A two-element planar multiple input multiple output array for ultra-wideband applications

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ABSTRACT

In this article, a planar monopole two-element multiple input multiple output (MIMO) array has been designed and characterized with the intention of ultra-wideband (UWB) applications. The array has a voltage standing wave ratio (VSWR) working bandwidth (BW) of 13.258 GHz between 3.394-16.652 GHz, with a fractional BW (FBW) of 132.28% with respect to a center frequency of 10.023 GHz. The two elements of the MIMO array are 900 polarizations mismatched for better isolation. Consequently, less than 20 dB of isolation has been achieved throughout the entire BW. Also observed was a good combined realized peak gain of up to 5.85 dBi and total efficiency of greater than 85%. For MIMO performance key parameters, the array exhibits the envelope correlation coefficient (ECC) <0.0033, diversity gain (DG) >9.983, total active reflection coefficient (TARC) <0.445, mean effective gain difference (MEG12) ≈0 dB, and the channel capacity loss (CCL) <0.4 bps/Hz. This design would encourage designers to create high-performance MIMO antennas for UWB frequency-related applications.

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1. INTRODUCTION

Since its introduction in 1993 [1], the multiple input multiple output (MIMO) antenna array technique has come a long way. MIMO techniques' effectiveness and necessity are well established in wireless communication systems such as mobile communication, smartphones, radar, astronomy, and so on. Furthermore, with the recent rollout of 5G technology [2], the importance of MIMO techniques has been elevated to the point where developing wireless communication without them is impossible, particularly in mobile communications for both base transceiver stations (BTS) and smartphones. This is because the MIMO techniques provide better spatial and spatial diversity for high data rates, better throughput, high signal selectivity, and quality beam-forming [3]–[5]. Again, in the domain of MIMO techniques, the design of the physical antenna array has a significant impact. An efficient and high-performance array design would take a lot of stress away from the overall system and would provide a quality service to the end user. However, the main challenge for the designers is to produce a MIMO array with an ultra-wideband (UWB) working frequency range while keeping the MIMO performance intact.

In recent times, researchers have proposed different types of MIMO configurations. Some people have proposed 10 elements [6], 8 elements [7]–[10], 6 elements [9], [11], 4/quad elements [12]–[16] antenna arrays with MIMO configuration for 5G bands. However, due to their ease of design and characterization, we will only discuss the two elements in this article. In a study [17], a 2-element U-shaped dielectric resonator antenna (DRA) has been proposed to work in the sub-6 GHz 5G frequency bands along with its filtering element. The antenna produces a good gain of 7.7 dBi, the envelope correlation coefficient (ECC) <0.008, channel capacity loss (CCL) <0.3, total active reflection coefficient (TARC) <-15 dB and diversity gain (DG) >9.99. However, the antenna could maintain the performance only for a few hundred MHz as it has a working BW of between 3.2-3.54 GHz. The authors have not given any mean effective gain (MEG) response, which is a very important MIMO performance parameter. The other problem with this design is the non-planar design, which would make it difficult to manufacture the antenna. Another two-port design has been presented in [18]. The antenna has been proposed to work in 5G smartphones with a dimension of 150×75×7 mm^3 (5.7 inches handphones). The authors have used the planar inverted F-antenna (PIFA) pairs to tune for the 3.3-7.5 GHz (-6 dB) BW. The strong point of this proposal is, the antenna can be printed on the side walls of the smartphone without disturbing the original circuit board. However, the isolation between the port is not so high as it comes down to as low as around -10 dB. As the standard isolation for the MIMO smartphones is at least -15 dB [19]–[21], it would degrade the whole performance of the phone. Also, the TARC, CCL and MEG responses are missing in that proposal, which are very important to assess the MIMO performance.

Pant *et al*. [22] have proposed a reconfigurable/switchable antenna with meandered-lines to work in 5G/4G applications. PIN diodes are used in this proposal to switch the antenna to tune at 2.4 GHz or 3.5 GHz. The antenna exhibits a good ECC of 0.0056 at 2.4 GHz and 0.0009 at 3.5 GHz and has a good gain of 3.7 and 4.2 dBi for 2.4 and 3.5 GHz respectively. Again, the most important parameter of any MIMO configuration is its isolation between the ports and in this proposal, it is very low going down around -12 dB (between port 1 and 2) which is not desirable and would hinder the overall MIMO performance. Another point, the total efficiency of this MIMO is as low as 60% and would lead to a low energy conversion and radiation performance. To solve the isolation issue, a side mounted T-shape 2 element MIMO antenna configuration has been proposed in [23]–[25] for smartphone application. The antenna exhibits a good isolation between ports of as low as -24 dB. However, to resolve the isolation issue the MIMO array suffers a low average antenna efficiency of around 54.5%. The ECC also goes as high as 0.16 inside the working BW between 3.4-3.6 GHz. Furthermore, the TARC, the CCL and the MEG response and analysis are also not presented by the authors in this proposal. Saurabh and Meshram [26] have proposed a simple 2-element electrically small design with a T-shape partial ground plane (PGP) technique is applied to create a good isolation of up to 20 dB between the ports. The ECC, TARC, MEG, DG and CCL are within the standard values. However, this antenna also has the same problem of only able to maintain a small 530 MHZ operational BW below -10 dB. Another proposal has made in [27], [28] for large operational BW (10 GHz) in mm wave between 28-38 GHz. The antenna is inherently small in size as it is tuned for a high frequency, however, the isolation goes as low as -15 dB, which is the minimum requirement for the MIMO techniques. In all these above-mentioned existing works even though the MIMO performances are good but the they suffer from small BW and not suitable for the UWB application such as Radar, wireless body area network (WBAN), and GPS. In this article, the proposal has been made to design a 2 element MIMO array which not only shoes UWB characteristics but also keeps the MIMO performances intact within the standard and acceptable values for 13.258 GHz between 3.394-16.652 GHz UWB range.

2. METHOD

Figure 1 comprises the geometry of the single element antenna (SEA) with their detailed dimensions along with the MIMO configuration of the antenna also. Figures 1(a) and 1(b) comprises the front and the back view of the SEA. The antenna is a keyhole shaped monopole applied with the microstrip feeding technique as shown in Figure 1(a). The monopole patch radiating patch contains a square and a circle together to form the keyhole shape. The center of the circle is at the mid-point of the upper side of the square, where the diameter of the circle and the length of the sides are equal (9 mm). The microstrip feed transmission line (TL) is designed for 50 Ω with the printed circuit board (PCB) substrate of Rogers RT 5880 (ε_r=2.2, h=0.508 mm and $tan\delta$=0.0009) which yields a width of 1.54 mm and after optimizing for a good matching, a length of 15 mm. From Figure 1(b), it can be seen that the PGP technique has been utilized to tune the antenna for its wide band characteristic. Figure 1(c) illustrates the 2 element (2×2) MIMO configuration using the polarization diversity to maximize the isolation between different ports. The antenna is called a 2×2 MIMO because the same SEAs work for both transmitter and receiver simultaneously. The final dimensions (length×width×height) of the MIMO array is 55×3×0.508 mm^3. All the SEA related dimensions that revealed in the Figure 1 are estimated by (1)-(9) [29]–[31]. The antenna has been simulated by CST microwave studio (CST MWS) 2021.

$$W = \frac{C_0}{2f_c\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{1}$$

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\frac{h}{W_p}\right]^{-\frac{1}{2}} \tag{2}$$

$$L_e = \frac{C_0}{2f_c\sqrt{\varepsilon_e}} \tag{3}$$

$$\Delta L = 0.412h\frac{(\varepsilon_e+0.3)(\frac{W_k}{h}+0.264)}{(\varepsilon_e-0.258)(\frac{W_k}{h}+0.8)} \tag{4}$$

$$L = L_e - 2\Delta L \tag{5}$$

$$L_g = 6h + L_k \tag{6}$$

$$W_g = W_g = 6h + W_k \tag{7}$$

$$r = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{\frac{1}{2}}} \tag{8}$$

$$F = \frac{8.791\times10^9}{f_c\sqrt{\varepsilon_r}} \tag{9}$$

Where, W and L are the width and length of the SEA. L_g is the length of the PGP and r is the radius (diameter/2) of the circular patch.

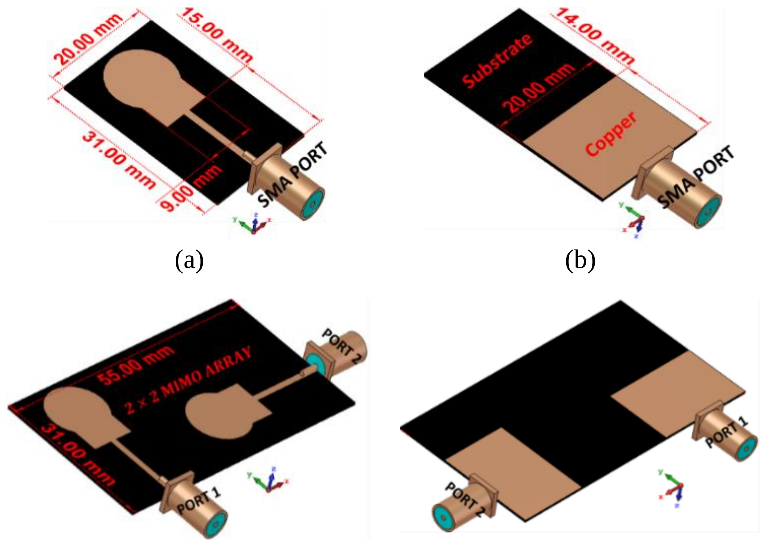


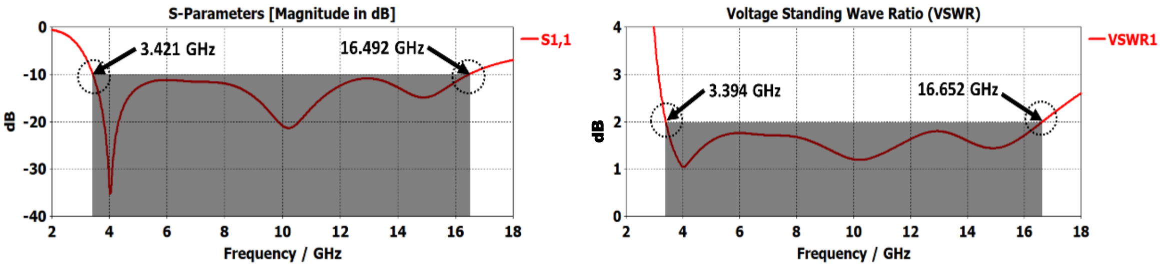
Figure 1. Geometry of the SEA and the MIMO array (a) front view, (b) back view, (c) MIMO front view, and (d) MIMO back view

3. RESULTS AND DISCUSSION

In this section, at first the results for the SEA have been illustrated and analyzed in terms of the justification of the bandwidth through the S-parameter and VSWR. After that the justification of the MIMO configuration on BW, isolation, radiation and total efficiencies, realized gain (RG) and radiation pattern have been presented and discussed. Finally, the MIMO performance has been evaluated by presenting the ECC, DG, TARC, MEG and CCL responses.

3.1. Bandwidth and isolation

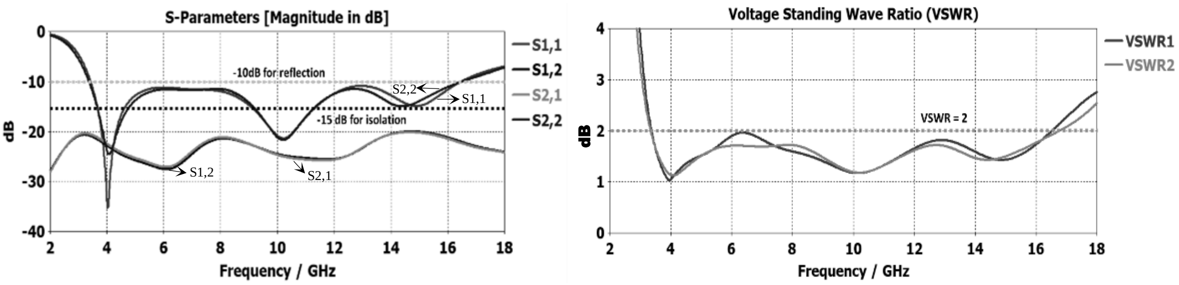
Figures 2(a) and 2(b) comprise the S-parameter (S_{11}) and the VSWR response vs frequency respectively for the SEA. It can be seen from the s-parameter response that the -10 dB starts from 3.421 GHz and stays below that value until it reaches 16.492 GHz. That makes a wide BW of 13.071 GHz. To analyze the further into the BW, the VSWR response has been analyzed. The standard VSWR value to determine the operational BW of any antenna is <2. From Figure 2(b) it is seen that the VSWR <2 starts at 3.394 GHz and stays below less than that until 16.652 GHz which makes the antenna working BW of 13.258 GHz with a center frequency of 10.023 GHz. That makes a fractional bandwidth (FBW) of around 132.28% of the center frequency of this proposed designed antenna.



(a) (b)

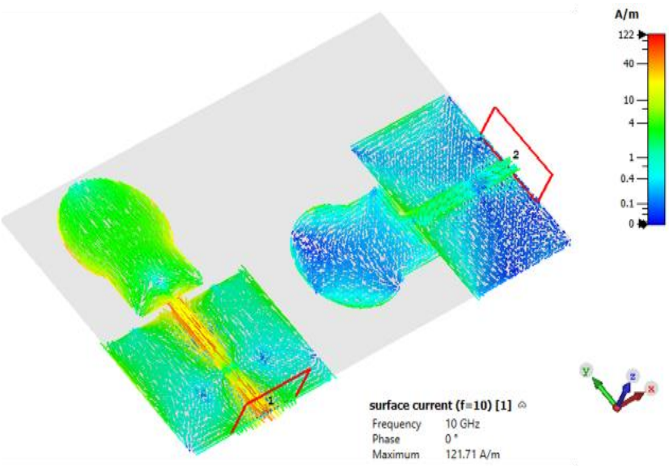
Figure 2. The bandwidth response of the SEA by (a) S-Parameter (S_{11}) and (b) VSWR

Next, the 2×2 MIMO structure as shown in Figure 1(c) has been simulated in CST MWS 2021. To assess the design integrity of any MIMO design, at first, the 2-port S-parameters are need to be analyzed to see the matching and isolation between the ports. This design has 2 ports so, there are 4 different S-parameter (S_{11}, S_{12}, S_{21}, and S_{22}) where the reflection parameters (S_{11} and S_{22}) are used for the checking the matching and initial BW determination. Where by the S_{12} and S_{21} are called the transmission parameters and used to determine the isolation between port 1 and 2 and should be as low as possible. Accordingly, it is seen from Figure 3(a) that the S_{11} and S_{22} responses are almost similar and hence confirming the good matching of the individual ports. Similarly, Figure 3(b) shows the VSWR for port 1 and port 2 where it can be also concluded the BW is intact as it was seen from Figure 2(b). Connecting back to Figure 3(a), from the S_{12} and S_{21} value it can be seen that the isolation between the ports is <-20 dB throughout the working BW. As the MIMO isolation standard value needs to be at least -15 dB or below between the ports, in this design its well below that value which shows the good quality of the design. To investigate further on the isolation, the surface current accumulation has been looked into at the center frequency for different ports and presented in Figure 4. By comparing Figures 4(a) and 4(b) it is seen that the very little current accumulates at port 2 while port 1 is excited and vice versa which exhibits another indication of good isolation.

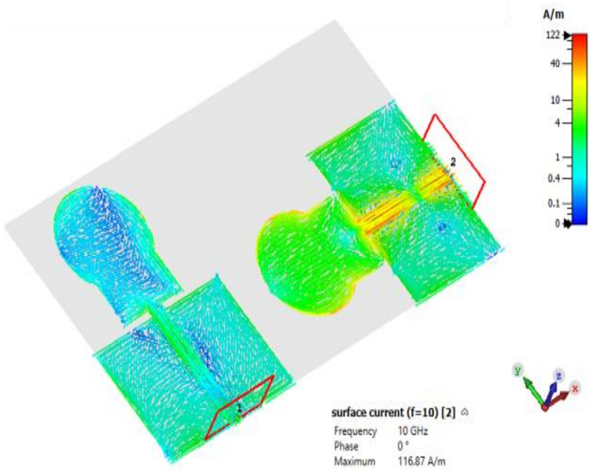


(a) (b)

Figure 3. The bandwidth response of the 2×2 MIMO by (a) 2-port S-parameters and (b) VSWR for port 1 and port 2



(a)



(b)

Figure 4. Surface current accumulation at when (a) port 1 and (b) port 2 excited respectively

3.2. Radiation pattern, efficiency and realized gain

Figure 5 (in Appendix) shows the 3-D and 2-D (polar) representations of the radiation pattern for 3.5 GHz, 10 GHz, and 16.5 GHz. Figures 5(a), 5(b), and 5(c) represent the responses of port 1, port 2, and the combined 3-D radiation pattern at 3.5 GHz. It can be seen that the antenna at port 1 radiates mainly on the x-z plane (E-plane) whereby the port 2 antenna radiates on the y-z plane (E-plane) and consequently, from the combined radiation pattern as shown in Figure 5(c) it is clearly visible that the MIMO actually covers all direction which is suitable for the smartphones and also for RF energy harvesting where the RF energy is anticipated isotropic direction. Similarly, Figure 5(d) represents the 2-D polar representation of E- and the H-plane pattern, where, it can be seen that the E-plane is uniform in all directions whereby the H-plane, even though has some deformity, it radiates in all directions. At 10 GHz and 16.5 GHz, only the combined results are presented. Likewise, it is also seen from the 3-D and 2-D responses at 10 GHz as shown in Figures 5(e) and 5(f) and 16.5 GHz as shown in Figure 5(g) and 5(h), that the MIMO antenna is able to maintain an all-direction radiation pattern in terms of the E-plane, however, the H-plane changes as the frequency increases and the MIMO configuration achieves a quasi-omnidirectional pattern.

Figures 6(a), 6(b) and 6(c) comprise the radiation efficiency (RE) and total antenna efficiency (TE) of the SEA, RE and TE (combined) of the MIMO and the RG responses of the MIMO respectively. From Figure 6(a) and 6(b) it is clearly visible that for both of the efficiencies, the value is mostly maintaining similarity throughout the working BW. As the RE goes as high as 99% and 98% for the SEA and the MIMO respectively. Whereas, the TE combined for MIMO is mostly from 97% to 84% which is also an indication of a good design. Figure 6(c) illustrates the RG in different individual ports and also combined RG for MIMO array. It can be seen that all the RG responses are between 2-5.85 dBi, as the combined RG achieves the maximum point.

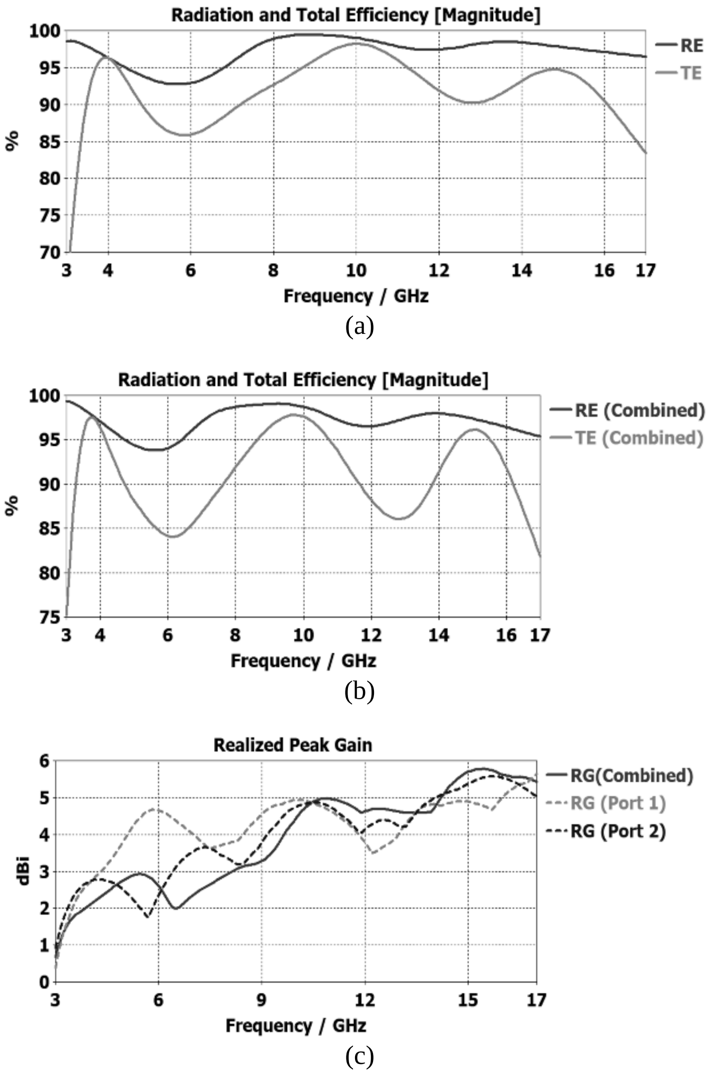


Figure 6. The RE, TE and RG responses of the SEA and MIMO design: (a) RE and TE of the SEA; (b) Combined RE and TE of the MIMO; and (c) Pot 1, port 2, and the combined RG

3.3. MIMO performance

Figure 7 comprises the parameters for MIMO performance evaluation. The ECC, DG, TARC, MEG and CCL respectively presented in Figures 7 (a)-7(e). These parameters are calculated by using the formulas from (10)-(14) respectively [19], [32], [33]. The ECC and the DG is basically the measure of how the ports are isolated from each other. A good isolation between ports would prevent any crosstalk/interferences while sending/receiving the signal. As the ECC is expected to be as low as possible (standard value is <0.5) and the DG is expected to be as close as 10, it can be seen from Figures 7(a) and 7(b) that they are well within the standard value. The highest ECC reaches as low as 0.0033 whereby it stays below that value throughout the entire working BW.

Again, DG value touches as high as 10 and always keeps itself below 9.983 in the working BW. Figure 7(c) illustrates the TARC which gives a measure of the matching quality of the ports in a MIMO configuration. The standard value is <0.4 and it is seen that in the working BW, is it below that value and reaches as low as 0.1 within the band. Figure 7(d) reveals the MEG for different ports and the difference between them, MEG_{12}. The standard value of MEG for individual port is <-3 dB and $MEG_{12} \cong 0$ dB and the responses are fully in agreement with the standard values. It is clearly seen that the MEG_1 (port 1) and MEG_2 (port 2) is below -3 dB. Similarly, the MEG_{12} is around 0 dB throughout the BW. Lastly, Figure 7(e) shows the CCL of this proposed MIMO design. The designed loss is expected to be as low as possible (as close to zero) whereby the standard value is <0.4 bps/Hz. Accordingly, it is seen that from 3.394 to 16.652 GHz, the CCL is below 0.4 bps/Hz and drops as low as 0.005 bps/Hz showing the good quality of this design.

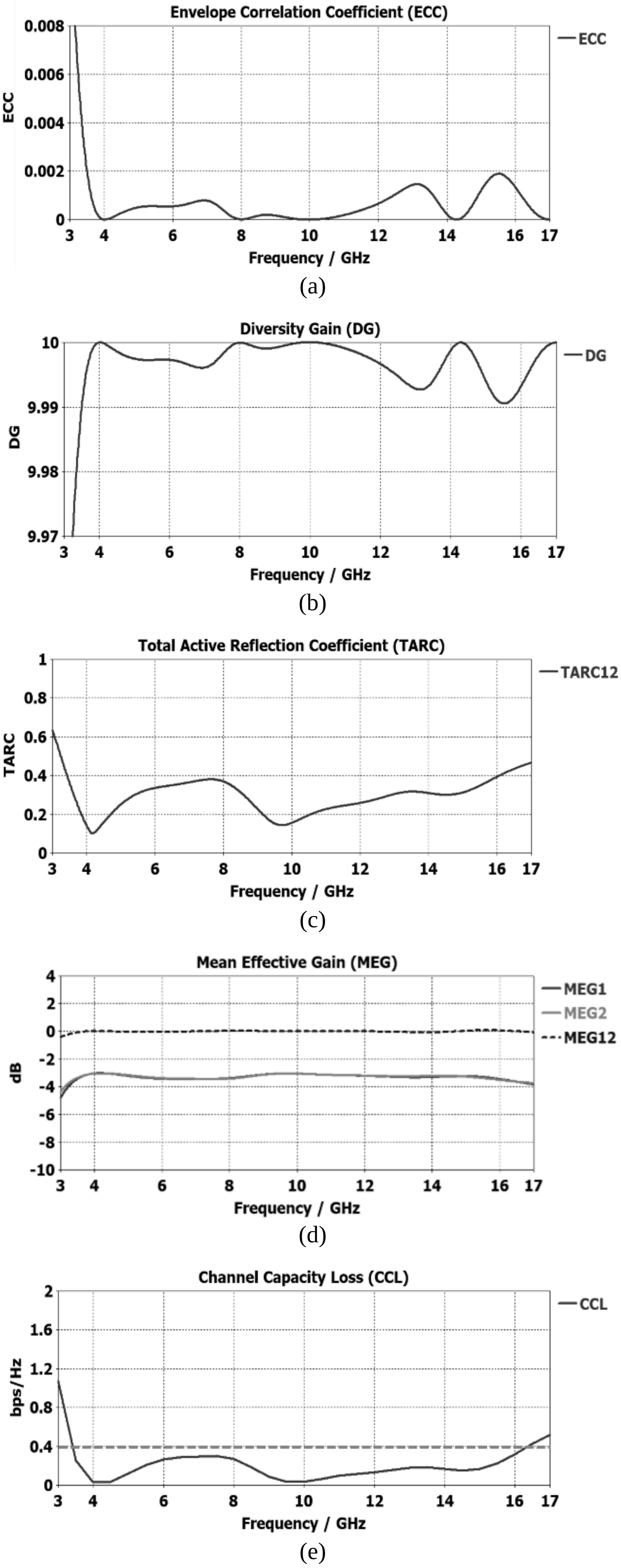


Figure 7. The MIMO performance parameters (a) ECC, (b) DG, (c) TARC, (d) MEG, and (e) CCL

$$ECC = \frac{|S_{11}^{*}S_{12}+S_{12}^{*}S_{22}|^2}{(1-(|S_{11}|^2+|S_{12}|^2))(1-(|S_{11}|^2+|S_{12}|^2))} \quad (10)$$

$$DG = 10\sqrt{1-|ECC|^2} \quad (11)$$

$$TARC = \sqrt{\frac{|S_{11}+S_{12}|^2+|S_{21}+S_{22}|^2}{2}} \quad (12)$$

$$MEG = 0.5\left[1-\sum_{j=1}^{M}\left|S_{ij}\right|^2\right] \quad (13)$$

$$CCL = -\log_2 \det(\eta) \quad (14)$$

where,

$$\eta = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix}$$

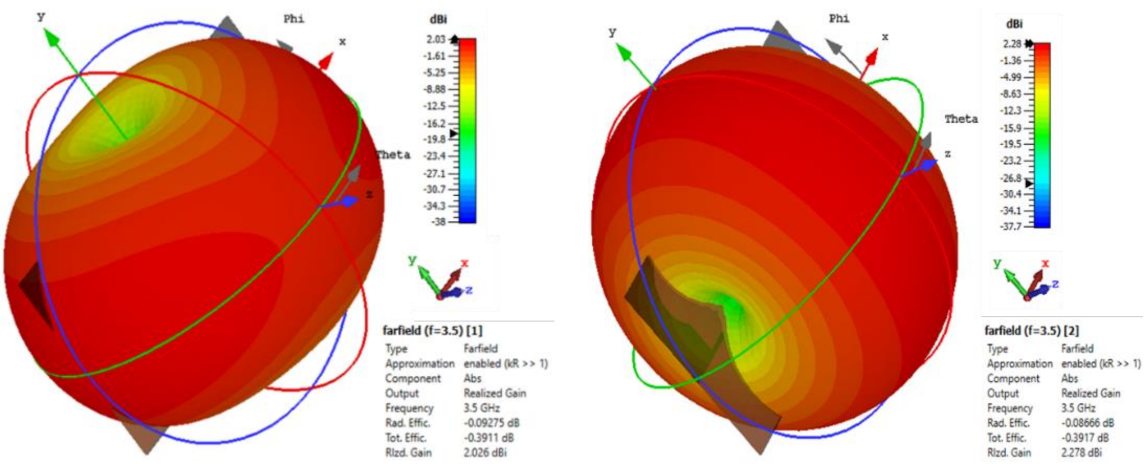
also,

$$\sigma_{ii} = 1-\left(|S_{ii}|^2-\left|S_{ij}\right|^2\right) \, and \, \sigma_{ij} = 1-\left(S_{ii}^{*}S_{ij}+S_{ji}S_{ij}^{*}\right)$$

4. CONCLUSION

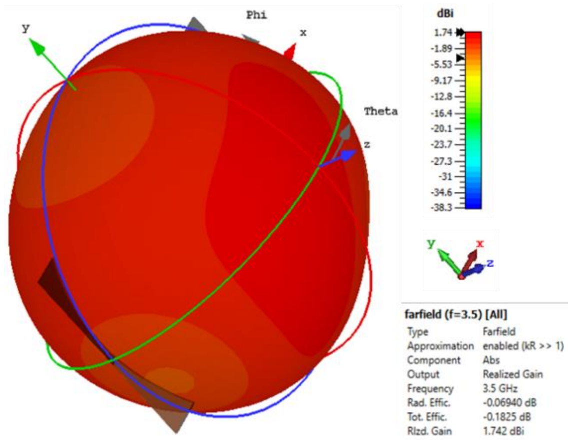
A two-element 2×2 MIMO configuration array has been designed and characterized in this article. The array antenna is designed with two planar keyhole shaped single element antennas using the PGP technique to get a large VSWR <2 ultra-wide BW of 13.258 GHz between 3.394-16.652 GHz that is suitable for any UWB application. To have better isolation, the polarization diversity technique has been utilized, where the antennas are physically separated with 900 apart that gives a good isolation of <-20 dB between port 1 and 2 where the standard is <-15 dB. The array has a good TE and RE of 85% and 98% respectively with a maximum combined RG of 5.85 dBi inside the working BW. The MIMO performance parameters such as the ECC (<0.0033), DG (>9.983), TARC (<0.445), MEG12 (<0 dB) and CCL (<0.4 bps/Hz) all are well within the acceptable standards showing the quality performance of the proposed design.

APPENDIX

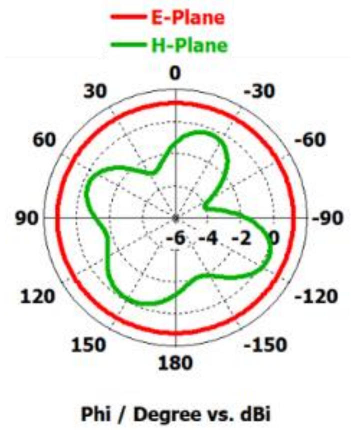


(a) (b)

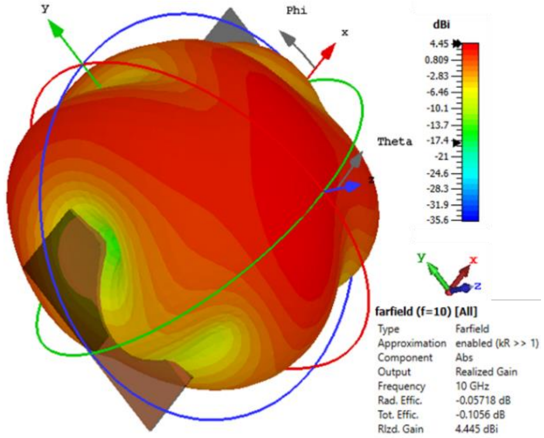
Figure 5. 3-D and 2-D radiation patterns at different frequencies (a) 3.5 GHz port 1, (b) 3.5 GHz port 2, (c) 3.5 GHz combined, (d) 3.5 GHz combined, (e) 10 GHz combined, (f) 10 GHz combined, (g) 16.5 GHz combined, and (h) 16.5 GHz combined (*Continue*)



(c)



(d)



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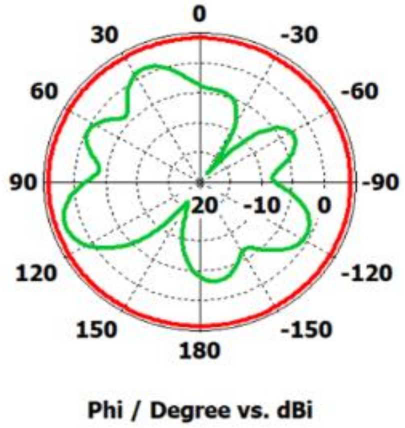
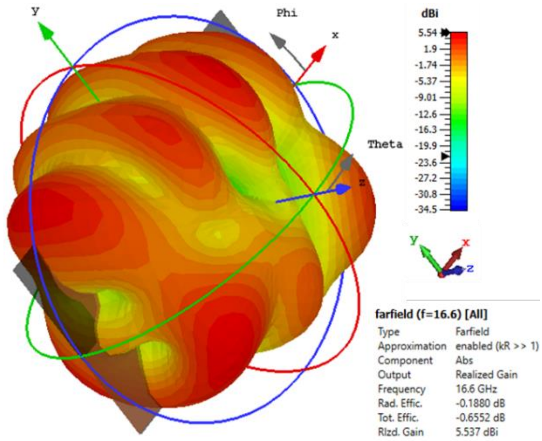


(f)



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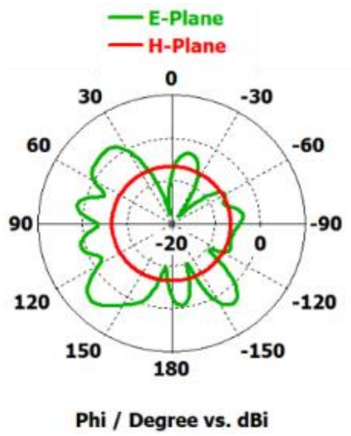

(h)

Figure 5. 3-D and 2-D radiation patterns at different frequencies (a) 3.5 GHz port 1, (b) 3.5 GHz port 2, (c) 3.5 GHz combined, (d) 3.5 GHz combined, (e) 10 GHz combined, (f) 10 GHz combined, (g) 16.5 GHz combined, and (h) 16.5 GHz combined

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