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Design of Integrated Duplexing and Multi-Band Filtering Slot Antennas

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ABSTRACT In this paper, a duplexing antenna and two multi-band filtering antennas using resonator loaded slot are presented. The loaded slot can be flexibly designed as a dual-band or a tri-band antenna by changing the number of the loaded resonator. The operating frequencies of the slot antenna can be easily controlled through tuning the lengths and positions of the loaded elements. By integrating the multi-band antenna and the multi-mode resonator, duplexing and filtering antennas can be realized. The duplexing antenna consists of two single-mode resonators, a dual-mode stub-loaded resonator as the junction resonator and a dual-band slot antenna. The dual-band and tri-band filtering antennas each contains a dual-mode resonator or a tri-mode resonator, radiating through resonator loaded slot antenna. Since the slot is the only radiation element, all the operating bands of the three antennas show good bi-directional radiation patterns. For validation, all of the antennas are designed, manufactured and measured.

INDEX TERMS Duplexing antenna, filtering antenna, multi-band, slot antenna.

I. INTRODUCTION

In modern communication systems, more and more attention has been paid to the investigation of slot antennas because of the attractive features including low cost, low profile and light weight [1]. In these focuses, multi-band slot antennas have been of great interest due to the co-exist of multiple communication systems which can reduce the size of RF front end by integrating the multi-bands into one antenna [2], [3].

Filtering and duplexing antennas help to improve the frequency selectivity of the system by eliminating the mismatch and losses between the antenna and filter network [4], [5]. In conventional transceiver system, the use of different frequency bands leads to dedicate signal path, such as one broadband antenna together with single-band filters or multiple antennas, resulting more volume, mass and higher insertion loss. The integration of some important components, like power divider, duplexer and antenna in the RF front end, can further augment functionalities. For example, an antenna and a duplexer can be integrated as a duplexing antenna [6]–[12]. In [9], the duplexer and the patch antenna are designed separately and then combined using mix electromagnetic coupling. The dual-band patch antenna is used only as a radiation element which means that it doesn't participate in resonating. Likewise, in [10], a duplexing dual circularly-polarized antenna was proposed using a shared radiator which doesn't resonate at the operating frequency. In [12], the duplexing filtering antenna radiate through a common slot loaded cavity which can obtain a compact size.

To obtain multi-band filtering antenna, the patch antennas have been widely studied [13], [14]. In [13], the triple-band antenna is achieved in one radiation element by employing TM10 mode together with modified TM20 and TM30 modes. In [15]–[17], different radiation elements radiate at different operating bands, which can relatively be easier to obtain the same radiation properties. To reduce the size of the whole antenna, the radiation elements can be integrated into one. However, the main challenge in designing multi-band antennas under one radiation element is how to maintain the stability of radiation patterns at the same time [18]. For slot antennas, the method to obtain multi-band function is various including stepped impedance slot [19], stair-shaped slot [20], multi-branch slot [21], [22], comb-like slot [23] and H-shaped slot [24]. Additionally, slot antennas with multi-resonant modes are not only suitable to improve the

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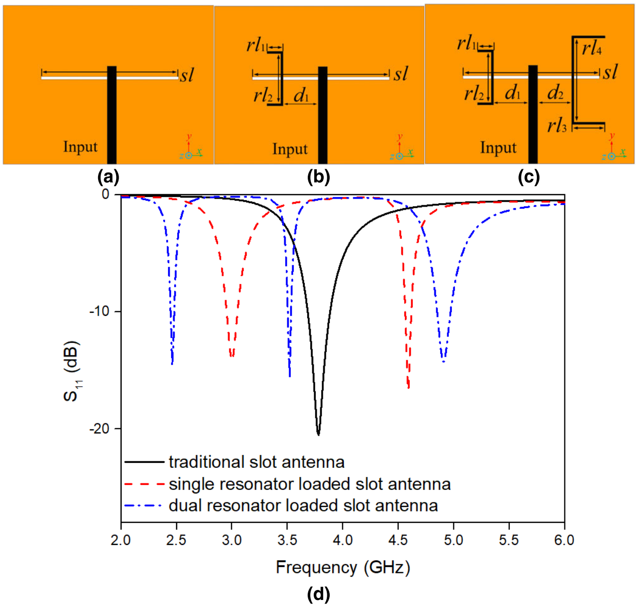

FIGURE 1. **(a) Traditional slot antenna. $sl = 28.25$ mm. (b) Dual-band slot antenna. $sl = 34.25$ mm, $rl_1 = 4.5$ mm, $rl_2 = 11.8$ mm, $d1 = 13$ mm. (c) Tri-band slot antenna. $sl = 32.15$ mm, $rl_1 = 4$ mm, $rl_2 = 15.1$ mm, $rl_3 = 6.8$ mm, $rl_4 = 17.7$ mm, $d_1 = 5.82$ mm, $d_2 = 14.25$ mm. (d) Simulated reflection coefficients.**

impedance bandwidth [25], but also have great potential to design multi-band antennas [26].

The duplexing/dual/tri-band filtering antennas are mainly designed by patch antenna, with parasitic patches stacked on the top of the ground plane [8]–[11], [13], [14]. Little research has been done to obtain multi-band filtering antenna with single-layered structure. In this design, the proposed duplexing/dual/tri-band filtering antennas are designed on single-layered PCB, which provides many advantages, such as low profile, light weight, low cost and easy fabrication. Based on our further investigation, the method of antenna and bandpass filter (BPF) co-design is applied to the slot antenna. A duplexing and two multiband filtering antennas using the proposed multiband antennas are presented in this paper. The duplexing antenna is composed of two single-mode resonators with different operating frequencies, one dual-mode resonator and a dual-band slot antenna. The multi-band filtering antennas are designed by integrating the multi-mode resonators and multiband slot antennas. To validate the theory, three antennas are designed, fabricated and measured.

II. MULTI-BAND SLOT ANTENNAS

In our previous work, we proposed a resonator-loaded multi-band microstrip slot antenna [27], which will be used as a building block in this paper. Fig. 1 (a)-(c) show the configuration of the proposed multiband resonator-loaded slot antennas as well as a traditional slot antenna. The multi-band antennas consist of a 50 Ω microstrip feedline, a rectangular slot etched in the ground plane and resonator(s) loaded on it. The loaded resonators and feedline are located on the top layer of the

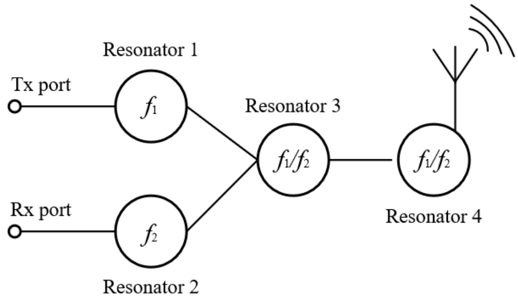

FIGURE 2. **Equivalent topology of the duplexing antenna.**

substrate while the slot is placed on the ground plane which is perpendicular to the loaded resonators and the feedline. Due to the non-radiating property, the loaded resonator can be folded to reduce the whole structure size in the design. All the antennas are designed on a substrate with dielectric constant $\varepsilon_r = 2.55$, loss tangent $\delta = 0.0029$ and thickness $h = 0.8$ mm.

The simulated reflection coefficients of the three antennas are shown in Fig. 1 (d). The traditional slot antenna can serve both as a single-mode resonator and a radiator. When loading a half-wavelength resonator on the one side of the feedline as shown in Fig. 1 (b), the whole structure operates as a dual-mode resonator and still radiates through the slot at two bands. When loading another resonator on the other side of the feedline as shown in Fig. 1 (c), the slot antenna acts as a tri-mode resonator and operates at three bands.

III. DUPLEXING AND MULTI-BAND FILTERING ANTENNAS

A. DUPLEXING ANTENNA

Based on the dual-band slot antenna, a duplexing antenna is developed and denoted as Design-I. The equivalent topology is shown in Fig. 2. The design prototype is shown in Fig. 3(a) and the equivalent circuit model of the filtering duplexing antenna is shown in Fig. 3 (b). As analyzed above, the single-resonator loaded slot antenna can act as a dual-mode resonator (resonator 4 in Fig. 2), and is coupled to a common dual-mode resonator (resonator 3). The resonator 3 acts as a junction section and is realized by the stub loaded resonator (SLR) with two controllable frequencies [28], [29]. Two single-mode resonators (resonators 1 and 2) with different operating frequencies extract the two signals from the shared SLR separately. So the transmitting path contains resonators 1, 3 and 4 while the receiving path contains resonators 2, 3 and 4. This realizes a third-order filtering response of each channel, which can improve the impedance bandwidth of the slot antenna.

As shown in Fig. 3 (b), the two half-wavelength resonators and the SLR operating at different passbands are modeled by parallel $L_{i1}C_{i1}$ and $L_{i2}C_{i2}$ resonators (i =1 for the low band and i =2 for the high band), and the dual-mode slot antenna are modeled as $R_C L_C C_C$. The values of lumped elements and the coupling parameters can be obtained by using the

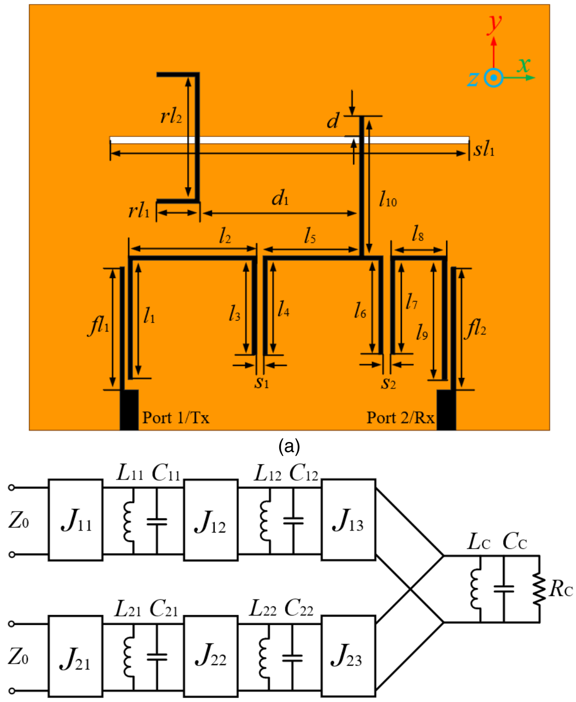

FIGURE 3. (a) Simulated prototype of the single-resonator loaded duplexing antenna. The optimized parameters are (mm): $rl_1 = 4.5$, $rl_2 = 12.9$, $d = 0.7$, $d_1 = 15.56$, $sl_1 = 27.7$, $l_1 = 9.1$, $l_2 = 13.6$, $l_3 = 7$, $l_4 = 7$, $l_5 = 10.2$, $l_6 = 7$, $l_7 = 7$, $l_8 = 5$, $l_9 = 8.6$, $l_{10} = 12.8$, $fl_1 = 9.7$, $fl_2 = 8.2$, $s_1 = 0.75$, $s_2 = 0.25$. (b) Equivalent circuit of the proposed duplexing antenna.

bandpass filter synthesis theory [30]

$$R_c = \frac{Z_0}{g_3} \tag{1}$$

$$C_{i1} = C_{i2} = C_c^i = \frac{g_3}{2\pi f_i Z_0 \Delta} \tag{2}$$

$$L_{i1} = L_{i2} = L_c^i = \frac{1}{4\pi^2 f_i^2 C_c} \tag{3}$$

$$J_{i1} = \sqrt{\frac{\Delta}{g_o g_1}\frac{2\pi f_i C_1}{Z_0}} \tag{4}$$

$$J_{i2} = 2\pi f_i \Delta \sqrt{\frac{C_1 C_2}{g_o g_1}} \tag{5}$$

$$J_{i3} = 2\pi f_i \Delta \sqrt{\frac{C_2 C_c^i}{g_1 g_2}} \quad (i = 1, 2) \tag{6}$$

where g_j are the standard g values of the filter and Δ is the fractional bandwidth. Based on the above analysis, the required external Q-factor and coupling coefficients of the synthesis process can be calculated as follows:

$$Q_{ei} = \frac{1}{Z_0 J_{i1}}\sqrt{\frac{C_1}{L_1}} = \frac{g_o g_1}{\Delta} \tag{7}$$

$$M_{12}^i = \frac{J_{i2}}{2\pi f_i \sqrt{C_{i1} C_{i2}}} = \frac{\Delta}{\sqrt{g_1 g_2}} \tag{8}$$

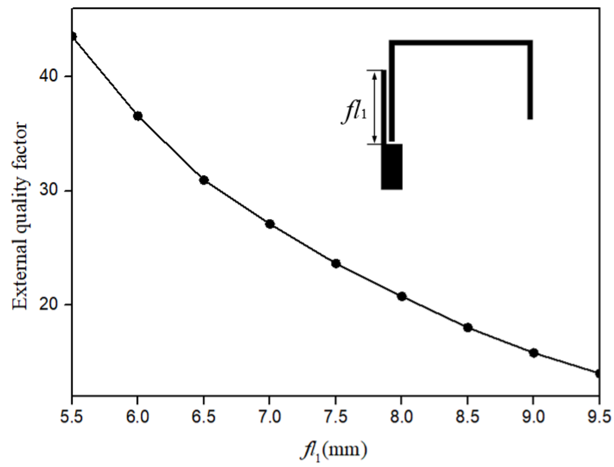

FIGURE 4. Q_{e1} as the function of fl_1 and the test structure.

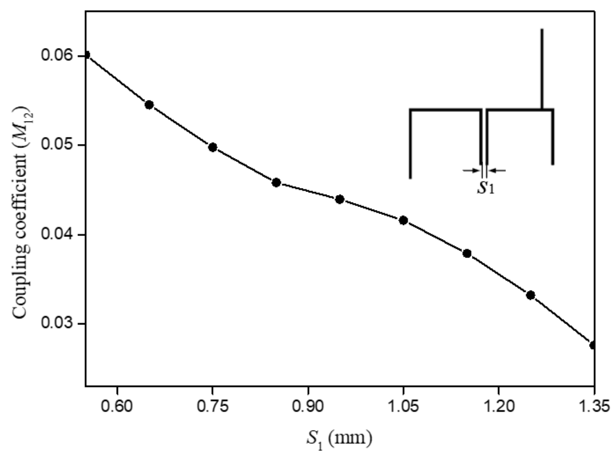

FIGURE 5. M_{12}^1 as the function of S_1 and the test structure.

An experimental duplexing antenna is designed for demonstration. The channel frequencies are set as 3.5 GHz and 5.2 GHz with fractional bandwidth of 5.7% and 10.4%, respectively. For the third-order 0.4-dB ripple level Chebyshev response, the normalized lowpass filter prototype element values are: $g_o = 1$, $g_1 = 1.4909$, $g_2 = 1.1180$, $g_3 = 1.4909$, $g_4 = 1$. The parameter values calculated by (1)-(8) are: $R_c = 33.5\ \Omega$, $C_{11} = 23.8$ pF, $L_{11} = 86.9$ pH, $C_{21} = 8.8$ pF, $L_{21} = 106.8$ pH, $Q_{e1} = 26.16$, $Q_{e2} = 14.34$, $M_{12}^1 = 0.044$, $M_{12}^2 = 0.081$.

The external coupling strength of the two channels can be achieved simply by changing the dimensions of the feeding structure (fl_1 and fl_2). Fig. 4 depicts the test structure of the low band channel and the full-wave simulated Q_{e1}. The coupling strength between the adjacent resonators can be realized by tuning the space between them (s_1, s_2, d, d_1). Fig. 5 demonstrates the test structure and the coupling strength as the function of S_1. The insert of the feedline across the slot is adequate for the impedance matching. According to the external quality factors and coupling coefficients derived

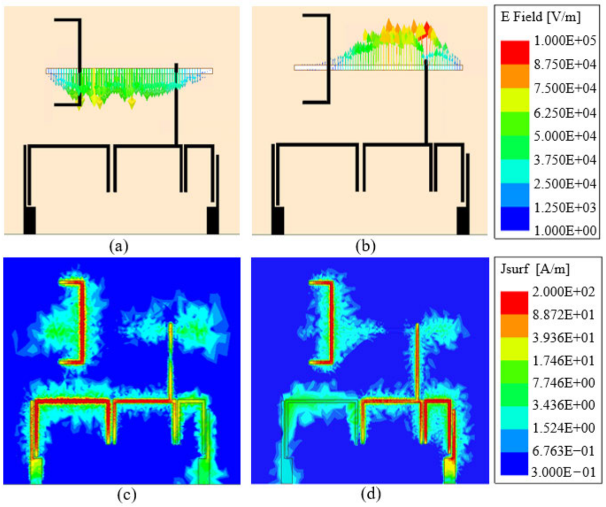

FIGURE 6. Simulated electric field distribution of the duplexing antenna: (a) low channel. (b) high channel. Simulated current distribution of the duplexing antenna: (c) Port 1 is excited, at low channel. (d) Port 2 is excited, at high channel.

above, the optimizations were performed using HFSS and the optimized dimensions are presented in the caption of Fig. 3. A unique feature of this duplexing antenna is that the single-resonator loaded slot not only resonates at the two channel frequencies but also acts as a radiation element without introducing extra radiation elements, which can reduce the size of the duplexing antenna.

Fig. 6 shows the electric field distribution and current distribution at the two operating bands of the duplexing antenna. As can be observed in Fig. 6 (a) and (b), the whole slot participates in radiating at low channel while the right side of the slot radiates at high channel. The results show that different proportions of the slot determine the radiation at two operating bands which indicates that both the two bands can realize good bi-direction radiation. Fig. 6 (c) and (d) show the current distribution of the duplexing antenna on the top layer of the substrate. When antenna works at low channel (port 1 is excited), strong current flows along the single-mode resonator of the low-band channel and adjacent part of the shared SLR. At the same time, the current on the high channel is very weak. The situation is similar when port 2 is excited. It can be observed that the current on the loaded resonator is strong no matter port 1 or port 2 is excited. This is mainly because the resonator loaded slot (resonator 4 in Fig. 2) is a dual-mode resonator which operates at two channels.

Experiment was conducted to verify the duplexing antenna design. Fig. 7 depicts the front- and back view of the proposed antenna. The simulated and measured S-parameters results are shown in Fig. 8. The measured 10 dB impedance bandwidth for the two bands are 3.43 - 3.65 GHz and 4.93 - 5.53 GHz and the measured isolation between the two channels is 20.3 dB. Fig. 9 shows the simulated and measured gain for the two channels, while the measured realized gains are 4.67 and 6.3 dBi, respectively. It is worth mentioning that

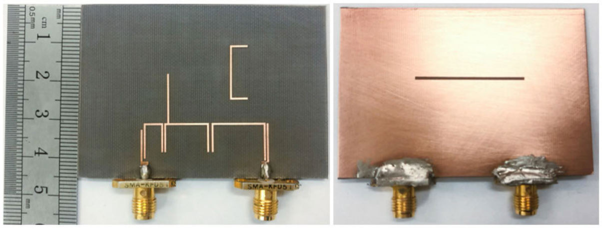

FIGURE 7. Photograph of the duplexing antenna at front- and back- view.

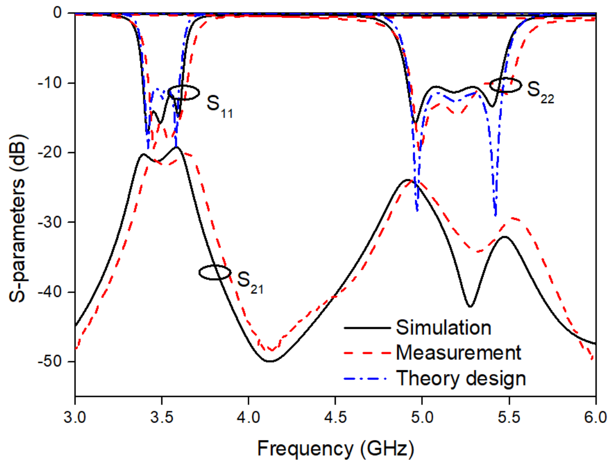

FIGURE 8. Calculated, simulated and measured results.

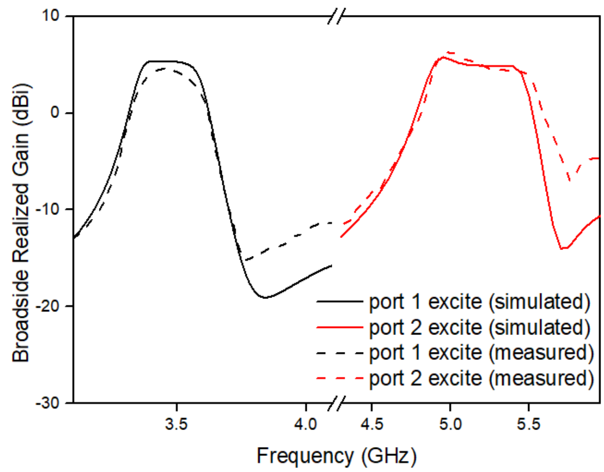

FIGURE 9. Simulated and measured broadside realized gain of the third-order duplexing antenna.

the null point at 5.7 GHz is concerned with the direction. This is because the phase distribution of electrical fields at 5.7 GHz on the radiation slot is unequal, which distorts the radiation pattern. Fig. 10 shows the simulated and measured radiation patterns in the E-plane and H-plane of the proposed duplexing antenna at the two operating bands. The two bands both achieve good bi-directional radiation patterns. The simulated and measured radiation efficiency is given in Fig. 11. It can be observed that the radiation out of the operating bands is

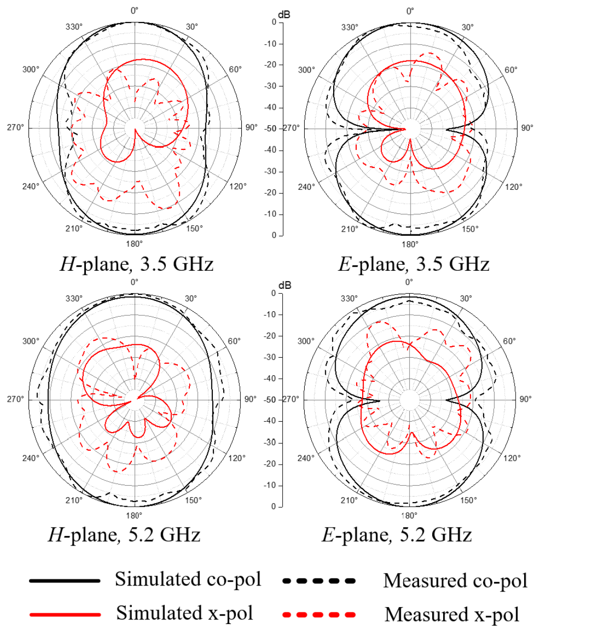

FIGURE 10. Simulated and measured radiation patterns of the duplexing antenna.

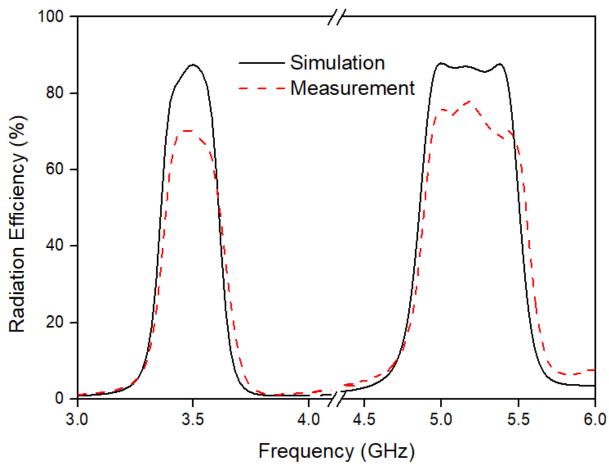

FIGURE 11. Simulated and measured radiation efficiency of the duplexing antenna.

well suppressed. This result indicates that the proposed antenna possesses good filtering performance.

A comparison between the proposed duplexing antenna and other duplexing antennas are given in Table 1. As can be observed that the proposed duplexing antenna (Design-I) can achieve wider impedance bandwidth. Furthermore, the realized gain is slightly higher than other duplexing slot antennas [11], [12].

B. DUAL-BAND AND TRI-BAND FILTERING ANTENNA

Based on the dual-band slot antenna, a 2nd-order dual-band filtering antenna can also be designed, denoted as Design-II. The configuration is shown in Fig. 12 (a). It consists of a single-resonator loaded slot antenna, a dual-mode

TABLE 1. Comparison between the proposed duplexing antenna and reported ones.

Antennas	Order of each passbands	Gain (dBi)	Relatively impedance bandwidth	Size (*λ_g)
[8]	3	5.4 / 4.2	10.6% / 6.9%	1.1*1.1*0.13
[10]	2	6 / 8	4.7% / 7.3%	--*--*0.044
[11]	2	2.3 / 3.6	4.5% / 5.5%	1.2*1.2*0.029
[12]	2	2.7 / 2.65	4.5% / 3.6%	2.82*0.92*0.02
Design-I	3	4.67 / 6.3	6.3% / 11.5%	1.16*0.84*0.01

*λ_g is the guided wavelength on the substrate at the lower frequency of the operation band.

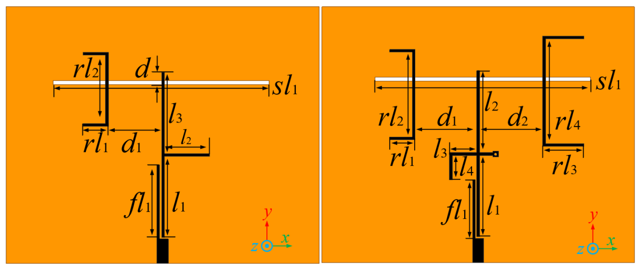

FIGURE 12. (a) Prototype of the second-order dual-band filter antenna. The optimized parameters are (mm): $rl_1 = 4.5$, $rl_2 = 12$, $d_1 = 7.95$, $sl_1 = 28$, $l_1 = 14.2$, $l_2 = 7.9$, $l_3 = 14.2$, $fl_1 = 10$. (b) Simulated prototype of the dual-resonator loaded tri-band antenna. The optimized parameters are (mm): $rl_1 = 4.5$, $rl_2 = 14.9$, $rl_3 = 7.3$, $rl_4 = 18.4$, $d_1 = 6.85$, $d_2 = 6$, $sl_1 = 31.5$, $l_1 = 14.3$, $l_2 = 14.4$, $l_3 = 4.8$, $l_4 = 4.3$, $fl_1 = 10.3$.

stub-loaded resonator and a microstrip feedline. The dual-band slot antenna is fed by the stub loaded resonator which provides two controllable frequencies. As mentioned in section II, the single-resonator loaded slot operates at two bands. This results in a second-order filtering response in each band. The required coupling strength between the SLR and the single-resonator loaded slot can be obtained by adjusting the offset distance (*d* in Fig. 12 (a)). The center frequencies of the dual-band antenna are set as 3.5 GHz and 5.2 GHz. The optimized dimensions are presented in the caption of Fig. 12(a).

Similarly, based on the tri-band antenna designed above, a tri-band filter antenna operating at 2.5 GHz, 3.5 GHz and 5.1 GHz is further designed using the dual-resonator loaded slot antenna as shown in Fig. 12 (b), denoted as Design-III. The tri-band slot antenna is fed by a tri-mode crossed resonator, also resulting in a second-order filtering response at three passbands. The crossed resonator is a tri-mode resonator and the details are given in [31]. The slot serves as a shared radiation element in this tri-band filtering antenna design.

Fig. 13 shows the simulated and measured S-parameters together with realized peak gain in the direction of +Z of the dual-band antenna. The insert shows front- and back-view of the fabricated antenna. The measured range for S11<-10 dB for the two operating bands are 3.44 GHz - 3.73 GHz and 5.08 GHz - 5.42 GHz with peak gains of 5.47, 5.1 dBi, respectively. Fig. 14 shows the photograph of the tri-band antenna and Fig. 15 shows the simulated and

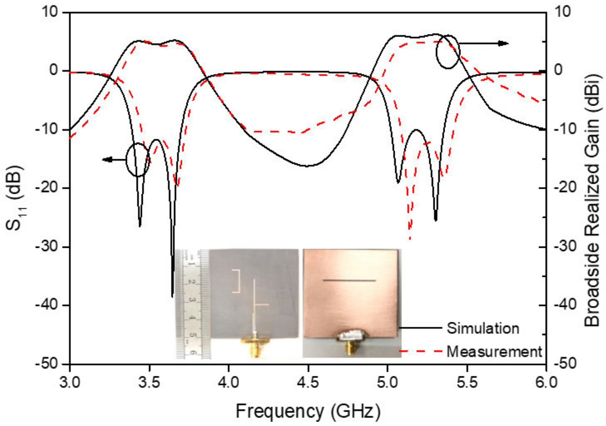

FIGURE 13. Simulated and measured S-parameters and broadside realized gain of the second-order dual-band antenna.

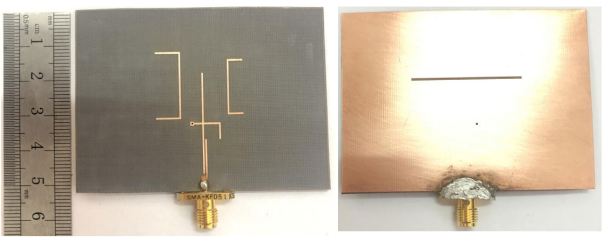

FIGURE 14. Photograph of the tri-band antenna at front- and back- view.

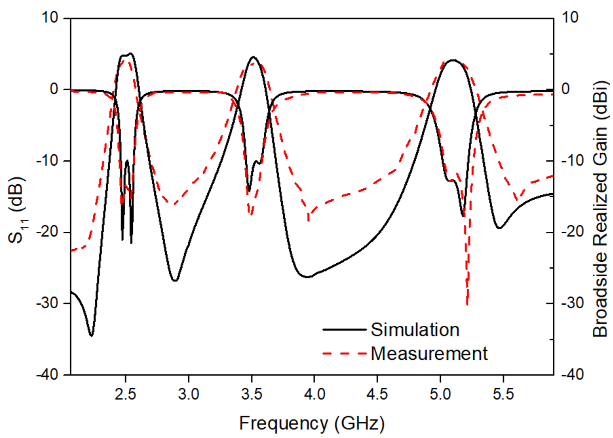

FIGURE 15. Simulated and measured S-parameters and broadside realized gain of the tri-band antenna.

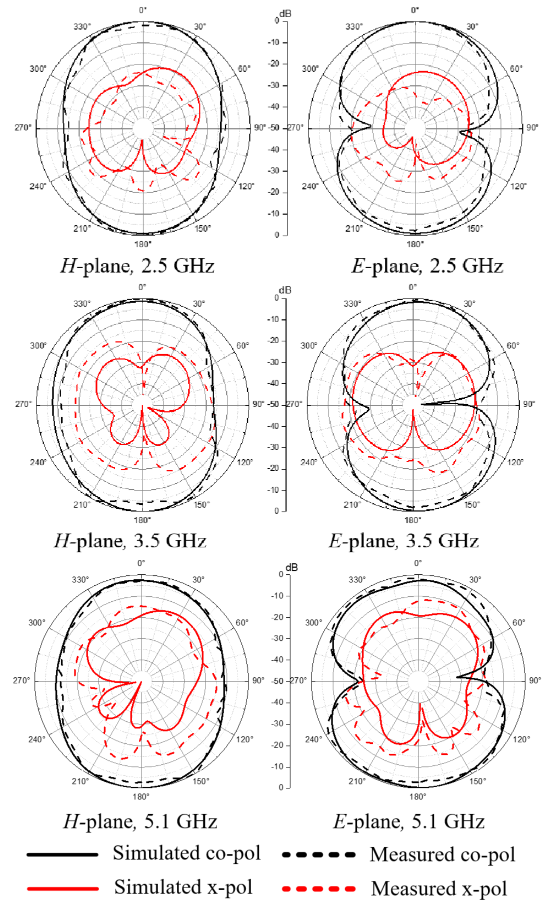

FIGURE 16. Simulated and measured radiation patterns of the tri-band antenna.

TABLE 2. Comparison between the proposed tri-band filtering antenna and reported ones.

Antennas	Number of passbands	Gain (dB)	Size (*λ_g)	Filtering feature
[19]	3	5.34 4.02 4.72	1.83*0.81*0.01	No
[21]	2	4 / 6.8	----	No
[26]	1	5	1.94*0.79*0.02	Yes
Design-III	3	4.10, 3.78, 4.10	0.96*0.69*0.01	Yes

*λ_g is the guided wavelength on the substrate at the lowest frequency of the operation band.

measured S-parameter and gain in the direction of +Z of the tri-band antenna. The measured 10 dB impedance bandwidths of the three bands are 2.46-2.56, 3.45-3.56, and 5.01-5.26 GHz with the measured gains of 4.10, 3.78 and 4.10 dBi, respectively. Both of the dual- and tri-band antenna exhibits good filtering performance with a sharp skirt in the stop-band. The impedance bandwidth has been both enhanced by introducing another resonant mode in the operating frequency band. Fig. 16 shows the simulated and measured radiation patterns in the E-plane and H-plane of the proposed tri-band filtering antenna. The three bands also achieve good bi-directional radiation patterns.

It is worth mentioning that a feeding cable is used in the measurement of the radiation pattern and gain while in computer simulation, no feeding cable is used. Some unwanted current may appear on the outer surface of the feeding cable. This effect will deteriorate the measured results of the radiation pattern and gain [32], [33]. To stabilize the radiation patterns and obtain flat gain response, the lengths between the radiation slot and the edges of ground plane are set to be approximate a quarter wavelength at the lowest frequency to minimize this effect.

A comparison between the proposed tri-band filtering antenna and other slot antennas is given in Table 2. To our best knowledge, this is the first time a tri-band filtering antenna utilizing slot has been presented.

IV. CONCLUSION

This paper has proposed a duplexing antenna, a dual-band and a tri-band filtering antenna using resonator loaded slot. The impedance bandwidth can be widened by applying the multi-mode resonator to feed the slot. All of the operating bands show good bi-directional radiation pattern. To validate the concept, a duplexing antenna, two multi-band filtering antennas are designed, manufactured and measured. The measured results agree well with the simulated one.

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