A Compact Reconfigurable Antenna Using SIRs and Switches for Ultra Wideband and Multi-Band Wireless Communication Applications

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Abstract ─ In this paper, a novel coplanar waveguide (CPW) fed ultra wideband (UWB) antenna with reconfigurable functions and notch band characteristics is proposed for wireless communication applications. The proposed UWB antenna has two stop bands that are achieved by using the stepped impedance stub (SIS) loaded stepped impedance resonators (SIRs). The reconfigurable functions are obtained by means of two ideal switches that are implemented on the proposed two SIRs. By controlling the status of the ideal switches ON/OFF, the proposed antenna can work in UWB operation band with both switches OFF and the antenna can be used as a dual notch band UWB antenna when the status of both switches is ON. The frequency domain characteristics are investigated, and the time domain characteristics, such as group delay, have been studied in details as well. The simulation and experiment results demonstrate that the proposed reconfigurable antenna can well meet the requirement for the UWB communication, notch band UWB, and multiband communication.

Index Terms ─ Multiband antenna, notch band antenna, reconfigurable antenna, time domain characteristic, and UWB antenna.

I. INTRODUCTION

With the rapid development of wireless communication, low power and high data rate communication systems have been becoming the key technologies in wireless communications. Especially, after the federal communications commission (FCC) has released the bandwidth ranging from 3.1 GHz to 10.6 GHz for indoor UWB communication applications in 2002 [1]. The UWB systems and radio frequency front-end based on ultra wideband technology operated in short distance has attracted more attention in both academic and industrial fields. Nevertheless, the ultra wideband antenna that is used as a transmitting and receiving component plays a critical role in the UWB systems. For the indoor communication applications, the UWB antenna should be small, low cost, and omni-directional for practical applications. In addition, the UWB antenna should also have a wide impedance bandwidth covering the entire bandwidth ranging from 3.1 GHz to 10.6 GHz. For the reasons above, a lot of printed UWB antennas have been developed to meet the requirements [2-8]. However, several narrow band communication systems, C-band at 4.4 GHz - 5 GHz for C-band satellite communication, HIPER-LAN/2 bands at 5.15 GHz - 5.35 GHz and 5.47 GHz - 5.725 GHz in Europe, and IEEE 802.11a/h/j/n bands at 4.9

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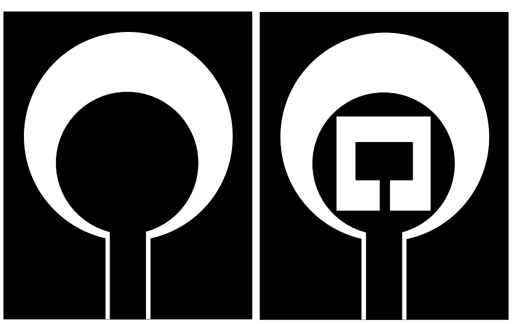
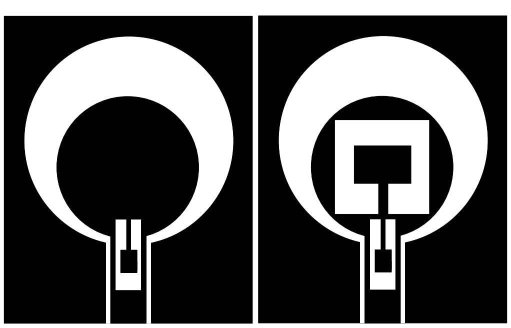
GHz - 5.0 GHz, 5.035 GHz - 5.055 GHz, and 5.25 GHz - 5.725 GHz in Japan; 5.15 GHz - 5.35 GHz and 5.725 GHz - 5.825 GHz in US and X-band at 8.5 GHz - 9.5GHz for deep space communication, have been used for a long time [9]. For reducing or avoiding the potential interference between UWB systems and the narrow systems, the band-stop filters should be added at the end of the antenna or equipment. Thereby, both the cost and weight of the equipment will increase. Recently, printed UWB antennas with band notch functions have been proposed for reducing the potential interferences [10-24]. Though, these antennas can reduce the interference, most of the notch band antennas in the literatures have a complex structure, which would be difficult to redesign and the notch band is not tunable either. Furthermore, those notch band UWB antennas usually use various slots on either radiation patch or ground plane. These slots may result in the leaking of electromagnetic wave, which in turn, deteriorates the radiation patterns. To overcome the drawbacks, the most effective method is to insert open circuited stubs [17-18] into the UWB antenna, and integrate filters [24] in the fed line and active region. M. Ojaroudi et al. have also proposed a method by using tuning stubs to perturb matching impedance and create an open circuit to form a notch band at the undesired frequencies [25]. Some antennas using SRRs in the fed structures [19-20] are also utilized to improve the band limitation. However, those antennas are just used as UWB antennas or notch band UWB antennas. It is difficult to use the UWB antenna for two modes. Moreover, a lot of switchable antennas have been used for multimode communication applications [26-36]. In addition, most UWB antennas in the literatures are only investigated in the frequency characteristics. In this paper, a CPW feed wide slot UWB antenna with reconfigurable functions and notched band characteristics is presented and investigated numerically and experimentally. The proposed UWB antenna has two stop bands that are realized by using SIRs. Two ideal switches are used to control the mode of the proposed reconfigurable antenna. In this paper, the proposed reconfigurable UWB antenna consists of a dual-notch band UWB antenna and two ideal switches. The two notch band obtained using SIRs, which can be designed using SIRs theory. So, the notch can be designed flexibly and easily by means of the method proposed in [37]. Both, the frequency domain and time domain characteristics are investigated and discussed. The proposed antenna was designed, fabricated, and analyzed in details. The antenna parameters such as reflection coefficient, radiation pattern and group delay are discussed in this paper.

II. ANTENNA DESIGN

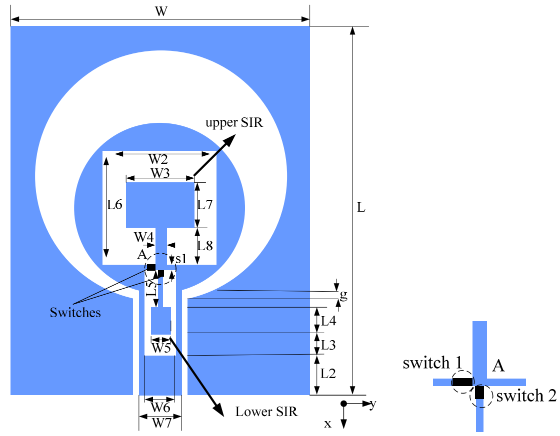
Figure 1 illustrates the geometry of the proposed UWB antenna with reconfigurable functions and dual notch band characteristics. The proposed reconfigurable UWB antennas are printed on a thin substrate plate with a relative permittivity of 2.65, a loss tangent of 0.002 and a thickness of h = 1.6 mm. The dimensions of the antenna structure are 32 mm in length, 24 mm in width, and 1.6 mm in height. The proposed UWB antenna consists of a circular slot on a rectangular PEC plate, a circular radiation patch inside the slot, two SIRs (upper and lower SIR), two ideal switches, and a 50 Ω CPW-fed structure. The black and blue parts indicate the PEC structure in Fig. 1. The 50 Ω CPW fed structure consists of the CPW transmission signal strip line with a signal strip width W7 = 3.6 mm, and a gap between the CPW ground plane and the transmission signal strip with width 0.2 mm. The 50 Ω CPW structure of the proposed UWB antenna is designed by using the formulas in [38]. The configuration of the proposed reconfigurable UWB antenna is shown in Fig. 1 (e). The detailed design procedure is illustrated in Figs. 1 (a) to 1 (f). First, a circular slot UWB antenna with a circular radiation patch has been proposed in Fig. 1 (a), which is referred as antenna1. In order to design a notch band UWB antenna, a SIR denoted as an upper SIR is etched on the circular radiation patch to reduce un-required signal from IEEE 802.11a and C-band. The upper SIR works at 5.5 GHz, and the proposed UWB antenna with an upper SIR is shown in Fig. 1 (b). Furthermore, a lower SIR is embedded inside the CPW excitation signal line to produce another notch band, which works in the X-band. The proposed UWB antenna with a lower SIR is shown in Fig. 1 (c). Figure 1 (d) is an UWB antenna with a dual notch band integrated with an upper and lower SIR. In order to make the proposed dual notch band UWB antenna for multiple modes, two ideal switches are employed in this design, for example, the two ideal switches are cooperated into the two SIRs and denoted as switch 1 (SW1) and switch 2 (SW2). The reconfigurable UWB antenna is shown in Fig. 1 (e). Figure 1 (f) indicates the positions of the two ideal switches. In this design, SW1 and SW2 control the status of the proposed reconfigurable antenna. By adjusting the status of the proposed switches, the antenna can work as an UWB antenna or a dual notch UWB antenna/tri-band antenna. In this paper, the designed reconfigurable UWB antenna is denoted as antenna5 and shown in Fig. (e). The position of the ideal switches are shown in Fig. 1 (f). The proposed reconfigurable UWB antenna without the two ideal switches is a dual-notch band UWB antenna with two notch bands at 5.5 GHz and 9.2 GHz, respectively. This dual-notch band UWB antenna integrated with both SIRs is named antenna4 and is shown in Fig. 1 (d). Antenna4 with only upper SIR denoted as antenna2 has a notch band at 5.5 GHz. Antenna4 with only lower SIR denoted as antenna3 also has a notch band at 9.2 GHz. Antenna with neither lower SIR nor upper SIR is an UWB antenna and is denoted as antenna1.



(a) (b)



(c) (d)



(e) (f)

Fig. 1. Design flowchart of the proposed reconfigurable antenna for the (a) proposed UWB antenna (antenna1), (b) UWB antenna with an upper SIR (antenna2), (c) UWB antenna with a lower SIR (antenna3), (d) UWB antenna with both the upper and lower SIR (antenna4), (e) reconfigurable antenna (antenna5), and (f) position of ideal switches.

III. RESULTS AND DISCUSSES

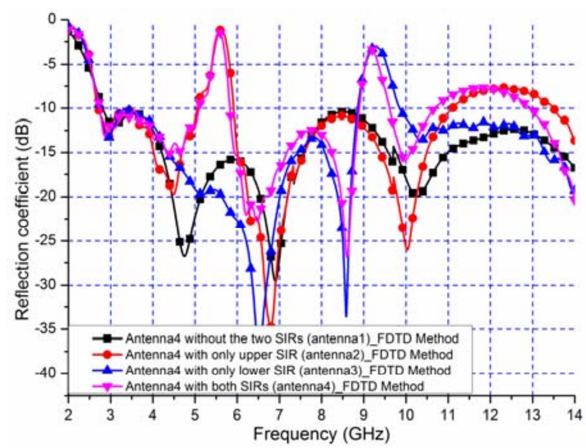
The proposed reconfigurable antenna is formed using the dual-notch band antenna4 and the two ideal switches. The center frequency of the notch band can be tunable by adjusting the dimensions of the two SIRs. In this section, we will discuss the simulation and measurement results for the proposed antenna structures. We begin with the notch band antenna.

A. Notch characteristics of proposed antennas

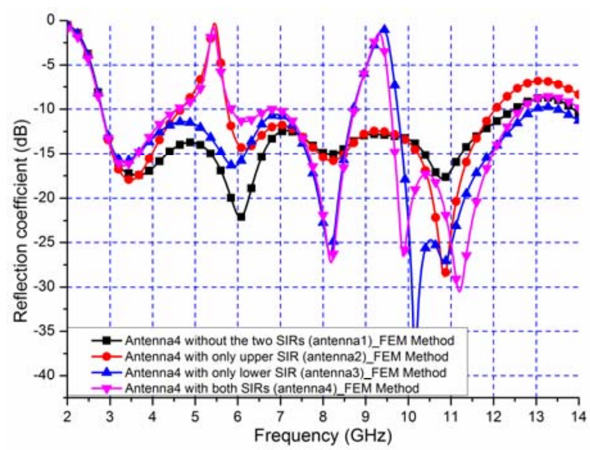
Figure 2 illustrates the notch characteristics of the proposed antennas. The results are obtained by using the finite element method (FEM) [39-41] and the finite difference time domain (FDTD) method [42-45]. Antenna4 without the two SIRs is an UWB antenna covering the entire UWB band ranging from 3.1 GHz to 10.6 GHz. This is also denoted as antenna1 in this paper. Antenna4 with only an upper SIR (antenna2) is an UWB antenna with a notch band near 5.5 GHz. This antenna can reduce the potential interference between the UWB systems and WLAN. Antenna4 with only a lower SIR is also an UWB antenna with a notch band at 9.2 GHz, which can suppress the un-required signal in the X-band. Antenna4 including two SIRs is an UWB antenna with two stop bands. It is observed from Fig. 2 that the notch band near 5.5 GHz is generated by the upper SIR and the notch band near 9.2 GHz is given by the lower SIR. The impedance characteristics of antenna4 without SIRs, with one upper SIR and one lower SIR and two SIRs are obtained using the FEM method [32-34] and compared in Fig. 3. It is obvious from Fig. 3 that the real curves of the proposed antennas are around 50 Ω except the notch bands, which indicates the good impedance matching across the entire operating frequency band. It can be observed from Fig. 3 that the real parts of the impedance for the notch band antennas reach nearly zero at the lower notch band near 5.5 GHz and reach 100 Ω at the higher notch band near 8.7 GHz. The imaginary parts of the notched antennas also change sharply. The results illustrate that the inclusion of the SIRs causes the antennas non-responsive at the rejection bands.

B. Reconfigurable characteristics of proposed antenna

The proposed reconfigurable antenna with two ideal switches is shown in Fig. 1 (e). The reconfigurable antenna referred as antenna5 is based on antenna4 using two ideal switches, which are shown in Fig. 1 (f). The two ideal switches, switch 1 (SW1) and switch 2 (SW2), are metal bridges. In this paper, the ideal switch using the metallic copper strip is to approximate the switching devices [34]. During the simulation, the metal bridges with dimensions of 0.9 mm × 0.7 mm are used to approximate the SW1. SW2 is replaced by a microstrip line with a length of 0.8 mm and width 0.4 mm. The presence of the metal bridge represents that the switch status is ON; in contrast, the absence of the metal bridge represents that the switch status is OFF [29-30]. The simulated results for antenna5 are shown in Fig. 4. It can be observed from Fig. 4 that antenna5 with two switches OFF is an UWB antenna, which covers the entire UWB band with below -10 dB reflection. Antenna5 with SW1 OFF and SW2 ON is also an UWB antenna having a bandwidth of 7.8 GHz. Antenna5 with SW1 ON and SW2 OFF is a notch band UWB antenna or a dual band antenna. The notch band is near 5.5 GHz. Antenna5 with both switches ON is an UWB antenna with two rejection filter bands at 5.5 GHz and 9.2 GHz, respectively. This is also antenna4. Antenna5 with both switches ON can also be used as a tri-band antenna covering 2.8 GHz-5.0 GHz, 5.9 GHz-8.9 GHz, and 9.6 GHz-10.7 GHz. It is worth noticing that the proposed antenna without the two ideal switches is a dual band-notch UWB antenna and is denoted as antenna4 in this paper. The notch band of the proposed antenna is tuneable by adjusting the parameters of the SIRs.



(a)



(b)

Fig. 2. Notch band characteristics of the proposed antennas (antenna4) using (a) the FDTD and (b) FEM methods.

The impedance versus frequency of the proposed antenna5 in the different status including, both switches OFF, with SW1 ON and SW2 OFF and with SW1 OFF and SW2 ON are plotted in Fig. 5 by using the FEM method. The antenna5 with both switches ON is also a dual notch band antenna, which is referred as antenna4. We can observe from Fig. 5 that the real part of the impedance of antenna5 with switches OFF fluctuates around 50 Ω, which implies a good match over the UWB band. The reconfigurable antenna5 with SW1 ON and SW2 OFF is a notch band antenna and has a notch near 5.5 GHz. The real part of antenna5 with SW1 ON and SW2 OFF reaches zero near 5.5 GHz and the imaginary part of the impedance changes to 60 Ω. This results in no-responsive at 5.5 GHz. The reconfigurable antenna5 with SW1 OFF and SW2 ON is also an UWB antenna and the real part of the impedance is around 50 Ω, which coincides with the S-parameter results illustrated in Fig. 4.

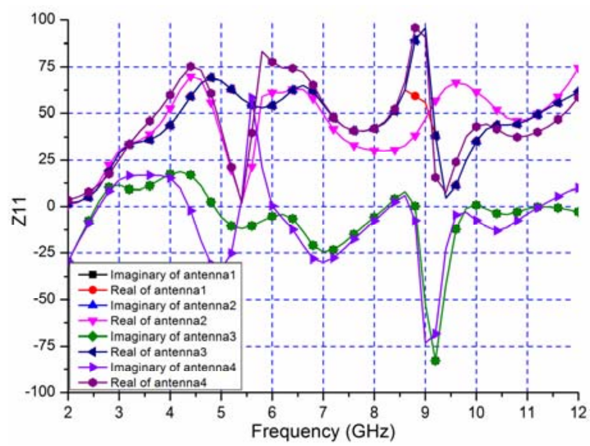
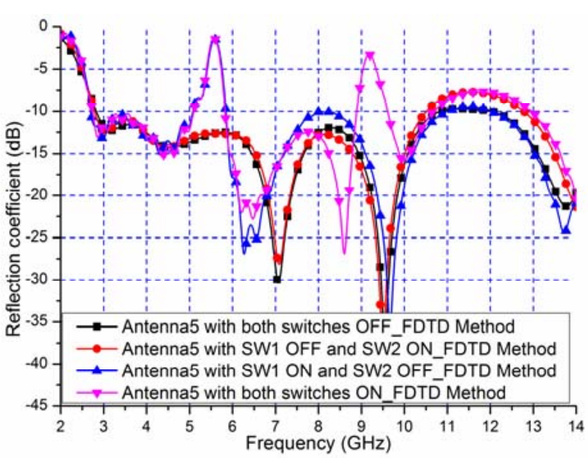
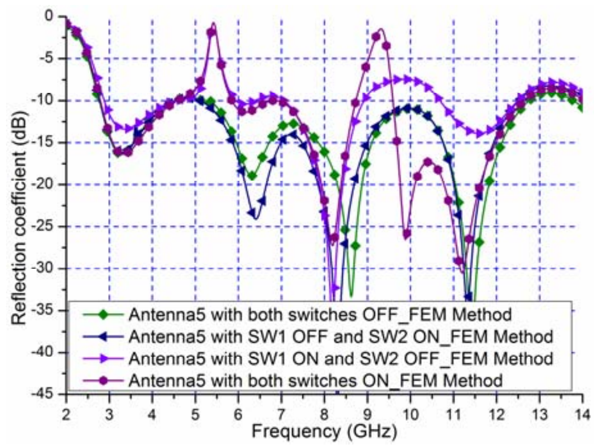


Fig. 3. Impedance characteristics of proposed notch band antennas.



(a)



(b)

Fig. 4. Switchable characteristics of the proposed reconfigurable antenna (antenna5) using (a) FDTD and (b) FEM methods.

C. Measurement result analysis

To validate the simulation results above, the proposed antenna5 with both switch ON and OFF are optimized and the optimized parameters are as follows: W = 24 mm, L = 32 mm, D = 23.2 mm, D1 = 13 mm, W2 = L6 = 8 mm, L1 = 1.9 mm, L7 = 3 mm, W3 = 4 mm, L8 = 2 mm, W4 = 0.4 mm, W5 = 1.4 mm, W6 = 2.7 mm, L2 = 3 mm, L3 = 1.8 mm, L4 = 1.5 mm, L5 = 2.5 mm, W7 = 3.6 mm, and s1 = 0.7 mm. In order to verify the simulation results, two modes of the proposed reconfigurable antenna is fabricated and measured. The two fabricated antennas are just two states of the reconfigurable antenna. Here, we fabricate two antennas represented by two states. We believe that this approximation is acceptable and suitable to demonstrate the basic switching concept. In the practical application, the copper strip can be replaced by PINs and real RF switching circuits [34]. The optimized antennas, as shown in Fig. 6, are also fabricated and measured using HP8757D scalar network analyzer. The measurement results are illustrated in Fig. 7.

It can be seen from Fig. 7 that antenna5 with both switches ON is a dual notch band UWB antenna, and antenna5 with both switches OFF is an UWB antenna. The measurement results agree well with the simulated ones, which help to verify the accuracy of the simulation. The differences between the simulated and measured curves may be due to the errors of manufactured antennas.

Thereby, we can control the switches ON and OFF to let the proposed antenna work in an UWB mode, dual notch UWB mode/tri-band antenna mode, and a notch UWB/dual band antenna mode. The measured radiation patterns at 3.5 GHz, 7.0 GHz, and 10.0 GHz are shown in Fig. 8.

It is worthwhile to know from the radiation patterns that the radiation patterns of the reconfigurable antennas are omni-directional in the H-plane, which is also denoted as xz-plane and dipole-like in the E-plane, which is also denoted as yz-plane when both switches are turned ON or OFF, respectively. The E-plane radiation patterns of antenna5 with both switches ON have a little distortion, which is caused by the power leaking of two excited SIRs. In this paper, two SIRs etched on the radiation patch and the CPW-fed line will also leak electromagnetic wave, which deteriorates the radiation patterns a little. It is evident from the measurement and simulation results that the proposed reconfigurable antennas using the ideal switches well satisfy the requirement of the wideband communication applications. The peak gains of antenna5 with both switches ON and OFF are obtained by comparing with a double ridged horn antenna.

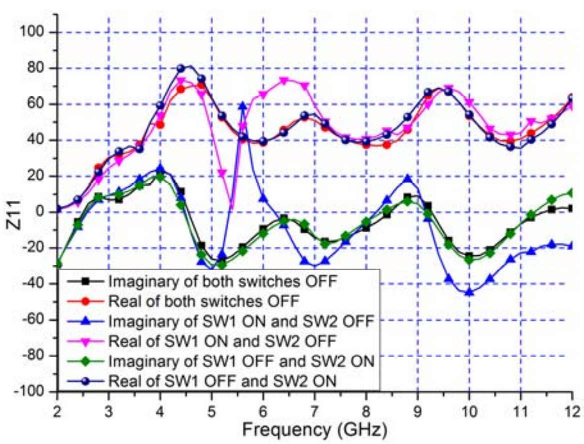


Fig. 5. Impedance characteristics of the proposed reconfigurable antennas.

The measured peak gains of the fabricated antennas are illustrated in Fig. 9. It is obvious from Fig. 9 that the stable gains of the fabricated antenna have been obtained throughout the operation band except the notched frequencies. As expected, antenna5 with both switches ON has two sharp gains, which decrease in the vicinity of 5.5 GHz and 9.2 GHz, namely, the gains drop deeply to –6.1 dBi and –4.6 dBi, respectively. The gain in this paper is little lower because of the two SIRs, which also leak energy. However, the antenna5 with both switches OFF has stable gains over the UWB band. The increased gains in the high frequency may be attributed to the deteriorated E-plane radiation patterns.

(a)

(b)

Fig. 6. Prototypes of the fabricated antennas (antenna5) used in the measurement when both switches are turned (a) ON and (b) OFF.

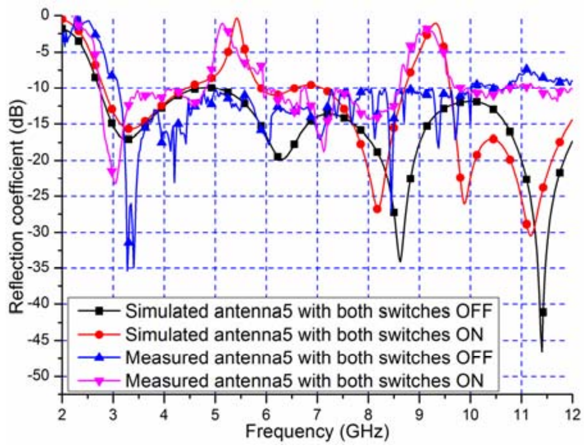


Fig. 7. Reflection coefficients of the fabricated antenna5 when switches are turned ON or OFF.

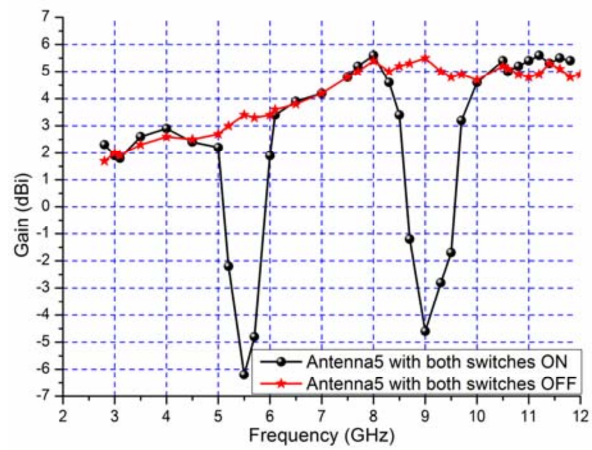


Fig. 9. Gains of the fabricated antennas when the status of the switches is ON or OFF, respectively.

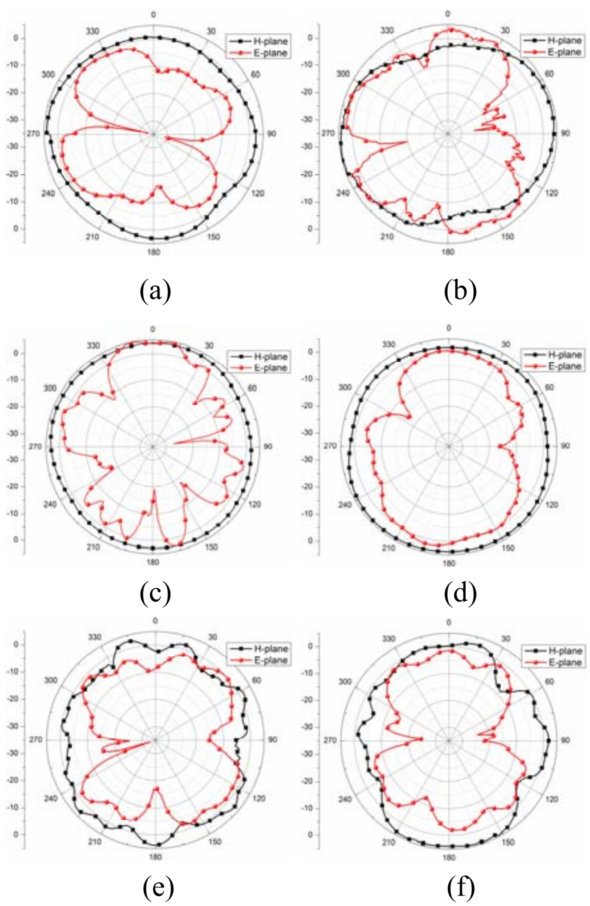


Fig. 8. Radiation patterns of antenna5 at different switch status and frequencies for (a) both switches ON at 3.5 GHz, (b) both switches ON at 7.0 GHz, (c) both switches ON at 10.0 GHz, (d) both switches OFF at 3.5 GHz, (e) both switches OFF at 7.0 GHz and (f) both switches OFF at 10.0 GHz.

D. Efficiency

The efficiency of the proposed reconfigurable antennas with both switches ON and OFF is obtained by using the FDTD method [37] and shown in Fig. 10. The antenna5 with both switches ON has an efficiency over 90 % during the UWB band except the two notch bands. In the notch band, the efficiency is reduced very quickly. The efficiency is 35 % in the lower notch band, which is near 5.5 GHz and the efficiency is 55 % in the higher notch band at 9 GHz. The antenna5 with both switches OFF has a stable efficiency in UWB band. In the operation band, the antenna5 with both switches OFF has a high efficiency, which is greater than 90 %.

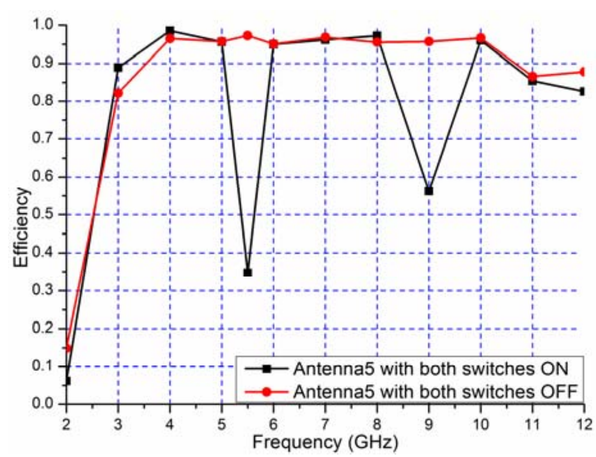


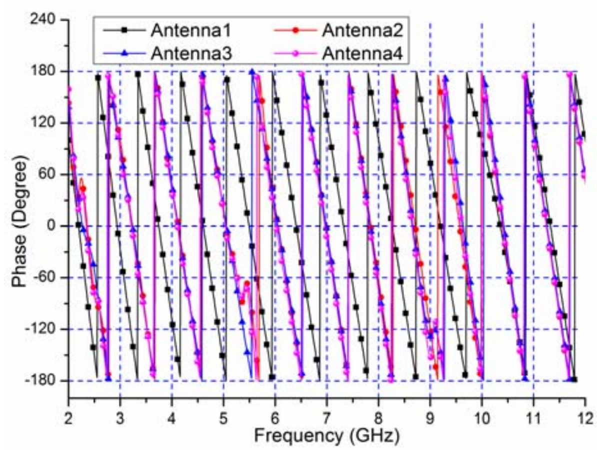
Fig. 10. Efficiency of the proposed antennas when the status of the switches is ON or OFF, respectively.

E. Group delay

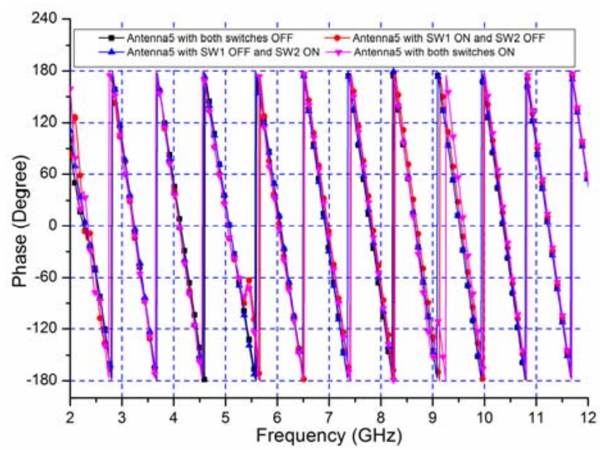
As well-known fact, an UWB antenna should cover a wide band from 3.1 GHz to 10.6 GHz. Therefore, the analysis of the group delay is very important. An UWB antenna can be regarded as a filter by means of magnitude and phase responses [46]. When a signal goes through a filter, the signal will distort in both amplitude and phase. This distortion depends on the characteristics of the designed filter, which can determine the communication quality. By representing the transmitting and receiving antennas as a filter, the phase linearity and group delay at the operation band are very important for designing UWB antennas. The phase of the proposed notch band antennas and the reconfigurable antennas are shown in Fig. 11. It is interesting to notice that the inductance property abruptly changes to the capacitance property in the notch band of the proposed notch band antennas and the reconfigurable antenan5 with both switches ON, SW1 ON and SW2 OFF. The antenna1 and the reconfigurable antenna5 with both switches OFF, SW1 OFF and SW2 ON have a good linearity. The group delay is defined as the measurement of the signal transition time though a device. For the notched UWB antennas, the altered inductance properties result in a group delay of UWB antennas. We use the definition of the group delay [46] through the derivative of phase, which is expressed as,

$$\tau(\omega) = -\frac{\partial \varphi(\omega)}{\partial \omega}, \quad (1)$$

where $\varphi(\omega)$ and ω are the phase and angular frequencies, respectively. The group delay characteristic of the proposed notch band antennas and the reconfigurable antenna5 with switches ON and OFF are shown in Fig. 12. It is observed form Fig. 12 (a) that the group delay of antenna1 is less than 2 ns. The group delays of the notch band UWB antennas are less than 2 ns except the notch band. For the lower notch band near 5.5 GHz, the group delay is about 7 ns. For the higher notch band at 9 GHz, the group delay is about 6 ns. This also implies that the two notch band can reduce to void the potential interference from the narrow band, such as C-band and IEEE 802.11a.

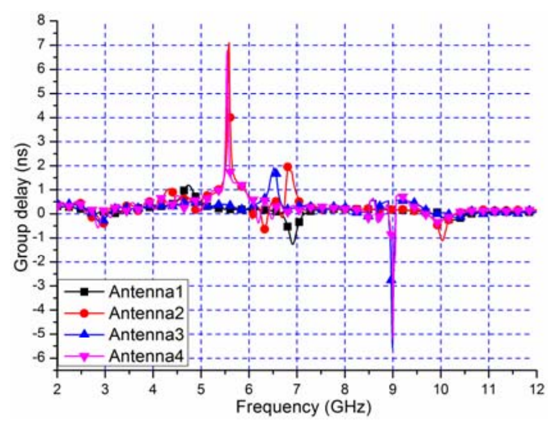


(a)

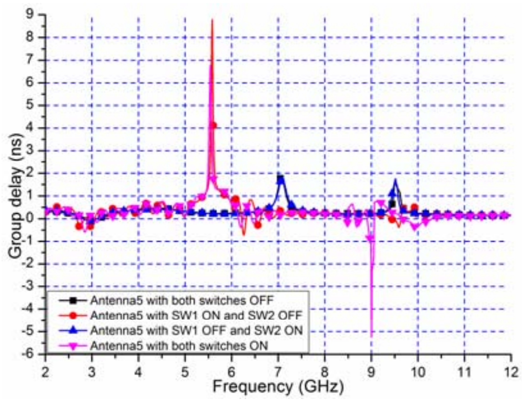


(b)

Fig. 11. Phase behaviour of the proposed antennas when the switches are in the different status for (a) the notch band UWB antennas and (b) the reconfigurable UWB antennas.



(a)



(b)

Fig. 12. Group delay characteristic of the proposed antennas when the switches are in the different status for (a) the notch band UWB antennas and (b) the reconfigurable UWB antennas.

For the reconfigurable antennas, the notched UWB antennas also have a high group delay at the notch band. The reconfigurable antenna5 with both switches OFF and antenna5 with SW1 OFF and SW2 ON are UWB antennas and the group delays are less than 2 ns over the operation band. For the UWB antenna1, the group is about 1 ns. The group of other antennas may be affected by the two SIRs in the UWB operation band. The group delay is caused by the SIRs, which change the inductance and capacitance of the antennas at the notch bands.

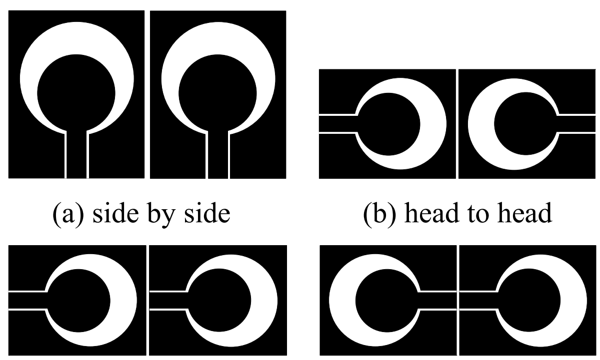
F. UWB system with two UWB antennas

To investigate the performance of the proposed antennas as a transmitter and a receiver in an UWB system [47], two identical antennas are mounted on the surface of the dielectric surface with 100 mm shift of their center points, and the antenna orientations are arranged in the four cases, as shown in Fig. 13. One of them works in the transmitting mode, and another one works in the receiving mode. The antenna in the transmitting mode is excited by using a modulated Gaussian pulse as shown in Fig. 14 (a). The received signal at the notch antennas and the reconfigurable antennas with different orientations are shown in Figs. 14 (b) and 14 (c).

It is observed from Fig. 14 that the received signals have been dispersed and distorted compared with the excitation pulse, which is caused by the free space attenuation [47-49]. The signal amplitudes of the received signals are also decreased due to the attenuation. The received signal of antenna5 with both switches ON deteriorates quickly than both switches are OFF. The distortion signal may be also attributed to the excited SIRs that result in the power leaking. This can also be assessed using fidelity and given as follows [47],

$$F = \max\left[\frac{\int_{-\infty}^{+\infty} s_t(t)s_r(t+\tau)d\tau}{\int_{-\infty}^{+\infty} \left|s_t(t)\right|^2 dt \int_{-\infty}^{+\infty} \left|s_r(t)\right|^2 dt}\right] \quad (2)$$

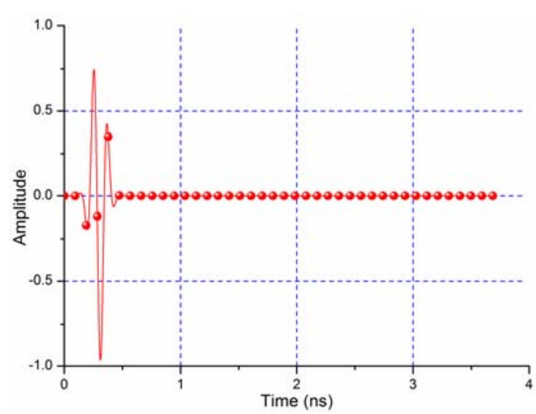
where $S_t(t)$ is the source pulse and $S_r(t)$ is a received signal in the far field zone. The fidelity (F) is the maximum correlation coefficient of the two signals by varying the time delay τ. In fact, the fidelity reflects the similarity between the transmitted and received signals. The group delay of antenna1, antenna5 with both switches OFF and antenna5 with both switches ON are also investigated herein and illustrated in Fig. 15.



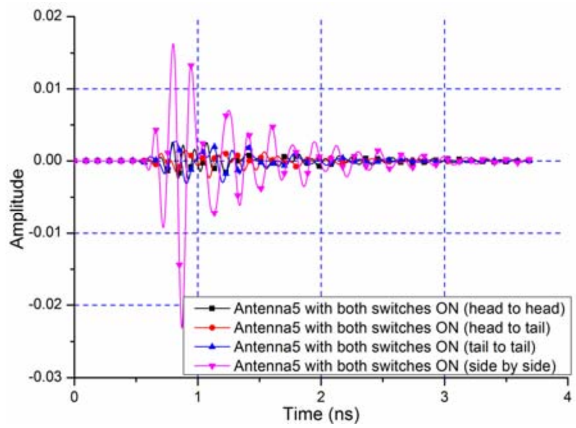
(a) side by side (b) head to head

(c) head to tail (d) tail to tail

Fig. 13. Relative positions of the two antennas for evaluating group delay.



(a)



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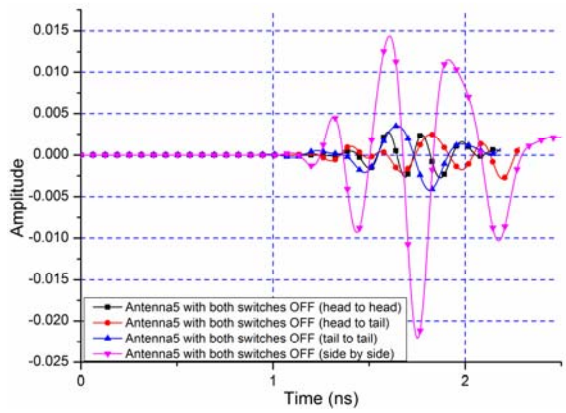
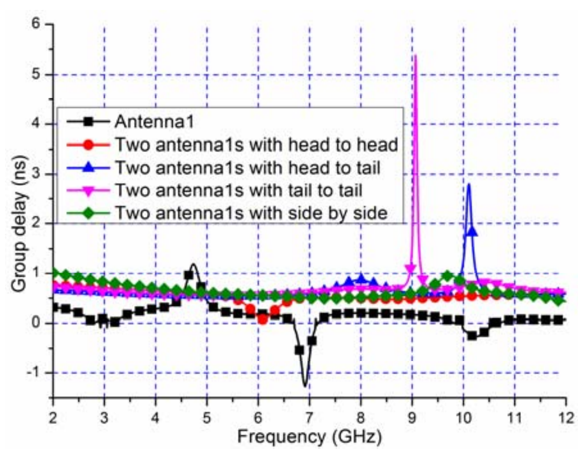
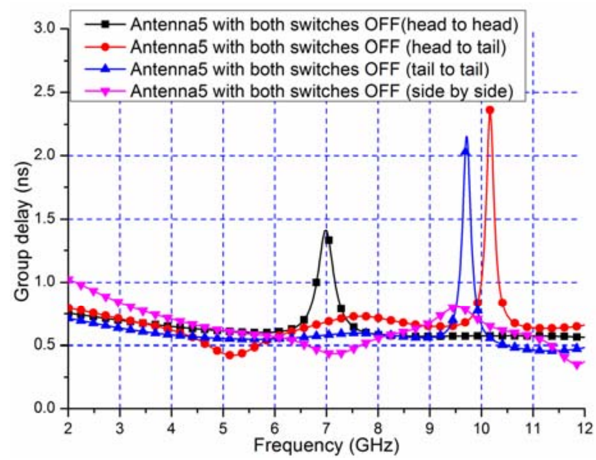


(c)

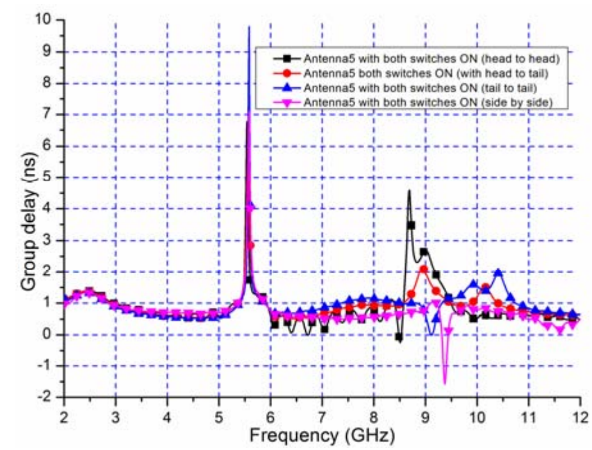
Fig. 14. Time domain characteristic of the proposed reconfigurable antennas for the different switch status: (a) excitation pulse used in the transmitting antenna, (b) Transmitted time domain signal measured at the antenna 5 with both switches ON, and (c) Transmitted time domain signal measured at the antenna5 both switches OFF.



(a)



(b)



(c)

Fig. 15. Group delay characteristic of two antenna systems for the different relative locations for (a) antenna1, (b) antenna5 with both switches OFF, and (c) the antenna5 with both switches ON.

It can be seen from Fig. 15 (a) that antenna1 has a small group delay except the tail to tail case. When the antennas are placed in the tail to tail position, the signal has a longer path than other positions, which results in a larger group delay. For the proposed reconfigurable antennas, the antenna5 with both switches OFF has a small group delay, and however, the antenna5 with both switches ON has a large group delay at the notch bands. The group delays of antenna5 are similar to antenna1 expect in the notch bands.

IV. CONCLUSION

In this paper, a compact reconfigurable antenna for UWB and multi-band communication applications has been investigated numerically and experimentally. The reconfigurable functions are obtained using two ideal switches on SIRs. By switching ON and OFF status of the two switches, the proposed reconfigurable antenna can work in three modes, namely, UWB mode, notch band UWB mode/dual band antenna mode and dual notch band UWB mode/tri-band antenna mode. The switchable characteristic and notch functions are numerically investigated. The proposed switchable antenna with both switches ON and OFF are fabricated and measured. The impedance, group delay, and phase of the proposed antenna are also analyzed in this paper. We believe that PIN diodes or MEMS switches can be used to replace ideal switches to realize reconfigurable characteristics in the practical engineering. As a result, the proposed antenna can well meet the UWB communication requirement and effectively reduce the potential interference between UWB systems and existing narrow band systems.

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