Multi-Functional Ultra-Wideband Monopole Antenna with High Frequency Selectivity

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Abstract **─** A multi-functional microstrip-fed ultra-wideband (UWB) monopole antenna has been presented. By loading two dual-mode resonators and shunt metallic strips on the reference UWB antenna, two additional operational states are created, including band-notched UWB response (i.e., 3.1~11.5 GHz passband response except the notched band of 5.15~5.8 GHz) and narrow bandpass response (5.5-5.95 GHz) with high frequency selectivity. Moreover, the frequency characteristics of bandpass filtering antenna is also studied when we solder two lumped-chip 0 Ω resistors instead of the shunt metallic strips. Four antenna prototypes are designed, fabricated and measured to validate the design concept. Full-wave electromagnetic simulator HFSS is used for the antenna design optimization and performance prediction. The measured results are presented including return losses, gains and radiation patterns, declaring that the proposed antennas have good impedance matching performance and radiation patterns.

Index Terms **─** High frequency selectivity, monopole antenna, notched band, ultra-wideband.

I. INTRODUCTION

Since the Federal Communications Commission (FCC) released the bandwidth of 3.1-10.6 GHz as the ultra-wideband (UWB) [1] and the concepts of software defined radio (SDR) and cognitive radio (CR) were redefining the design of wireless systems [2], UWB communication systems applied to SDR or CR have attracted great attention in the wireless world due to their advantages including high-speed data rate, flexibility and high capacity. Planar monopole antennas are found as good candidates for UWB applications [3-5] owing to their fascinated features, such as ease of fabrication, simple structure, and good radiation properties. However, in practical applications, in order to eliminate the frequency interference between UWB system and other wireless communication systems, it is significantly necessary to design UWB antennas with notched bands. Meanwhile, for most of the existing SDR and CR antennas, more than one antenna radiator is needed to achieve multi-function performance, and additional isolation techniques are also needed for mutual coupling reduction [6]. It significantly increases design complexity. Thus, the antenna with a single radiator but multiple operational states is highly required. Some multi-functional UWB antennas based on the same radiator were reported [7-8]. A novel multi-state RF MEMS switch was developed in 2013 [7] to achieve multiple operational states. Recently, the split ring resonators and short strips were used to realize transformation between band-notched UWB and narrow band response [8]. However, the bandwidths and the frequency selectivity of these designs are limited due to the inherent narrowband nature of these structures. Although great efforts have been made to achieve higher selectivity [9-13], these designs were realized by altering the structure of the radiation element, which may be not easily applied to other UWB antennas with different radiation elements. Moreover, some of them [10], [11] utilized two resonators with two different resonant frequencies to create a wide notched band, which would lead to an increase of the design complexity. In our previous work [14], a UWB antenna with dual notched bands with high frequency selectivity are presented.

In this paper, a novel multi-functional planar monopole antenna with high frequency selectivity is proposed. By placing two dual-mode resonators beside the feed line of UWB antenna, a band-notched UWB response with two reflection zeros at either side of the notched band is generated. Based on the same structure, the narrow bandpass filtering characteristic will be created when two metallic shunt strips are added. Moreover, two lumped-chip 0 Ω resistors instead of the shunt strips are utilized in the bandpass filtering antenna to obtain a simple, flexible and reconfigurable design.

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II. ANTENNA DESIGN AND ANALYSIS

Three antenna prototypes named Antennas A, B and C with varied loadings of dual-mode resonators and metallic shunt strips have been proposed as shown in Fig. 1. Antenna A is a basic UWB antenna regarded as the reference antenna. Antenna B is developed with a pair of dual-mode resonators along the feed line based on the reference antenna, as seen in Fig. 1 (b). Moreover, two shunt strips are added for Antenna C as depicted in Fig. 1 (c). The added strips are located to align with the symmetric axis of the loading resonators. On the bottom layer, there is a metallic ground plane with a size of $L_5 \times W$ as seen in Fig. 2, where a square shaped slot with a size of $L_6 \times W_3$ is etched. This slot is employed to improve the return losses of the UWB antenna.

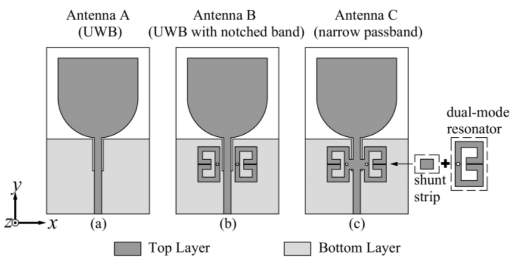

Fig. 1. Schematic view of: (a) Antenna A, (b) Antenna B, and (c) Antenna C.

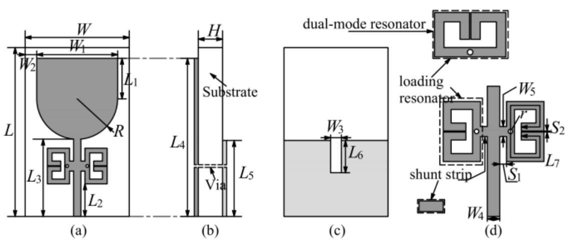

Fig. 2. Geometry of Antenna C: (a) top view, (b) side view, (c) bottom view, and (d) schematic of feed line loaded with dual-mode resonators and shunt strips.

The proposed resonator with a metallic via loaded in the center can be seen as a second-order quarter-wavelength resonator [15] or a short-circuited stub-loaded half-wavelength resonator with the zero stub length [16], which is a dual-mode resonator. The center frequency f_r of the notched band or the passband in the antenna design can be approximately calculated by:

$$f_r = \frac{c}{\lambda_g \sqrt{\varepsilon_{eff}}} \approx \frac{c}{2L_7\sqrt{(\varepsilon_r + 1)/2}}, \quad (1)$$

where λ_g denotes the guided wavelength, c is the light velocity in free space, L_7 is the whole length of the resonator, ε_{eff} and ε_r denote the effective dielectric constant and relative dielectric constant of the substrate, respectively.

To investigate the frequency characteristics of the proposed antenna structures loaded with the dual-mode resonators, Fig. 3 demonstrates the frequency responses of the Antennas B and C with respect to different L_7 and S_2 while other dimensions of the loading resonators are fixed as follows: W=30, W_1=20, W_2=5, W_3=1, W_4=1.1, W_5=1.5, L=37, L_1=10, L_2=4.85, L_3= L_5=11.5, L_4=37, L_6=5, S_1=0.1, and the radius of the via r =0.2, all in mm. They are all modeled on the substrate with a relative dielectric constant ε_r =3.66 and a thickness H=0.508 mm. The physical dimensions of radiators and feed lines are all identical. The notched band of the Antenna B and the passband of the Antenna C are designed to operate at the frequency of f_r to tune the parameter L_7 according to the Equation (1). For instance, when L_7=16.5 mm, the theoretical center frequency of two bands is around 5.95 GHz, which almost agree with the simulated results in Figs. 3 (a) and (c). On the other hand, the bandwidth of the notched band is mainly determined by the two resonant frequencies of the resonator, which can be adjusted by the intra-coupling of the dual-mode resonator, i.e., the parameter S_2.

For Antenna B, the center frequency of the notched band can be tuned by controlling the parameter L_7 while other parameters are fixed (see Fig. 3 (a)). Besides, the parameter S_2 affects the bandwidth of the notched band as demonstrated in Fig. 3 (b). Meanwhile, the frequency characteristics of the narrow bandpass filtering antenna (Antenna C) is plotted in Figs. 3 (c) and (d), where the center frequency and bandwidth of the passband can also be controlled by L_7 and S_2, respectively. Thus, the frequency characteristics of the notched band and passband responses can be flexibly adjusted by the loading resonators without tuning the antenna radiator parameters. In addition, it is worthwhile to highlight that two reflection zeros are located at the edges of the notched band, thus high frequency selectivity can be achieved. Compared with the proposed single-mode resonator in [8], this design can obtain wider bandwidth due to the dual-mode feature.

Furthermore, to switch from band-notched UWB state to narrow bandpass state (or vice versa) conveniently, two lumped-chip 0 Ω resistors with each size of 1 mm × 0.5 mm are soldered to replace the shunt strips in Antenna C, paving the way to realize antenna reconfigurable design. Figure 4 shows the schematic view of this antenna, namely, Antenna D, whose dimensions are the same as those of Antenna C. Figure 5 displays the frequency responses of Antenna D when the parameters L_7 and S_2 are varied while other parameters are fixed. It manifests that Antenna D exhibits similar bandpass filtering response compared to Antenna C, where center frequency and bandwidth of the passband can also be easily controlled by altering the loading resonator dimensions. Two resonant modes can be also seen within the passband. Therefore, the variations of the notched band and passband with the changes of the loading resonator parameters, and the switch from Antenna B to Antenna C can be both exploited in future by introducing varactors, PIN diodes or memristors [17] for practically reconfigurable achievement.

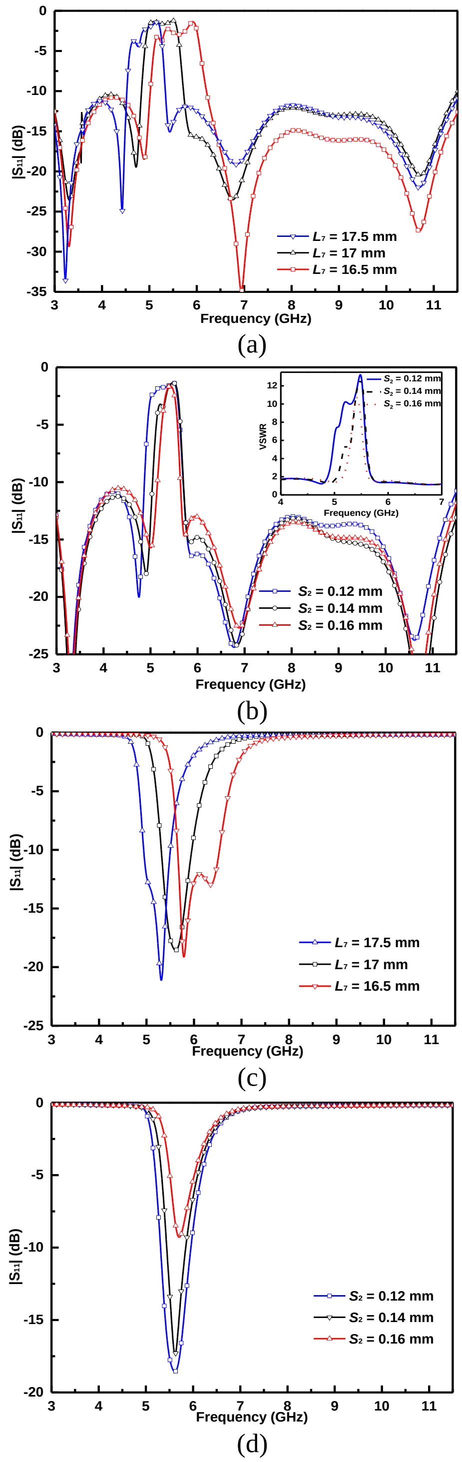

Fig. 3. Simulated reflection coefficients of Antenna B with varied (a) L_7 and (b) S_2, as well as Antenna C with varied (c) L_7 and (d) S_2.

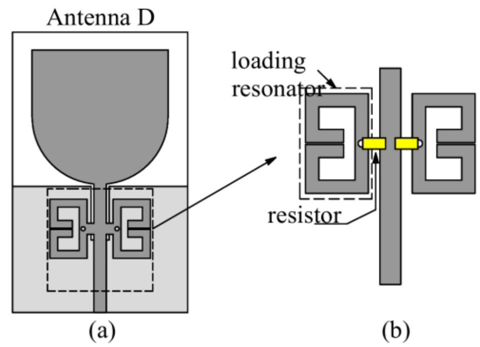

Fig. 4. Schematic view of: (a) Antenna D and (b) corresponding details of the loading resonators.

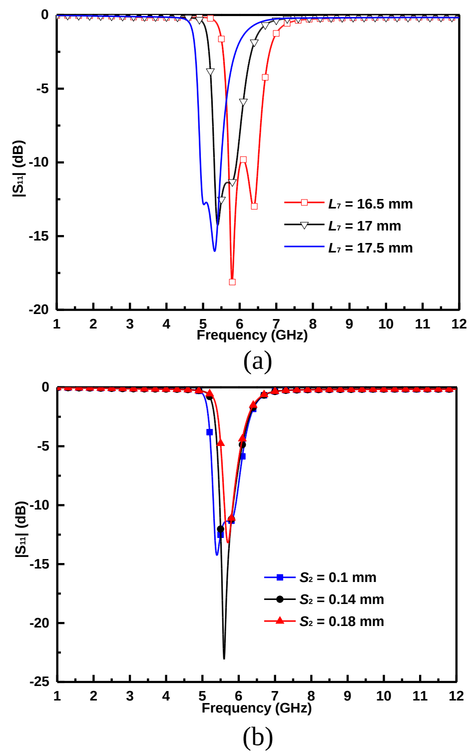

Fig. 5. Simulated reflection coefficients of Antenna D with respect to varied dimensions of the loading resonators.

III. MEASUREMENTS AND DISCUSSION

In order to validate the proposed idea, Antennas A, B, C and D with desired resonant frequencies are designed, simulated, and implemented based on the analysis above. The dimensions of the four antennas are determined as follows (all in mm): W=30, W_1=20, W_2=5, W_3=1, W_4=1.1, W_5=1.5, L=37, L_1=10, L_2=4.85, L_3=11.5, L_4=37, L_5=11.5, L_6=5, L_7=17, S_1=S_2=0.1. The simulated and measured reflection coefficients of the four antennas are illustrated in Fig. 6, using the full-wave electromagnetic simulator HFSS and Agilent E8363B vector network analyzer, respectively.

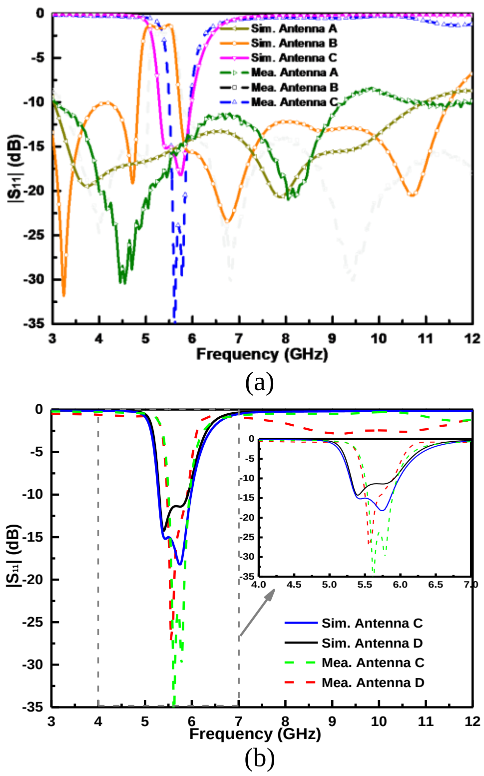

Fig. 6. (a) Simulated and measured reflection coefficients of Antennas A, B and C, and (b) reflection coefficient comparisons between Antennas C and D.

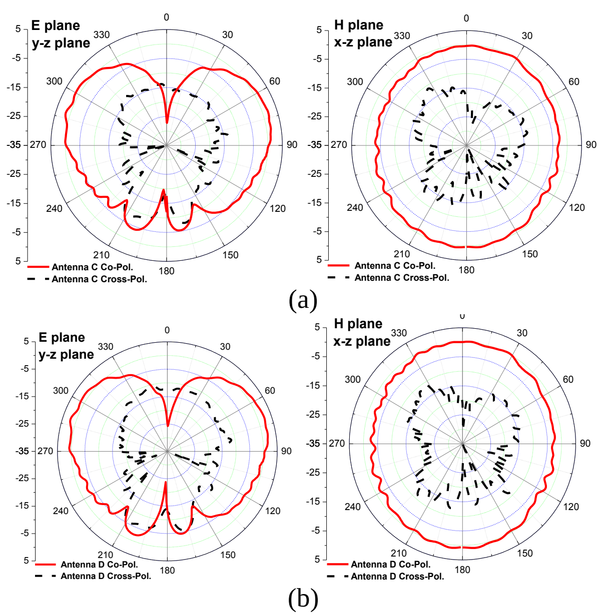

Fig. 7. Measured co-polarized and cross-polarized radiation patterns of: (a) Antenna C in E- and H-planes, and (b) Antenna D in E- and H-planes at 5.6 GHz.

For Antenna B, the return loss is below -10 dB from 3.1 to 11.5 GHz except the notched band with the 10-dB return loss bandwidth of 5.15-5.8 GHz which can be used to reject the 5.2/5.8-GHz (5.15-5.35/5.725-5.825 GHz) WLAN bands. Two reflection zeros are observed at both sides of the notched band, which ensures high frequency selectivity. For Antenna C, a narrow passband filtering antenna of 5.5-5.95 GHz ($S_{11} < -10$ dB) with two resonant modes is achieved. Since the value of resistance in a lumped *RLC* boundary in HFSS must be at least 10 μΩ, the resistor of 10 μΩ in the simulation is taken place of the practical soldering 0 Ω resistor in Antenna D. The reflection coefficients of Antenna D and Antenna C are in agreement, which mean that 0 Ω resistor has nearly the same effect as the metallic strip. The slight discrepancy between these two antennas may be attributed to the non-ideal resistance behavior, width differences of the strip or errors caused by soldering. In addition, the center frequencies of the notched band and the narrow passband are both close to the resonant frequencies of the loading resonators.

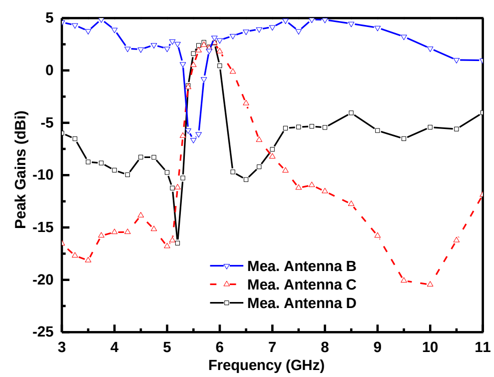

Fig. 8. Measured peak gains of Antennas B, C and D.

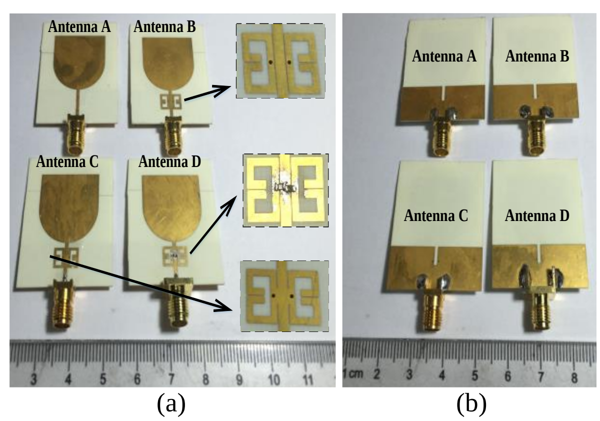

Fig. 9. Photographs of the four fabricated antennas: (a) top view and (b) bottom view.

Figure 7 shows the measured co-polarized and cross-polarized radiation patterns of the Antennas C and D in E- and H-plane at 5.6 GHz. We can see that both of the antennas have good dipole-like co-polarized radiation patterns in E-plane and omnidirectional patterns in H-plane. Moreover, the measured peak gains of Antennas B, C and D are plotted in Fig. 8. The peak gain of Antenna B significantly decreases at the notched bands due to the function of the loading resonator, while both of Antennas C and D have opposite effects compared to Antenna B. The photograph of the four fabricated prototypes is displayed in Fig. 9. Table 1 exhibits the comparisons between the proposed design and the previous reported work, which shows that our work has the advantages of high frequency selectivity, multiple operation states and miniaturized size.

Table 1: Performance comparisons with some previous antennas

	Frequency Selectivity	Technique of the Notched Band	No. of Operation States	Antenna Size $\lambda_g \times \lambda_g^*$
[8]	Poor	A pair of SRRs	3	1.54×1.54
[9]	Good	Nonuniform stub + coupled-line + two substrate layers	1	1×0.92
[11]	Good	Two slots + two stubs	2	0.94×0.8
[13]	Moderate	Folded strips	1	1.14*1.26
This work	**Good**	**Dual-mode resonators**	**3**	**1×0.8**

$^*\lambda_g$ is the guided wavelength of 50 Ohm microstrip line on the substrate at the center frequency of their corresponding notched bands.

IV. CONCLUSION

A planar multi-functional microstrip-fed UWB antenna with high frequency selectivity has been studied and investigated. By loading a pair of dual-mode resonators and the metallic shunt strips, the antenna exhibits band-notched UWB response and narrow bandpass response. High frequency selectivity is obtained by the intrinsic feature of the loading resonators. To verify the proposed idea, four practical antennas have been fabricated and measured. Due to its simple structure, flexible design and excellent performance, the proposed antennas are expected to be good candidates for use in UWB systems.

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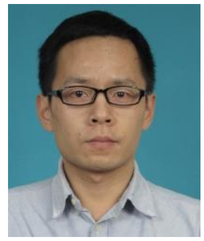

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