A Wideband High Front-to-Back Ratio Directional Filtering Slot Antenna and its Application in MIMO Terminals

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***Abstract* –** In this paper, a directional filtering slot antenna with a wideband high front-to-back (F/B) ratio is proposed, which aims to improve the anti-interference capability of the unit antenna in the spatial and frequency domains and reduce the coupling between MIMO units. The fundamental structure of this antenna is a transformed defective ground slot antenna, featuring superior filtering attributes in the frequency domain. To achieve a wideband F/B, boost the directional characteristics, and further augment the anti-interference capabilities of the filtering slot antenna, the leading terminal and slot are, respectively, integrated into the filtering antenna. A 2×2 MIMO antenna ensemble is also designed, utilizing the directional filtering slot antenna as the element. This antenna not only exhibits commendable filtering proficiency across the frequency and spatial domains but also effectively inhibits the surface wave and space wave coupling between MIMO antenna units. The simulated and measured results show that the operating bandwidth of the directional filtering slot antenna is 2.8-11.3 GHz, the F/B of the radiation pattern is larger than 15 dB, and the isolation between the 2×2 MIMO antenna units is greater than 20 dB without any decoupling structure.

***Index Terms* –** Directional antenna, front-to-back (F/B) ratio, slot antenna.

I. INTRODUCTION

Ultra-wideband (UWB) slot antennas have received extensive attention and research because of their simple structure, good plasticity, and low cost, such as the miniaturization of slot antennas [1–4], the filtering techniques of slot antennas [5–7], MIMO technology [8], the reconfigurability of slot antennas [9], and the band-edge selectivity of slot antennas [10]. All the above works expand the types and applications of slot antennas and play an important role in the development of slot antennas.

This paper provides an in-depth exploration of the unidirectional radiation of slot antennas, which plays a crucial role in improving the radiation power and anti-interference ability of antennas in specific applications. Furthermore, studying the unidirectional radiation characteristics of slot antennas holds significant value in advancing and refining slot antenna technology for MIMO terminals.

As a consequence, unidirectional antennas have already attracted much attention in recent years and antennas with directional characteristics have been reported. In [11], a unidirectional antenna with a high front-to-back (F/B) ratio of 10 dB in operating frequency 2.00-3.06 GHz is presented. However, the measured bandwidth of the proposed antenna is only 41.9%. In [12], the antenna, which uses defected ground structure (DGS) and a parasitic slot near the stepped slot,

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has achieved good out-of-band rejection and sharp cut-off at band-edge. Nevertheless, the actual average gain is less than 2.5 dB. In [13], two asymmetrical slits in the ground plane of the slot antenna are designed to decrease the back-lobe and enhance radiation directivity. The F/B ratio of the referenced antenna is better than 10 dB, however, the size of the antenna is 105 mm×120 mm, which is too large to integrate with other UWB devices. In addition, some designs have also been proposed to achieve directional radiation patterns by employing a large ground plane as frequency selective surface placed below the antenna element [14–15]. Still, the frequency selective surface is relatively large and it is not easy to integrate with other devices. More importantly, this method is suitable for narrowband antennas, and it is difficult to apply in UWB antennas [16].

In this paper, a compact filtering slot antenna with enhanced directional radiation characteristics and a 2×2 MIMO antenna is proposed. Different from other slot antennas reported in the literature [2–11], a slot antenna with good filtering ability and wide-band directional property has been developed in this work. The unit antenna performs a stable directional radiation pattern over an UWB (3-11 GHz), and the compact size is 29×27 mm (0.96×0.9λ_g). The measurements indicate that both the reflection coefficient and gain curve of the antenna demonstrate outstanding band-edge selectivity performance, and out-of-band suppression feature. The F/B ratio of the slot antenna exceeds 15 dB, which attests to its desirable directivity in the expansive operating bandwidth it covers. The MIMO antenna, in turn, exhibits superb isolation performance, without necessitating any additional decoupling structures, with a maximum isolation that fares above 20 dB in the operating band.

II. ANTENNA STRUCTURE

Figure 1 shows the final structure diagram of the 2-D MIMO antenna, which consists of two slot antennas with

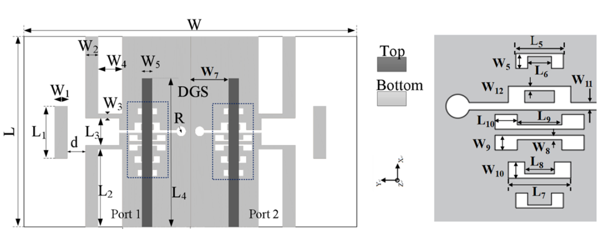
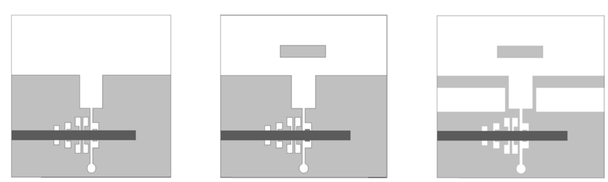


Fig. 1. Configuration of the compact wideband filtering antenna. $L_1 = 8$, $L_2 = 12.5$, $L_3 = 4.2$, $L_4 = 22$, $L_5 = 3.2$, $L_6 = 1.6$, $L_7 = 4.2$, $L_8 = 2$, $L_9 = 3$, $L_{10} = 1.5$, $W_1 = 2$, $W_2 = 2$, $W_3 = 0.65$, $W_4 = 4$, $W_5 = 2$, $W_6 = 2$, $W_7 = 6$, $W_8 = 0.3$ mm, $W_9 = 1$ mm, $W_{10} = 1.1$, $W_{11} = 0.5$, $W_{12} = 0.2$, $R = 0.8$, and $d = 3$ (unit: mm).

directional and filtering characteristics that are placed back-to-back. The proposed antenna was printed on an RT/duroid 5880 substrate of thickness h = 0.787 mm and relative permittivity $\varepsilon_r = 2.2$. The size of the proposed MIMO antenna is 29×54 mm. The directional filtering slot antenna has good suppression ability of space waves and surface waves. On the one hand, the filtering characteristics and directional characteristics of the MIMO unit antenna can achieve better anti-interference ability in the frequency domain and space domain. On the other hand, the coupling of surface waves and space waves between antenna elements can be effectively suppressed, and good isolation of the 2-D MIMO antenna can be accomplished without adding any decoupling structure.

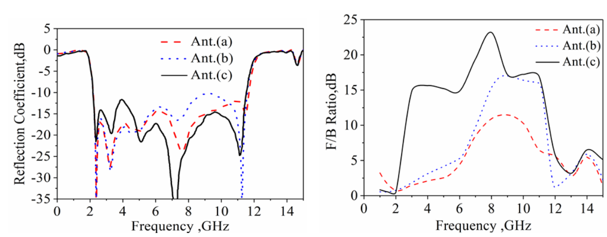
A. Single filtering antenna with wideband high F/B characteristics

The evolution process of the filtering slot antenna with wideband high F/B characteristics is depicted in Fig. 2 and the corresponding reflection coefficients and F/B ratio are shown in Fig. 3. The basic structure of the single antenna is a modified defective ground slot antenna [12], which exhibits good filtering characteristics in the frequency domain, as seen in Fig. 3 (a). Figure 3 (b) demonstrates the F/B ratio curve of the unmodified Ant.(a) slot antenna. It can be observed from Fig. 3 (b) that Ant.(a) shows a high F/B ratio in the frequency range of 8-10 GHz, whereas the F/B ratio is lower in the 3-7 GHz frequency range. To obtain better directivity of the filter slot antenna in a wide band, a



(a) (b) (c)

Fig. 2. Evolution of the single filtering antenna with wideband high F/B characteristics.



(a) (b)

Fig. 3. (a) Reflection coefficients and (b) F/B ratio of the single filtering antenna in Fig. 2.

passive terminal and a pair of rectangular slots are introduced on the Ant.(a), named Ant.(b) and Ant.(c), as illustrated in Figs. 2 (b) and (c), respectively. It can be seen from Fig. 3 (b) that Ant.(b), which introduces passive termination, achieves a significant improvement in the ratio of F/B at 8-11 GHz, compared to Ant.(a). Ant.(c), which introduces a pair of rectangular slots, achieves an overall improvement in the ratio of F/B at 2-12 GHz compared to the previous two antennas, and the ratio of F/B is more than 15 dB. In addition, the introduction of slots on both sides of the Ant.(c) does not have a negative impact on the sideband selection characteristics and in-band impedance of the slot antenna, as shown in Fig. 3 (a).

Figure 4 (a) gives the current distribution of Ant.(a) at a low frequency of 4 GHz and a high frequency of 9 GHz before the improvement. It can be seen from Fig. 4 (b) that, compared to low frequency, the lead terminal has a more obvious influence on the current distribution of high frequency. The current distribution of the slot antenna near the lead terminal and in the direction of the opening is significantly enhanced. To further enhance the F/B ratio and directivity of the filtering slot antenna at low frequencies (3-7 GHz), a pair of rectangular slots are etched on both sides of the slot antenna as seen in Fig. 2 (c). It is observed from Fig. 4 (c) that well-designed rectangular slots can reduce the distribution of low-frequency current on both sides of the slot antenna and enhance the current intensity of the slot antenna at the low-frequency band along the X-direction, thus increasing the distribution of low-frequency current on the main vibrator.

In this paper, there are many parameters: we take d and L_1 as examples. The specific parameters are analyzed as follows. The length of the active array of the slit antenna is L_1, the length of the passive array is L_2, and the distance between the passive terminals and the active array is d. In order to form a strong directivity, the lead antenna oscillator spacing should not be too large, and it is generally $d/\lambda < 0.4$. The effects of the distance between the arrays and the length of the oscillators on the F/B ratio are shown in Fig. 5.

Figure 6 shows the changes in the E-plane and H-plane of the normalized pattern before and after the improvement of the slot antenna at low and high frequencies. It can be seen from Fig. 5 (a) that the passive terminal has little effect on the radiation pattern at low frequency (4 GHz), but it has a more obvious effect on the radiation pattern at high frequency (9 GHz). After adding the passive terminal, the back lobe of the slot antenna in the high-frequency pattern is reduced, and the maximum F/B ratio of the pattern is more than 15 dB, as shown in Fig. 5 (b). This further shows that the passive terminal can enhance the directivity of the

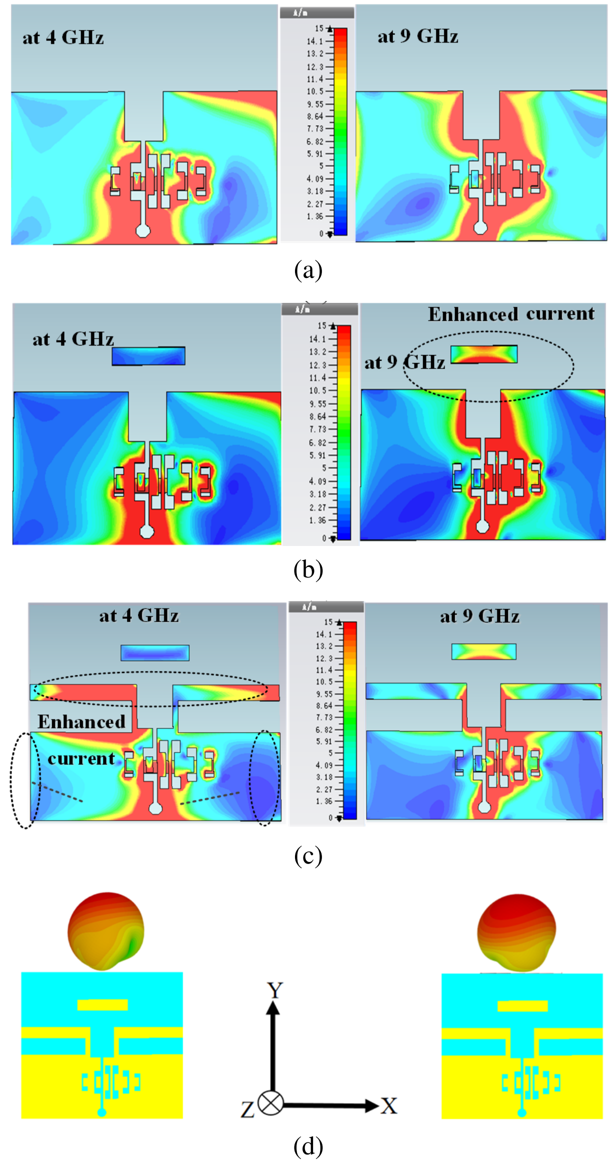


Fig. 4. Current distributions (a), (b), (c) at 4 GHz and 9 GHz of the slot antenna Ant.(a), Ant.(b), and Ant.(c) in Fig. 2. Main vibrator (d), (e) at 4 GHz and 9 GHz of the slot antenna Ant.(c).

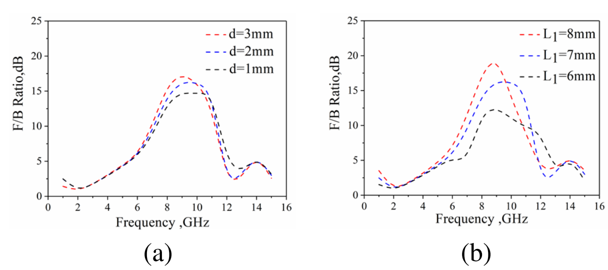
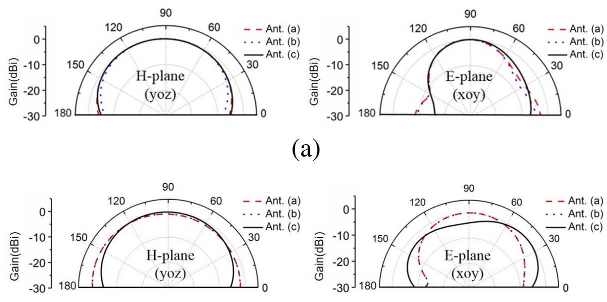


Fig. 5. Effects of the distance between the arrays and the length of the oscillator on F/B ratio (a) d and (b) L_1.



(a)

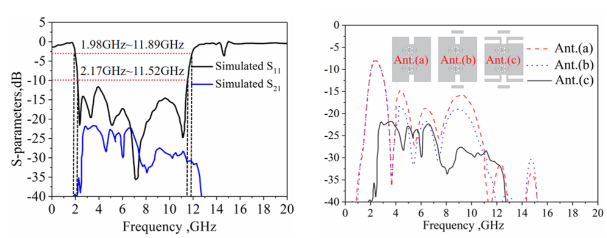
(b)

Fig. 6. Effects of the passive terminal and rectangular slots on radiation pattern at (a) 4 GHz and at (b) 9 GHz.

slot antenna at high frequencies and has the function of guiding electromagnetic waves to propagate in a certain direction.

B. 2×2 MIMO antenna designed using directional filtering slot antenna as the element

In this design, two modified directional slot antennas are placed back-to-back, and the directivity of the directional slot antennas is used to achieve pattern diversity. Good isolation between MIMO antenna units can be achieved without using complex decoupling structures, as seen in Fig. 1. Figure 7 shows the simulated reflection coefficient and isolation of the UWB slot MIMO antenna. It can be seen from Fig. 7 (a) that the working bandwidth of the slot MIMO antenna is 2.8-11.2 GHz, which meets the application range of UWB. At the same time, due to the good filtering characteristics of the antenna unit, it shows obvious advantages in out-of-band harmonic suppression and coupling suppression. Furthermore, the MIMO slot antenna has high isolation ($S_{21}<-20$ dB) in the working frequency band without adding any decoupling structures. To further prove the element antenna orientation characteristics and wide F/B ratio have a significant effect on coupling suppression,



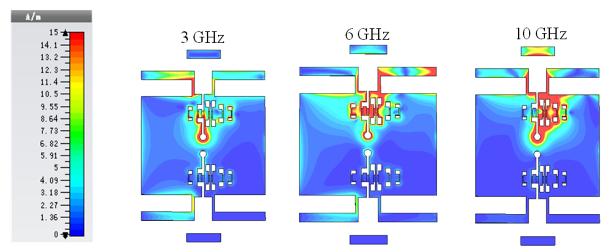
(a)

(b)

Fig. 7. (a) Simulated S-parameters of the proposed MIMO slot antenna and (b) simulated transmission coefficient of antenna Ant.(a), Ant.(b) and Ant.(c) placed back-to-back.

Figs. 3, 6, and 7 (b) show the relationship among the F/B ratio, antenna orientation characteristics, and isolation S_{21} of the MIMO antenna. It can be seen from Fig. 7 (b) that Ant.(c) has the greatest the F/B ratio, the strongest direction, and the best isolation between the two unit antennas.

To better illustrate the effect on coupling between the MIMO slot antennas after adding lead terminals and slots, Fig. 8 shows the current distributions of the UWB slot MIMO antenna at 3 GHz, 6 GHz, and 10 GHz, respectively. In the MIMO filtering slot antenna, one of the ports is excited and the other is terminated with a 50 Ω load. It can be seen that when Port 1 adds incentives and Port 2 connection load, the current of each frequency point is mainly distributed in the upper half, and the lower part is small. Current distributions of the MIMO slot antenna are in agreement with the simulation S_{21} in Fig. 7. It is also proven that the MIMO slot antenna with a well-designed filtering directional element can enhance isolation of the proposed design.

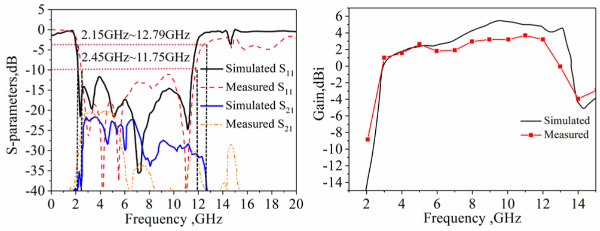


(a) (b) (c)

Fig. 8. Current distribution of the UWB MIMO slot antenna in different frequency bands: (a) 3 GHz, (b) 6 GHz, and (c) 10 GHz.

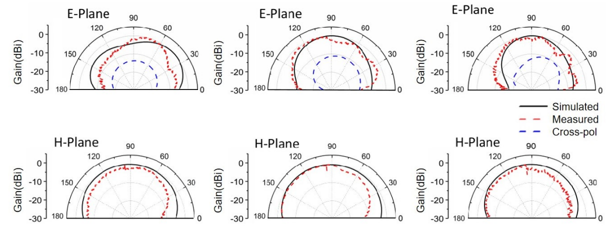
III. RESULTS AND DISCUSSION

To further verify the effectiveness of the directional filtering slot antenna, the design was processed and measured. Figure 9 illustrates the measured and simulated results of the presented antenna. It can be seen in Fig. 8 (a) that the experimental reflection coefficient S_{11} is far below -10 dB within 2.8-11.3 GHz (120%), exhibiting desirable sideband selection property. In addition, clear out-of-band suppressions can be also found through the low band (0-2 GHz) and high band (13-20 GHz). Meanwhile, according to equation (1), the rectangularity coefficient K of the antenna has a simulated value of 1.059 and a measured value of 1.144, both of which are close to 1 (shown Figs. 9 (a) and 7). The above results show that the antenna has excellent band-edge selectivity and out-of-band rejection characteristics. The resonance point at 15 GHz is mainly caused by the coupling of the radiation slot and DGS and does not affect the performance of the



(a) (b)

Fig. 9. (a) Measured and simulated reflection coefficient and (b) measured and simulated gain.



(a) (b) (c)

Fig. 11. Measured radiation patterns at (a) 3.0 GHz, (b) 6 GHz, and (c) 10 GHz.

antenna. As can be seen in Fig. 8 (b), the maximum gain of the antenna is 5.5 dBi, and efficiency is greater than 80% in the operating band. Furthermore, compared with references [2–5,11–14], the antenna shows better filtering performance.

$$K = \frac{BW_{-3dB}}{BW_{-10dB}}. \tag{1}$$

Figure 10 shows the simulated and measured results of the F/B ratio of the antenna. It can be seen from Fig. 9 that the measured results of the F/B ratio agree well with the simulation results. In addition, the measured F/B ratio is greater than 15 dB in a wide bandwidth (114%), which means that the proposed design has outstanding directional characteristics.

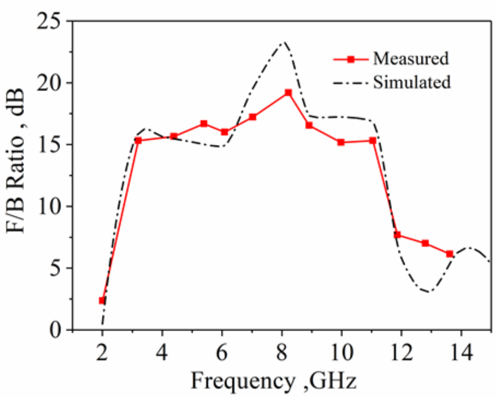


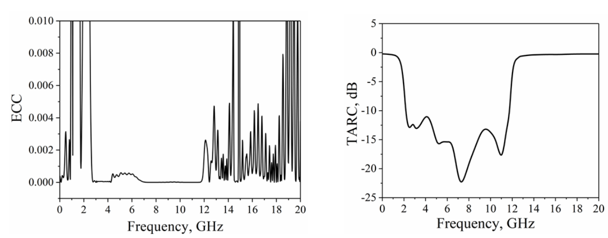
Fig. 10. Measured and simulated F/B ratio of the antenna radiation pattern.

Figure 11 plots the simulated and measured far-field radiation patterns of the directional filtering slot UWB antenna in the E-plane (XOY-plane) and H-plane (YOZ-plane) at 3.0 GHz, 6 GHz, and 10 GHz, respectively. The cross-polarization radiation patterns at three points in the E-plane are also shown. From the radiation pattern, it can be observed that the experimental measurements are in good agreement with the simulation results, and the performance of the proposed design is acceptable over the operating frequency band. The plots also reveal the unidirectional radiation characteristics of the antenna. In addition, the cross-polarization level on the E-plane at 3 GHz, 6 GHz, and 10 GHz are less than 20 dB.

For a MIMO antenna, ECC is a parameter describing the degree of correlation between MIMO antenna channels and is an important indicator for judging whether the MIMO antenna can be applied in a MIMO system. Figure 12 (a) shows the ECC curve calculated by the two-unit MIMO slot antenna. It can be seen from Fig. 12 (a) that the ECC curve corresponds to its reflection coefficient. In the working frequency band, a lower ECC<0.002 illustrates that the antenna has better diversity performance. At the same time, TARC is below -10 dB across the operating frequency band in the Fig. 12 (b), indicating that the designed MIMO antenna exhibits low reflection loss and excellent phase stability, which ensures reliable signal transmission.

In addition, due to the filtering characteristics of the antenna itself, the ECC curves calculated from the S-parameters show obvious differences between in-band and out-of-band, which further illustrates that with the improvement of antenna functionalization requirements in current wireless communication systems. The comprehensive performance of the two-unit MIMO filtering slot antenna in the performance has good competitiveness and application prospects in subsequent UWB system applications.

To highlight the novelty of the proposed design, a comparative study of some other competitive antennas



(a) (b)

Fig. 12. (a) ECC and (b) TARC of the MIMO slot antenna.

is presented in Table 1. Merits of the proposed design can be observed: good bandwidth, band-edge selectivity, out-of-band suppression, and high F/B ratio across the UWB band. This means that the directional filtering slot antenna can suppress out-of-band interference in the frequency domain and interference from other directions in the space domain, which has obvious advantages compared to other broadband antennas.

Table 1: Comparison with reported antennas

Ref.	ε_r	**Size (mm^2)**	**BW$_{-10dB}$ (GHz)**	**Filtering Function**	**F/B (dB)**	**Radiation Bandwidth F/B> 15 dB**
[2]	3.5	8.93×17.9	3.1-11	No	<10	-
[3]	4.4	40×32	3-11	No	<10	-
[4]	3.55	7.5×20	3-20	No	<10	-
[5]	2.2	24×12	3.1-11	Yes	<10	-
[11]	2.55	22×15	3.8-11	No	<10	-
[12]	3.48	55×60	0.689	No	14	-
[13]	4.4	105×135	1.68-3.97, 2.4-4.09	No	>10	-
[14]	3.3	80×90	2.4-2.5, 4.9-5.9	No	>15	13%
This design	2.2	29×27	2.8-11.3 (120%)	Yes	>15	114%

IV. CONCLUSION

In this paper, a directional filtering slot antenna that boasts a wideband high F/B is proposed. Compared to conventional unit cell structures, our proposed antenna facilitates easy design with high-quality filtering and directional features. The unit element's filtering and directional characteristics can be independently adjusted through the use of slot DGS and leading terminal, respectively. Measured results indicate a -10 dB reflection coefficient bandwidth of 2.8-11.3 GHz (120%), displaying significantly better sideband selection characteristics and effective out-of-band suppression. F/B remains above 15 dB with excellent directivity throughout the operational frequency. The simulations and experimental results of the MIMO antenna show good agreement, highlighting the proposed design as an outstanding option for portable UWB communication systems. Furthermore, the lower ECC (ECC<0.002) in the wide working band underscores the antenna's optimal diversity performance.

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