



# Compact high isolation UWB MIMO antennas

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Accepted: 7 March 2022 / Published online: 5 April 2022  
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## Abstract

In this work, two elements (with two versions) compact UWB MIMO antennas are designed and fabricated. CST software is used in the simulation process. The two elements MIMO antenna have a size of  $29.5 \times 60 \text{ mm}^2$ . Measured S parameters show that the MIMO antennas work well from 3 GHz up to 20 GHz (representing the maximum working frequency of the measurement instruments). Measurement results show that the isolation between the antenna elements is higher than 23 dB for the first version of the two elements UWB MIMO antenna. In addition, measurement results show that the isolation between the antenna elements is higher than 30 dB for the second version of the two elements UWB MIMO antenna. Measurements show a channel capacity loss lower than 0.4 bps/Hz and a low group delay variation.

**Keywords** MIMO antenna · UWB Antenna · Coupling · Isolation, ECC · Diversity gain, CCL · Group delay

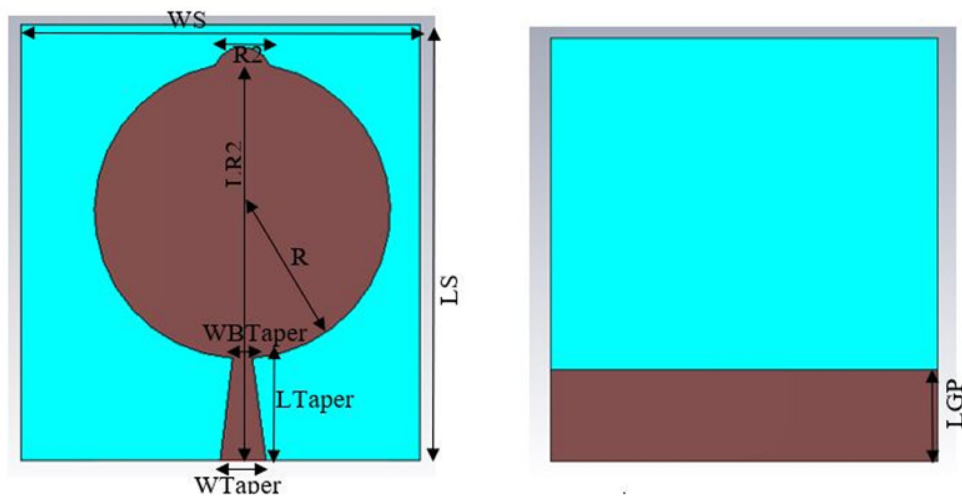
## 1 Introduction

In the twentieth century, very little work on the UWB antennas has been carried out. But, since the FCC assignment (at 2002) of the band 3.1–10.6 GHz for UWB applications, a huge increment of investigation work at the field of UWB antennas has been noticed [1]. To increase the data rate of any communication system such as mobile communication systems, the Multiple-Input Multiple-Output (MIMO) technique is used. One of this system requirement is to have an antenna with multiple (2, 4, 8, 16, 32 or even more) separated ports. System bit rate can be easily increased by more than one fold using for example  $16 \times 16$  MIMO antennas at the transmitting and receiving parts [2–4]. Works [5–8] give detailed design procedure and thoroughly performance analysis of various types of UWB MIMO antennas working at different bands to serve in the deployment of different communication systems. One of the major requirements of a good MIMO antenna is to have

a high isolation (ideally infinite isolation) among its ports. An isolation of 15 dB is considered as the minimum acceptable isolation among ports. To meet this essential requirement, different effective isolation increment techniques such as using diversity polarization, defected ground structure (DGS), neutralization lines, parasitic structures, periodical resonant structures or metallic barriers have been studied and implemented. In work [9], a two elements MIMO antenna that works at both the C band and the X band has been presented. To increase the isolation between its two elements, a defected ground structure (DGS) technique is implemented. This technique increases the isolation between ports up to 30 dB. In [10], to have an inter-ports isolation higher than 30 dB, decoupling network (having a U shape) has been connected between the two F-shaped radiating elements of the double band WLAN MIMO antenna. In [11], a compact UWB MIMO antenna with two orthogonal elements is presented. To further increase the isolation between the two ports of the UWB MIMO antenna, a fork-shaped slot within the ground plane is used. Measurement results show that the antenna-working band (with  $S_{11}$  lower than  $-10$  dB) extends from 2.85 GHz up to 11.9 GHz and that isolation between ports is higher than 20 dB. Recently, various novel types of UWB antennas (with and without notch filters) that serve to construct MIMO antennas are presented in [12–19]. Various MIMO antennas are presented in [20–24]. Despite the 15 dB isolation criterion, it is better to have higher

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**Fig. 1** Single element UWB antenna geometry

isolation among the antenna ports in order to have better MIMO performance.

The main contribution of this article is to design two versions of compact two elements Ultra-Wide Bandwidth MIMO antennas that work well up to 20 GHz with an isolation between ports higher than 23 dB.

The organization of the rest of this works is as follows. In Sect. 2, the design procedure and simulated performance of the two elements MIMO antennas are given in details. Section 3 presents and discusses the antennás experimental results (S parameters and MIMO figures of merit). Finally, conclusions are presented in Sect. 4.

## 2 Antenna design

The main objective of this section is to design two and four elements UWB MIMO antennas that comply the following conditions:

- To have reflection parameters lower than -10 dB at the whole or almost the whole UWB classical band of 3.1 GHz to 10.6 GHz and beyond.
- To have coupling parameters lower than - 20 dB at the whole or almost the whole UWB classical band of 3.1 GHz to 10.6 GHz and beyond.

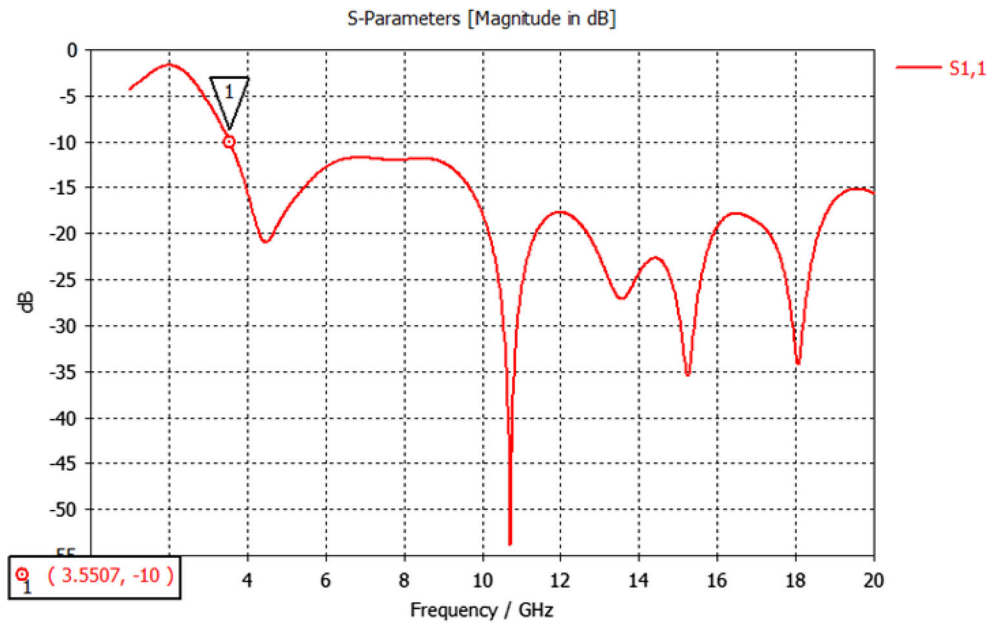
To design and construct the antennas, the inexpensive FR4 material with a thickness of 1.6 mm is used. The FR4

material has a dielectric constant of 4.4 and a loss tangent of 0.02. The copper layer at both sides of the substrate has a thickness of 35  $\mu\text{m}$ . FR4 material has a reasonable performance up to 10 GHz. At higher frequencies, radiation efficiency drops. Despite the reduction of the radiation efficiency, antenna fabricated using FR-4 can be used up to 20 GHz (with lower radiation efficiency) if it is necessary. The CST software is used in the simulation process.

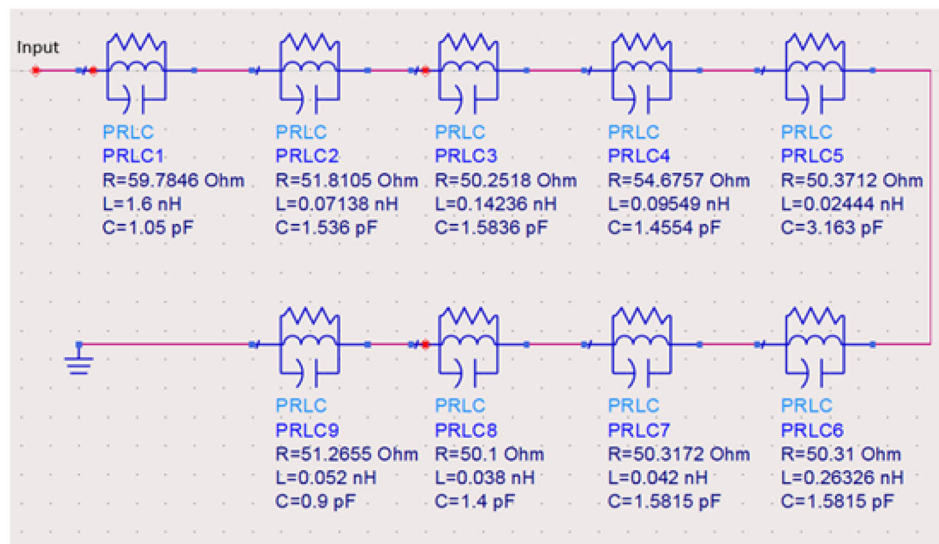
In this section, the design process of a single element UWB antenna, two elements UWB MIMO antenna in two versions will be given.

**Table 1** Physical dimensions of the single element UWB antenna

| Parameter | Value (mm) |
|-----------|------------|
| WTaper    | 3.1        |
| LTaper    | 7.5        |
| WB Taper  | 1.2        |
| R         | 10         |
| R2        | 2          |
| LS        | 29.5       |
| WS        | 32         |
| LR2       | 26         |
| LGP       | 7.4        |



(A) Simulated S11 of the single element UWB antenna.



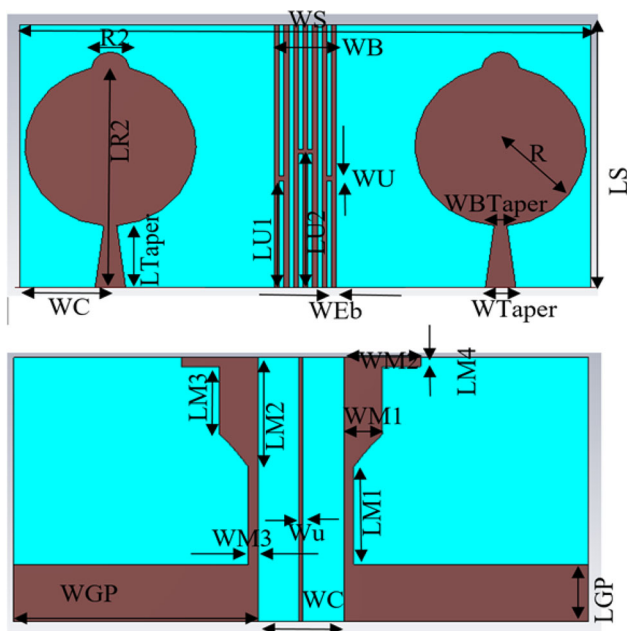
(B) Equivalent circuit of the single element UWB antenna.

Fig. 2 Simulated S11 and equivalent circuit of the single element UWB antenna

### 2.1 Single element UWB antenna

First, the design procedure and simulation performance of the single element UWB antenna that will be used as a

design platform for the two and four elements UWB MIMO antennas is presented. Figure 1 shows the single element UWB antenna geometry. In the front side of the antenna, the radiating element and the feeding line are printed. The radiating element is a circle with a radius R.



**Fig. 3** Geometry of the two elements UWB MIMO antenna (version 1)

**Table 2** Physical dimensions of the two elements UWB antenna (version 1)

| Parameter | Value (mm) |
|-----------|------------|
| WTaper    | 3.1        |
| WB Taper  | 1.2        |
| LTaper    | 7.5        |
| R         | 9          |
| R2        | 2          |
| LR2       | 24.5       |
| LU1       | 12         |
| LU2       | 15         |
| WB        | 6.5        |
| WEb       | 0.5        |
| WU        | 0.5        |
| WC        | 9.5        |
| Ws        | 60         |
| Ls        | 29.5       |
| WGP       | 25.5       |
| WC        | 9          |
| WM1       | 4          |
| WM2       | 8          |
| WM3       | 1          |
| LM1       | 10.86      |
| LM2       | 12.24      |
| LM3       | 7.5        |
| LM4       | 1          |
| LGP       | 6.4        |

Small hemisphere with radius R2 are printed on the top of the main circle. A tapered feeding line connecting the antenna port with the main patch is applied to smooth the current’s path, thus providing wider impedance bandwidth. The tapered feeding line has with a lower part width of 3.1 mm to match the 50 ohms connector of the antenna. The upper part of the taper has a width of 1.2 mm to have the maximum possible working band of the antenna. A partial ground plane can be noticed in the rear side of the antenna.

Table 1 shows the physical dimensions of the single element UWB antenna. It can be noticed that the antenna has a size of (29.5\*32) mm<sup>2</sup>.

Figure 2A shows the simulated S11 of the single element UWB antenna. It can be seen that the impedance-working band of the antenna (with S11 lower than - 10 dB) extends from 3.55 GHz up to 20 GHz covering almost all of the classical UWB band and beyond. Figure 2B shows the equivalent circuit of the UWB antenna. It can be seen that it is represented by nine parallel RLC circuits connected in series. The impedance band (with S11 lower than - 10 dB) of this equivalent circuit is 3.5–21.4 GHz.

### 2.2 Two elements UWB MIMO antenna (Version 1)

In this sub-section, a parallel feed two elements MIMO antenna is designed. It is well known that parallel feed MIMO antennas have lower isolation than orthogonally feed MIMO antenna [25–29]. Figure 3 shows the geometry of the two elements parallel feed UWB MIMO antenna (version 1). In the front side of the antenna, seven vertical metallic barriers have been added to increase the isolation between the two radiating elements of the antenna. To further increase the isolation between the two elements of the antenna, two L-like stubs and a vertical metallic barrier have been added in the rear side of the antenna. To have a compact antenna, lower radiating element radius is used.

Table 2 shows the physical dimensions of the two elements UWB antenna (version 1). It can be noticed that the antenna has assize of (29.5\*60) mm<sup>2</sup>.

Figure 4 shows the simulated S11 of the two elements UWB antenna (version 1). It can be seen that the impedance-working band of the antenna (with S11 lower than - 10 dB) extends from 3.05 GHz up to 20 GHz covering all of the classical UWB band and beyond. S21 has a value lower than - 20 dB at the band (3.38–20.0) GHz.

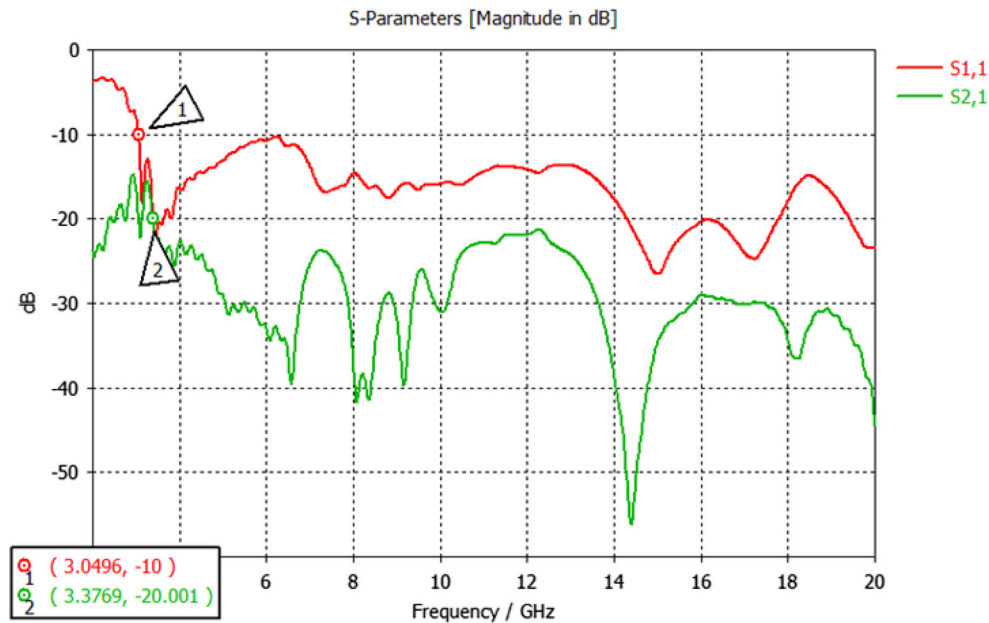


Fig. 4 Simulated S11 of the two elements UWB antenna (version 1)

Figure 5 shows the simulated far field directivity (E-plane and H-Plane) of the two elements UWB MIMO antenna (version 1). It can be seen that the H-plane radiation pattern is omnidirectional meanwhile; the E-plane radiation pattern has a deformed 8-shape.

Table 3 shows the radiation parameters of the two elements UWB MIMO antenna (version 1). Maximum realized gain is got at 7 GHz. Radiation efficiency measured in dB is negative since it is lower than 100%. Despite the low radiation efficiency at 19 GHz, antenna can be used at this frequency and 20 GHz if it is necessary.

### 2.3 Two elements UWB MIMO antenna (Version 2)

Figure 6 shows the geometry of the two elements UWB MIMO antenna (version 2). In the front side of the antenna, two L-like stubs are added at the top of each one of the

radiating elements to increase the isolation between the two radiating elements of the antenna.

Table 4 shows the physical dimensions of the two elements UWB antenna (version 2). It can be noticed that the antenna has assize of (29.5\*60) mm<sup>2</sup>.

Figure 7 shows the simulated S11 of the two elements UWB antenna (version 2). It can be seen that the impedance-working band of the antenna (with S11 lower than  $-10$  dB) extends from 3.78 GHz up to 20 GHz. S21 has a value lower than  $-20$  dB at the band (3.06–20) GHz covering almost all of the classical UWB band and beyond. In addition, it can be seen that S21 has a value lower than  $-25$  dB at the major part of the working band of the antenna.

Figure 8 depicts the simulated far field directivity (E-plane and H-Plane) of the two elements UWB MIMO antenna (version 2). It can be noticed that the H-plane radiation pattern is omnidirectional meanwhile; the E-plane

**Fig. 5** Simulated far field directivity (E-plane and H-Plane) of the two elements UWB MIMO antenna (version 1)

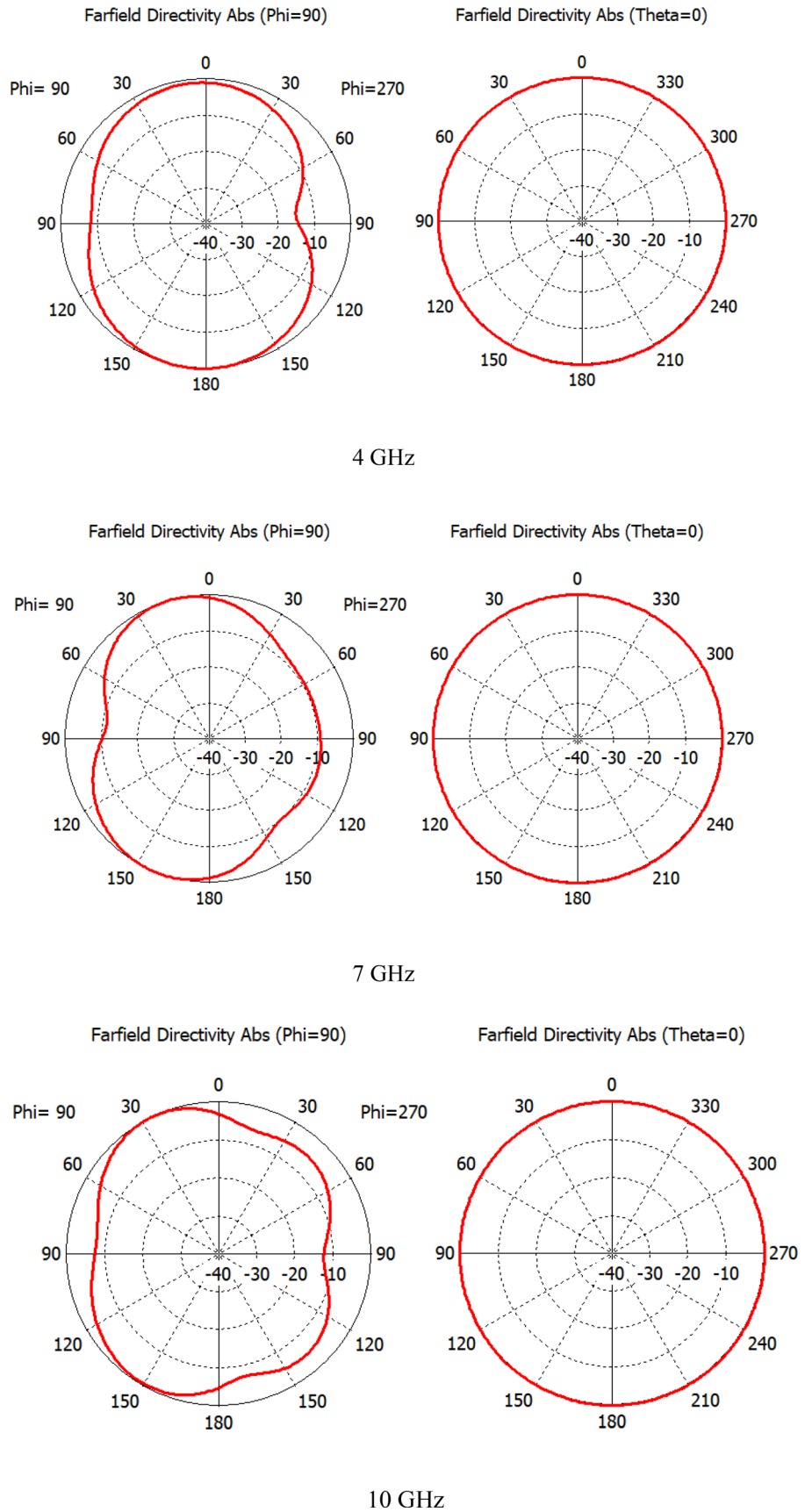
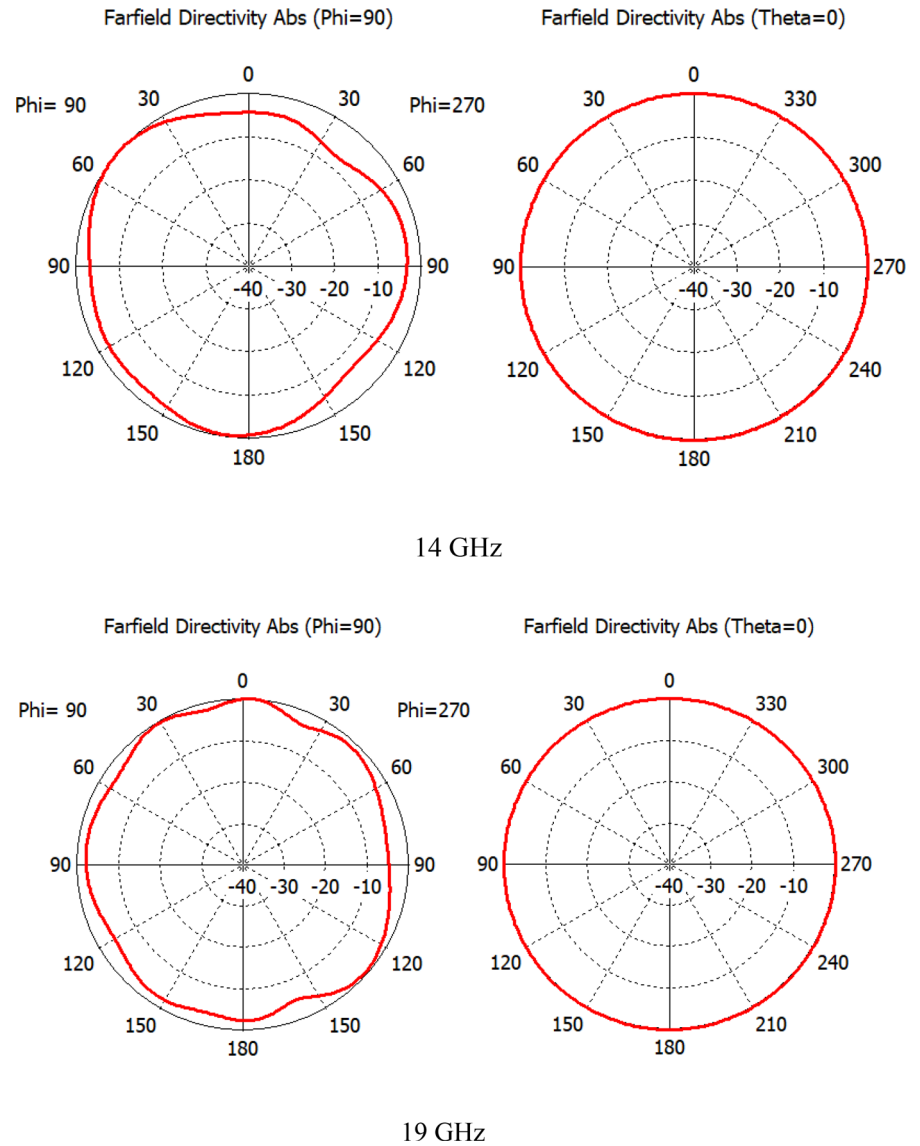


Fig. 5 continued



radiation pattern has a deformed 8-shape.

Table 5 shows the radiation parameters of the two elements UWB MIMO antenna (version 2). Maximum realized gain is got at 10 GHz. Radiation efficiency measured in dB is negative since it is lower than 100%.

### 3 Experimental results

Antennas have been fabricated using the PCB milling machine LPKF ProtoMat S100. 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.





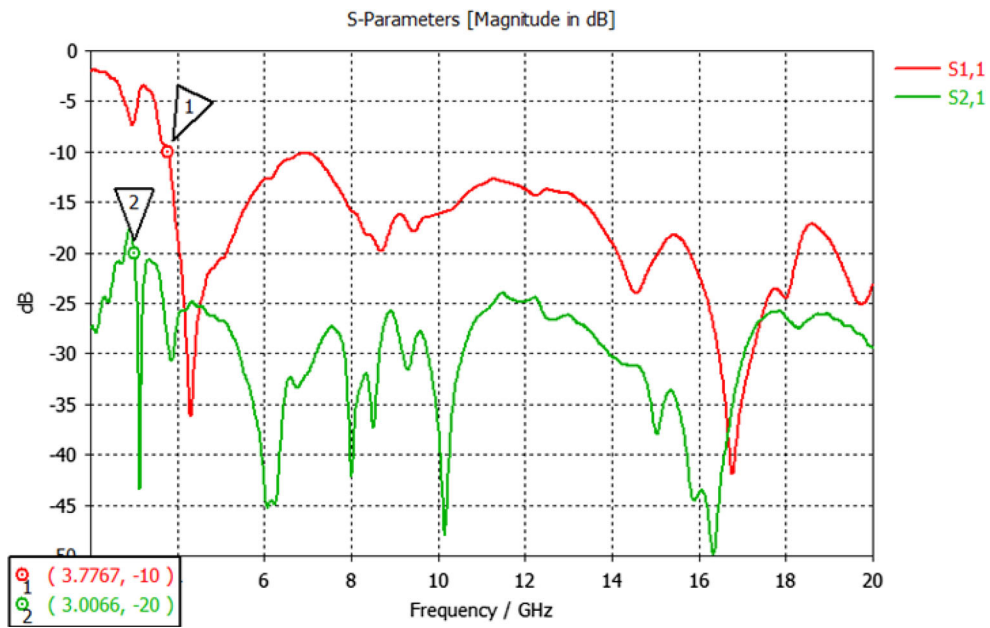


Fig. 7 Simulated S11 of the two elements UWB antenna (version 2)

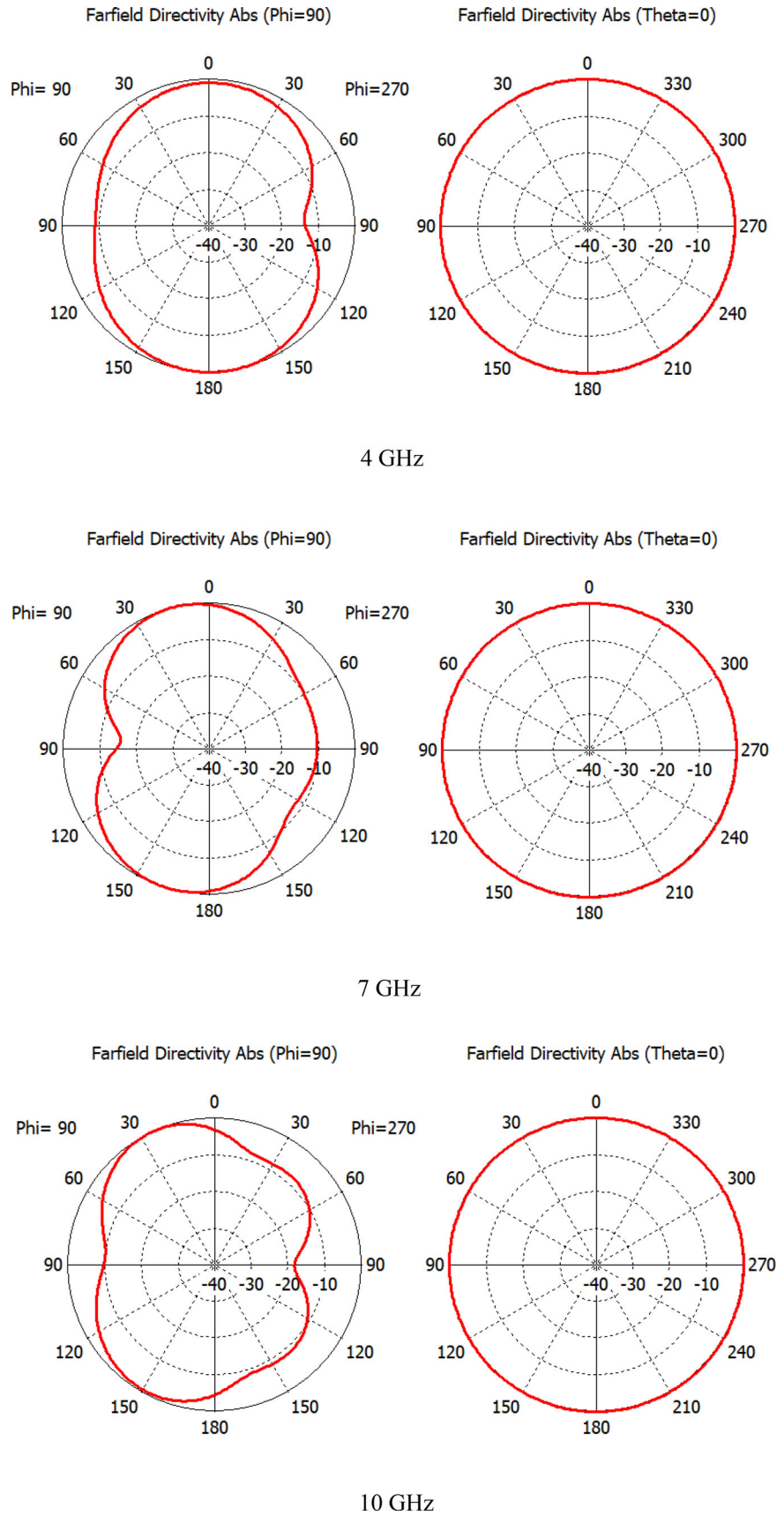
$$ECC = \frac{|s_{11}^* s_{12} + s_{21}^* s_{22}|^2}{|1 - (|s_{11}|^2 + |s_{21}|^2)| |1 - (|s_{12}|^2 + |s_{22}|^2)|} \tag{1}$$

Figure 14 shows the ECC of the two elements UWB MIMO antenna (version 1). It can be seen that it has value lower than 0.001 at the band 3 GHz up to 20 GHz.

Figure 15 shows the Diversity Gain of the two elements UWB MIMO antenna (version 1). It can be seen that it has value very near to 10 dB at the band 3 GHz up to 20 GHz.

Figure 16 shows the Channel Capacity Loss (CCL) of the first version of the two elements UWB MIMO antenna. CCL has a maximum value of 0.396 bps/Hz at 3 GHz. At other frequencies, it has a value lower than 0.3 bps/Hz. The maximum accepted value of CCL is 0.4 bps/Hz.

**Fig. 8** Simulated far field directivity (E-plane and H-Plane) of the two elements UWB MIMO antenna (version 2)



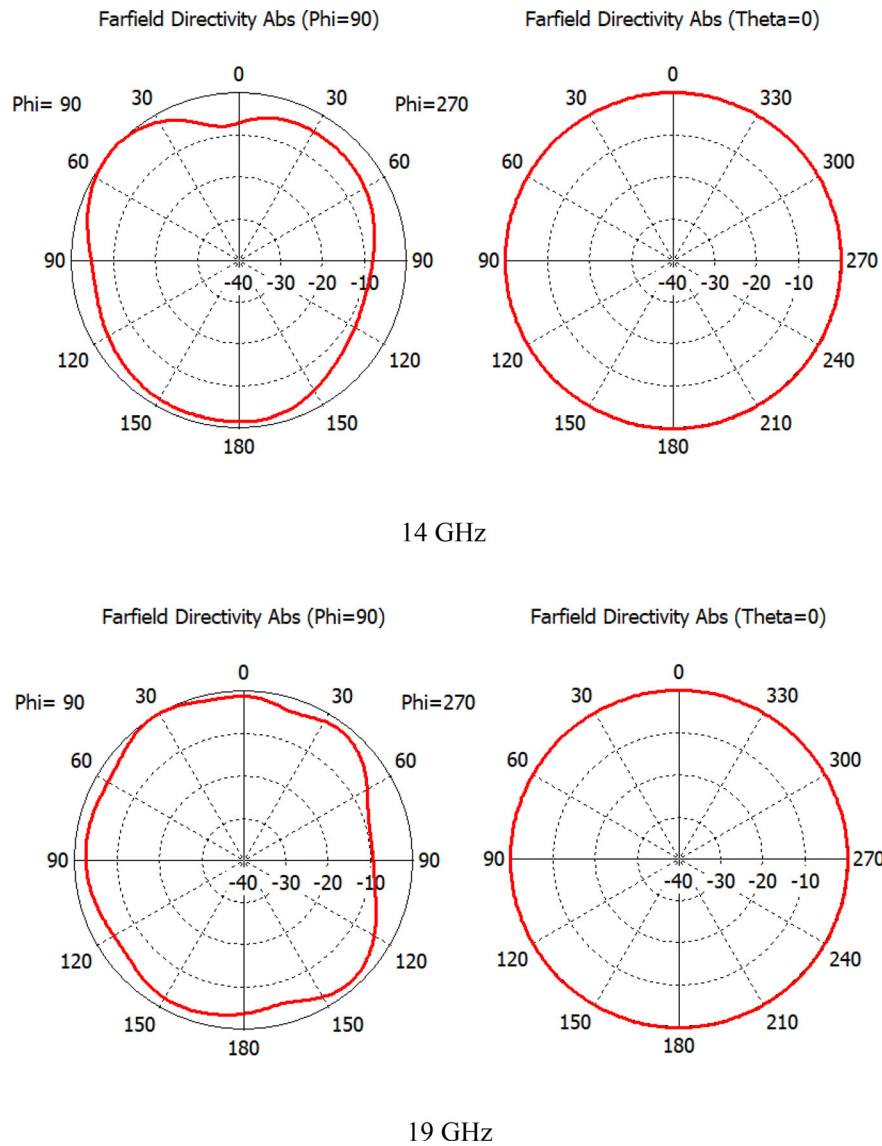


Fig. 8 continued

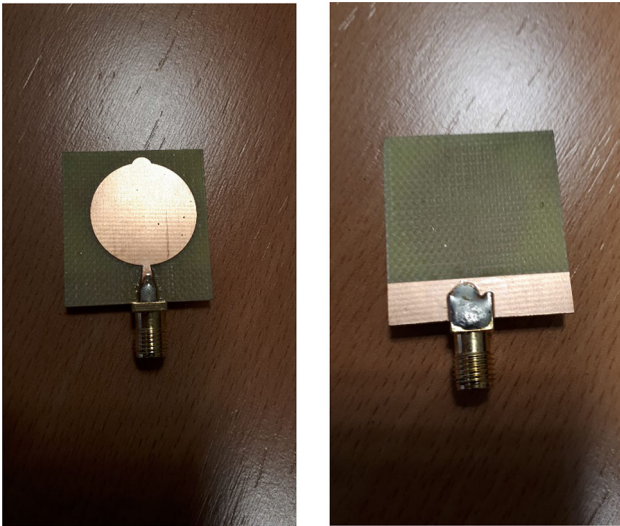
To measure the group delay of the first version of the two elements UWB MIMO antenna, two antennas are placed face to face at a distance between them of 30 cm. Figure 17 shows the measured group delay of the two

elements UWB MIMO antenna. It can be seen that the group delay fluctuates around 1.2 ns.

Figure 18 shows the measured radiation pattern of the two elements MIMO antenna at three frequencies. It can be

**Table 5** Radiation parameters of the two elements UWB MIMO antenna (version 2)

| Parameter                 | 4 GHz    | 7 GHz    | 10 GHz  | 14 GHz  | 19 GHz  |
|---------------------------|----------|----------|---------|---------|---------|
| Directivity (dBi)         | 4.180    | 5.037    | 6.601   | 5.474   | 7.194   |
| Radiation efficiency (dB) | − 0.7492 | − 0.8281 | − 1.104 | − 1.399 | − 2.208 |
| Gain (dBi)                | 3.4308   | 4.2089   | 5.497   | 4.075   | 4.986   |
| Total efficiency (dB)     | − 0.8237 | − 1.273  | − 1.211 | − 1.457 | − 2.277 |
| Realized Gain (dBi)       | 3.3563   | 3.764    | 5.39    | 4.017   | 4.917   |

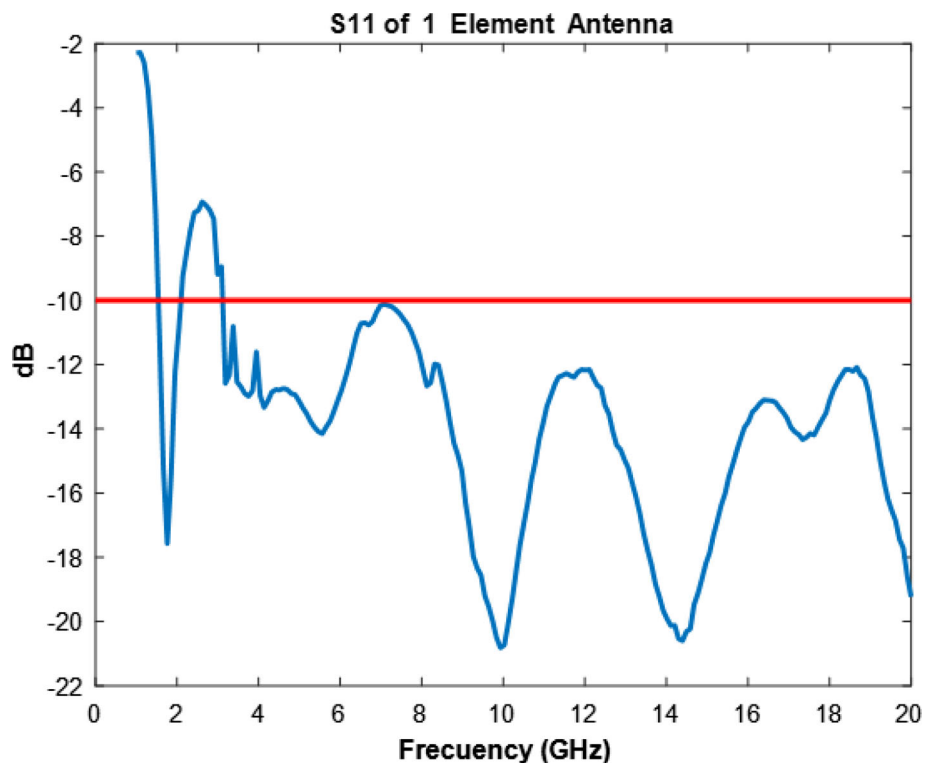


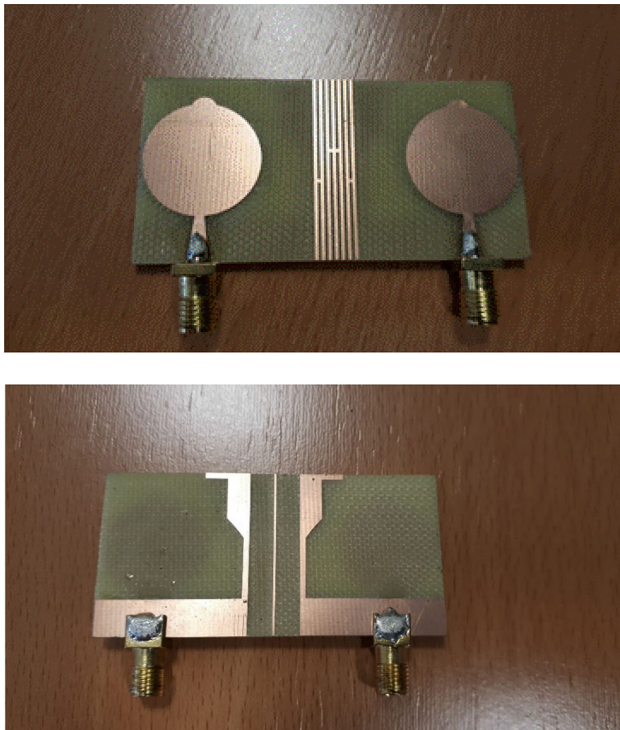
**Fig. 9** Photograph of the fabricated single element UWB antenna

seen that the H-plane radiation pattern is almost omnidirectional and that the E-plane radiation pattern has two minima at almost 90 and 270 degrees.

To measure the UWB MIMO antenna time-domain characteristics, two identical antennas were used as the receiving device (Rx) and transmitting device (Tx) to construct the time-domain simulation scene. The distance between the two antennas is 300 mm, which satisfies the far-field radiation conditions. The signal source uses a modulated Gaussian pulse, and the corresponding spectrum is 3.0–11 GHz. Figure 19 shows the time-domain impulse response of the two elements UWB MIMO antenna where

**Fig. 10** Measured S11 of the single element UWB antenna





**Fig. 11** Photograph of the fabricated two elements UWB MIMO antenna (version 1)

the normalized amplitudes of the transmitted and received pulses are presented. The fidelity factor is 85%.

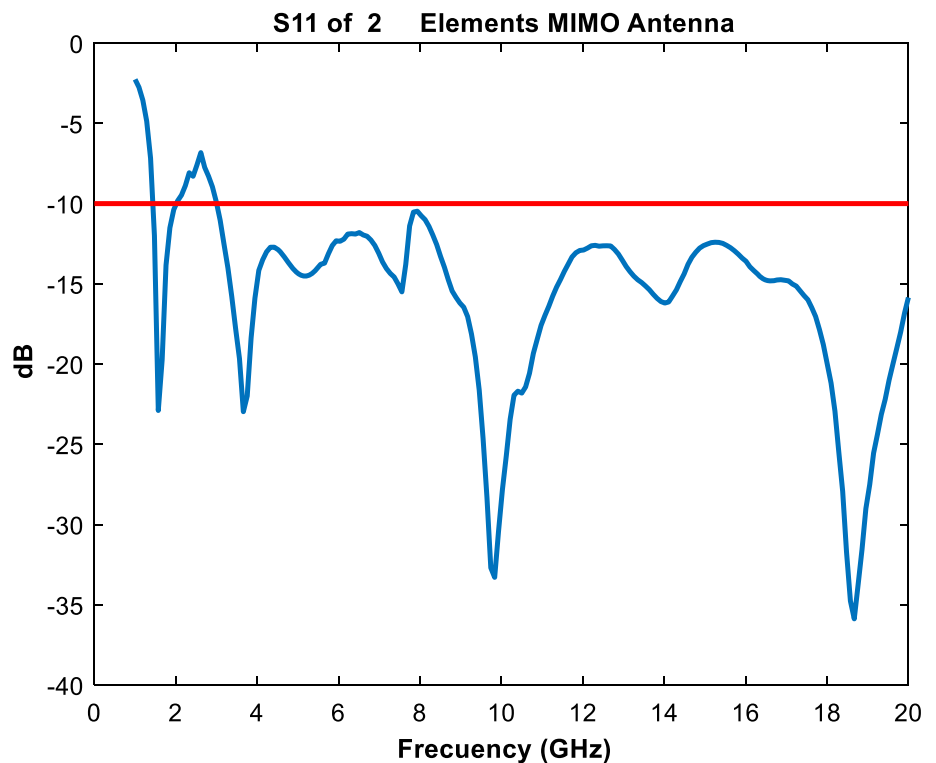
Figure 20 shows a photograph of the two sides of the fabricated two element UWB MIMO antenna (version 2).

Figure 21 shows the measured S11 of the two elements UWB MIMO antenna (version 2). It can be seen that S11 is lower than  $-10$  dB at the band that extends from 3.1 GHz up to 20 GHz covering almost all of the classical UWB band and beyond.

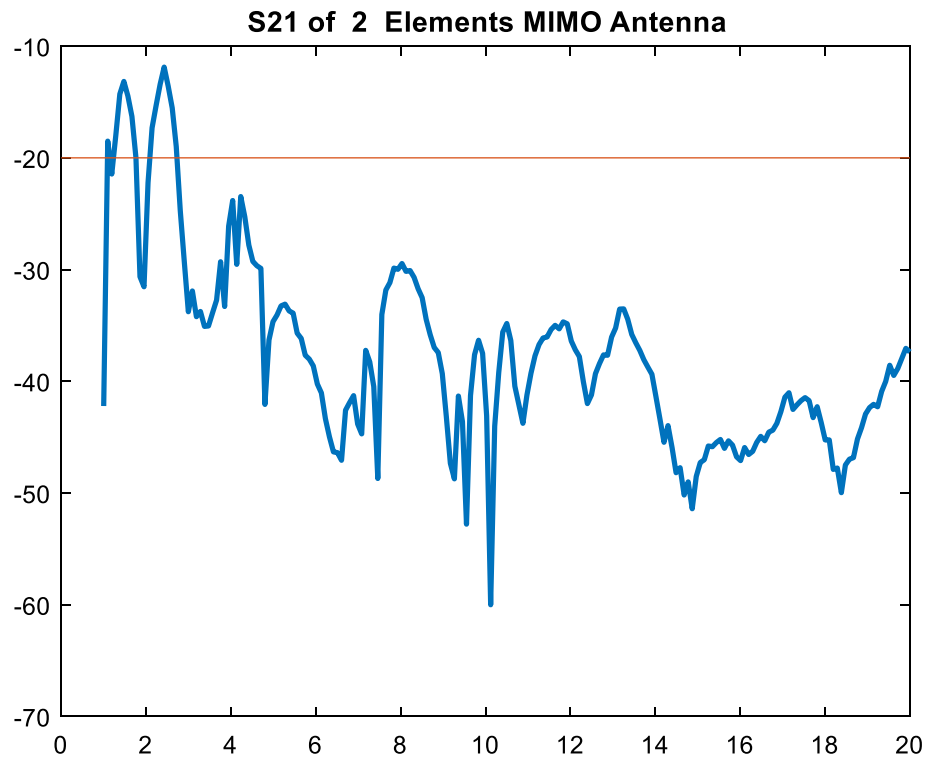
Figure 22 shows the measured S21 of the two elements UWB MIMO antenna (version 2). It can be seen that S21 is lower than  $-20$  dB at the band that extends from 1.7 GHz up to 20 GHz. In addition, it can be seen that, S21 is lower than  $-30$  dB at the band that extends from 3.05 GHz up to 20 GHz.

The ECC of the two elements UWB MIMO antenna (version 2) has value lower than 0.00012 at the band 3 GHz up to 20 GHz. The Diversity Gain of the two elements UWB MIMO antenna (version 2) has value very near to 10 dB at the band 3 GHz up to 20 GHz. The Channel Capacity Loss (CCL) of the second version of the two elements UWB MIMO antenna has a maximum value of 0.325 bps/Hz at 3 GHz. At other frequencies, it has a value

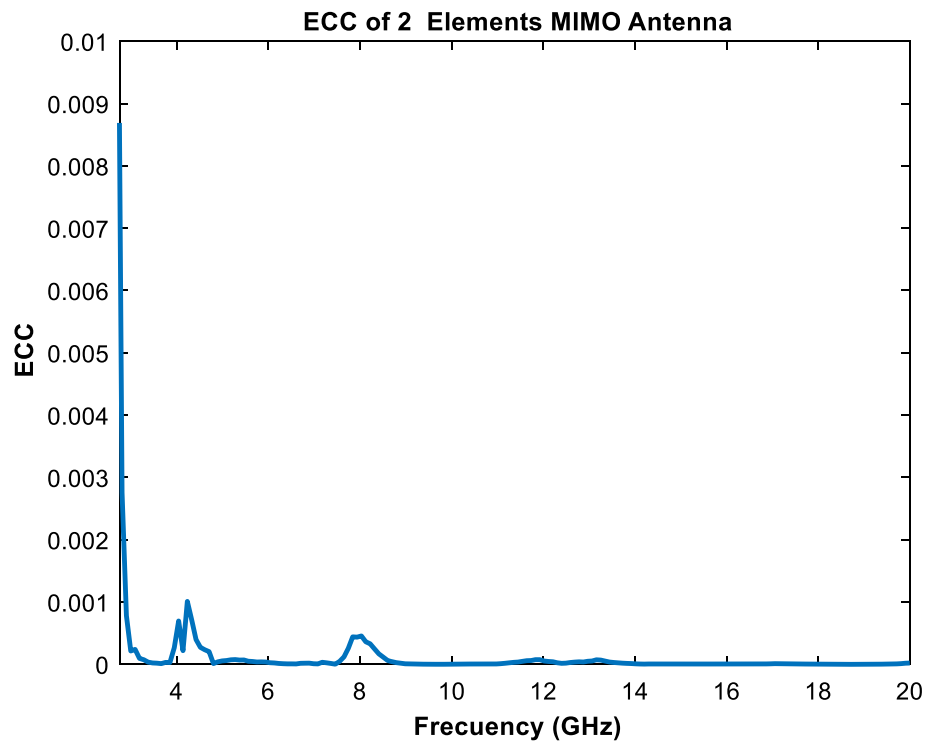
**Fig. 12** Measured S11 of the two elements UWB MIMO antenna (version 1)



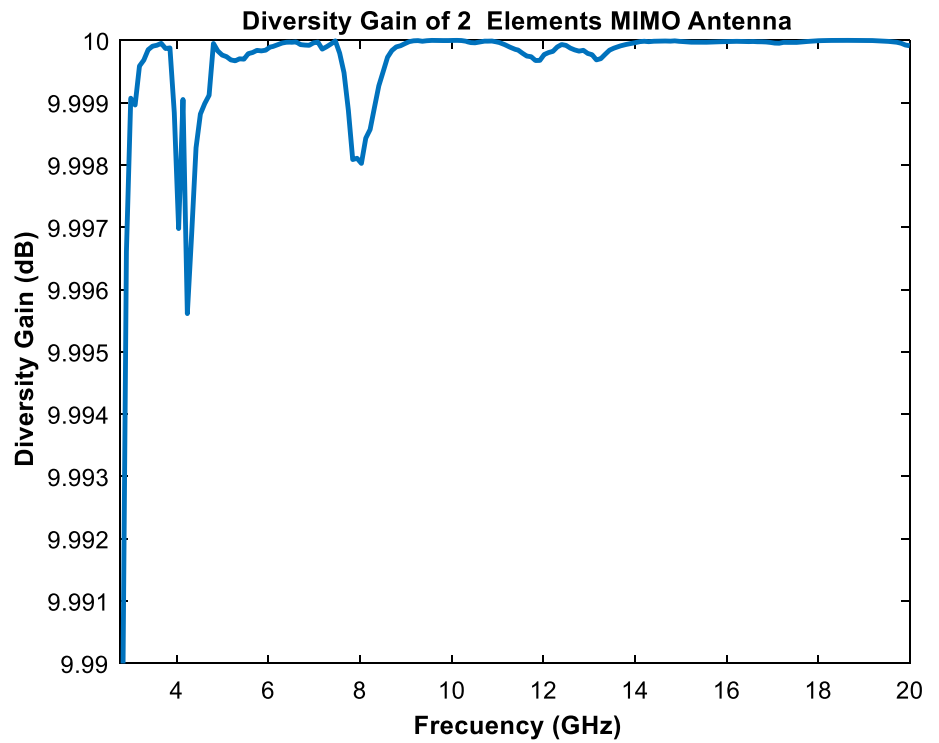
**Fig. 13** Measured  $S_{21}$  of the two elements UWB MIMO antenna (version 1)



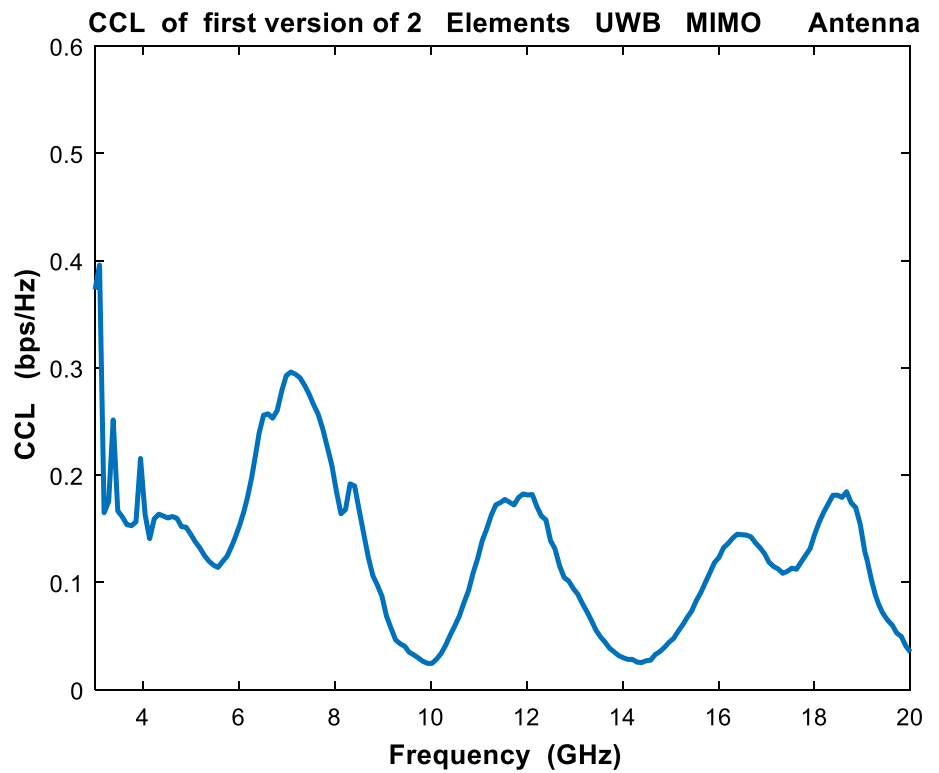
**Fig. 14** ECC of the two elements UWB MIMO antenna (version 1)

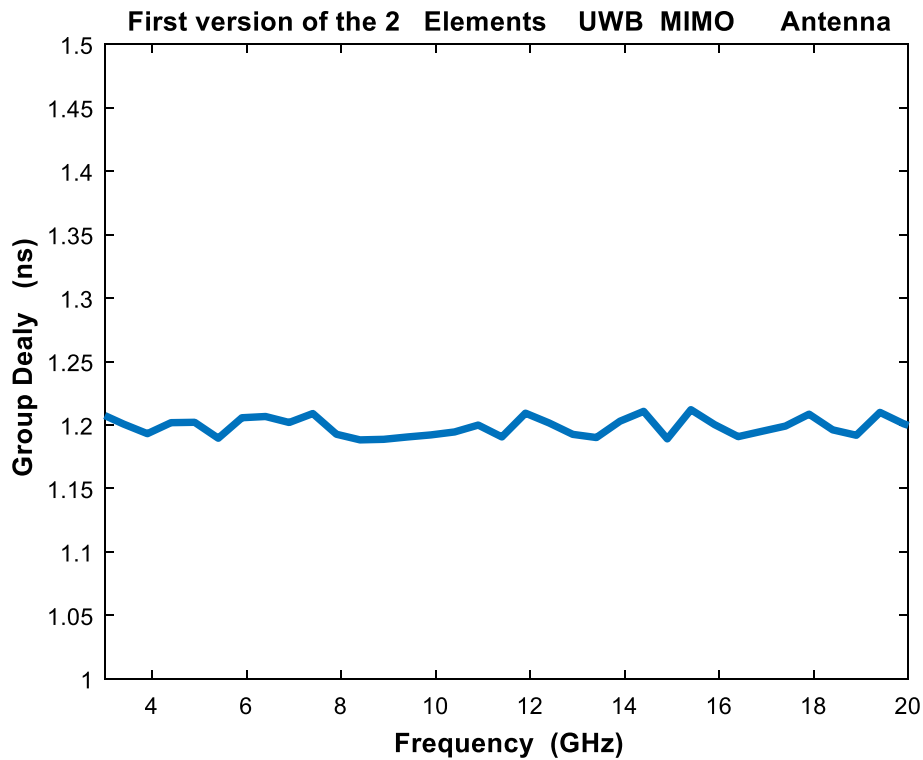


**Fig. 15** Diversity Gain of the two elements UWB MIMO antenna (version 1)



**Fig. 16** Channel Capacity Loss (CCL) of the first version of the two elements UWB MIMO antenna (version 1)



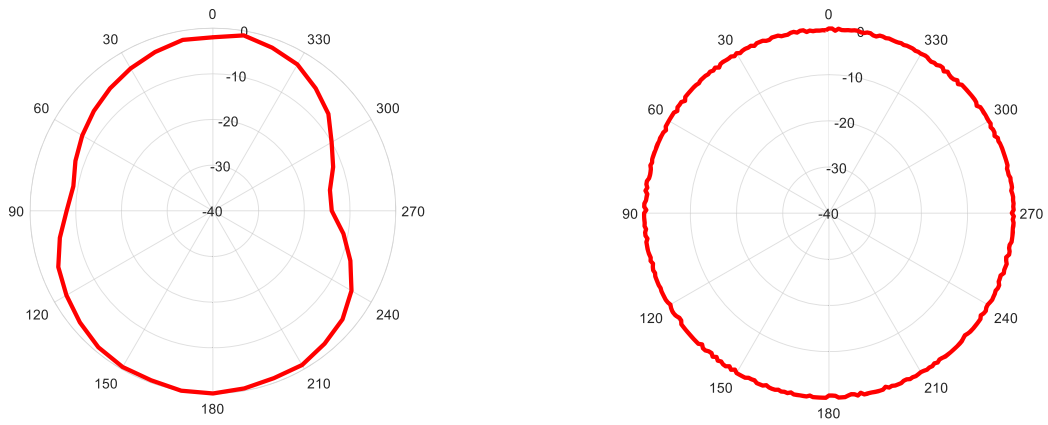


**Fig. 17** Measured group delay of first version of the two elements UWB MIMO antenna (version 1)

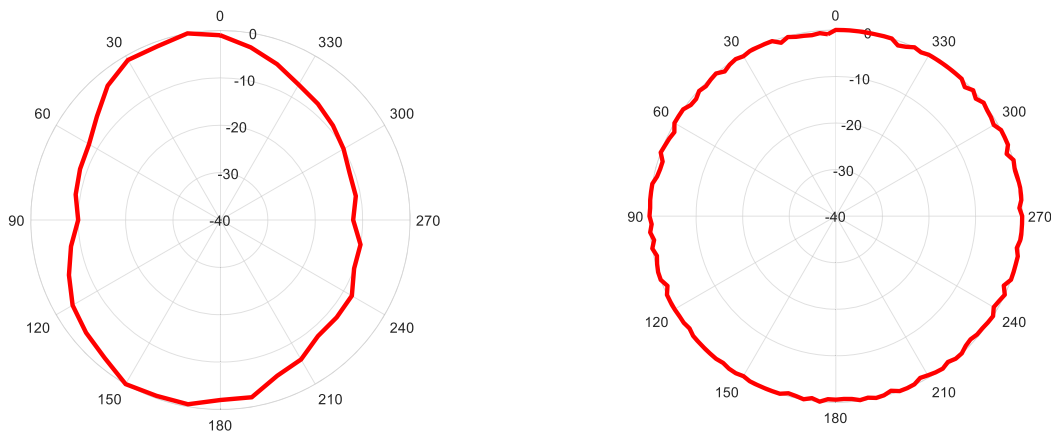
lower than 0.23 bps/Hz. To measure the group delay of the second version of the two elements UWB MIMO antenna, two antennas are placed face to face at a distance between them of 30 cm. The measured group delay of the two elements UWB MIMO antenna has a small fluctuates around 1.2 ns.

Figure 23 shows the measured radiation pattern of the two elements MIMO antenna at three frequencies. It can be seen that the H-plane radiation pattern is almost omnidirectional and that the E-plane radiation pattern has two minima at almost 90 and 270 degrees.

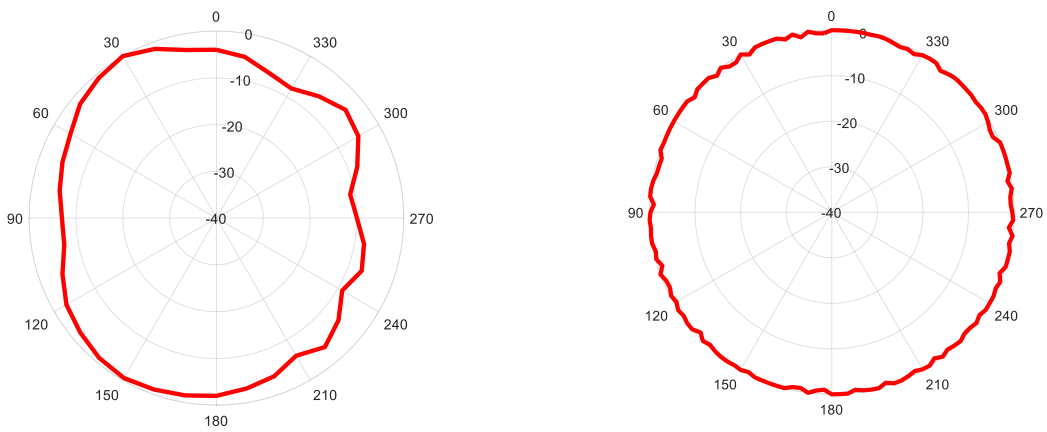




E-plane and H-plane radiation patterns at 4 GHz



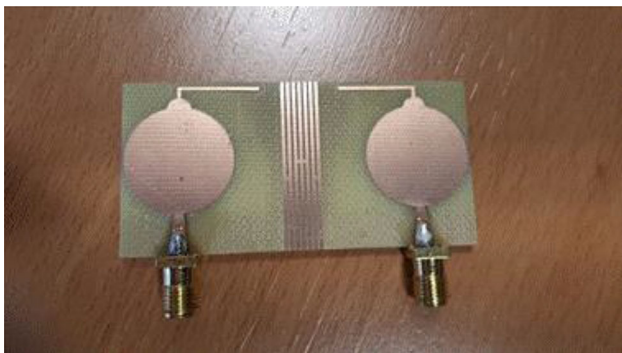
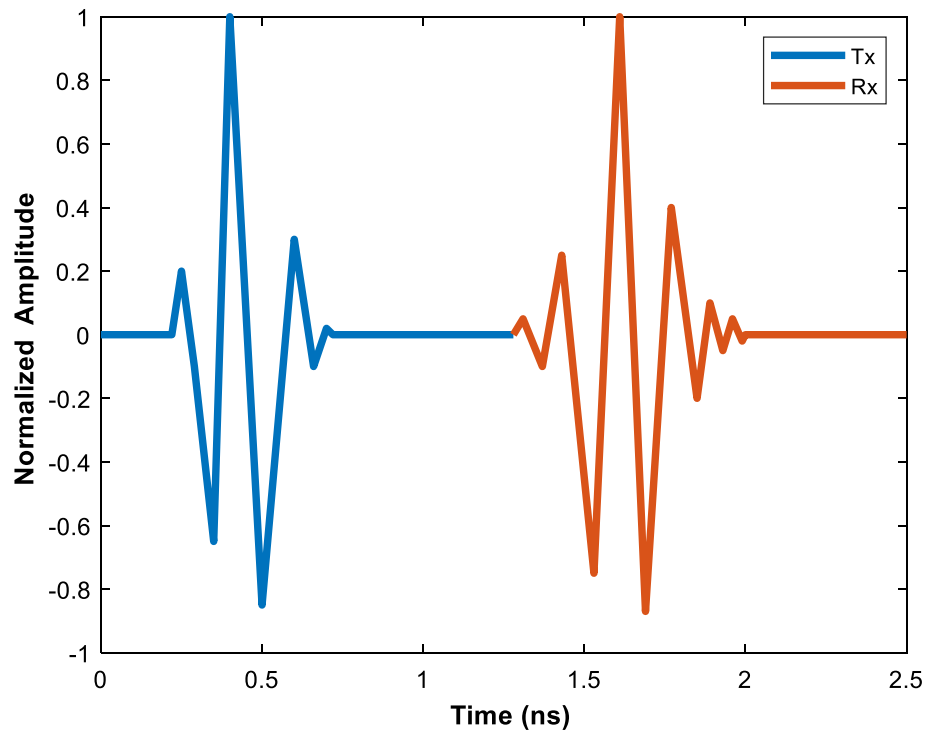
E-plane and H-plane radiation patterns at 7 GHz



E-plane and H-plane radiation patterns at 10 GHz

Fig. 18 Measured radiation pattern of the two elements MIMO antenna at three frequencies

**Fig. 19** Time-domain impulse response of the two elements UWB MIMO antenna (version 1)



**Fig. 20** Photograph of the two sides of the fabricated two element UWB MIMO antenna (version 2)

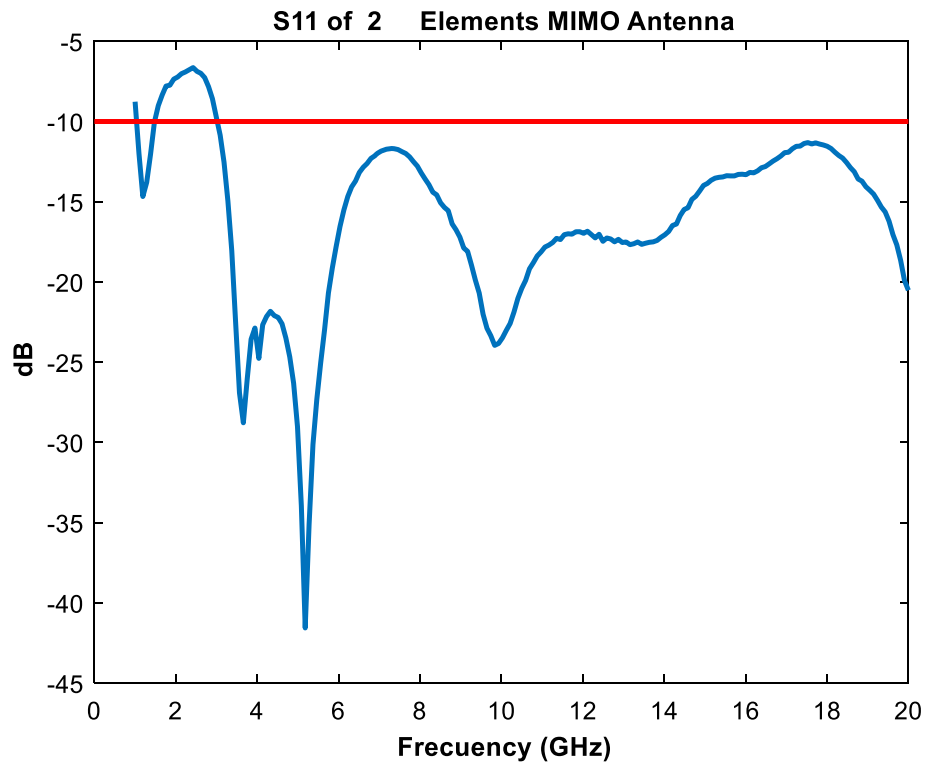
Figure 24 shows the time-domain impulse response of the two elements UWB MIMO antenna (version 2). Here, also the fidelity factor is 83%.

A comparison of the designed structures and previously designed structures is given in Table 6. It can be noticed that, the our first MIMO antenna (version 1) has a very good isolation and wider working band. Also, it can be noticed that our second MIMO antenna (version 2) has wider working bands and higher isolation between ports in comparison with all other antennas represented in Table 6.

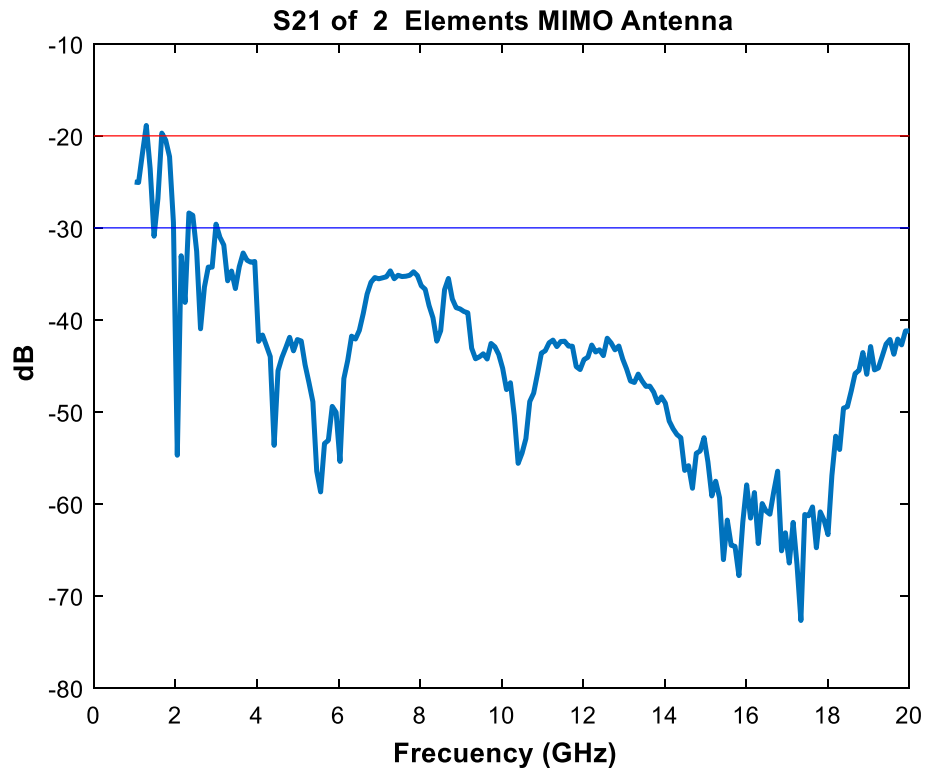
## 4 Conclusions

In this article, two elements (with two versions) compact UWB MIMO antennas are designed and fabricated. CST software is used in the simulation process. Measured S parameters show that the MIMO antennas work well from 3 GHz up to 20 GHz (maximum working frequency of the measurement instruments). The two elements MIMO antennas have a size of  $29.5 \times 60 \text{ mm}^2$ . Measurement results show that the isolation among the antenna elements is higher than

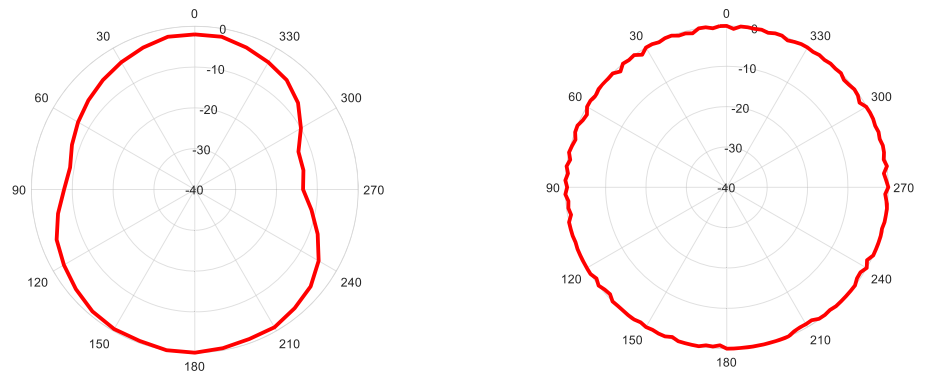
**Fig. 21** Measured  $S_{11}$  of the two elements UWB MIMO antenna (version 2)



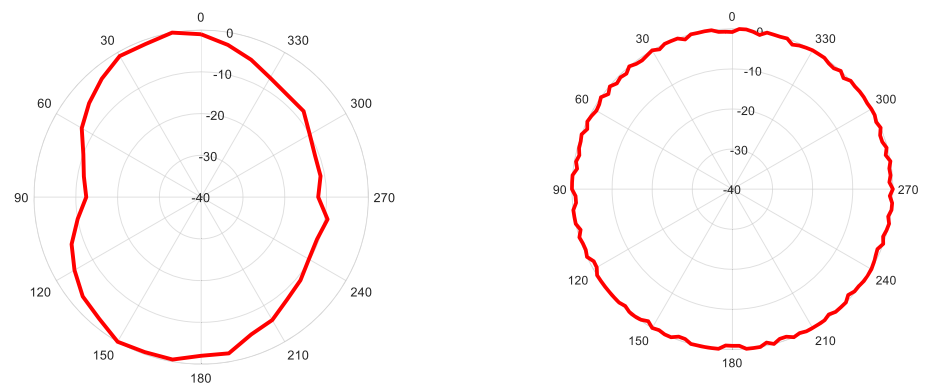
**Fig. 22** Measured  $S_{21}$  of the two elements UWB MIMO antenna (version 2)



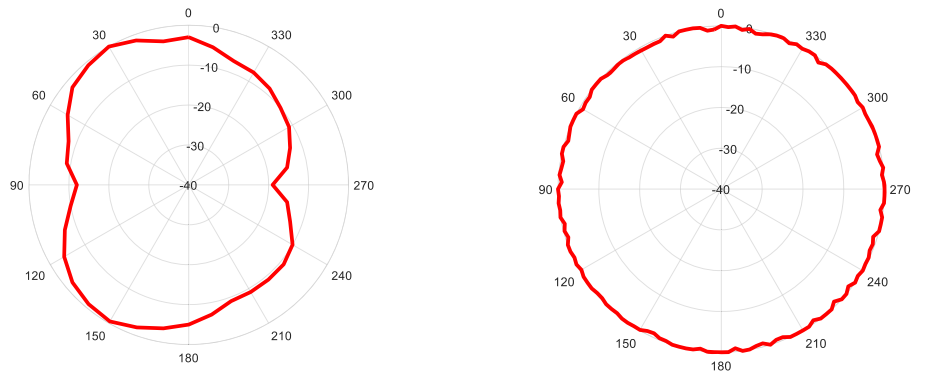
**Fig. 23** Measured radiation pattern of the two elements MIMO antenna (version 2) at three frequencies



E-plane and H-plane radiation patterns at 4 GHz

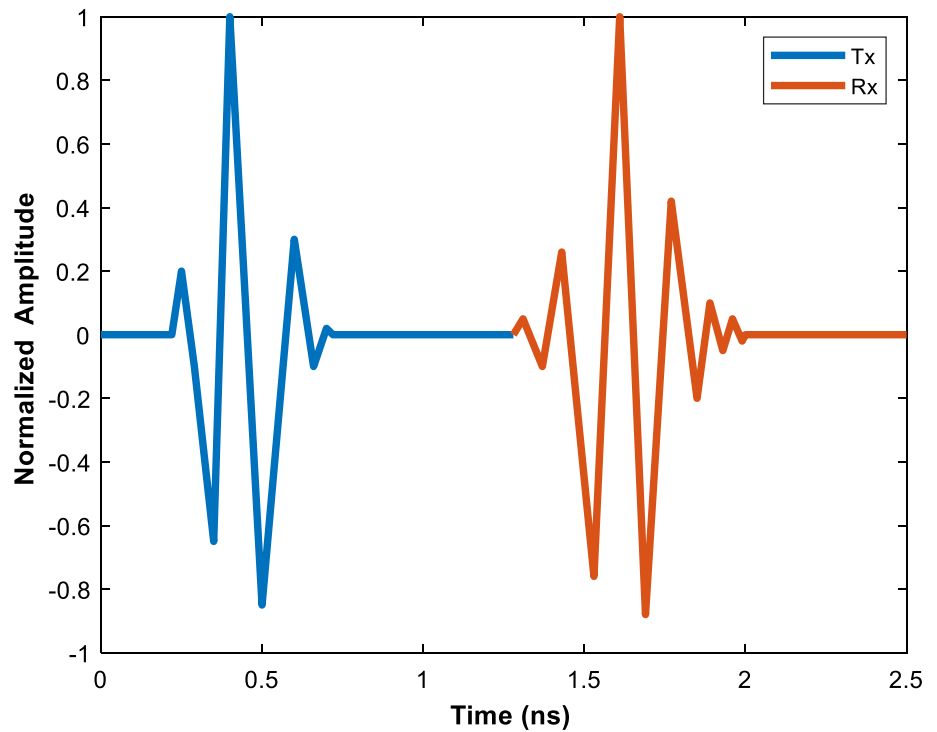


E-plane and H-plane radiation patterns at 7 GHz



E-plane and H-plane radiation patterns at 10 GHz

**Fig. 24** Time-domain impulse response of the two elements UWB MIMO antenna (version 2)



**Table 6** Comparison with previously designed MIMO antenna

| Reference             | Working band (GHz) | Isolation (dB) |
|-----------------------|--------------------|----------------|
| 20                    | 1.9–14.0           | < 20           |
| 21                    | 2.5–11.0           | < 20           |
| 22                    | 2.5–13.0           | < 20           |
| 23                    | 3.0–11.0           | < 25           |
| 24                    | 2.7–11.0           | < 20           |
| 30                    | 3.1–10.6           | < 15           |
| 31                    | 3.1–10.6           | < 13           |
| 32                    | 3.1–10.6           | < 17           |
| 33                    | 3.1–10.6           | < 11           |
| 34                    | 2.5–11.0           | < 15           |
| This work (version 1) | 2.7–20.0           | < 23           |
| This work (version 2) | 3.1–20.0           | < 30           |

23 dB for the first version of the two elements UWB MIMO antenna. In addition, measurement results show that the isolation between the antenna elements is higher than 30 dB for the second version of the two elements UWB MIMO antenna.

**Funding** Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. No funding has been received.

**Data availability** All data generated or analyzed during this study are included in this published article.

## 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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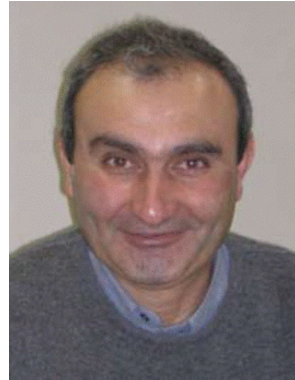
## References

- Federal Communications Commission. (2002). Federal Communications Commission revision of Part 15 of the commission's rules regarding ultra-wideband transmission systems. FCC, Washington, DC, First Report and Order FCC, 02. V48
- Sturm, C., Porebska, M., Timmermann, J., & Wiesbeck, W. (2007, September). Investigations on the applicability of diversity techniques in ultra wideband radio. In 2007 International Conference on Electromagnetics in Advanced Applications (pp. 899–902). IEEE.
- Rajagopalan, A., Gupta, G., Konanur, A. S., Hughes, B., & Lazzi, G. (2007). Increasing channel capacity of an ultrawideband MIMO system using vector antennas. *IEEE Transactions on Antennas and Propagation*, 55(10), 2880–2887.
- Ben, I. M., Talbi, L., Nedil, M., & Hettak, K. (2012). MIMO-UWB channel characterization within an underground mine gallery. *IEEE Transactions on Antennas and Propagation*, 60(10), 4866–4874.
- Lee, J. M., Kim, K. B., Ryu, H. K., & Woo, J. M. (2012). A compact ultrawideband MIMO antenna with WLAN band-rejected operation for mobile devices. *IEEE Antennas Wireless Propagation Letter*, 11, 990–993.
- Hong, S., Chung, K., Lee, J., Jung, S., Lee, S. S., & Choi, J. (2008). Design of a diversity antenna with stubs for UWB applications. *Microwave and Optical Technology Letters*, 50(5), 1352–1356.
- Zhang, S., Ying, Z. N., Xiong, J., & He, S. L. (2009). Ultrawideband MIMO/diversity antennas with a tree-like structure to enhance wideband isolation. *IEEE Antennas Wireless Propagation Letter*, 8, 1279–1282.
- See, T. S. P., & Chen, Z. N. (2009). An ultrawideband diversity antenna. *IEEE Trans. Antennas Propagation*, 57(6), 1597–1605.
- Pouyanfar, N., Ghobadi, C., Nourinia, J., Pedram, K., & Majidzadeh, M. (2018). A compact multi-band MIMO antenna with high isolation for C and X bands using defected ground structure. *Radioengineering*, 27(3), 686–693.
- Liu, P., Sun, D., Wang, P., & Gao, P. (2018). Design of a dual-band MIMO antenna with high isolation for WLAN applications. *Progress In Electromagnetics Research Letters*, 74, 23–30.
- Tao, J. (2016). Quan yuan Feng, “Compact isolation-enhanced UWB MIMO antenna with band-notch character.” *Journal of Electromagnetic Waves and Applications*, 30(16), 2206–2214.
- Jaglan, N., Gupta, S. D., Thakur, E., Kumar, D., Kanaujia, B. K., & Srivastava, S. (2018). Triple band notched mushroom and uniplanar EBG structures based UWB MIMO/Diversity antenna with enhanced wide band isolation. *AEU-International Journal of Electronics and Communications*, 90, 36–44.
- Mewara, H. S., Jhanwar, D., Sharma, M. M., & Deegwal, J. K. (2018). A printed monopole ellipzoidal UWB antenna with four band rejection characteristics. *AEU-International Journal of Electronics and Communications*, 83, 222–232.
- Sharma, M., Dhasarathan, V., & Pateld, S. K. (2020). Truong Khang Nguyenb”, An ultra-compact four-port 4×4 superwide-band MIMO antenna including mitigation of dual notched bands characteristics designed for wireless network applications”. *AEU - International Journal of Electronics and Communications*. <https://doi.org/10.1016/j.aeue.2020.153332>, August
- Khorramizadeh, M., & Mohammad-Ali-Nezhad, S. (2021). Radar cross-section reduction of an UWB MIMO antenna using image theory and its equivalent circuit model. *International Journal of RF and Microwave Computer-Aided Engineering*. <https://doi.org/10.1002/mmce.22563>
- Abdulkawi, W. M., Malik, W. A., Rehman, S. U., Aziz, A., Sheta, A. F. A., & Alkanhal, M. A. (2021). Design of a compact dual-band MIMO antenna system with high-diversity gain performance in both frequency bands. *Micromachines*. <https://doi.org/10.3390/mi12040383>
- Ahmed, B. T., Olivares, P. S., Campos, J. L. M., & Vazquez, F. M. (2018). (3.1–20) GHz MIMO Antennas. *AEU - International Journal of Electronics and Communications*, 94, 348–358.
- Ahmed, B. T., Carreras, D. C., & Marin, E. G. (2021). Design and implementation of super wide band triple band-notched MIMO antennas. *Wireless Personal Communications*, 121, 2757–2778.
- Khalid, M., Naqvi, S. I., Hussain, N., Rahman, M., Mirjavadi, S. S., Khan, M. J., & Amin, Y. (2020). 4-Port MIMO antenna with defected ground structure for 5G millimeter wave applications. *Electronics*, 9, 71. <https://doi.org/10.3390/electronics9010071>
- Wang, M., Nan, J., & Liu, J. (2021). High-isolation UWB mimo antenna with multiple x-shaped stubs loaded between ground planes. *International Journal of Antennas and Propagation*, 2021, 1155471.
- Saleem, S., Kumari, S., Yadav, D., & Bhatnagar, D. (2020). A High Isolation UWB-MIMO Antenna with Dual Band Rejection Property. In 2020 IEEE International Conference on Computing, Power and Communication Technologies (GUCON) (pp. 212–216). IEEE.
- Wang, L., Du, Z., Yang, H., Ma, R., Zhao, Y., Cui, X., & Xi, X. (2019). Compact UWB MIMO antenna with high isolation using fence-type decoupling structure. *IEEE Antennas and Wireless Propagation Letters*, 18(8), 1641–1645.
- Malekpour, N., & Honarvar, M. A. (2016). Design of high-isolation compact MIMO antenna for UWB application. *Progress in Electromagnetics Research C*, 62, 119–129.
- Ibrahim, A. A., & Ali, W. A. (2022). High isolation 4-element ACS-fed MIMO antenna with band notched feature for UWB communications. *International Journal of Microwave and Wireless Technologies*, 14(1), 54–64.
- Addepalli, T., Babu Kamili, J., Kumar Bandi, K., Nella, A., & Sharma, M. (2022). Lotus flower-shaped 4/8-element MIMO antenna for 5G N77 and N78 band applications. *Journal of*

*Electromagnetic Waves and Applications*. <https://doi.org/10.1080/09205071.2022.2028683>

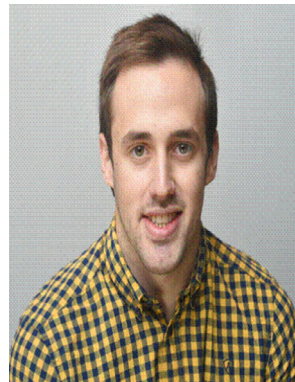
26. Sharma, M., Vashist, P. C., Alsukayti, I., Goyal, N., Anand, D., & Mosavi, A. H. (2021). A wider impedance bandwidth dual filter symmetrical MIMO antenna for high-speed wideband wireless applications. *Symmetry*, *14*(1), 29.
27. Hadda, L., Sharma, M., Gupta, N., Kumar, S., & Singh, A. K. (2021). On-demand reconfigurable WiMAX/WLAN UWB-X band high isolation 2 x 2 MIMO antenna for imaging applications. *IETE Journal of Research*. <https://doi.org/10.1080/03772063.2021.1986153>
28. Sharma, M., Singh, S., & Varma, R. (2021). Computational design, analysis and characterization of beetle shaped high isolation multiple-input-multiple-output reconfigurable monopole-antenna with dual band filters for wireless applications. *Wireless Personal Communications*, *119*(2), 1029–1049.
29. Sharma, M., Vashist, P. C., Ashtankar, P. S., & Mittal, S. K. (2021). Compact  $2 \times 2/4 \times 4$  tapered microstrip feed MIMO antenna configuration for high-speed wireless applications with band stop filters. *International Journal of RF and Microwave Computer-Aided Engineering*. <https://doi.org/10.1002/mmce.22500>
30. Najam, A., Duroc, Y., & Tedjni, S. (2011). UWB-MIMO antenna with novel stub structure. *Progress In Electromagnetics Research C*, *19*, 245–257.
31. Mondal, S., Mandal, K., & Sarkar, P. P. (2018). Design of MIMO antenna for ultra-wideband applications. *IETE Journal of Research*, *64*, 497–502.
32. Haq, M. A. U., & Kozie, S. (2018). Ground plane alterations for design of high-isolation compact wideband MIMO antenna. *IEEE Access*, *6*, 48978–48983.
33. Jehangir, S. S., & Sharawi, M. S. (2017). A miniaturized UWB biplanar yagi-like MIMO antenna system. *IEEE Antennas and Wireless Propagation Letters*, *16*, 2320–2323.
34. Lin, G.-S., Sung, C.-H., Chen, J.-L., Chen, L.-S., & Houg, M.-P. (2017). Isolation improvement in UWB MIMO antenna system using carbon black film. *IEEE Antennas and Wireless Propagation Letters*, *16*, 222–225.

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