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Compact slot antenna with enhanced band-edge selectivity and switchable band-notched functions for UWB applications

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Abstract: In this study, a new reconfigurable stepped slot antenna with enhanced band-edge selectivity of the UWB passband and switchable band-notched characteristic is presented. Good out-of-band rejection and sharp cut-off at band-edge are achieved by the use of defected ground structure (DGS) and a parasitic slot near the stepped slot. The well-designed DGS not only produces transmission zero to obtain good cut-off property in upper sideband but also provides better impedance matching of in-band. The frequency range of the proposed antenna is from 3.1 to 11.1 GHz (114%) with the reflection coefficient < − 10 dB. The shape factor is 1.05, which indicates that the proposed design has an excellent selectivity. To obtain the notched band, two passive strip lines near the feeding line are designed. Furthermore, the reconfigurable function with four states can be easily realised by the control of two diodes between the passive strip line and the ground. The structures of the notched band and bias circuit are relatively simple and independent of antenna radiation structure. The performance of the antenna is presented and compared with other competitive antennas. The proposed design has many significant advantages in dimension, good out-of-band characteristics, and controllable states for different UWB applications.

1 Introduction

Ultra-wideband (UWB) communication system has achieved an unprecedented improvement since the FCC in the USA designated the 3.1–10.6 GHz operation band for commercial applications [1]. As a key part of the RF front-end in the UWB system, antennas and filters are usually studied and designed as two separate devices [2]. Due to the wide operating band of the UWB system (3.1–10.6 GHz), UWB systems are vulnerable to interference from narrowband signals in the UWB band and other wireless communication systems out of band. The unwanted in-band and out-of-band signals will cause electromagnetic interference on the UWB system. Usually, we avoid the out-of-band interference signals and improve the selectivity of the UWB system by designing a filter with bandpass characteristics at the end of the antenna. However, this method increases the dimension and costs of RF front-end in the UWB system and leads to the loss of insertion between the antenna and filter. [2, 3] Hence, it is a valuable point to propose a filtering UWB antenna to improve the RF front-end performance with compact size and low cost.

Many UWB antennas with good performance have been reported in [3–8]. It is found that the authors are more concerned to the size of structure [3, 4], bandwidth [5, 6], and radiation characteristics of the antenna [7, 8], but little attention is paid to the sideband selection characteristics of antennas and the suppression of out-of-band systems. In [9], an impulse UWB design with good bandpass characteristics is obtained by etching a bandpass filter on the feeding line. However, the filter characteristics of the design are not discussed in detail in the article. The dimension of the design is about 35 × 34 mm. By cascading the feeding line with bandpass filter function with the radiation patch, integrated filter antennas [10, 11] with improved band-edge selectivity are achieved. However, cascaded filter and radiation patch will inevitably increase the size of antenna. The demotions the filter antennas are 53 × 22 [10] and 53 × 42 mm [11], which are bigger than most UWB antennas in [1–9]. In [12], a slot UWB antenna with good band-edge selectivity using stepped impedance resonator feeding line is proposed. Although it plays a key role in improving the upper band-edge selectivity, the low-pass feeding line has a negative effect on radiation efficiency. The radiation efficiency of the referenced antenna in [12] was about 80%. Also, the impedance characteristics in the UWB band are not ideal, and the reflection coefficient of the proposed design is only −10 dB.

To overcome some system signals in the UWB band such as the WiMAX and WLAN operating in the 3.3–3.6, and 5.15–5.825 GHz [5, 6], various notched band techniques are applied in operating band to reject the unwanted signals. The most common techniques were etching various slots on the radiating patch [5, 6, 13, 14] or the ground plane [15, 16], or adding parasitic structure near the feeding line [17–19]. However, all these notch approaches are used for supressing the changeless band of interference signals. No matter whether the interference band exists or not, the notch function is always in operation. In order to solve these problems, several designs with reconfigurable characteristics have been reported [20–22]. When multiple functions are implemented on an antenna through the reconfigurable structures and switches, the reconfigurable antenna becomes more efficient and cost-effective. In [20], band notch characteristics are achieved by etching two modified slots in the radiating patch. Reconfigurability is obtained by controlling the bias statuses of the switches along the slots. In [21], the reconfigurable structure is achieved by adding a PIN diode on the π-shaped slot. When the PIN diode is turned on, the π-shaped slot is divided into two C-shaped slots, and a new resonance frequency is generated at 5–6 GHz. In [22], a reconfigurable UWB antenna with switchable dual band-notches is designed. Three different states at UWB, or the antenna with notched frequencies at WiMAX or WLAN band could be obtained by using five PIN diodes. In [23], a stepped slot antenna with reconfigurable is proposed, due to the loss on the feed microstrip line, the antenna exhibits poor impedance characteristics. In [24], a small slot antenna with switchable frequency bands is designed. Total four switchable states in communicating are designed by the employ of multiple PIN diodes, i.e. 2.8–10.7 GHz in UWB band, 3.2–4.5, 4.3–7.8, and 7.9–11.2 GHz. The improved design of the ladder slot is beneficial to the improvement of the impedance in the slot antenna band and the design of the reconfigurable structure. However, the reconfigurable structure and bias circuit on the radiation patch will have more influence on the antenna.

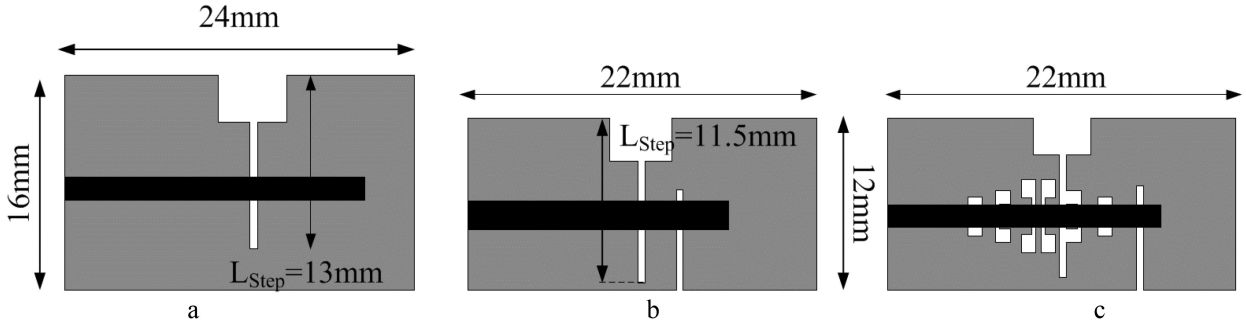

Fig. 1 *Development of the proposed design*
(a) Antenna 1, ***(b)*** Antenna 2, ***(c)*** Antenna 3

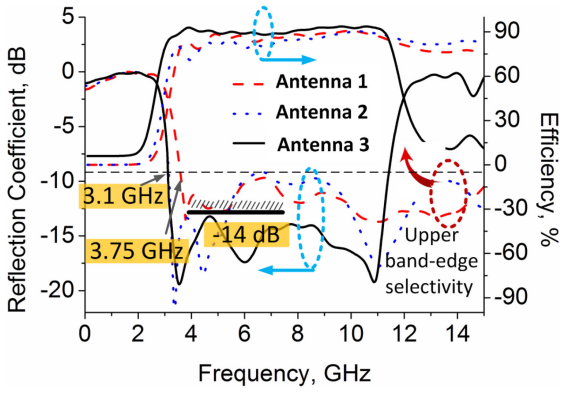

Fig. 2 *Radiation efficiency and Reflection coefficient curves comparison of three antennas shown in Fig. 1*

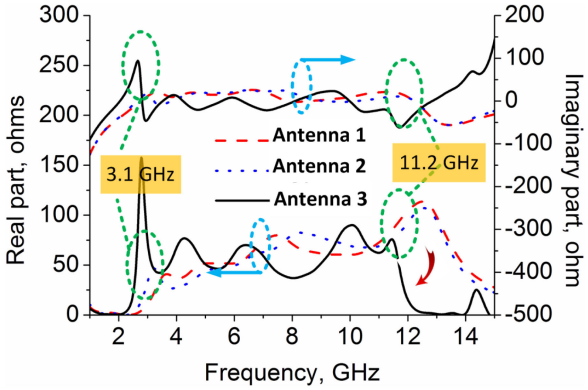

Fig. 3 *Simulated input impedance curves comparison of three antennas shown in Fig. 1*

Inspired by the referenced antenna in [25], a compact reconfigurable UWB slot antenna with enhanced band-edge selectivity and switchable band-notched functions is presented. First, a modified slot with defected ground structure (DGS) is proposed. The well-designed DGS not only produces transmission zero to obtain good cut-off property in upper sideband but also provides better in-band impedance matching. Second, by the addition of a parasitic slot near the stepped slot, the operating band and the characteristics of frequency selection at low frequency have also been improved [12]. What's more, to filter out some wireless communication systems in the UWB band, such as WLAN and WiMAX, two microstrip lines and feeding line are placed in parallel. (Total four configurations could be achieved from the parallel strips and the ground shorting with PIN diodes.) The bias circuit is simple and independent, which will reduce the complexity of the antenna and the influence of the bias circuit on the antenna. The dimension of the proposed design is 22×12 mm^2, which is more compact than most of antennas reported in [3–23]. The shape factor of the proposed antenna is 1.05, which is very close to the 1. Compared with the referenced antennas in [9–11], the shape factor of the antenna in this study has improved by 6, 4, and 4%, respectively. Moreover, the bias circuit and the notch structure are not directly connected to the radiation patch, which does not affect the overall dimension and performance of the antenna. Compared with the slot antenna in [12], the proposed design with reconfigurable function has many controllable states for different UWB applications.

2 Antenna design and performance

2.1 UWB antenna with improved band-edge selectivity

The development of the presented design is illustrated in Fig. 1. Fig. 1*a* exhibits the prototype of the design, named antenna 1. The size of the antenna 1 is 24×16 mm^2. The design is fabricated on an RO-5880 substrate with dielectric constant $\varepsilon_r = 2.2$ and height of 0.787 mm. Several resonant frequencies and UWB functions are realised by using 50 Ω microstrip feeding line to excite the slot embedded at the centre of the ground plane [12]. The simulated reflection coefficient is shown in Fig. 2. It can be observed in Fig. 3 that the antenna 1 has poor selectivity in the high-frequency band, and the start frequency of the passband bandwidth is 3.75 GHz, which does not satisfy the needs of the UWB with a low operating band of 3.1 GHz. As we all know that the length of the slot and the dimension of the antenna have a decisive effect on the first resonant frequency [12]. Therefore, for the slot antenna, the lower resonant frequency means a longer stepped slot length. However, the length of the slot of the antenna is difficult to increase due to the smaller size of the antenna. To solve the problems mentioned above, a paralleled slot close to the radiation slot is added [12]. The start resonance frequency could be effectively decreased and a new reflection zero near the band-edge is generated. In this way, the antenna 2 is designed with small size (22×12 mm), as illustrated in Fig. 1*b*. From what we can see in Fig. 2, the lower initial frequency is also developed by decreasing from 3.75 to 3.1 GHz.

As shown in Fig. 2, although the selectivity and bandwidth of the low-frequency band have been improved, the selectivity of the upper band has not been improved. In order to improve selectivity at high frequencies, the modified stepped slot with three pairs of DGS structure is designed. The DGS structure can be seen as a filter, it can generate resonant frequency and stop band characteristics in corresponding frequency band. [24, 25]. Then,

the problem that the antenna size increases and the low radiation efficiency caused by filter-fed microstrip line can be avoided by the use of modified stepped slot with DGS. In [24], three pairs of DGS structures are studied and applied to create the transmission zero in the high-frequency band, which can improve the selectivity of upper band. Therefore, three pairs of DGS structures with different size are co-designed with stepped slot, as seen in Fig. 1*c*. As shown in Fig. 2, the impedance and sideband selectivity of antenna 3 are improved by using modified stepped slot with DGS structure. The maximum reflection coefficient of antenna 3 is 14 dB, which is about 40% higher than that of antenna 1 and antenna 2. In addition, the simulated radiation efficiency of the proposed design with DGS is about 90%, which is about 12.5% higher than the antenna in our previous design [12]. This is because the improved stepped slot can have more resonant modes, which is beneficial to the improvement of the in-band impedance. At the same time, the improvement of the in-band impedance characteristics is beneficial to the improvement of the radiation efficiency. The DGS structure can avoid the problem of poor impedance characteristics and low radiation efficiency caused by stepped feed microstrip line in [12]. Compared with the design in [12], the antenna in this study not only has good band-edge selectivity, but also has improved in-band impedance and radiation efficiency. In addition, this paper will discuss the in-band notch and reconfigurable structure of the antenna in the following sections. This is conducive to further improvement of slot antennas.

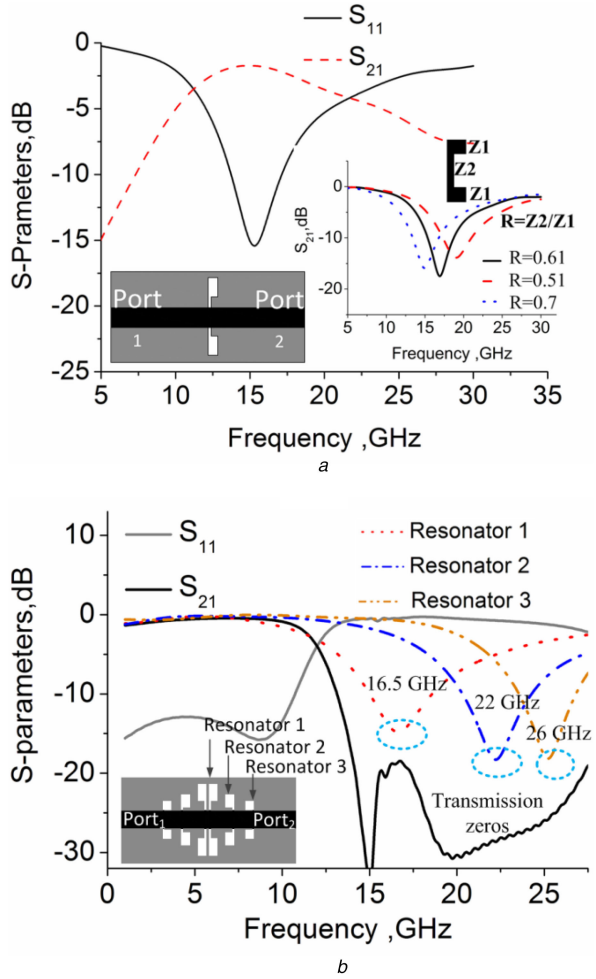

Fig. 4 *S-parameters of DGS*

(a) Reflection coefficient of DGS unit. (S21 varies with the impedance ratio of DGS cell), ***(b)*** The transmission zeros of three DGS units with different sizes and the S-parameters of DGS

To better understand the improved selectivity of the proposed design, the corresponding input impedance curves are also given in Fig. 3. It is observed that the characteristics of both the imaginary and real parts of the design in the upper and lower frequency of the passband have changed sharply after the narrow-band slot and DGS type are added. Eventually, this steep change of impedance produces a steep change of reflection coefficient and gain. Then, this steeply varying impedance produces a highly selective reflection coefficient and gain in the side bands.

Fig. 4*a* shows the schematic view and simulated S-parameter of the DGS unit. In order to further obtain the different performance of the DGS, the DGS units with different impedance ratio are also studied as shown in Fig. 4*a*. The simulated results show that each DGS unit designed in the ground plane of the design can generate stop band and transmission zero characteristics at the corresponding resonant frequency. The corresponding resonant can be shifted by the adjusting the impedance ratio of DGS. Transmission zeros built at upper stop band is favourable for obtaining good band-edge selectivity and harmonic suppression [26]. As seen in Fig. 4*b*, three pairs of DGS with different dimensions are proposed to achieve wide upper stop band. The simulated transmission zeros of three different DGS resonators are 16.5, 22, and 26 GHz, respectively.

Table 1 shows the comparison of antenna parameters before and after improvement. It is clear from Table 1 that the dimensions, impedance of in the UWB band, bandwidth, and selectivity of antenna 3 have been significantly improved.

2.2 Antenna with reconfigurable band-notched characteristics

Fig. 5*a* shows an improved final design of reconfigurable filtering antenna. In order to achieve notch function, two parasitic microstrip lines near the feeding line are designed. The coupled current flows through the parasitic microstrip line with a short circuit to the ground plane. The notched band of the design is related to the length of the current path, as seen in Fig. 6. It can be seen from the diagram that the longer the current path, the lower the resonance frequency [12]. The length of the current path is about $\lambda/4$ of the corresponding frequency. The adjustable frequency range is 3.2–6 GHz, which includes the interference bands of WiMAX and WLAN. Therefore, the reconfigurable function of antenna can be easily realised by replacing short circuit with two PIN diodes. The equivalent circuit of the PIN diode is shown in Fig. 5*b*. BAR64-02 V PIN diode model is selected, which is applied to connect the microstrip line and the ground plane. To active the diode, a DC forward voltage (VF) of 1.8 V is used. To provide RF isolation and limit the DC current the inductors and resistors of 22 nH and 100 Ω are used in the circuit. Four states of the proposed design are summarised in Table 2. The corresponding reflection coefficients and the surface currents of the proposed design with different states are presented in Fig. 7. It is found in Fig. 7*a* that when the two diodes are off (in state I), the current mainly concentrates near the step slot and parasitic strip slot. The current is concentrated near the stepped slots and the DGS, which means that the stepped slot is strongly coupled with the DGS resonators and resonating on desired operating band. The optimal operating band of the antenna is 3.1–11 GHz, which shows good band-edge selectivity. In addition, the phenomenon of the current distribution demonstrates that when the two diodes are all off, the notch structure has almost no effect on the bandwidth and shape factor of the antenna operating in state I. In state II, state III, and

Table 1 Comparison of antenna parameters before and after improvement

Antenna	ε_r	Size, mm^2	L_{Step}, mm	−10 dB bandwidth, GHz	Maximum reflection coefficient of in-band, dB	Shape factor, K
antenna 1	2.2	24 × 16 = 384	13	3.75–15	−10	(>1.64)
antenna 2	2.2	24 × 12 = 288	11	3.5–11	−9.7	(1.09)
antenna 3	2.2	24 × 12 = 288	11	3.1–11.1	−14	(1.05)

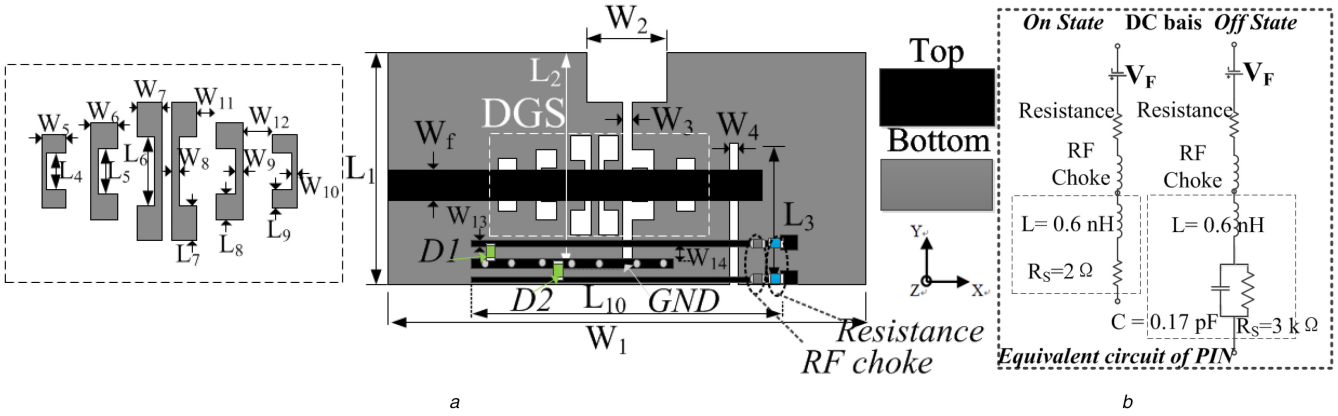

Fig. 5 *Proposed antenna*
(a) Geometry of the antenna, ***(b)*** Equivalent circuit of the PIN diode

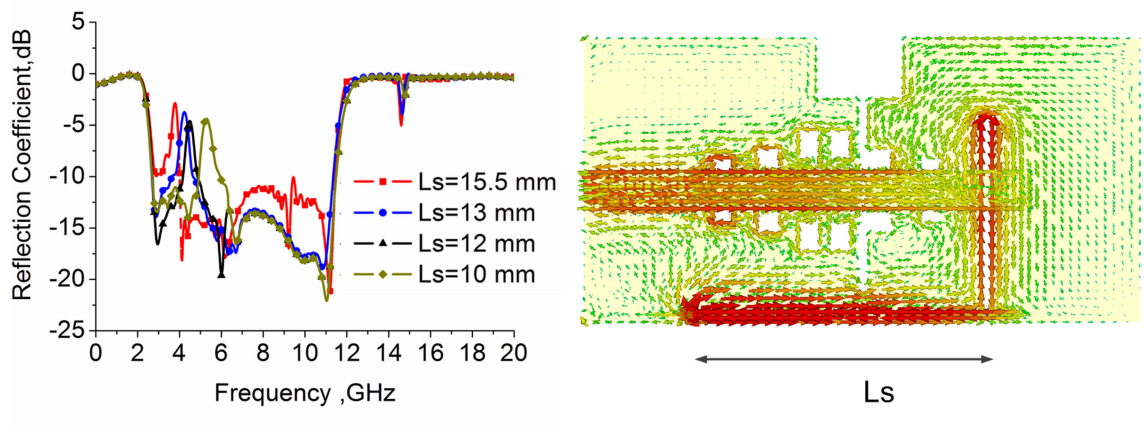

Fig. 6 *S-parameters of the presented design with various current path Ls (Ls is the path length of the current, which can be regulated by the position of the PIN diode)*

Table 2 Various states of the reconfigurable slot antenna

State	*D*1	*D*2	Characteristics
state I	off	off	UWB (3.1–11.1 GHz)
state II	on	off	antenna with band-notched function at 3.5 GHz(WiMAX)
state III	off	on	antenna with band-notched function at 5.5 GHz(WLAN)
state IV	on	on	antenna with band-notched function at 3.5 and 5.5 GHz(WiMAX and WLAN)

state IV, Figs. 7(*b–d*), current is mostly flowing in parasitic strip line which confirm their stop band behaviour at corresponding frequencies. It is clearly shown that the simple and independent biasing circuit of the PIN diodes has little effect on the bandwidth and band-edge selectivity of the proposed design.

The proposed antenna is simulated by the adoption of commercially software CST microwave studio. The values of the optimised design are fabricated and shown in Table 3.

3 Results and discussion

To analyse the performance of the final design, the proposed design is fabricated and measured. This section introduces and discusses several simulations and test results of the design, including frequency domain analysis and time-domain analysis.

3.1 Frequency domain analysis

The fabricated slot antenna with a DC bias circuit is shown in Fig. 8. The bias lines and diodes cathode were isolated from the induced RF signal on the ground plane using 22 nH inductors. The 100 Ω limiting current resistances were used during measurements. The frequency responses of the simulated and measured reflection coefficient in four states of the reconfigurable slot antenna are shown in Fig. 9. Measured results show good agreement with the simulated results. As seen in Fig. 9*a*, when the antenna operates in sate I, the operating band with −10 dB reflection coefficient is from 3.1 to 11.1 GHz. Good bandpass filtering performance is obtained, the shape factor of the proposed antenna is 1.05. It can also be observed that the design has good in-band impedance matching and achieves a reflection coefficient of −14 dB. Figs. 9*b–d* show the reflection coefficients of the diode in the gated state and the antenna in sate II, state III, and state IV. The measured results are agreed well with the simulated results. By controlling the pin diode, the proposed design shows good in-band and out-of-band filtering characteristics.

Fig. 10 illustrates the measured and simulated gain and efficiency of the proposed design in four states. As seen in Fig. 10*a*, the simulated and measured peak gain in the operating band is about 1.3–4 dBi, the simulated and measured efficiency are >85% in the entire passband. Both gain and radiation efficiency of the proposed design exhibit good sideband selection characteristics. Figs. 10*b–d* show the measured and simulated gain and efficiency of the proposed design with the notched bands, the gain and efficiency are significantly reduced to −4 dBi and 50% at notch frequency, respectively.

To further understand the characteristics of band-edge selectivity and band-notched function of the proposed design, the simulated input impedance characteristics of the antenna in sate IV with band notch characteristics at 3.5 and 5.5 GHz are proposed in Fig. 11. It can be seen in Fig. 11 that the real and imaginary parts of

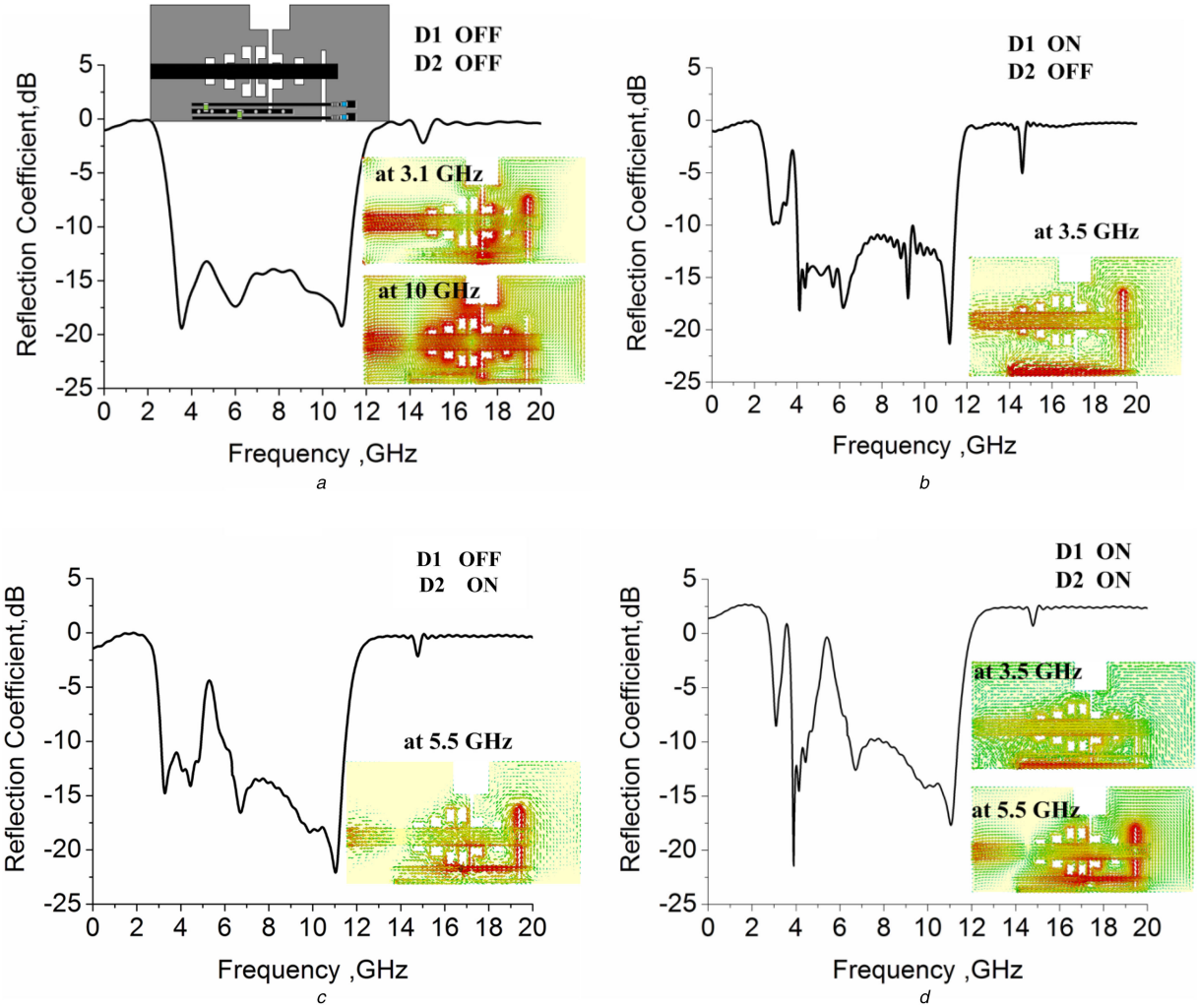

Fig. 7 *S-parameter and the surface current distributions of the proposed design in different states*
(a) State I, ***(b)*** State II, ***(c)*** State III, ***(d)*** State IV

Table 3 Dimensions of the proposed design

Parameters	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	W_1	W_2	W_3
value, mm	22	11.5	9	1.6	2	3	1.5	1.1	0.8	16	12	4.2	0.5
prameters	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	W_{11}	W_{12}	W_{13}	W_{14}	W_f	—
value, mm	0.5	1	1.2	1	0.3	0.2	0.2	1	2	0.3	0.6	2	—

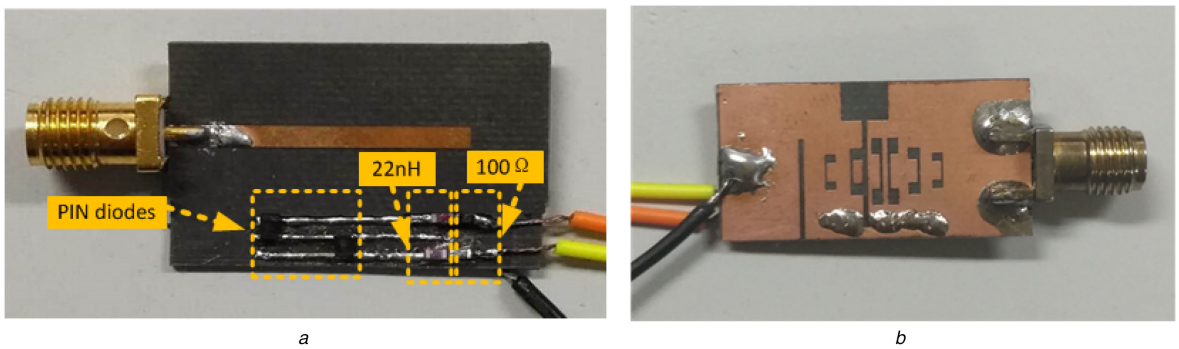

Fig. 8 *Photograph of the design*
(a) Top, ***(b)*** Bottom

the simulation are relatively flat in the entire bandwidth of UWB band, in which the real part of the design is tends to 50 ohms and the imaginary part is approximates to 0. As shown in Fig. 11, the impedance of the band-edge and notched bands decreases rapidly in both the real and imaginary parts, and exhibits significant changes. Then, the good band-edge selectivity and band-notched characteristics of the proposed antenna are obtained due to the band impedance mismatching at band-edge and notched band.

The normalised radiation patterns of the proposed design in state I mode at 3.1, 6, and 10 GHz are plotted in Fig. 12. In order to better understand the radiation, 3-D radiation patterns at 3.1 and 10 GHz and cross-polarisation at 6 GHz are also added. It is obvious that the measured radiation patterns in H planes are agreed

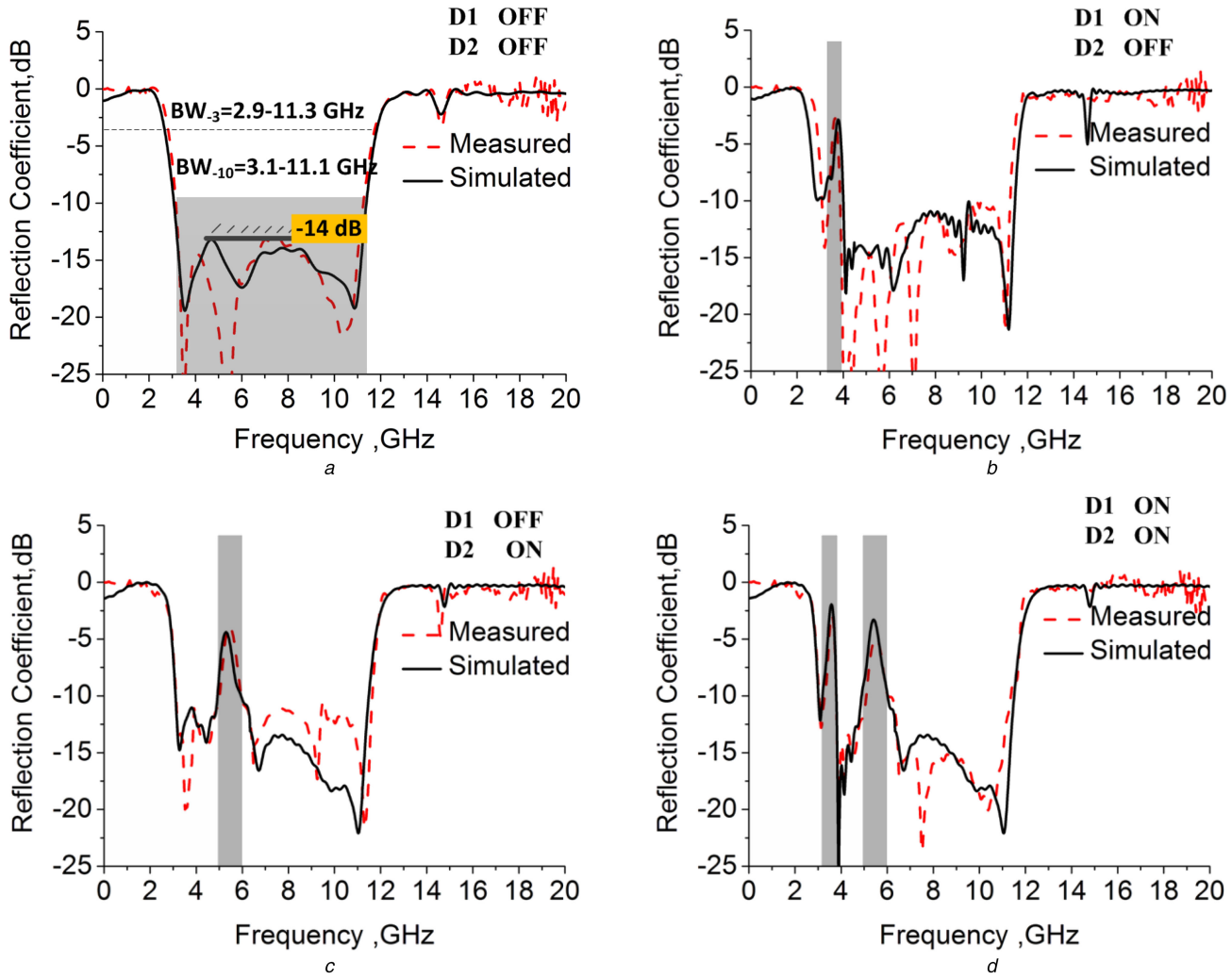

Fig. 9 *S-parameters of the proposed design in four states*
(a) State I, ***(b)*** State II, ***(c)*** State III, ***(d)*** State IV

well with the simulated results and show quasi-omnidirectional radiation pattern in operating frequencies. However, there have certain directional characteristics in E-plane at 10 GHz, which are mainly due to the imbalance of current distribution at higher frequencies. As shown in Fig. 12*b*, the cross-polarisation average value is −15 dB at 6 GHz, which show good cross-polar radiation. The experimental results show that the antenna performs well in the filtering the interference signals in the UWB band and out-of-band in the frequency domain.

3.2 Time-domain analysis

The UWB antenna is used to transmit time-domain pulse signals, it is also important to discuss the time-domain characteristics of the proposed design. In order to discuss both in-band and out-band time-domain characteristics, two identical antennas in sate IV are selected.

The measured group delay of the proposed design in state IV is shown in Fig. 13. Two identical antennas are placed face-to-face at a distance of 50 cm. It is observed that the variation of the antenna in sate IV is <0.5 ns across the entire bandwidth of UWB band except at the notched band, which indicates that the antenna has good linear transmission characteristics. It can also be observed that the antenna has a large group delay both in the sideband and out of the band, which is in sharp contrast to the in-band signal group delay. The measured result confirms that the good in-band and out-of-band filtering characteristics can also be demonstrated through the group delay of the antenna.

Fig. 14 shows the transfer function for two identical antennas with the distance of 50 cm. It can be seen in Fig. 14*a* that the transmission function amplitude of the antenna decreases rapidly in notch band and band-edge and has a better stability in band. The phase of the transmission function of the transceiver antenna group is basically linear in the whole bandwidth except for notched bands.

The input and received waveforms of the antenna are shown in Fig. 15. Two identical antennas are placed face-to-face and edge-to-side, respectively. One antenna is used as the transmitting antenna to excite a time-domain pulse signal and then the other antenna receives a time-domain pulse signal after a certain time delay. In order to satisfy the transmission power limit prescribed by FCC for UWB system [27], the fifth-order Gauss pulse signal is used as an excitation signal whose signal expression is given by (1)

$$s_1(t) = GM_5(t) = C\left(-\frac{t^5}{\sqrt{2\pi}\sigma^{11}} + \frac{10t^3}{\sqrt{2\pi}\sigma^9} - \frac{15t}{\sqrt{2\pi}\sigma^7}\right) \times \exp\left(-\frac{t^2}{2\sigma^2}\right) \quad (1)$$

where, $\sigma = 51$ ps, the constant C can be used to select the appropriate amplitude to make the pulse signal conform to the FCC radiation power spectrum. The time-domain waveform of the fifth-order Gauss pulse signal is presented in Fig. 15. It is found that when the two diodes $D1$ and $D2$ are on (in sate IV), the received signal of the antenna in both two cases (face-to-face and side-to-side) will produce ringing distortion, but when the PIN diodes $D1$ and $D2$ are off (in sate I) will not. It is because of the poor impedance characteristics of the antenna in notched band. It can also be found that when the two diodes are in the off state, the waveforms of the input and received signals are very close, which indicates that the signal is less affected in the process of receiving

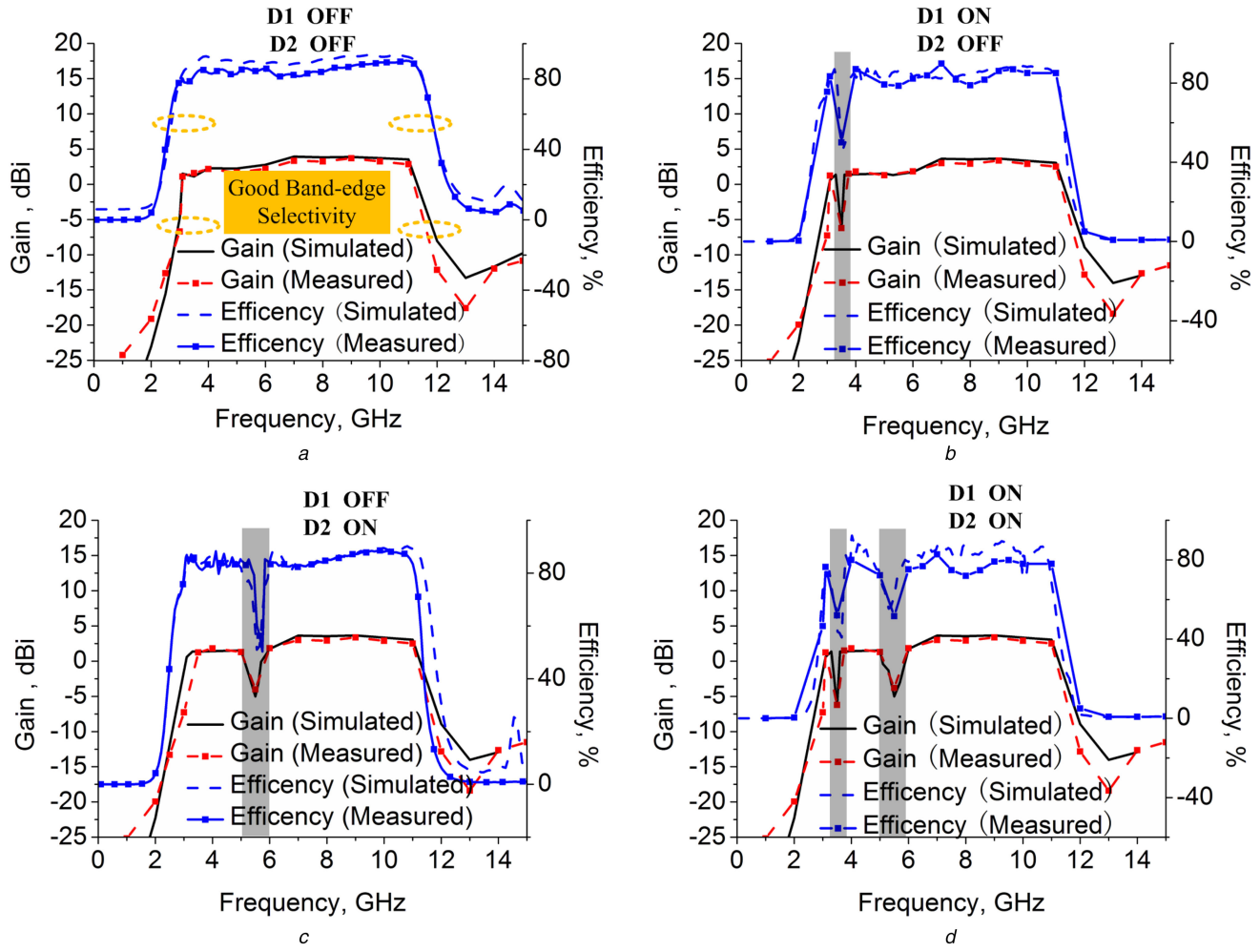

Fig. 10 *Gain and efficiency of the proposed design in four states*
(a) State I, ***(b)*** State II, ***(c)*** State III, ***(d)*** State IV

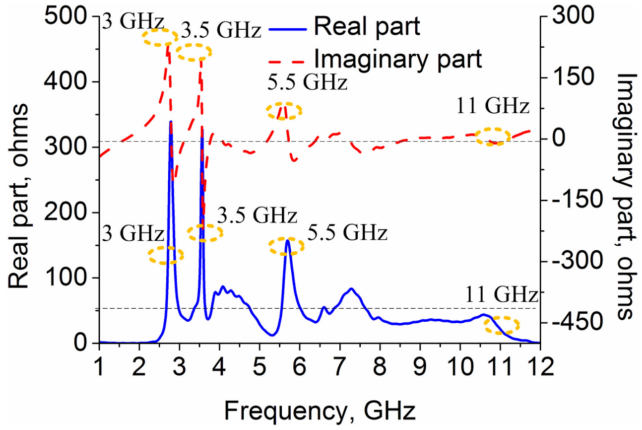

Fig. 11 *Input impedances of the proposed antenna in state IV with dual band-notched characteristics*

and transmitting. The proposed antenna exhibits good time-domain characteristics.

4 Conclusion

In this design, a compact reconfigurable slot antenna with bandpass filter characteristics and switchable band-notched function is presented. By etching the DGS and parasitic slot, both the upper and lower selectivity in the passband of the proposed design are improved and good filtering function is obtained. To reject the unwanted signals in the UWB band, two passive strip lines close to the feed microstrip line are applied. The reconfigurable structure of the design is relatively independent and simple and is easy to process. Furthermore, the dimension of the design is more compact than most of the reported antennas. The measurement and simulations match well. Both the time-domain and frequency-domain characteristics of the proposed design are very good. The proposed design has good function of in-band and out-of-band filtering, and it is very suitable for UWB system.

5 Acknowledgments

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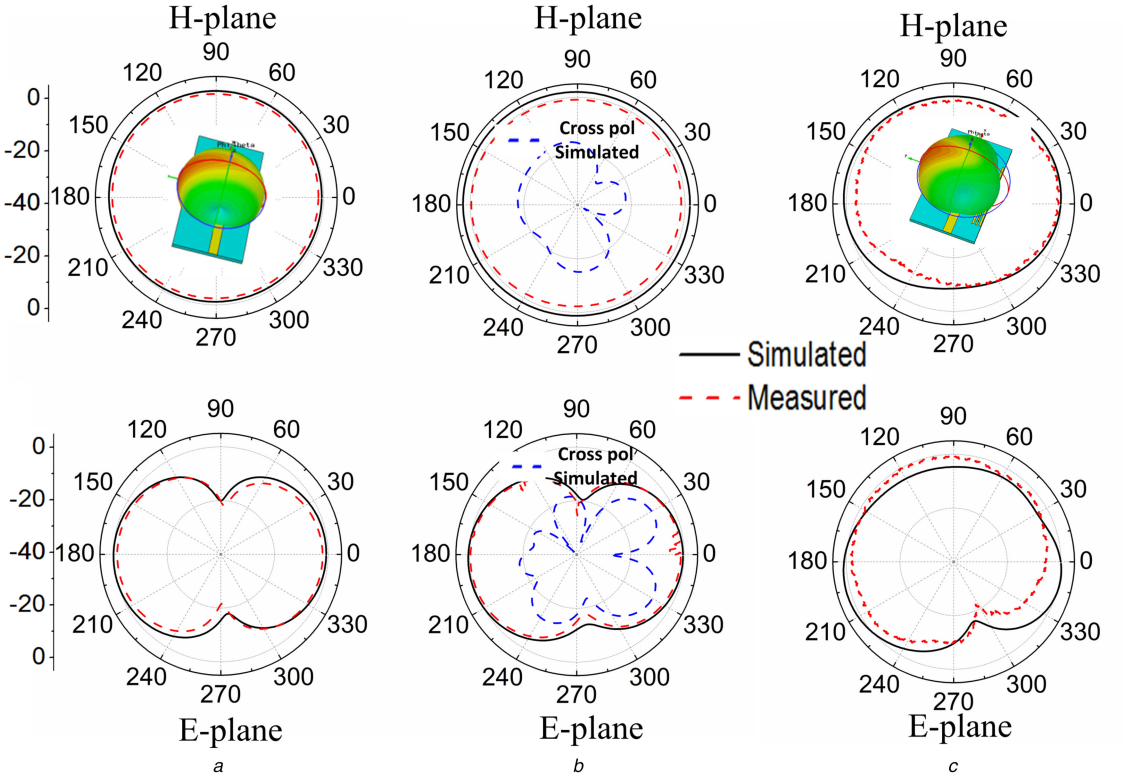

Fig. 12 *Simulated and Measured normalised radiation patterns of the proposed design in state I*
(a) 3.1 GHz, ***(b)*** 6 GHz, ***(c)*** 10 GHz

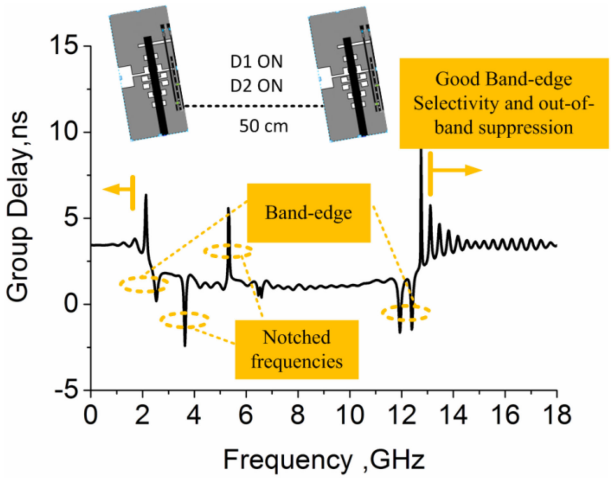

Fig. 13 *Group delay of the proposed design in state IV*

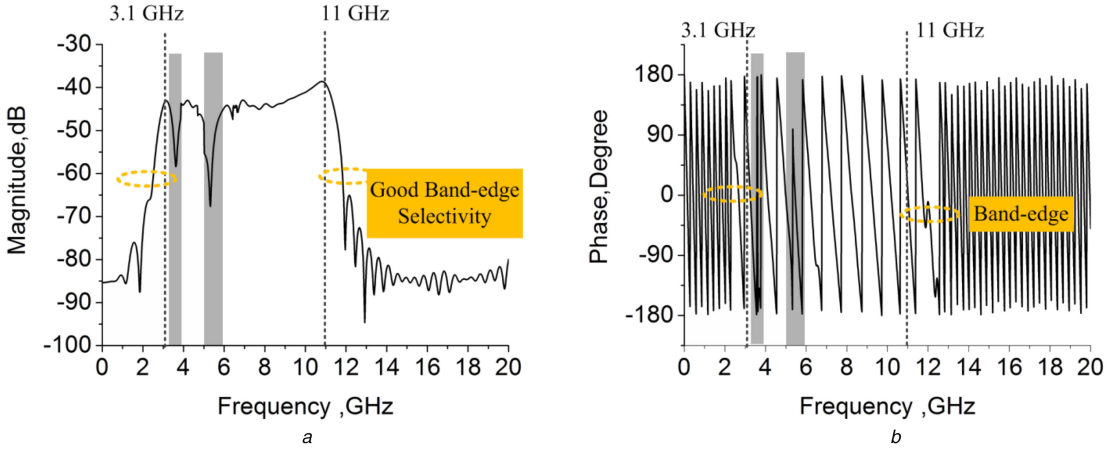

Fig. 14 *Transfer function of the proposed antenna in state IV*
(a) Measured magnitude, ***(b)*** Measured phase S21

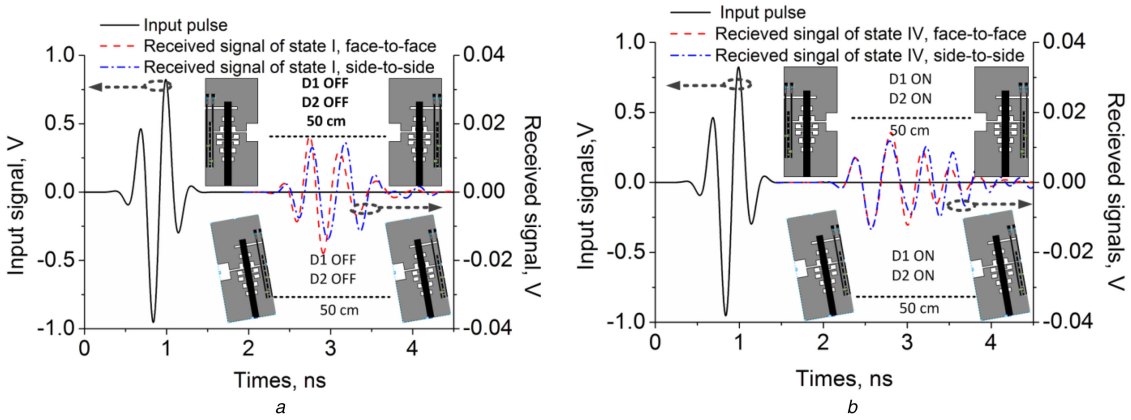

Fig. 15 *Input and received pulses in different cases of the UWB antenna in state I and state IV*
(a) State I, ***(b)*** State IV

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