



Design and Implementation of Super Wide Band Triple Band-Notched MIMO Antennas

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Abstract

In this article, a triple band-notched super-wideband (SWB) monopole antenna is designed and manufactured. The measured working frequency band (out of the filters working band) ranges from 2.5 to 20 GHz. A single radiating element is utilized to analyze and implement various MIMO antennas, with isolation between the antenna ports higher than 15 dB. Two parallel-fed elements SWB MIMO antenna and four parallel-fed elements SWB MIMO antennas are presented. Metallic barriers with different shapes are used to improve the isolation among ports from a low unacceptable value of 12 dB to a value higher than 20 dB within most of the working frequency band. S-parameters of the presented SWB MIMO antennas experimentally shows that antennas perform well up to 20 GHz, which is the highest frequency supported by the available Vector Network Analyzer used in the S parameters measurements. Satisfactory performance is observed up to 50 GHz by computer simulations using the CST software.

Keywords UWB antennas · SWB antennas · MIMO antennas · Band-notched antennas

1 Introduction

A great number of researches addressing the design and performance study of Ultra-Wide Band (UWB) antenna have been done since the introduction of unlicensed UWB band of 3.1–10.6 GHz at 2002 for Ultra-Wide Band communications [1].

To get a high bit rate over a super wide operating band, super wide band Multiple-Input Multiple-Output (MIMO) antennas should be designed. Super wide band communication systems suffer from interference due to other widely deployed systems such as WLAN systems. Thus, the main objective of this work is to design SWB MIMO antenna with band reject capability. This can be done designing SWB MIMO antennas adding to it band reject filters.

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MIMO is a technique used to increase drastically the channel's bit rate. To do this, antennas with multiple isolated ports are used. Using 2*2 MIMO antennas, bit rate can be doubled. Bit rate can be easily tripled or even quadrupled using 4*4 MIMO antennas as shown in [2–4].

In [5–8], various UWB MIMO antennas working at different bands are presented. In MIMO systems, MIMO antennas are designed to have a high isolation among (between) their radiating elements (with a minimum of 13 dB and possible isolation of 20 dB or more). To satisfy this requirement, different effective isolation increment techniques are implemented.

In [9], a defected ground structure (DGS) is used to increase the isolation between the antenna elements. In [10], to increase the isolation between the antenna elements, a decoupling network is inserted between the elements of the MIMO antenna.

Some of MIMO antennas have a band-notch action to reject the interference from and to other communications systems. The most common notched band is the (5.1–5.9) GHz representing the WLAN higher band. Another band is the (3.2–3.8) GHz band representing the mid band of the sub-6 GHz 5G system operating bands. The third one is the X-band satellite communication services (XSCS) with a band of (7.2–8.4) GHz.

In [11], an UWB MIMO antenna that consists of two simple square monopole antennas with slotted ground plane structure is presented. Measurements of scattering parameters show that this antenna has a working band of (2.2–10.8) GHz. To reject the WiMAX (3.3–3.8) GHz working band, a band-notch filter consisting of a combination of U-shaped and L-shaped slots is effectively utilized. In [12], an UWB MIMO antenna is presented. Scattering parameters measurements show that the antenna works at a band of (3.1–11) GHz with a rejected band at the WLAN higher band of (5.15–5.85) GHz. Isolation between radiating elements is higher than 15 dB.

In [13], an UWB MIMO antenna with band-notched characteristic is presented. Scattering parameters measurement results show that its working band extends from 2.85 GHz up to 11.9 GHz, and that its rejection band is (5.1–6.0) GHz. Moreover, various novel types of UWB antennas are presented in [14, 15].

Super Wide-Band (SWB) MIMO antennas are MIMO antennas that work at frequencies higher than 10.6 GHz and possibly reaching 20 GHz or higher. They can be used to support the new 5G mobile communications (at the millimeter band) and other future communication systems.

In this article a single element triple band-notched SWB antenna and two triple band-notched Super Wide Bandwidth MIMO antennas that work well up to 20 GHz (representing the maximum working frequency of the measurement instruments that are available at our school) will be presented. Theoretically (using simulations), antennas work satisfactorily up to 50 GHz (see "Appendix").

In Sect. 2 of this work, the design of various SWB MIMO antennas is explained. In Sect. 3, presents and discusses the antenna's measurements results. Finally in Sect. 4, conclusions are presented.

2 SWB MIMO Antennas Design and Simulation Results

SWB antenna is an antenna the works at a huge frequency band with an upper operating frequency to lower operating frequency of 10 or more.

In this section, two types of SWB MIMO (two ports and four ports) will be presented.

The dielectric material FR-35 with a dielectric constant of 3.5 and loss tangent of 0.0009 is used as a substrate in the design process of the three versions of SWB antennas

(Single element SWB and two SWB MIMO antennas). The dielectric material has a thickness of 1.575 mm.

It is well known that the antenna dimensions are related to its minimum operating frequency [16]. Antenna usually consists of a radiating element and a feeding line. Radiating element can have one of many possible shapes such as circular, semi-circular, rectangular, heptagonal, hexagonal or other shapes such as fractal shape. Input impedance of these radiating elements is usually higher than 100 ohms. Thus, a taper is required between the radiating element and the antenna connector to adapt the 50 ohms system to the antenna high impedance in order to obtain a wide working band.

The geometry of the single element antenna without any filter is shown in Fig. 1. The radiating element has a circular shape. 50 ohms feeding line with a length of L_f is followed by a trapezoidal taper that is used to match the 50 ohms system impedance to the radiating element input impedance that is higher than 100 ohms. To get an antenna with good performance at 3.0 GHz; it should be designed to work well at a frequency band starting at 2.8 GHz or little bit lower.

Table 1 gives the physical dimensions of the designed single elements SWB antenna.

The effective electrical length (l_{eff}) of the SWB antenna is given by [17]:

$$l_{eff} = (2R + Lg + g + Rp + Rg) \quad (1)$$

where.

- R is the radius of the circular radiating patch of the antenna
- Lg is the length of the ground plane
- g is the vertical gap between the circular radiating element and the back side ground plane = 1 mm.
- Rp is the electrical radius of the radiating patch = $R/4$.
- Rg is the electrical radius of the ground plane = $W/2\pi$.

From the dimensions given in Table 1, the electrical length of this antenna is calculated to be 56.8 mm.

The theoretical first resonance frequency of the SWB antenna (should be 3.0 GHz or lower) is given by [17]:

$$f_{min}(\text{GHz}) = \frac{144}{l_{eff}(\text{mm})} \quad (2)$$

Equation 2 gives a theoretical first resonance frequency of 2.53 GHz.

2.1 CST Software is used in the Simulation and Optimization Process

The simulated S_{11} of the single element SWB antenna is shown in Fig. 2. It can be noticed that its working band (with S_{11} lower than -10 dB) is 2.2–20 GHz and that the first resonance frequency is near to 2.6 GHz.

It can be seen that the antenna works well (with S_{11} lower than -10 dB) within the 2.2 to 20 GHz band. This makes the antenna susceptible to interference from other widely deployed systems. Thus, the next step is to introduce notch filters that work at three frequency bands, namely, 3.5, 5.5 and 7.5 GHz. The 3.5 GHz filter is a half wavelength U-shaped slot within the radiating patch. The 5.5 GHz filter consists of double U-shaped

Fig. 1 Geometry of single element SWB antenna

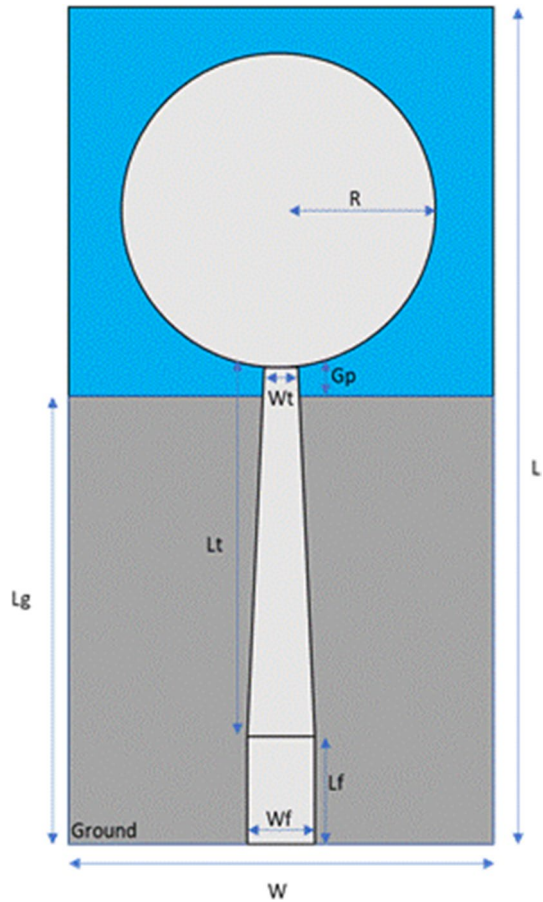


Table 1 Physical dimension of the single element SWB antenna

Parameter	Value (mm)
W	35
L	49
R	13
w_f	3.4
L_f	6.0
L_t	16.0
W_t	1.5
G_p	1.0
L_g	21.0

slots etched near to the feeding line. Finally, the 7.5 GHz filter is a half wave U-shaped slot within the feeding line. Figure 3 shows the physical geometry of triple band-notched SWB antenna.

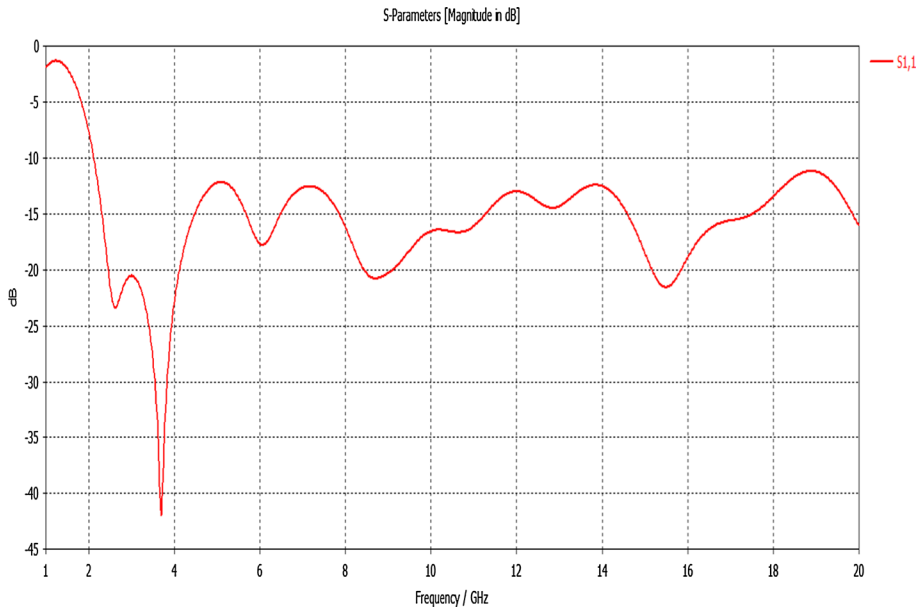


Fig. 2 Simulated S11 parameter of the SWB single element antenna

Total U-shaped slot length of filter 1 and 3 is given by:

$$L_U = \frac{\lambda_o/2}{\sqrt{\frac{\epsilon_r + 1}{2}}} \tag{3}$$

where.

- λ_o is the free space wavelength at the filter center frequency.
- ϵ_r is dielectric constant = 3.5

Table 2 shows physical dimension of the final band-notched SWB antenna.

Figure 4 depicts the simulated S11 parameter of the antenna. From it, it can be noticed that the first filter works at 3.3–3.7 GHz band. Second filter works at two sub-bands near to 5.5 GHz. The first sub-band extends from (5.02 to 5.34) GHz and the second one from (5.52 to 6.06) GHz. This filter has two sub-bands due to the different resonance frequency of its two horizontal parts. It can be seen that one part of it is over the ground plane while the other is only over the dielectric material. Also, the distance between the horizontal parts of this filter and the taper are different causing this double resonance of the filter. The third filter works at the band (6.99–8.07) GHz.

To construct SWB two elements MIMO antenna, a pair of the previously mentioned triple band-notched SWB antenna is used. The spacing between the two elements of the MIMO antenna is chosen in such a way to have isolation between them higher than 15 dB [16]. In order to increase the isolation between the antenna elements, T-shaped metallic parasitic line barrier printed within the gap between the radiating elements is used. Figure 5 shows the geometry of band-notched SWB two elements MIMO antenna with parallel feed.

Fig. 3 Geometry of band-notched simple SWB antenna

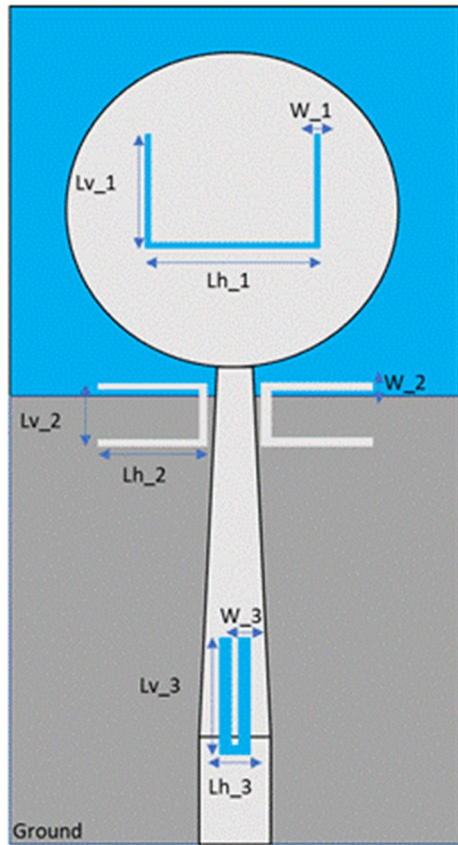


Table 2 Dimension of the band-notched SWB antenna

Parameter	Value (mm)
W1	0.3
Lh1	11.4
Lv1	9.06
W2	0.3
Lh2	8.87
Lv2	3
W3	0.8
Lh3	1.8
Lv3	6.9

Table 3 shows physical dimension of the final band-notched two elements SWB MIMO antenna.

Figure 6 represents the MIMO antenna simulated S11 and S21 parameters of the. First Filter working band is (3.19–3.81) GHz. Second filter sub-bands are (5.02–5.34) GHz and (5.51–6.06) GHz. Third filter working band is (6.99–8.08) GHz. Isolation higher than 20 dB can be noticed in the frequency band of (2.7–20) GHz.

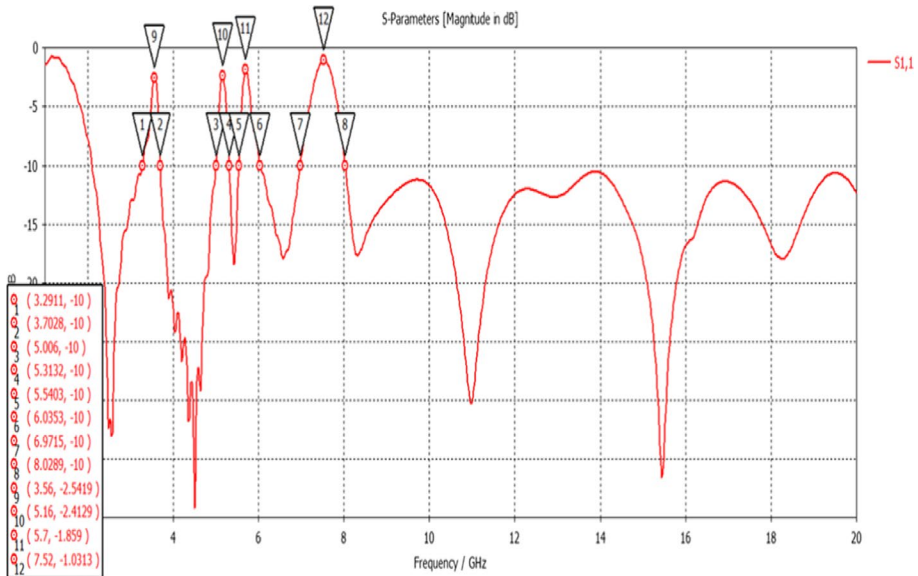


Fig. 4 Simulated S11 parameter of the triple band-notched SWB antenna

Figure 7 shows the four elements SWB MIMO antenna with up-down parallel feed configuration. Isolation increment is achieved using cross lines and a circular ring.

Table 4 gives some of the dimensions of the final four elements SWB MIMO antenna.

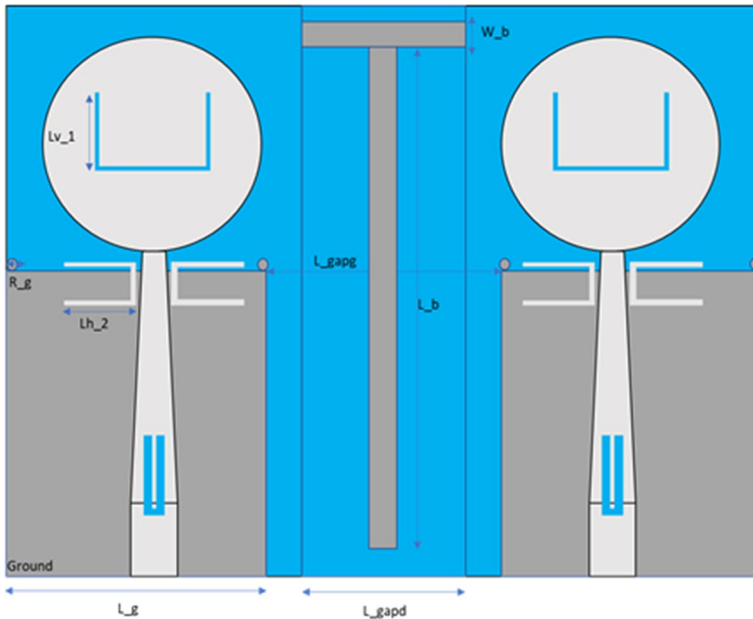


Fig. 5 Geometry of parallel feed band-notched two elements SWB MIMO antenna

Table 3 Triple Band-notched two elements SWB antenna dimensions

Parameter	Value (mm)
Lgapg	24
Lgapd	16
Lb	45
Wb	2
Rg	0.5
Lv1	8.86
Lh2	8.57
Lg	31

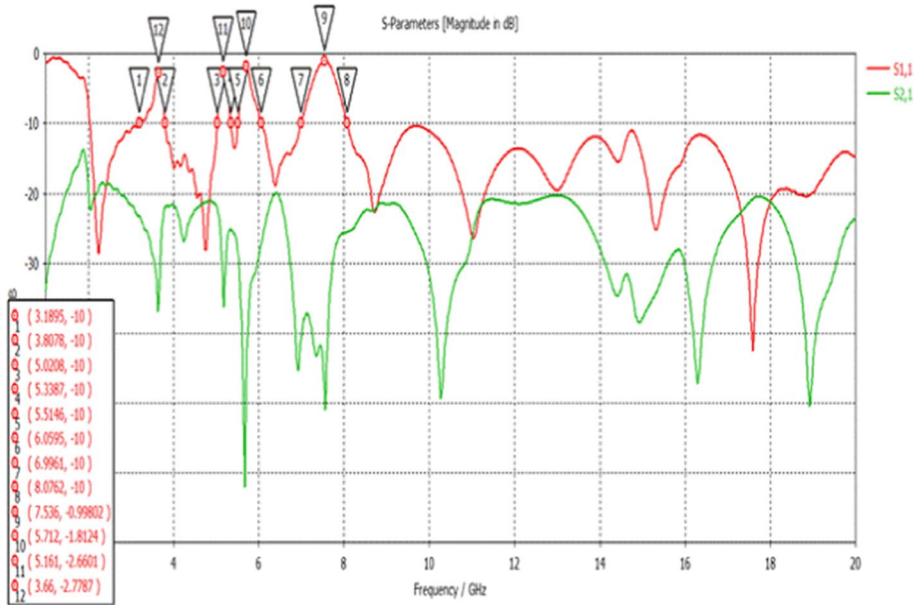


Fig. 6 Simulated S11 and S21 parameters of the triple band-notched SWB MIMO antenna

Figure 8 shows the simulated four S parameters of the designed MIMO antenna. It can be noticed that, the reflection parameter S11 is lower than -10 dB outside the filter’s bands. In the (3–20) GHz band, isolation (-S21, -S31 and -S41) between the elements is higher than 18 dB. The working band of the first filter is (3.2–3.8) GHz. The sub-bands of the second filter are (5–5.35) GHz and (5.55–6.16) GHz. The working band of the third filter is (7.04–8.09) GHz.

3 Measurements Results and Discussion

The dielectric material FR-35 with a dielectric constant of 3.5 and loss tangent of 0.0009 is used as a substrate in the fabrication process. The used substrate has a thickness of 1.575 mm. Antennas are fabricated using the LPKF S100 milling machine.

Fig. 7 Four elements parallel feed SWB MIMO antenna

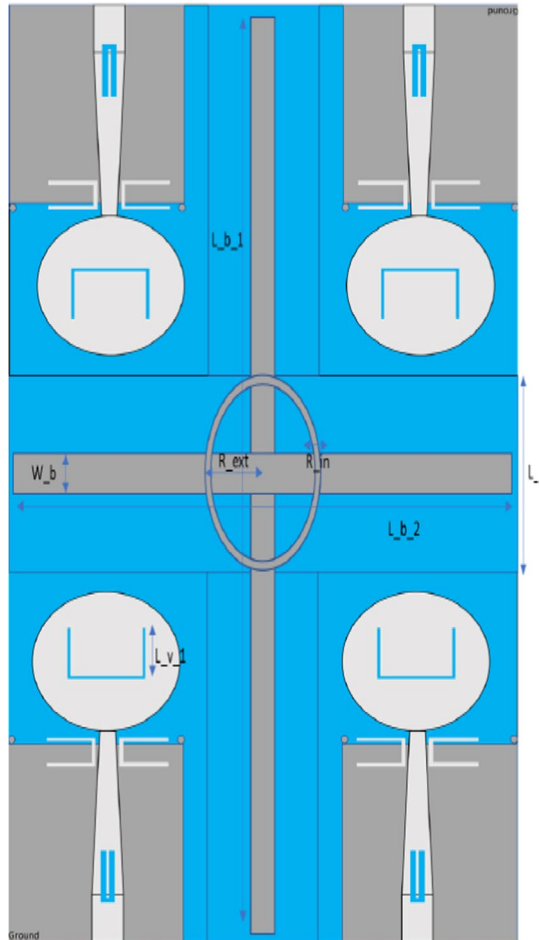


Table 4 Physical dimensions of the four elements SWB triple band-notched MIMO antenna

Parameter	Value (mm)
Lb1	116.5
Lb2	84.5
Wb	2
Lgapd	20
Lv1	8.96
Rext	10
Rin	9

The Vector Network Analyzer (VNA) E5071C of Agilent with a maximum operating frequency of 20 GHz is used to measure the S parameters of the fabricated antennas. An echoic chamber with instruments that work up to 18 GHz is used to measure the radiation pattern of the fabricated antennas.

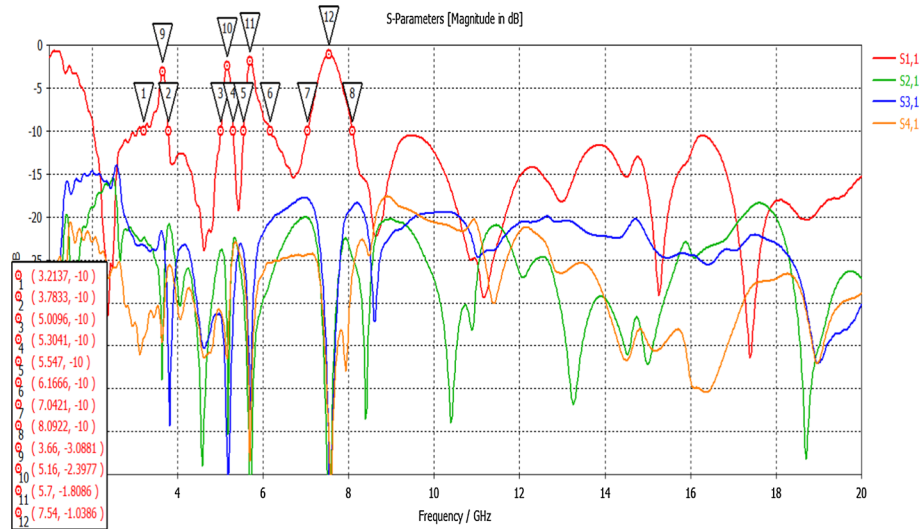


Fig. 8 Simulated S11, S21, S31 and S41 of the four elements SWB MIMO antenna

3.1 S Parameter Measurements

Figure 9 depicts a photograph of the front and rear views of the single element SWB antenna. SMA connector is used to connect the antenna with the measurement cable.

Figure 10 depicts the measured and simulated S11 parameter of the single element SWB antenna. From it, it can be seen the working bands of the three filters has been shifted to a higher frequencies. The discrepancy between the working bands of filters is due to the fabrication process and the change of the value of the dielectric constant at the high frequencies. Out of the filter's working bands, S11 is better (lower) than -10 dB.

Figure 11 shows the measured maximum gain of the single element antenna. It can be seen that the antenna maximum gain increases with the increment of frequency except at the filter's working bands. At 3 GHz, antenna gain is 3 dBi increasing to 5.2 dBi at 15 GHz.

Figure 12 represents a photograph of the two elements SWB MIMO antenna.

Figure 13 depicts the simulated and measured S11 parameter of the two elements SWB MIMO antenna. It can be noticed that the working bands of the three filters has been displaced to a higher frequencies. Out of the filter's working bands, S11 is lower than -10 dB. A way to have the filters working at the desired bands is to use little bit longer filters.

Figure 14 shows the measured and simulated S21 parameter of the two elements SWB MIMO antenna. It can be seen that the S21 is lower than -20 dB at the major part of the working band with points at -18 dB.

Figure 15 shows the simulated and measured S12 parameter of the two elements SWB MIMO antenna. It can be noticed that the S12 is better (lower) than -20 dB at almost the whole working band with some points at -18 dB.

Figure 16 illustrates the measured and simulated S22 parameter of the two elements SWB MIMO antenna. It can be seen that the working bands of the three filters has been shifted to a higher frequencies. Out of the filter's working bands, S22 is better (lower) than -10 dB.

Fig. 9 Single element SWB antenna front and back views

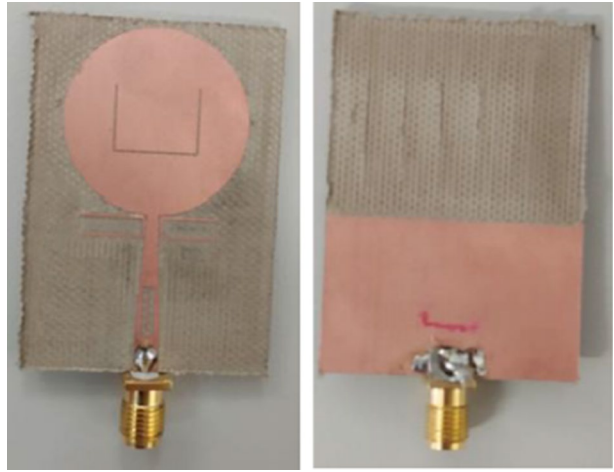
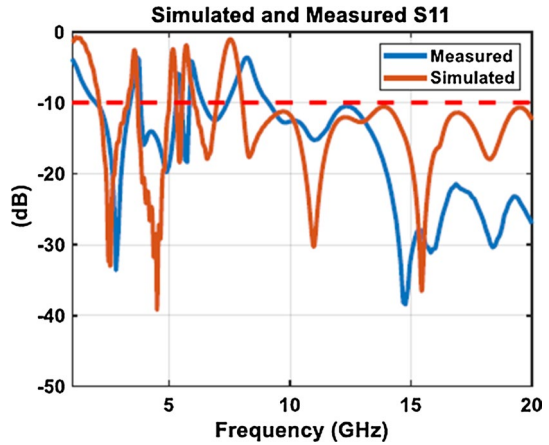


Fig. 10 Measured and simulated S11 parameter of the single element SWB antenna



The Envelope Correlation Coefficient (ECC) is given by:

$$ECC = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{[1 - (|S_{11}|^2 + |S_{21}|^2)][(1 - |S_{12}|^2 |S_{22}|^2)]} \tag{4}$$

Out of notch filters bands, the Envelope Correlation Coefficient (ECC) of the two elements SWB MIMO antenna is lower than 0.015.

Figure 17 depicts the four elements SWB MIMO antenna.

Figure 18 illustrates the measured and simulated S11 parameter of the fabricated four elements SWB MIMO antenna. From it, it can be noticed that the working bands of the three filters has been shifted to a higher frequencies. Out of the filter’s working bands, S11 is better (lower) than -10 dB.

Figure 19 depicts the measured and simulated S21 parameter of the four elements SWB MIMO antenna. It can be seen that the S21 is better (lower) than -20 dB at the major part of the working band with some points at -19 dB.

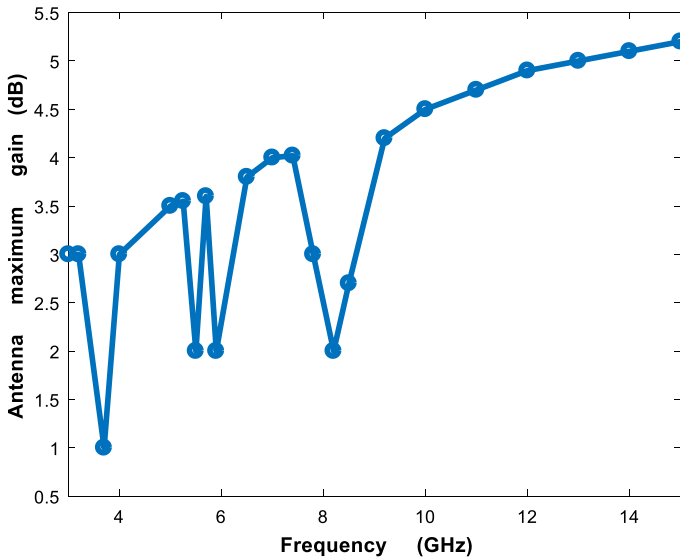


Fig. 11 Measured maximum gain of the single element antenna

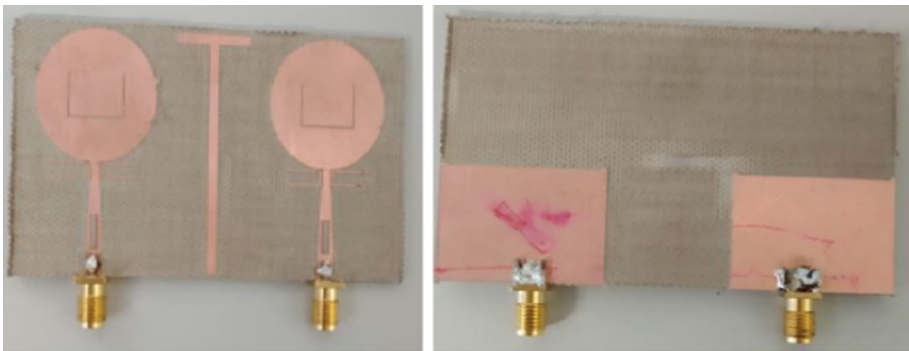


Fig. 12 Front and back views of the two elements SWB antenna

Figure 20 depicts the measured and simulated S_{31} parameter of the four elements SWB MIMO antenna. From it, it can be noticed that the measured S_{31} parameter is better (lower) than -20 dB at the whole working band of the antenna.

Figure 21 shows the simulated and measured S_{41} parameter of the four element SWB antenna. From this figure, it can be seen that the measured S_{41} is lower than -20 dB at the working whole working band of the antenna.

3.2 Radiation Pattern Measurements

Figure 22 shows the measured H-plane radiation pattern of the single element SWB antenna at 3, 4.5, 10 and 15 GHz respectively. From this figure, it can be seen that at

Fig. 13 Measured and simulated S11 parameter of the two element SWB antenna

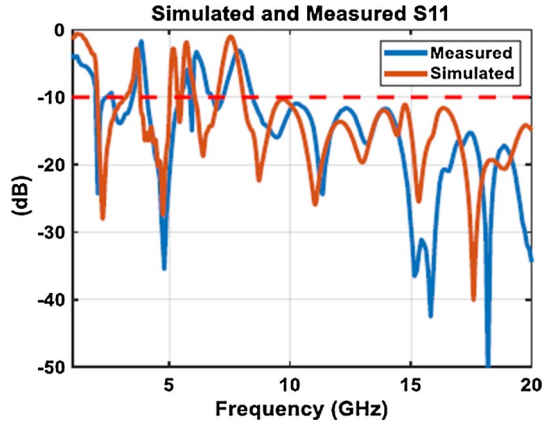


Fig. 14 Simulated and measured S21 parameter of the two element SWB antenna

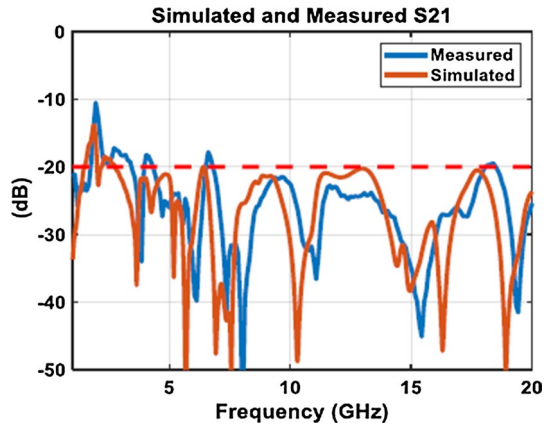


Fig. 15 Simulated and measured S12 parameter of the two element SWB antenna

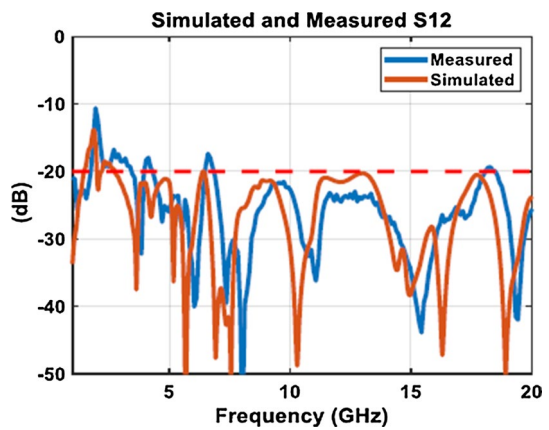


Fig. 16 Measured and simulated S_{22} parameter of the two elements SWB MIMO antenna

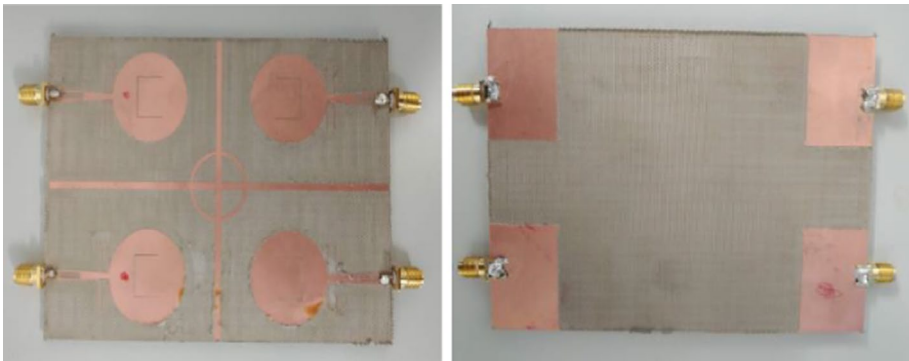
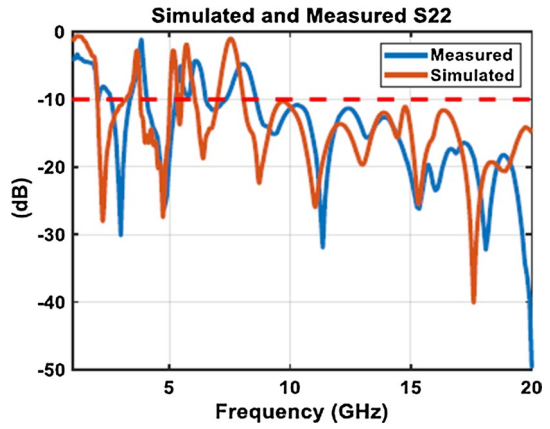


Fig. 17 Four elements SWB MIMO antenna

Fig. 18 Measured and simulated S_{11} parameter of the four elements SWB MIMO antenna

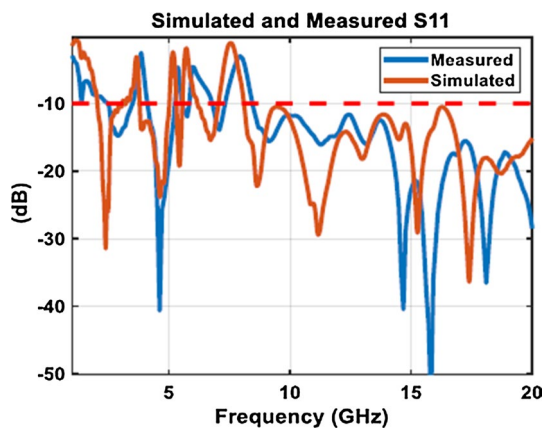


Fig. 19 Measured and simulated S_{22} parameter of the four elements SWB MIMO antenna

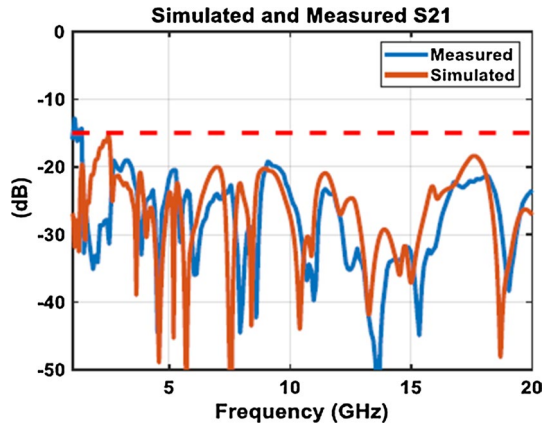


Fig. 20 Measured and simulated S_{31} parameter of the four element SWB antenna

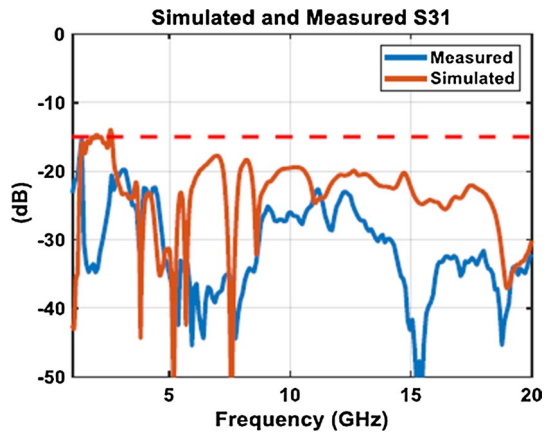
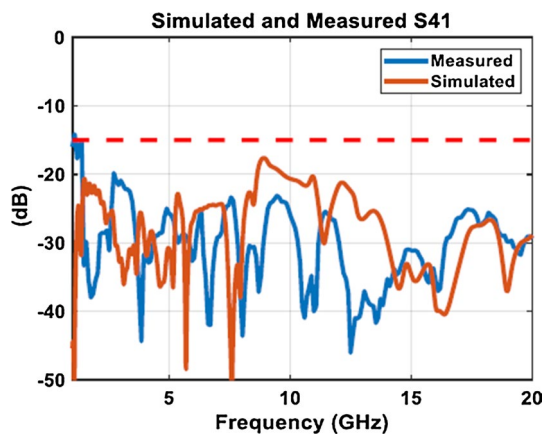


Fig. 21 Measured and simulated S_{41} parameter of the four elements SWB MIMO antenna



3 GHz, the single element SWB antenna is almost omnidirectional. Also it can be seen that at 4.5 GHz, the single element SWB antenna is almost omnidirectional. At 10 GHz, the H-plane has its maximum gain at 300° . Finally, at 15 GHz, the H-plane has its maximum gain at 270° . E-plane radiation pattern has the well known 8-like shape.

Now the measured radiation pattern of the two elements SWB MIMO antenna will be presented. Figure 23 shows the measured H-plane radiation pattern of one of the two elements element at 3, 4.5, 10 and 15 GHz respectively. From this figure, it can be seen that at 3 GHz, the single element SWB antenna is almost omnidirectional with its minimum value at 270° which represents the direction of the other element. At 5 GHz, the single element SWB antenna is almost omnidirectional with its minimum value at 270° . At 10 GHz, the H-plane radiation pattern is little bit directive with its minimum value at 270° . At 15 GHz, the H-plane radiation pattern is little bit directive. Its value at 270° is 8 dB lower than the maximum value. E-plane radiation pattern has the well known 8-like shape.

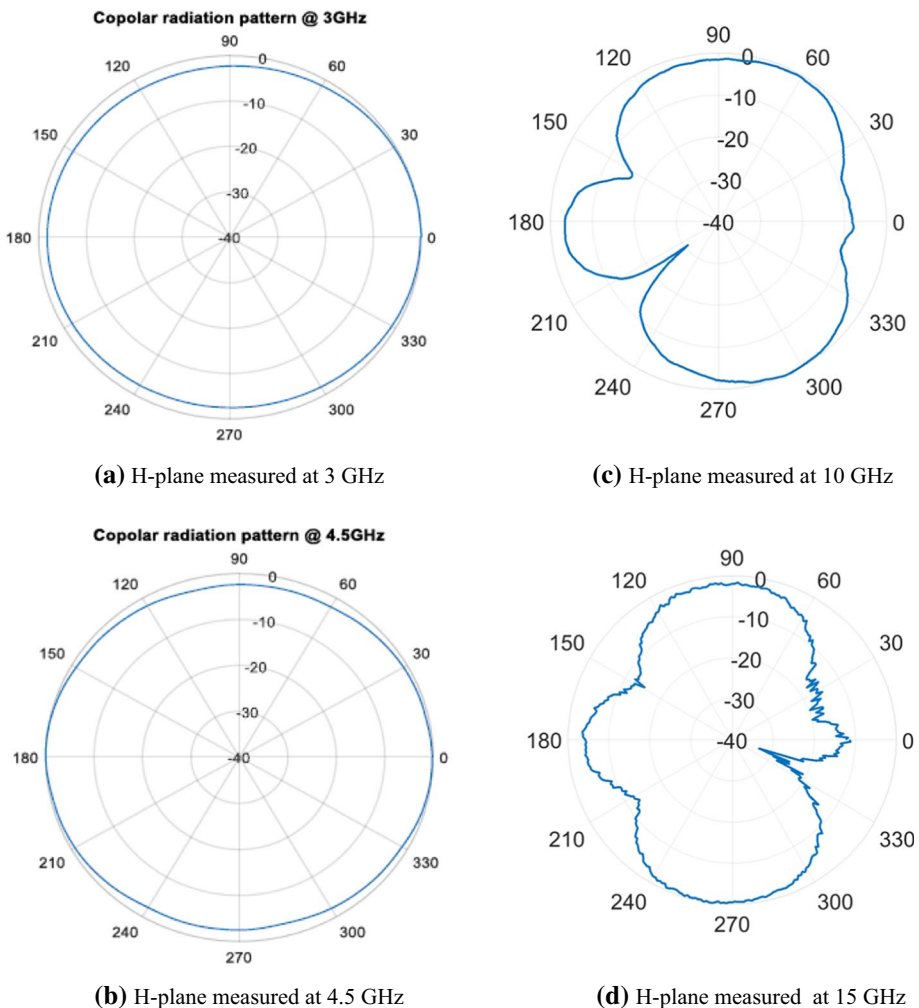


Fig. 22 Measured H-plane radiation pattern of the single element SWB antenna at 3, 4.5, 10 and 15 GHz

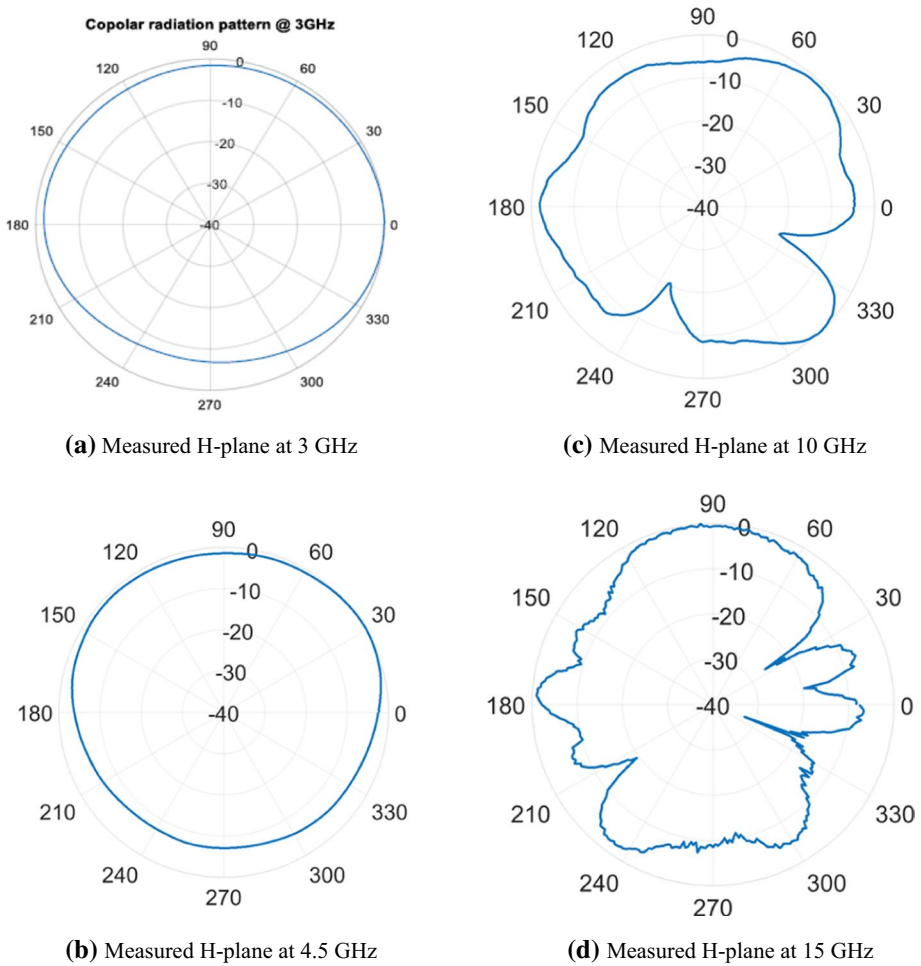
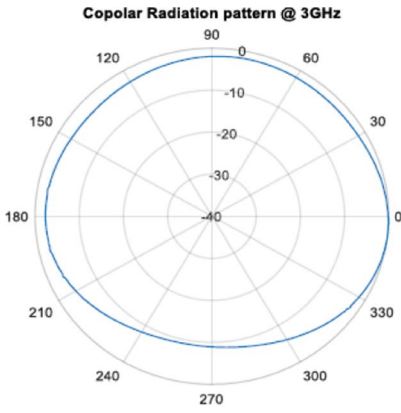


Fig. 23 Measured H-plane radiation pattern of the two elements SWB MIMO antenna at 3, 4.5, 10 and 15 GHz

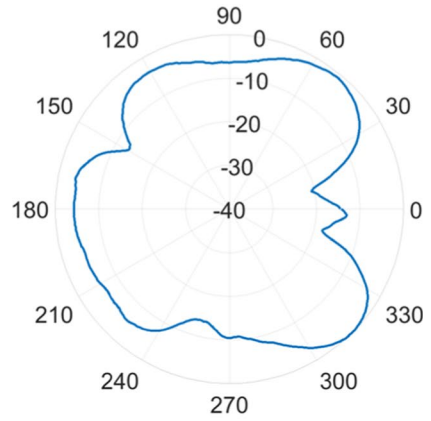
Next the four elements SWB MIMO antenna measured radiation pattern will be presented. Figure 24 shows the measured H-plane radiation pattern of one of the four elements element at 3, 4.5, 10 and 15 GHz respectively.

From this figure, it can be seen that at 3 GHz, the single element SWB antenna is almost omnidirectional with its minimum value at 270° which represents the direction of the other element. At 5 GHz, the single element SWB antenna is almost omnidirectional with its minimum value at 270°. At 10 GHz, the H-plane radiation pattern is little bit directive. Its value at 270° is 8 dB lower than the maximum value. Finally, at 15 GHz, the H-plane radiation pattern is little bit directive. Its value at 270° is 8 dB lower than the maximum value.

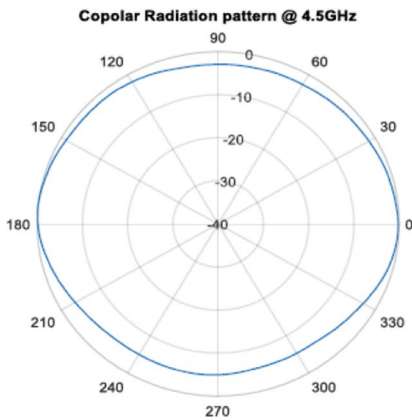
It has been noted that crosspolar normalized gain pattern is 15–20 dB lower than the copolar normalized gain pattern.



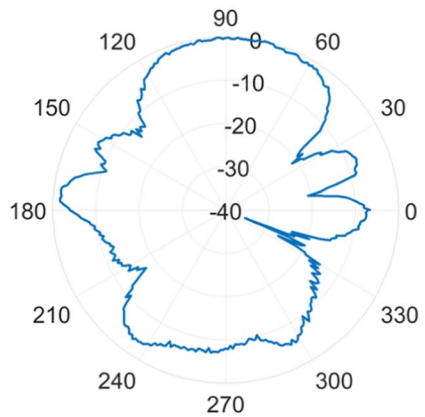
(a) Measured H-plane at 3 GHz



(c) Measured H-plane at 10 GHz



(b) Measured H-plane at 4.5 GHz



(d) Measured H-plane at 15 GHz

Fig. 24 Measured H-plane radiation pattern of the four elements MIMO antenna at 3, 4.5, 10 and 15 GHz

Table 5 Comparison between proposed antenna and other works

Reference	Operating band (GHz)	Notched bands (GHz)
18	(3.0–11.0)	(3.3–3.8) and (5.0–6.0)
19	(2.2–10.8)	(2.5–2.69) and (3.3–4.2)
20	(3.4–11.8)	(5.02–5.97) and (7.23–7.72)
21	(2.95–12.00)	(3.2–3.8) and (5.15–5.85)
This Work	(2.5–20)	(3.2–3.8), (5.00–5.35), (5.55–6.16) and (7.04–8.09)

Table 5 presents the comparison between the proposed antenna and other works in terms of working band and number of notched band. It can be observed from this table that the proposed antenna has the higher working band.

4 Conclusions

In this work, triple band-notched (SWB) MIMO antennas have been designed and manufactured. It has been shown that, the measured working frequency band (out of the filters working band) ranges from 2.5 to 20 GHz. A single radiating element SWB antenna has been used as the first pass to design several SWB MIMO antennas, with isolation between (among) the antenna ports better (higher) than 15 dB. Two-element and four parallel-fed SWB MIMO antennas have been presented. Metallic barriers have been used to improve the isolation among ports from a low unacceptable value of 12 dB to better (higher) than 20 dB within almost the whole working frequency band. Measured S-parameters of the presented SWB MIMO antennas shows good performance up to 20 GHz, which is the highest frequency supported by the available Vector Network Analyzer. Satisfactory performance has been observed up to 50 GHz through computer simulations using the CST software.

Appendix

Measurements of S parameters have been done using the Vector Network Analyzer (VNA) E5071C of Agilent with a maximum operating frequency of 20 GHz. To get an idea about the performance of the MIMO antenna at higher frequencies, simulations are done up to 50 GHz.

Figure 25 shows the simulated S11 of the single element antenna without notch filters. It can be seen that theoretically, the antenna works well (with S11 lower than -10 dB) up to 50 GHz.

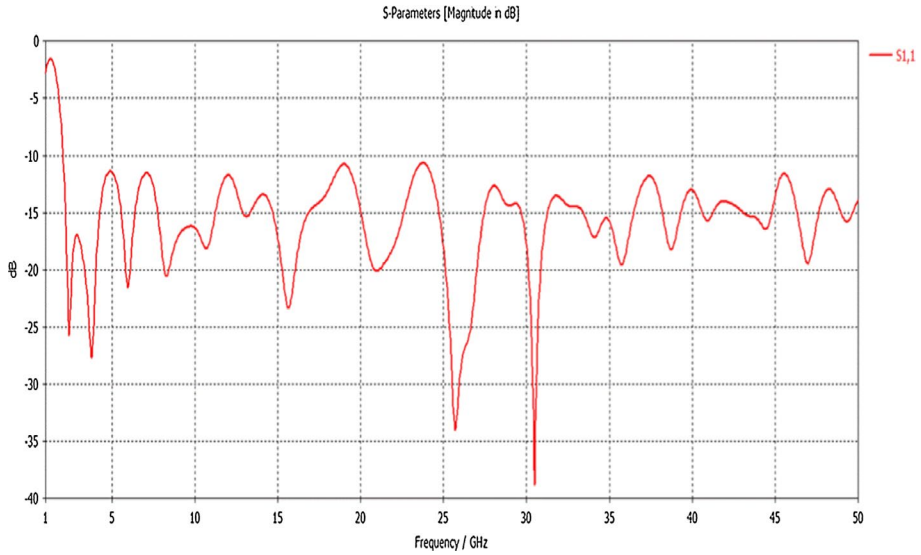


Fig. 25 Simulated S₁₁ of the single element antenna without notch filters

Figure 26 shows the simulated S₁₁ of the single element antenna with three notch filters. It can be seen that theoretically, the antenna works well (with S₁₁ lower than -10 dB)

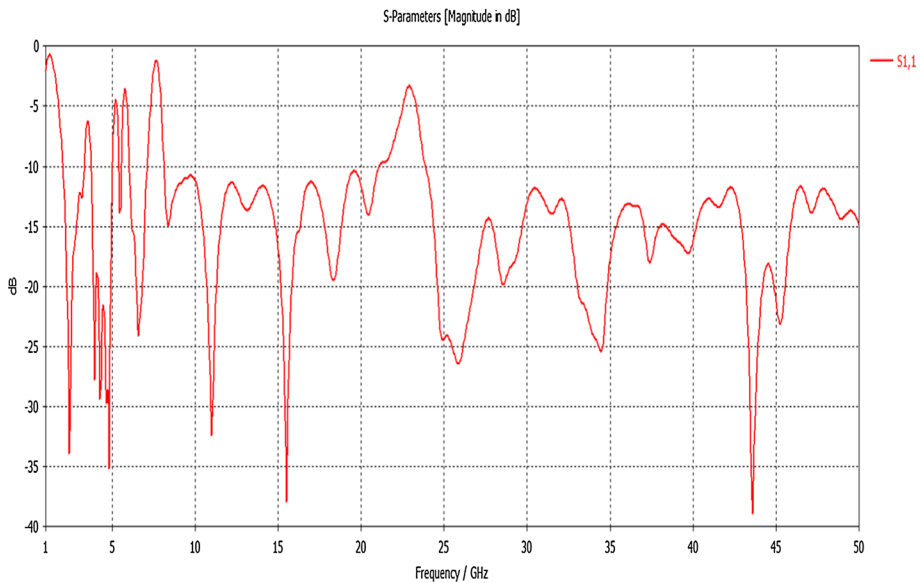


Fig. 26 Simulated S₁₁ of the single element antenna with three notch filters

up to 50 GHz and it has an extra notch action near to 23 GHz due to the third resonance of the third filter.

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Declarations

Conflict of interest The first author of the article, on his behalf and that of all the authors, declares that there is no potential conflict of interest related to the article.

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