHz and 38 GHz

The 2D radiation pattern in terms of E-plan an H-plan is shown in Fig.12. It is observed that both frequencies have a bi-directional radiation pattern.

The distribution of surface currents on the MIMO transparent antenna's surface is illustrated in Fig.13. The analysis indicates that the coupling between the two antenna elements is insignificant when port 1 is stimulated while port 2 remains terminated with a matched load of 50Ω.

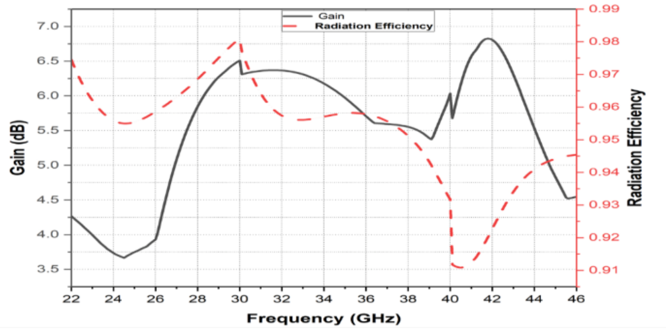


Figure 14. Radiation efficiency peak gain and versus frequency

Radiation efficiency and total gain are depicted in Fig.14. it is observed that the gain values are confined between 3.75 and 6.75 dB, the radiation efficiency values are confined between 0.98 (98%) and 0.91(91%).

1) MIMO diversity results and analysis

MIMO diversity performance metrics in terms of Total Active Reflection Coefficient (TARC), Mean Effective Gain (MEG), Channel Capacity Loss (CCL), Diversity Gain (DG), and Envelope Correlation Coefficient (ECC), will be discussed also in this section. it is verified that the proposed antenna fulfills the recommended diversity requirements in[1], [21], [22].

The ECC is an important parameter, it allows to describe the correlation between the signals received on the ports of a MIMO system. In fact, a weak correlation between the signals received on the different antennas is required. It can be calculated using the following equation[23]:

$$ECC = \left| \frac{\tilde{S}_{11}S_{12} + \tilde{S}_{21}S_{22}}{\sqrt{(1 - |S_{11}|^2 - |S_{21}|^2)(1 - |S_{22}|^2 - |S_{12}|^2)}} \right|^2 \quad (6)$$

Where, $\tilde{S}_{21}$, and $\tilde{S}_{11}$are the complex conjugates S_{12} of and S_{21}, respectively. A value of 0.5 or lower for ECC is considered sufficient to indicate a low level of correlation between the antenna elements [24]. ECC values versus frequency is displayed in Fig.15. It is observed that ECC values are less than 0.015.

Diversity GAIN (DG) represents the probability that the signal-to-noise ratio (SNR) of the combined relative signals is greater than a threshold. The desired value for DG is ideally set at 10 [25].

DG is calculated by follow equation:

$$DG = 10\sqrt{1 - |ECC|^2} \quad (7)$$

DG of the MIMO antenna is presented in Fig.16, the values of DG is between 9.99 and 10 dB.

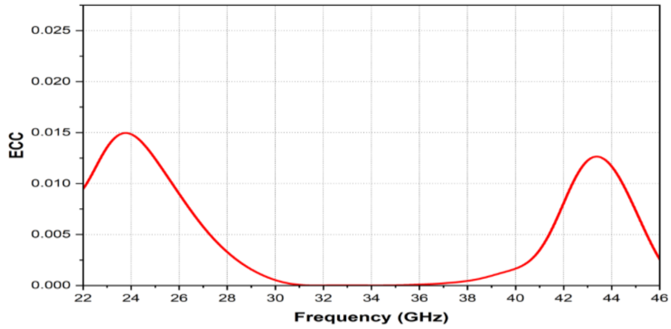
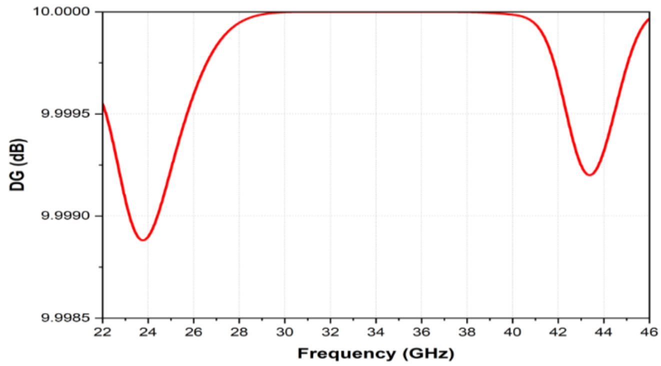


Figure 15. ECC versus frequency of the proposed MIMO antenna

MEG (Mean Effect Gain) is an important parameter to analyze diversity performance. It quantifies the average power received by a diversity antenna in a rich multipath fading environment, relative to the average power received by an isotropic antenna [26]. Equation (8) can calculate the MEG:

$$\text{MEG}_i = 0.5\left(1 - \sum_{j=1}^{k} |S_{ij}|^2\right) \quad (8)$$

To attain satisfactory diversity performance in practice, it is generally recommended to have MEG values within the range of -3 ≤ MEG (dB) < -12. It has been verified from Fig.17 that the MEG values for both antenna elements meet the predefined limit, thus confirming their compliance with the specified criteria. Additionally, it is visually observed that the ratio of MEG_1/MEG_2 is equivalent to unity, this indicates that this MIMO antenna system has successfully achieved improved

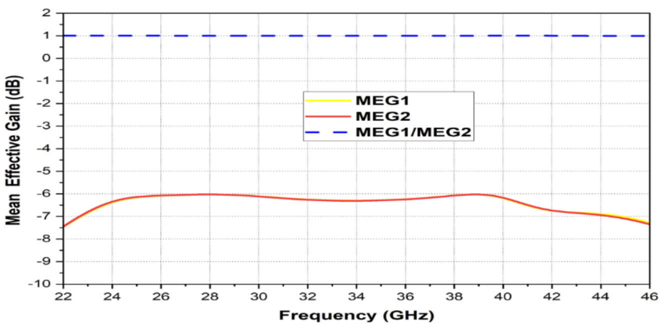


diversity performance in a multipath fading environment.

Figure 16. Simulated DG of the proposed antenna

Figure 17. Simulated MEG of the propose antenna

The total active reflection Coefficient $(TARC)$ is an additional parameter to determine the isolation performance of MIMO antennas. It quantifies the proportion of power levels between the incident and reflected waves. The equation (9) can calculate a TARC of MIMO antenna.



$$\text{TARC} = \left(\sqrt{\frac{\left|S_{ii} + S_{ij}e^{i\theta}\right|^2 + \left|S_{ji} + S_{jj}e^{i\theta}\right|^2}{2}} \right) \quad (9)$$

Where, the variable θ represents the input phase angle, which is systematically varied from 0° to 180° in increments of 30°. The parameters S_{ii} and S_{jj} correspond to the reflection coefficients antennas one and two, respectively. whereas, the terms S_{ij} and S_{ji} denote the port isolations, measured in decibels (dB) between the antenna elements.

The TARC values are displayed in Fig.18. Throughout the target band the TARC values are almost stable, this ensures that the proposed antenna has a high port isolation.

Chanel capacity loss (CCL) is one of the crucial parameters used in the examination of essential diversity performance for if the CCL values < 0.4 bits/s/Hz [27].

Chanel capacity is calculated using the following equation:

$$C_{loss} = -log_2 \det(A) \quad (10)$$

$$A = \begin{bmatrix} \sigma_{ii} & \sigma_{ij} \\ \sigma_{ji} & \sigma_{jj} \end{bmatrix} \quad (11)$$

$$\sigma_{ii} = 1 - \left(|S_{ii}|^2 - \left|S_{ij}\right|^2\right) \quad (12)$$

$$\sigma_{ij} = -\left(\tilde{S}_{ii} S_{ij} + \tilde{S}_{jj} S_{ij}\right) \quad (13)$$

Fig.19 illustrates the CCL values. Within the operating band, the CCL values remain below 0.4 bits/s/Hz.

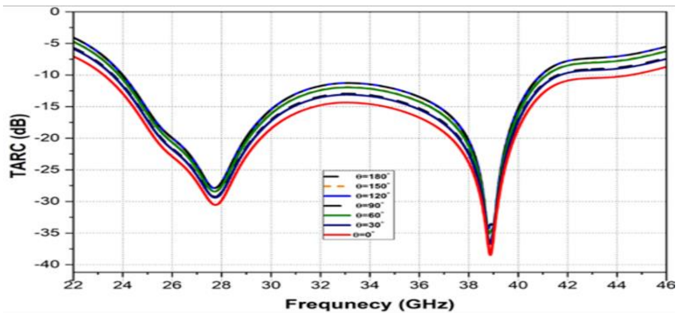


Figure 18. Simulated TARC of the proposed antenna versus frequency

The proposed antenna covers 5G applications for several countries like the USA, Korea, Japan, China, Sweden, and European Union (Table II)[18][6].

Transparent antennas have low efficiency and gain due to the low electric conductivity value of the material used[16].

Figure 19. Simulated CCL of proposed MIMO antenna

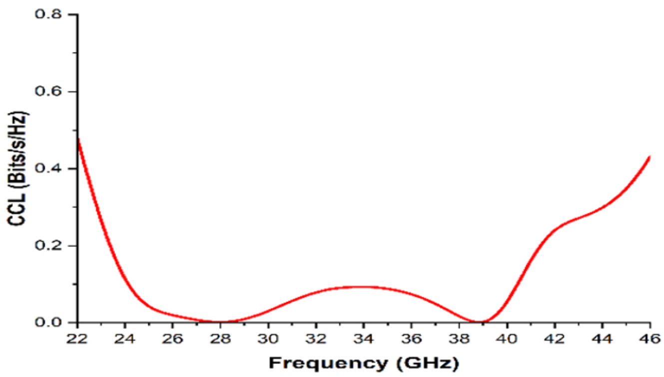


TABLE II. PROPOSED ANTENNA FREQUENCY BAND FOR DIFFERENT COUNTRIES

Countries	Frequency band range (GHz)
USA	37-43.5 27.5-28.35
China	37-43.5 25.3-27.5
Korea	34-37 26.5-29.5
Japan	36-42 27.5-28.28
Sweden	37.2-38 26.5-27.5
Europe	34-38 24.25-27.5

The performance of the reference antenna, the proposed transparent single antenna, and the two-element MMO antenna is illustrated in Table III. In both cases, the proposed antenna possesses a wider bandwidth compared to the reference antenna. However, it is important to note that the gain of the reference antenna is higher than that of the proposed antenna.

TABLE III. PERFORMANCE OF THE PROPOSED ANTENNA AND THE REFERENCE ANTENNA

Antenna	impedance Bandwidth (GHz)	Gain (dB)	transparency	Conductive sheet	Substrate material
Reference antenna	26-38.8	11.1 dB at 28 GHz 7.22 at 38 GHz	non	copper	Rogers
Proposed single element	22.94-44.71	6.07 dB at 28 GHz 6 dB at 28 GHz	yes	AGHT-8	Plexiglas

Prpoposed Two-element MIMO antenna	22.77 - 44.37	5.8 dB at 28 GHz 5.54 dB at 28 GHz	yes	AGHT-8	Plexiglas

TABLE IV. COMPARISON PERFORMANCES OF THE PROPOSED TRANSPARENT MIMO ANTENNA WITH OTHER MIMO ANTENNAS FROM LITERATURE

References	Physical dimension	Operating band	Substrate Material	Gain (dB)	MIMO Diversity Analysis			
					ECC	Isolation (dB)	TARC (dB)	MEG (dB)
[5]	24*20 4 elements	24.4-27.18 GHz 33-44.14 GHz	Plexiglas (Transparent)	-	<0.1	>16	-	>9.5
[24]	40 * 68 2 elements	3.1-10.6 GHz	FR4	-	-	>15	< - 9.5	
[25]	30*35 4 elements	28	Rogers	8.3	<0.01	-	-	>9.96
[27]	43.611×43.611 4 elements	28 38	Rogers RT/duroid 5880	7.9 13.7	2.5*10-4 3.5*10-5	>20 >30	-	>10
[16]	50*35 2 elements	2.65-2.97 GHz	Plexiglas (Transparent)	3.83	0.02	>17.10	>–10	1
[28]	66*45 4 elements	2.21-6 GHz	Malinex (Transparent)	-	<0.016	>15	-	-
[29]	20*24 Elements	27.6-28.7 GHz 37.4-38.6 GHz	Rogers-5880	7.9	<0.001	28	-	-
This Work	11*24.5 2 elements	22.77-44.37 GHz	Plexiglas (Transparent)	≤6.75	≤0.015	>32	<-10	>9.998

V. CONCLUSION

A new compact MIMO wideband transparent antenna for 5G mm-wave has been presented, simulated, and studied in this article. The proposed MIMO antenna operates in the 22.72 to 44.37 GHz band (65.54% bandwidth) with achieved isolation less than -32 dB. Additionally, the obtained ECC d values are below 0.015, and the Diversity Gain (DG) values are around 10 dB. The antenna exhibits a MEG ratio close to unity and the Chanel capacity loss (CCL) values are below 0.4 bits/s/Hz. The obtained gain values and radiation efficiency are greater than 3.75 dB and 91%, respectively. The proposed transparent CPW dual-element MIMO antenna is well-suited for IoT and vehicle applications utilizing mm-wave 5G in smart devices due to its ability to mitigate visual clutter, absence of co-site location issues, and complete transparency. In the future work the enhancement of the gain of the proposed antenna using metamaterials will be discussed.

VI. REFERENCE

[1] P. S. B. G, P. R. Mane, P. Kumar, T. Ali, and M. G. Nabi Alsath, “Planar MIMO antenna for mmWave applications: Evolution, present status & future scope,” Heliyon, vol. 9, no. 2. Elsevier Ltd, Feb. 01, 2023. doi: 10.1016/j.heliyon.2023.e13362.

[2] M. N. Hasan, S. Bashir, and S. Chu, “Dual band omnidirectional millimeter wave antenna for 5G communications,” J Electromagn Waves Appl, vol. 33, no. 12, pp. 1581–1590, Aug. 2019, doi: 10.1080/09205071.2019.1617790.

[3] A. R. Chishti et al., “Optically Transparent Antennas: A Review of the State-of-the-Art, Innovative Solutions and Future Trends,” Applied Sciences (Switzerland), vol. 13, no. 1. MDPI, Jan. 01, 2023. doi: 10.3390/app13010210.

[4] A. H. Desai and T. Upadhyaya, “Dual-band transparent and non-transparent antennas for wireless application,” International Journal of Electronics Letters, vol. 8, no. 2, pp. 170–179, Apr. 2020, doi: 10.1080/21681724.2019.1582703.

[5] 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, doi: 10.1109/ACCESS.2020.3033314.

[6] A. Desai, T. Upadhyaya, and R. Patel, “Compact wideband transparent antenna for 5G communication systems,” Microw Opt Technol Lett, vol. 61, no. 3, pp. 781–786, Mar. 2019, doi: 10.1002/mop.31601.

[7] S. Lakrit, S. Das, A. El Alami, D. Barad, and S. Mohapatra, “A compact UWB monopole patch antenna with reconfigurable Band-notched characteristics for Wi-MAX and WLAN applications,” AEU - International Journal of Electronics and Communications, vol. 105, pp. 106–115, Jun. 2019, doi: 10.1016/j.aeue.2019.04.001.

[8] A. Patel et al., “UWB CPW fed 4-port connected ground MIMO antenna for sub-millimeter-wave 5G applications,” Alexandria Engineering Journal, vol. 61, no. 9, pp. 6645–6658, Sep. 2022, doi: 10.1016/j.aej.2021.12.015.

[9] V. Sorathiya, A. G. Alharbi, and S. Lavadiya, “Design and investigation of unique shaped low-Profile material-based superlative two-element printed ultrawideband MIMO antenna for Zigbee/WiFi/5G/WiMAX applications,” Alexandria Engineering Journal, vol. 64, pp. 813–831, Feb. 2023, doi: 10.1016/j.aej.2022.10.051.

[10] J. Kulkarni, A. Desai, and C. Y. D. Sim, “Wideband Four-Port MIMO antenna array with high isolation for future wireless systems,” AEU - International Journal of Electronics and Communications, vol. 128, Jan. 2021, doi: 10.1016/j.aeue.2020.153507.

[11] B. Aghoutane, S. Das, M. EL Ghzaoui, B. T. P. Madhav, and H. El Faylali, “A novel dual band high gain 4-port millimeter wave MIMO antenna array for 28/37 GHz 5G applications,” AEU - International

Journal of Electronics and Communications, vol. 145, Feb. 2022, doi: 10.1016/j.aeue.2021.154071.

[12] S. Jabeen and Q. U. Khan, "An integrated MIMO antenna design for Sub-6 GHz & millimeter-wave applications with high isolation," AEU - International Journal of Electronics and Communications, vol. 153, Aug. 2022, doi: 10.1016/j.aeue.2022.154247.

[13] A. Omar, M. Hussein, I. J. Rajmohan, and K. Bathich, "Dual-band MIMO coplanar waveguide-fed-slot antenna for 5G communications," Heliyon, vol. 7, no. 4, Apr. 2021, doi: 10.1016/j.heliyon.2021.e06779.

[14] A. A. AL Rimi, K. Hati, A. Zugari, and M. Aghoutane, "High gain of 28 GHz transparent antenna for 5G NR Networks," in E3S Web of Conferences, EDP Sciences, May 2022. doi: 10.1051/e3sconf/202235101080.

[15] S. Azizi, L. Canale, S. Ahyoud, G. Zissis, and A. Asselman, "Design of Transparent Antenna for 5G Wireless Applications," MDPI AG, Dec. 2020, p. 54. doi: 10.3390/proceedings2020063054.

[16] A. Desai et al., "Transparent 2-Element 5G MIMO Antenna for Sub-6 GHz Applications," Electronics (Switzerland), vol. 11, no. 2, Jan. 2022, doi: 10.3390/electronics11020251.

[17] A. Desai, M. Palandoken, J. Kulkarni, G. Byun, and T. K. Nguyen, "Wideband Flexible/Transparent Connected-Ground MIMO Antennas for Sub-6 GHz 5G and WLAN Applications," IEEE Access, vol. 9, pp. 147003–147015, 2021, doi: 10.1109/ACCESS.2021.3123366.

[18] 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, doi: 10.1109/ACCESS.2020.3033314.

[19] S. F. Jilani, M. O. Munoz, Q. H. Abbasi, and A. Alomainy, "Millimeter-Wave Liquid Crystal Polymer Based Conformal Antenna Array for 5G Applications," IEEE Antennas Wirel Propag Lett, vol. 18, no. 1, pp. 84–88, Jan. 2019, doi: 10.1109/LAWP.2018.2881303.

[20] A. S. Thampy and S. K. Dhamodharan, "Performance analysis and comparison of ITO- and FTO-based optically transparent terahertz U-shaped patch antennas," Physica E Low Dimens Syst Nanostruct, vol. 66, pp. 52–58, 2015, doi: 10.1016/j.physe.2014.09.016.

[21] I. Elfergani et al., "Low-profile and closely spaced four-element mimo antenna for wireless body area networks," Electronics (Switzerland), vol. 9, no. 2, Feb. 2020, doi: 10.3390/electronics9020258.

[22] 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 Wirel Propag Lett, vol. 16, pp. 920–923, 2017, doi: 10.1109/LAWP.2016.2614577.

[23] A. Omar, M. Hussein, I. J. Rajmohan, and K. Bathich, "Dual-band MIMO coplanar waveguide-fed-slot antenna for 5G communications," Heliyon, vol. 7, no. 4, Apr. 2021, doi: 10.1016/j.heliyon.2021.e06779.

[24] A. Najam, Y. Duroc, and S. Tedjni, "UWB-MIMO ANTENNA WITH NOVEL STUB STRUCTURE," 2011.

[25] M. Khalid et al., "4-port MIMO antenna with defected ground structure for 5G millimeter wave applications," Electronics (Switzerland), vol. 9, no. 1, Jan. 2020, doi: 10.3390/electronics9010071.

[26] J. Kulkarni, A. Desai, and C. Y. D. Sim, "Wideband Four-Port MIMO antenna array with high isolation for future wireless systems," AEU - International Journal of Electronics and Communications, vol. 128, Jan. 2021, doi: 10.1016/j.aeue.2020.153507.

[27] B. Aghoutane, S. Das, M. EL Ghzaoui, B. T. P. Madhav, and H. El Faylali, "A novel dual band high gain 4-port millimeter wave MIMO antenna array for 28/37 GHz 5G applications," AEU - International Journal of Electronics and Communications, vol. 145, Feb. 2022, doi: 10.1016/j.aeue.2021.154071.

[28] A. Desai, M. Palandoken, J. Kulkarni, G. Byun, and T. K. Nguyen, "Wideband Flexible/Transparent Connected-Ground MIMO Antennas for Sub-6 GHz 5G and WLAN Applications," IEEE Access, vol. 9, pp. 147003–147015, 2021, doi: 10.1109/ACCESS.2021.3123366.

[29] K. Raheel et al., "E-shaped H-slotted dual band mmwave antenna for 5G technology," Electronics (Switzerland), vol. 10, no. 9, May 2021, doi: 10.3390/electronics10091019.