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Compact Dual-Polarized/Duplex Filtering Antenna With High Isolation

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ABSTRACT This paper introduces novel dual-polarized/duplex filtering antennas with a novel filtering feeding network. The feeding network consists of an all-resonator structure, which shares a common dual-mode resonator. This structure facilitates the isolation of two well-isolated channels through the exploitation of the even and odd modes of the dual-mode resonator. By applying balanced excitation to the odd mode and unbalanced excitation to the even mode, the two modes can be separated, creating a hybrid-like feeding structure. Despite the common resonator, the channels exhibit high isolation, and the overall size of the filtering circuit is much smaller than conventional cascaded-resonator designs. To demonstrate the effectiveness of the proposed feeding network, we have designed, fabricated, and measured a dual-polarized and a duplex filtering antenna. The simulated and measured results agree well, showing isolations greater than 34 dB and 38 dB for dual-polarized and duplex cases, respectively. Our proposed antennas are compared with state-of-the-art developments, demonstrating the advantages of compact size, flexible decoupling frequency ratio, and high isolation.

INDEX TERMS Compact, dual-polarized, duplex, feeding network, filtering antenna, high isolation, hybrid.

I. INTRODUCTION

IN RECENT years people have seen great changes on the modern communication system in their daily life. The electrical devices are becoming more powerful and portable. To meet multiple standards of our system, integration level of radio-frequency frontends has attracted more and more attention than ever before. Many integrated RF devices, such as filtering amplifiers [1], [2], [3], filtering antennas [4], [5], [6], [7], [8], [9], [10], [11], [12], filtering baluns [13], [14], [15], have been presented by researchers in recent years. Co-designed devices have shown to be advantageous over conventional cascaded structures, with smaller size and lower insertion loss.

As more microwave spectra are assigned for mobile communication, more standards need to be satisfied within a single system. Some of these operating bands are closely spaced, and isolation among these channels is critical for optimal performance. Usually, the isolations among these channels are realized by multiplexers [16] or time-division duplex (TDD) technology [17]. However, as more standards merge into a single device, the realization of high isolation becomes increasingly challenging.

To relieve the stress of multiplexer/filter, concept of multiplexing antenna has drawn much attention [18], [19], [20], [21], [22], [23], [24], [25], [26], [27]. In [18], a three-port triplex-antenna is realized by exciting three different modes of a wide rectangular slot antenna. Through properly arranged feeding locations, three orthogonal modes can be excited by three ports respectively with inter-channel isolation higher than 19 dB. In [19] a quadruplexing substrate integrated waveguide (SIW) cavity-backed slot antenna is presented. The proposed design achieves four isolated circularly polarized antennas at four corners of a single SIW cavity with isolations up to 26 dB. Some multiplexing antennas with filtering performance can also be found in the literature [23], [24], [25], [26], [27], [28]. In [23] a microstrip duplexer is co-designed with a dual-band patch antenna for duplex antenna application. A filtering duplex antenna excited by two different multi-mode resonators is presented in [25] for two closely arranged operating frequency bands. In this design, one channel is designed with a transmission zero at the operating frequency of the other channel for high isolation. However, the filtering circuit in this design occupies a considerably large area under the patch. By exciting two orthogonal modes of a SIW cavity and sharing a common half-mode radiator, a duplex filtenna is realized in [26]. The frequency ratio of the two bands is 1.16. Both channels show second-order Chebyshev filtering responses for its operating bands. However, the measured isolation is only 23 dB. Most of these works can only achieve isolations higher than 20 dB. Also, none of them concentrate on the decoupling between two contiguous bands.

Recently, researchers have applied the concept of even-odd-mode theory to realize two well-isolated antennas for duplex applications [28], [29], [30]. By utilizing the inherent orthogonal even and odd modes of a symmetric radiator, two theoretically perfectly isolated antennas can be achieved. The key factor dominating the isolation is the symmetry of the whole dual-antenna structure and the phase error of the differential excitation.

In this paper, the even-odd-mode theory is applied to design the filtering feeding network of a patch antenna for high isolation between two channels with either the same (dual-polarized) or contiguous (duplex) operating bands. The structure is more robust to phase error of the differential port compared to conventional designs. Through this study, it is demonstrated that utilizing this characteristic, very high isolation can be obtained for two channels operating over the same or adjacent frequency bands.

On the one hand, two highly isolated operating bands can be obtained by exploiting the even and odd mode of a stub-loaded resonator. On the other hand, the coupled-resonator circuit provides a Chebyshev filtering performance for the antennas using a more compact structure as two channels share a common resonator. Besides, other works on odd-even-mode duplex usually use the odd-even structure as the radiator [28], [29], [30]. This makes the isolation response very sensitive to the surroundings. Thus, it is hard to realize a high suppression level. In this work, the odd-even structure is only used for the nonradiative feeding structure. So, its isolation is more robust to the surroundings.

II. DUAL-POLARIZED FILTERING ANTENNA
A. ANTENNA CONFIGURATION
To demonstrate the proposed concept, a dual-polarized filtering antenna was developed. The antenna structure is depicted in Fig. 1 and comprises two substrates separated by a 2-mm air gap. The inclusion of an additional substrate reduces the quality factor of the antenna resonator, leading to a broader bandwidth. The feeding circuit, composed of cascaded resonators and feedlines, is situated on the bottom side of the first substrate. The shorting vias in the design have a diameter of 0.4 mm. The common ground plane is located on the upper surface of the bottom substrate and contains three apertures that facilitate coupling between the feeding structure and the radiating patch. The patch is fabricated on the upper surface of the top substrate. For this design, Rogers 4003 substrates with a dielectric constant of 3.55, a loss tangent of 0.0027, and a thickness of 0.813 mm were utilized. The detailed dimensions for the structure are given as follows: l_1 = 18.45 mm, l_2 = 18.55 mm, l_3 = 13 mm, l_4 = 12.05 mm, l_5 = 7.9 mm, l_6 = 6.25 mm, l_7= 13.25 mm, l_8 = 4 mm, l_9 = 9.25 mm, l_{10} = 4.7 mm, l_p = 46.9 mm, w_p = 47.3 mm, l_{s1} = 20.2 mm, l_{s2}= 12.6 mm, w_{s1} = 1.2 mm, w_{s2} = 2 mm, s_1 = 0.2 mm, s_2 = 0.72 mm, s_3 = 0.25 mm, s_4 = 1.55 mm.

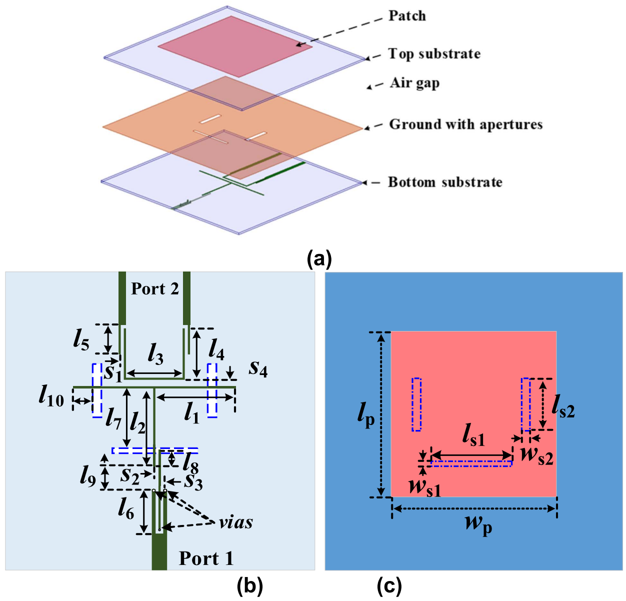


FIGURE 1. Configurations of the dual-polarized filtering antenna. (a) Exploded view. (b) Bottom view. (c) Top view.

B. HYBRID FEEDING STRUCTURE
To comprehend the mechanism of the proposed dual-polarized antenna, it is imperative to investigate the feeding network. The stub-loaded resonator, as illustrated in Fig. 2, is commonly employed in bandpass filter designs due to its dual-mode characteristic and uncomplicated structure [31], [32], [33]. This resonator is composed of a half-wavelength main resonator and an open-ended stub positioned at its center. For this symmetrical configuration, even-odd-mode analysis can be utilized, which supports two modes: an even mode with a magnetic wall at its symmetric plane and an odd mode with an electrical wall at its symmetric plane, as shown in Fig. 2. The main resonator with a characteristic impedance of Z_1 and an electrical length of θ_1 governs the resonances of both modes, while the stub length (θ_2) only affects the resonance frequency of the even mode.

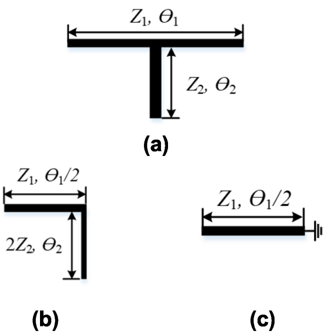


FIGURE 2. Equivalent circuit for the stub-loaded resonator. (a) stub-loaded resonator. (b) even mode. (c) odd mode.

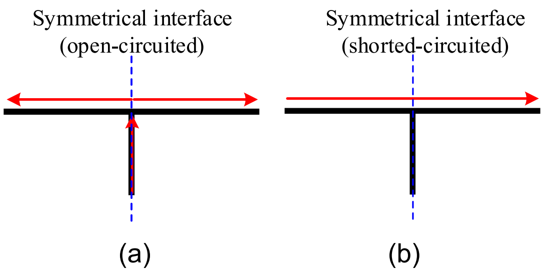


FIGURE 3. Even and Odd modes field distributions. (a) even mode. (b) odd mode.

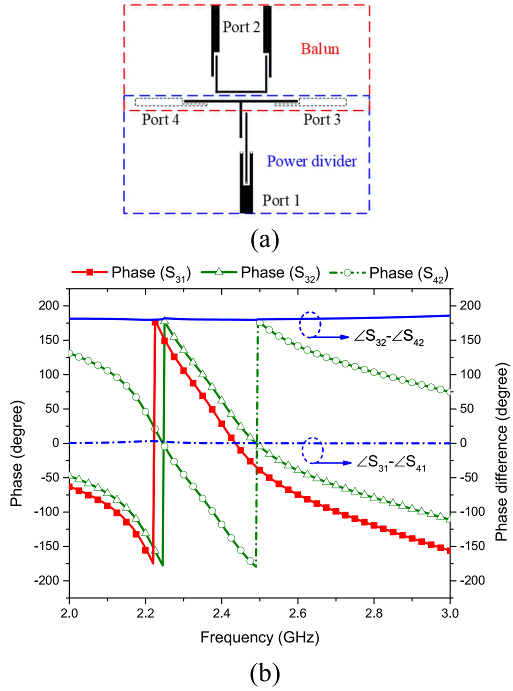


FIGURE 4. Even and Odd modes field distributions. (a) even mode. (b) odd mode.

Consequently, the resonance frequencies of these two modes can be adjusted independently by altering the dimensions of the dominant structure of each mode. In this study, it has been discovered that two highly isolated channels can be attained if each mode can be stimulated by an individual port.

Fig. 3 displays the current distributions of both modes at their resonance frequencies. For the even mode, the current on the main resonator is out of phase on its two arms, which is similar to a T-junction. The current flows from the two arms of the main resonator to the open end of the stub. For the odd mode, the current on the main resonator is in phase, behaving like a conventional half-wavelength resonator with its central point virtually shorted to the ground, and ideally, no current shows on the stub. Therefore, if a balanced excitation is used to excite the stub-loaded resonator from its two arms, only the odd mode will be excited. In contrast, if an unbalanced excitation is used, only the even mode will be excited.

Based on these analyses, the feeding network shown in Fig. 4 (a) is considered, and two virtual ports are added to investigate the behavior of the energy coupled to the patch. It consists of a differentially-fed balun and a T-junction power divider. The differential port (Port 2) excites the even mode of the half-wavelength resonator. Due to the standing wave characteristic, this open-ended half-wavelength resonator can operate as a wideband balun. Therefore, port 2 only excites the odd-mode of the common resonator. Thus ports 3 and 4 give out-of-phase signals. The even mode of the common resonator is excited from the stub of the dual-mode resonator by another resonator, and only the even-mode of the shared resonator is activated. The stub-loaded resonator behaves as a 3-dB power divider and divides power from port 1 to ports 3 and 4 equally. In summary, for the odd mode-driven channel, the structure functions as a balun, while for the even mode-driven channel, it operates as a 3-dB power divider.

Such a four-port network is a well-known 3 dB 180° hybrid. When a signal is injected into the port 1, two equal amplitude in-phase outputs can be obtained at port 3 and port 4. A signal injected into port 2 will be divided equally into port 3 and port 4 but will be 180-degree out of phase. Then these two out-of-phase signals will cancel out with each other at the point where the stub is loaded, such that ideally port 1 and port 2 are perfectly isolated according to the reciprocity. Fig. 4 (b) plots the phase responses of the test structure in Fig. 4 (a). As a symmetric structure is used, only the phase of $S_{31}$is shown here. The in-phase and out-of-phase relationship maintains over a very wide frequency range, which means this decoupling mechanism is frequency independent over this frequency range. Thus, it is easy to understand that the isolation between two ports is highly related to the symmetry of the feeding structure and purity of the differential excitation.

C. WORKING MECHANISM OF THE DUAL-POLARIZED FILTERING ANTENNA

By using such a hybrid-like structure as the feeding network of a patch antenna, a filtering dual-polarized antenna is realized. The feeding network is coupled to the radiating patch through three apertures on the ground. To get an insight into the working mechanism of the dual polarization, the current

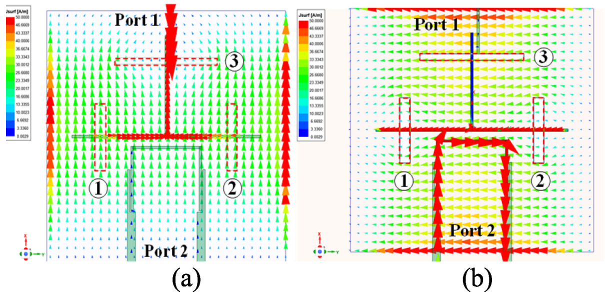


FIGURE 5. Current distributions for different channels. (a) Even mode driven channel. (b) Odd mode driven channel.

distributions are given in Fig. 5 for even and odd modes operations, respectively.

When port 1 is activated, the even mode of the stub-loaded resonator will be excited as show in Fig. 5 (a). The feeding structure acts as a 3dB power divider, so the current on the two arms of the stub-loaded resonator is in phase as indicated. Consequently, for the case shown in Fig. 5 (a), the effect of the equivalent magnetic current related to apertures 1 and 2 will cancel with each other when they are coupled to the same patch. As a result, the horizontal polarization will not be excited and only the vertical polarization will be excited by aperture 3 for the first channel.

For the odd-mode-driven channel, the corresponding field distributions are shown in Fig. 5 (b). For this case, the current mainly concentrates on the central half-wavelength resonator, while almost no current can be found on the stub. So, aperture 3 can hardly be excited. Besides, the current on the main resonator is in phase for its two arms, which makes the equivalent magnetic current in the aperture 1 and 2 in phase. As a result, only the horizontal polarization of the patch will be excited for this channel. By this means two highly isolated channels with orthogonal polarizations can be achieved using this hybrid feeding network.

D. EXPERIMENTAL DEMONSTRATION

A prototype with a centre frequency of 2.4 GHz is designed, fabricated and measured to demonstrate the idea. All the simulations are carried out in the High Frequency Structure Simulator (HFSS) [34]. In this design, both channels are designed with 3rd order Chebyshev responses. The synthesis procedure follows the common methods in the open literature [4], [5], [6], [7], [8]. For brevity, it is not presented here.

The simulated and measured S parameters and gain are shown in Fig. 6. During the gain measurement a balun is used for a differential input for the port 2. The antenna gain is characterised as the realized gain in the +z direction when the corresponding port is activated while the other one is 50-Ohm terminated. The measured −10dB impedance bandwidth for both channels is 2.31GHz - 2.49 GHz (7.1%). The maximum measured realized gains for both channels are 8.14 dBi and 8.27 dBi, respectively. As can be observed from Fig. 7 the isolation between two channels is measured to be

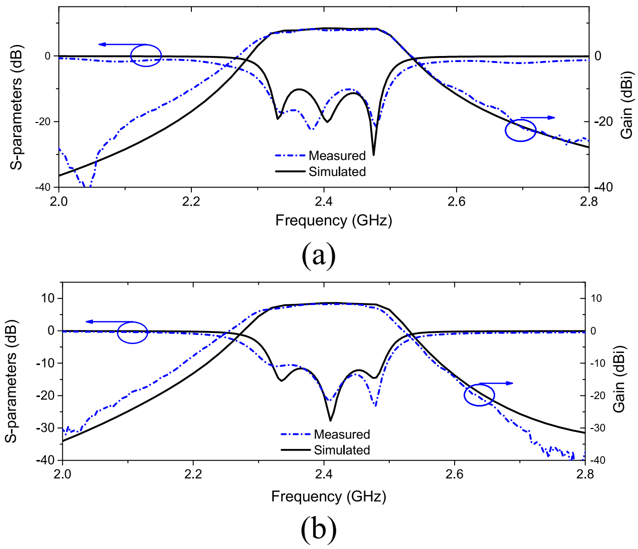


FIGURE 6. Simulated and measured S-parameters and gains of the dual-polarized antenna. (a) Even-mode driven. (b) Odd-mode driven.

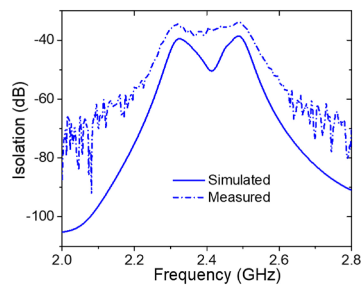


FIGURE 7. Simulated and measured isolations.

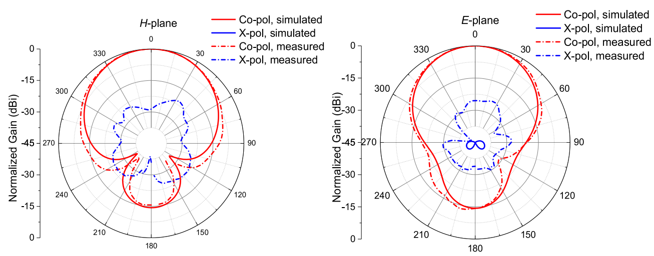


FIGURE 8. Radiation patterns of the proposed dual-polarized antenna when the differential port is excited.

higher than 39 dB over the operating band. A gap of about 3 dB between the measured and simulated isolation can be observed here. The discrepancy on the isolation is attributed to the measurement tolerance and fabrication error. It should be noted here that if an unbalanced excitation scheme is used for port 2, the isolation will decrease to 30 dB in the simulation according to our study.

Fig. 8 shows the measured and simulated radiation patterns of the fabricated antenna. For conciseness, only the radiation patterns for odd-mode driven channel are shown here. The measured results agree well with the simulations,

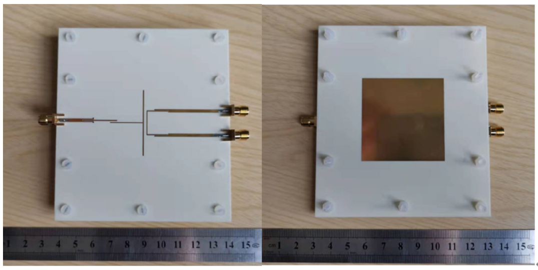
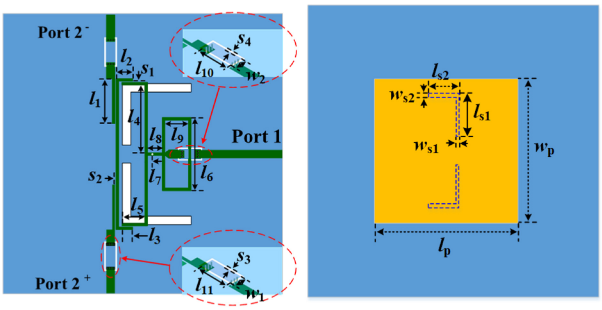
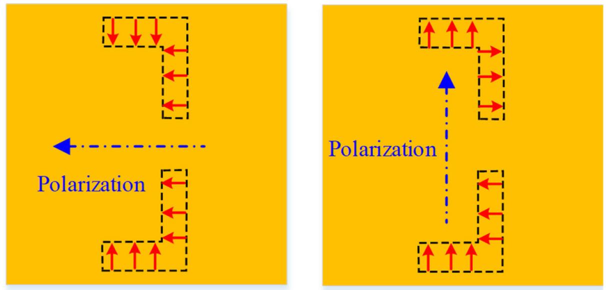


FIGURE 9. Fabricated dual-polarized antenna.



(a) (b)

FIGURE 10. Configurations of the duplex filtering antenna. (a) Bottom view. (b) Top view.



(a) (b)

FIGURE 11. Electrical field distributions in the apertures. (a) Port 1 activated. (b) Port 2 activated.

showing high cross-polarization suppression up to 25 dB. Fig. 9 shows a photograph of the fabricated antenna.

III. DUPLEX FILTERING ANTENNA

As mentioned above, the isolation mechanism of the proposed feeding network is realized by the interaction between a wideband balun and a power divider. According to Fig. 4 (b), the resonator-based balun shows out-of-phase outputs over a very wide bandwidth. Besides, the power divider used can be regarded as a T-junction, which exhibits in-phase output characteristics due to its symmetry and always provides in-phase signals at its two output ports over a wideband frequency range too. That is, even if the operating frequencies of both channels are different, these conditions can still be satisfied, ensuring good isolation. To verify this, a duplex antenna operating at two different bands is designed for the LTE B40 band (2300MHz – 2400MHz) and 2.4 GHz WiFi band (2401MHz – 2495MHz).

A. ANTENNA STRUCTURE

Fig. 10 shows the structure of the proposed filtering duplex antenna. The antenna's stack-up is similar to that of the dual-polarized one. Several modifications were made to reduce the overall size of the structure. First, the original three apertures on the ground plane are merged into two L-shaped apertures. Fig. 11 shows the field distributions in the apertures for both channels. These modified apertures and their arrangement guarantee low cross-polarization and low mutual coupling for both channels.

In addition, the open-end stub is changed into a shorted one. As we mentioned before, the centre of the main resonator is virtually shorted for odd mode. So, putting a short pin at this point will not influence the resonating characteristic of the odd mode. Then another quarter-wavelength resonator is coupled to the shorted stub through the short circuit via by magnetic coupling [33]. After this, to reduce the area occupied by the resonator but not destroy the symmetry of the structure, the single open-ended quarter-wavelength resonator is replaced by a loop structure. In this way, this loop stub structure will not affect the behaviour of the odd mode of the resonator. Due to the open-circuited boundary condition in the symmetric plane, these modifications do not affect the even mode's behavior too.

B. MULTI-PATH COUPLING SCHEME

The coupling topology of the proposed duplex antenna is modified to introduce multiple gain zeros for higher selectivity. A novel source-patch coupling structure is introduced for the first time to achieve gain zeros. As widely known the maximum achievable transmission zeros for an Nth order Chebyshev filter is $N-2$ without considering source/load coupling [35]. For a filtering antenna, it is not applicable to introduce source-load coupling as the output port is a radiative aperture that is coupled to the free space. So, to introduce one more gain zero for such a third-order filtering circuit multi-path source-resonator coupling is utilized.

Take the even-mode-driven channels for example. The tapped excitation will introduce an inherent transmission zero at the frequency when the open-ended stub length equals a quarter wavelength. In this structure, this gain zero will appear at the higher stopband. Then to improve the selectivity at the lower stopband, the feedline is cross-coupled to the radiation patch, which works as the last stage of the corresponding filtering circuit.

This coupling topology is seldom used in filter designs because it is not very practical to couple a resonator to both input and output ports simultaneously in a planar filter [36], [37], [38]. However, the multi-layer structure used here, which can be found in many antenna designs, makes it possible to realize such a coupling structure. A similar

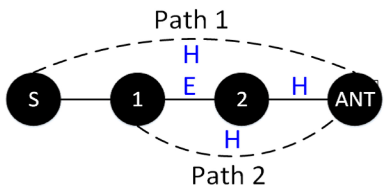


FIGURE 12. Coupling typology for the higher band channel.

coupling topology is also used for the odd-mode-driven channel.

To get an insight into the physical realization of such a coupling topology, the mechanism of the higher band channel is explained as an example. The corresponding coupling topology for the higher channel is shown in Fig. 12 according to the theory in [35], where *S* represents the source and circles with numbers represent cascaded resonators. The solid lines mean direct coupling while dash lines mean cross-coupling. *E* represents the electrical coupling and *H* means the magnetic coupling. As can be seen, there are two cross-coupling paths in this topology. Path 1 represents the coupling between the source and patch and path 2 represents the coupling between the first resonator and patch. Path 2 introduces a well-known cascaded trisection (CT) structure here and realizes a lower band gain zero for the channel [35]. The key problem for such a topology is to control the coupling mechanism of every two elements which are shown in Fig. 12, including the coupling between source to resonators and resonators to resonators, such that the phase relationships between every path can be fulfilled.

In this design, the feeding network and upper radiator are coupled through the apertures on the ground. This coupling structure is widely used for patch antennas. The operating mechanism for such a coupling method has been theoretically analysed by some researchers [39], [40], [41]. For a strong coupling between the microstrip line and the patch, a long, thin rectangular slot has been proven to be optimal. By locating the aperture at the center of the patch, the magnetic dipole coupling effect can be maximized while the electrical dipole coupling is small [39]. For this design, all the coupling between the resonators and the patch will be magnetic. Then to realize the electrical coupling between the first two resonators they are coupled to each other face to face by their open ends, where the electric fields are strongest. The electrical coupling for source-resonator coupling is realized by a crossover structure built on the 50 Ohm feedline as shown in the inset of Fig. 10 (a). Cross-coupling is much weaker compared with the main-path coupling, so such a narrow aperture is a very good option. For such a small ground aperture etched away from the centre of the patch, the magnetic dipole effect is minimized and then electric coupling between source and patch can be obtained.

C. EXPERIMENTAL DEMONSTRATION AND DISCUSSION

For validation, the duplex filtering antenna is fabricated and measured. The detailed dimensions are given in Table 1. The measured and simulated frequency responses are shown

TABLE 1. Dimensions of the duplex antenna (unit: mm).

Parameter	l_1	l_2	l_3	l_4	l_5	l_6	l_7
Value	8.9	3.21	1.885	13.05	4.425	13.8	0.85
Parameter	l_8	l_9	l_{10}	l_{11}	l_p	w_p	l_{s1}
Value	3	4.25	4	5	48	44.6	10.9
Parameter	l_{s2}	w_{s1}	w_{s2}	s_1	s_2	s_3	s_4
Value	12.5	1.9	1.6	0.2	0.2	0.7	0.3

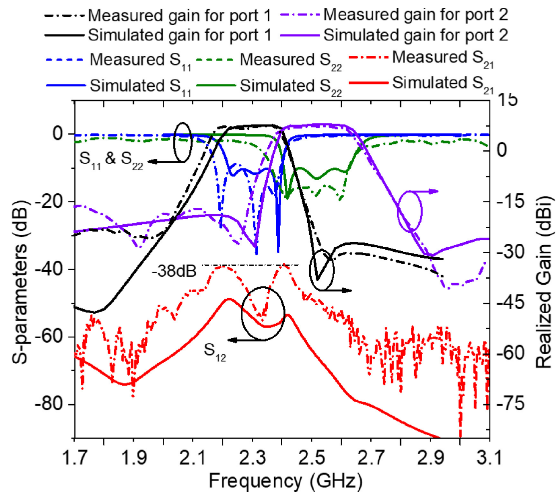


FIGURE 13. Simulated (solid lines) and measured (dashed lines) performance for the duplex filtering antenna.

in Fig. 13. The simulated bandwidths for both channels are 2.21 – 2.4 GHz (channel 1) and 2.41-2.62GHz (channel 2). The corresponding measured results are 2.18 GHz-2.40 GHz (channel 1) and 2.37-2.62GHz (channel 2). The measured bandwidths are slightly wider than those obtained through simulation. The measured isolation between both channels is higher than 38 dB over the operating bands, which is 48 dB for the simulated one. The difference between the measured and simulated results may be due to errors in fabrication and measurement. Such a low-magnitude response is very sensitive to the environment and fabrication tolerance.

Fig. 14 shows the radiation patterns of the duplex antenna. Some of the simulated cross-polarizations are not visible in this figure due to their small magnitude. Both channels show high polarization purity. In the main beam direction, the measured co-polarizations for both the *E* and *H* planes are at least 25 dB higher than the cross-polarizations. In contrast, the simulated results show a difference of approximately 35 dB. A photograph of the fabricated antenna is shown in Fig. 15. As can be seen, the feeding network only occupies a small area of 0.62 λ_g *0.34 λ_g, where λ_g is the guided wavelength at the centre frequency of the lower passband. Compared to other methods, the feeding network used in this design can be confined to the area beneath the radiation patch, which minimizes the surface area required on the system's printed circuit board.

Table 2 compares the performance between other presented designs and this work. As can be observed, this work realizes high isolation for both in-band and out-of-band

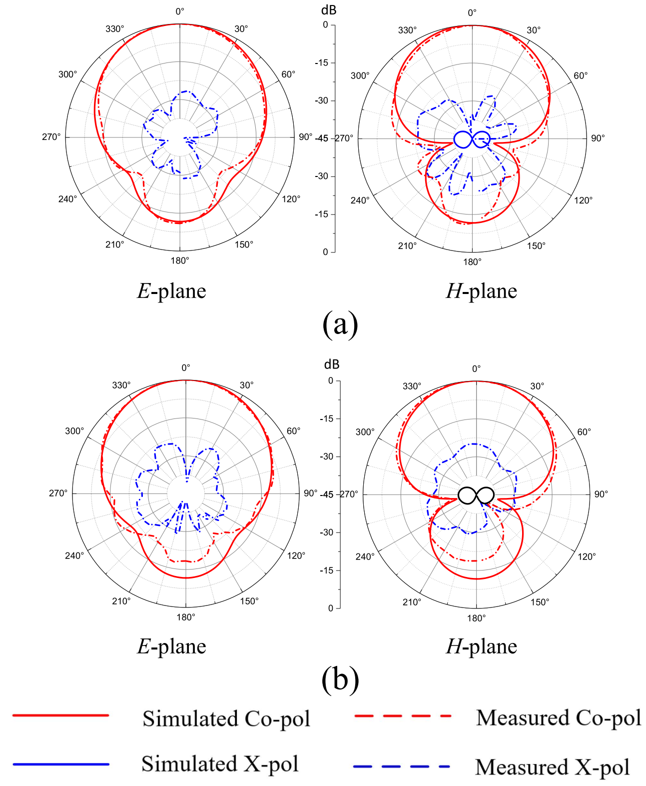


FIGURE 14. Radiation patterns of the proposed duplex filtering antenna. (a) Port 1 activated. (b) Port 2 activated.

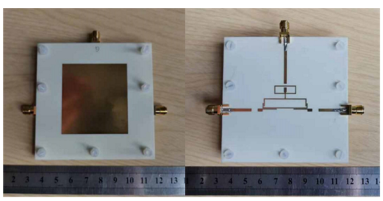


FIGURE 15. Fabricated antenna.

operations. Besides, it is the only work which can decouple two continuous filtering channels with no guard band between them. Most methods for decoupling two antennas either suffer from a high-frequency ratio or can only serves for dual-polarized operation. The characteristic of frequency-independent isolation makes this method a better option for the design of two decoupled filtering antennas. It can relieve the requirement on the filters behind the antennas and offer two well-isolated channels operating over a very small frequency ratio. Also, as the filtering circuit is involved, the potential of the impedance bandwidth of the antenna is released. All the antennas provide sufficient bandwidth to support most modern wireless communication standards with a very low profile of only 0.028 λ_0.

IV. CONCLUSION

This paper introduces a novel dual-channel feeding network with high isolation for the application of dual-polarized/duplex filtering antennas. The proposed feeding network is realized based on the control of the even and odd modes of a dual-mode resonator. Through a properly designed excitation structure, the odd and even modes of the resonator have been separated and serve two distinct channels. This hybrid feeding network is designed using coupled-resonator circuit theory for filtering performance. The operation frequencies of both channels are also very flexible. Good isolations have be achieved whether they share the same frequency bands or operate for different standards. For demonstration, two prototypes are designed, fabricated and measured. The simulated and measured results agree well for both dual-polarized and duplex antennas. With the advantages of low mutual coupling, good filtering performance and compact size, the designs are attractive candidates for modern communication systems.

TABLE 2. Comparison of the performance between different works in the literature and this work.

Ref.	Dual-polarized /Duplex	Frequency ratio	Isolation (dB)	FBW	Profile (λ_0)
[9]	Dual-polarized	N.A.	20	4.8%	0.04
[10]	Dual-polarized	N.A.	20, 24	3.8%, 6%	0.063
[11]	Dual-polarized	N.A.	25	27.6%	0.11
[12]	Dual-polarized	N.A.	37	12.3, 7.6	0.13
[23]	Duplex	1.1	32	5%, 4.2%	0.05
[24]	Duplex	2.16	20	4.5%,5.5%	0.014
[25]	Duplex	1.26	45	10.6%, 6.9%	0.08
[26]	Duplex	1.16	23	3.2%,3.9%	0.03
This work	Duplex	N.A.	30	2.4%	0.08
This work	Both	1.08	34/38	7.8%,8.8%	0.028

Note: λ_0 is the guided wavelength in the substrate at center frequency.

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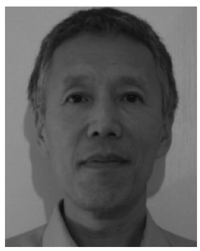

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