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A Left/Right-Handed Dual Circularly-Polarized Antenna With Duplexing and Filtering Performance

JIAN-FENG LI[1], DUO-LONG WU[1], (Senior Member, IEEE), GARY ZHANG[2], (Senior Member, IEEE), YAN-JIE WU[1], AND CHUN-XU MAO[3]

[1]School of Physics & Optoelectronic Engineering, Guangdong University of Technology, Guangzhou 510600, China
[2]School of Information Engineering, Guangdong University of Technology, Guangzhou 510600, China
[3]Department of Electrical Engineering, Pennsylvania State University, University Park, PA 16801, USA

Corresponding author: Jian-Feng Li (li.jf01@gdut.edu.cn)

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ABSTRACT A shared-radiator dual-band dual-sense circularly-polarized (CP) microstrip antenna with duplexing and filtering functions is presented. For each band, there is a coupling network, which consists of a hairpin resonator, a straight slot, and a U-slot, and thus two paths with an inherent 90° or -90° phase difference are available for the input signal to couple to the patch, left-handed CP (LHCP) characteristic and right-handed CP (RHCP) characteristic are respectively realized at different bands for the proposed antenna with a single patch. Such a dual-band dual-sense CP patch antenna is highly integrated and outperforms other traditional CP antennas state-of-the-art. Moreover, the duplexing and filtering functions are seamlessly integrated into the dual-band patch antenna with a low-profile ($0.044\lambda_o$), and application of such an integrated device in wireless systems can potentially reduce the volume, complexity, and cost of RF front-ends. Based on resonator-based topologies, the principles of achieving the dual-sense CP, duplexing, and filtering functions are illustrated. As a proof-of-concept, an antenna working at C-band is prototyped and tested. Good agreements between the measured and simulated results are achieved, showing an LHCP radiation characteristic for the low-band operation and a RHCP radiation characteristic for the high-band operation, respectively. The antenna also exhibits very good frequency selectivity and out-of-band rejection performance. At the low-band, the impedance and 3-dB axial-ratio (AR) bandwidths are 4.7% and 1.1%. At the high-band, the impedance and AR bandwidths are about 7.3% and 3.2%. The isolation between the two channels/bands is over 24 dB.

INDEX TERMS Antenna, patch antenna, dual-band, dual-polarized, circularly-polarized, filtering antenna, duplexing antenna.

I. INTRODUCTION

With advantages of immunity to antenna orientations and ability to reduce multi-path effects [1], circularly-polarized (CP) antennas have been widely employed in wireless systems, for example, satellite communications, global positioning systems (GPS), and intelligent transport systems (ITS). Various types of CP antenna such as helix antenna [2], spiral antenna [3], dielectric resonator antenna [4], slot antenna [5], cross-dipole [6], and microstrip patch antenna [7] have been investigated during the past decades. Among them, CP microstrip antennas have attracted intensive research interests because of its advantages of low cost, low profile and easy for fabrication.

Antennas with different frequency bands are highly desired in wireless systems for facilitating the uplink and downlink simultaneously. Thus, dual/multiple band CP microstrip antennas are highly demanded [8], and a variety of approaches of achieving dual/multiple bands CP microstrip antennas have been reported [9]–[14]. In [9], the radiation elements at different frequencies were interlaced and fed separately, leading to a large and complicated design. Compact dual-band CP patch antennas using a combined feed were achieved by employing the stacked patches [10] and

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coplanar parasitic patches [11] or by loading slots and stubs on the patches [12]. However, most of these CP antennas have the same CP characteristic (both are right-hand CP (RHCP) or are left-hand CP (RHCP)) for the two bands. In practice, high channel isolation is demanded to avoid the interferences between uplink and downlink channels, and that can be improved by applying dual-band antenna with orthogonal polarizations for the low- and high- band. The radiation characteristics for both two bands of the antennas [13], [14] could be either X- or Y-polarization, but not LHCP/RHCP.

On the other hand, the signals received from an antenna at different frequencies have to be separated by passing through the duplexers and bandpass filters for facilitating the processing of backend systems. To reduce the weight, size and cost of wireless systems, it is worthwhile to integrate the duplexers, bandpass filters and interfaces into antenna design [15]–[20]. There is only one path available for the input signal to couple to the patch resonator, so the filtering antennas [15]–[17] are impossible to obtain CP. Moreover, antennas [15], [16] with a single operation band are not suitable for duplexing application. In [17], a linearly polarized dual-band filtering antenna was reported, but it has the same polarization at its two bands, and it is not suitable for reducing the interferences between uplink and downlink channels. In [21], a single-feed resonator could excite two orthogonal modes to produce CP radiation by using two coupling paths, and which was then expanded to a dual-band shared-aperture CP array antenna with the same RHCP radiation characteristics at both bands. Recently, some dual-band dual-sense CP antennas with integrated filtering function and orthogonal CPs were reported [22]–[24], but they are suffering from high profile and bulky feeding network. Therefore, to the authors' best knowledge, very few works have been reported focusing on the low-profile dual-band patch filtering antenna with orthogonal CPs for the low and high bands.

In the paper, a low-profile single-radiator dual-band dual CPs patch antenna with integrated duplexing and filtering functions is proposed. LHCP and RHCP characteristics are achieved for the low-band and high-band operation, simultaneously. The two orthogonal CPs are generated by combing the electrical characteristics and physical configuration to form cross coupling. In this design, the duplexing and filtering functions are highly integrated in the antenna design, generating two individual channels/ports for low- and high-band operations without cascading any duplexers or filters. Based on an all-resonator-coupled topology, the principles for the generation of the orthogonal CPs as well as the principles for realizing the duplexing/filtering functions by a single patch are illustrated. These concepts have been verified by an antenna prototype working at C-band (4.5/5.6 GHz).

II. ANTENNA DESIGN

A. CONFIGURATION AND TOPOLOGYC

Fig. 1 shows the configuration of the proposed antenna consisting of two substrates and a 2 mm thick Rohacell foam

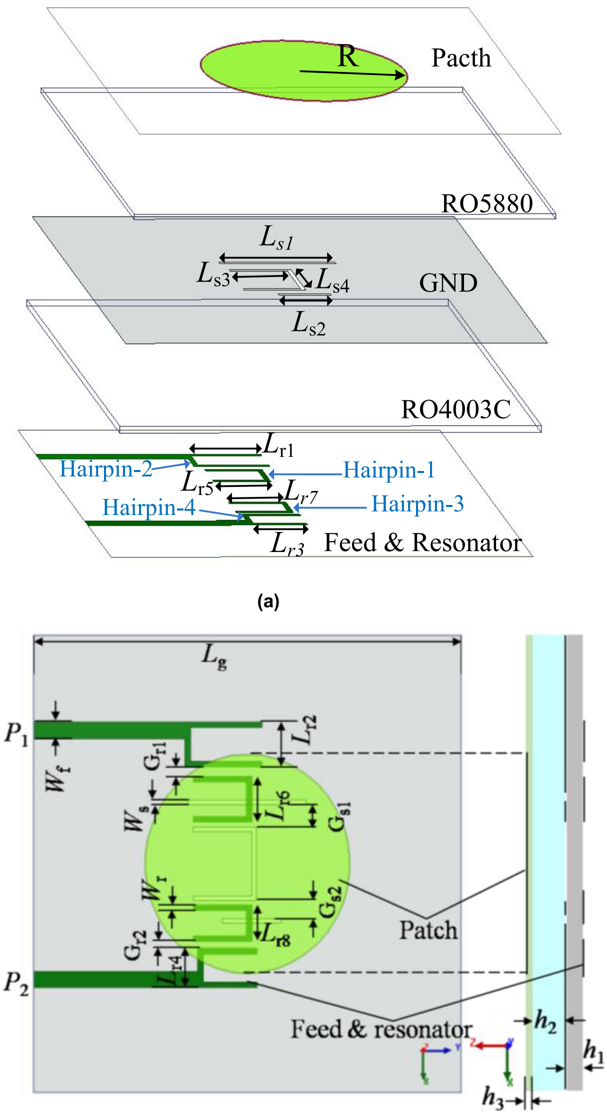


FIGURE 1. Configuration of the proposed antenna: (a) exploded view, (b) top view. $L_g = 50$ mm, $R = 12$ mm, $L_{r1} = 9$ mm, $L_{r2} = 4.7$ mm, $L_{r3} = 6.9$ mm, $L_{r4} = 4.1$ mm, $L_{r5} = 6.8$ mm, $L_{r6} = 5.4$ mm, $L_{r7} = 6.8$ mm, $L_{r8} = 4.5$ mm, $L_{s1} = 13.8$ mm, $L_{s2} = 6.2$ mm, $W_s = 0.5$ mm, $W_r = 1$ mm, $W_f = 1.8$ mm, $G_{S1} = 2.6$mm, $G_{S2} = 2.0$mm, $G_{r1} = 1.2$mm, $G_{r2} = 0.9$mm, $h_1 = 0.8$ mm, $h_2 = 2$ mm, $h_3 = 0.254$ mm.

between them. The radiation element is a circular patch printed on the top layer of the upper substrate. The microstrip feed and hairpin resonators are printed on the bottom layer of the lower substrate. A U-shaped slot and two straight slots with different lengths are inserted in to the ground plane, which is placed on the top layer of the lower substrate. RO5880 with permittivity of 2.2 and loss tangent of 0.0009 is used as the upper substrate, whereas RO4003C with a permittivity of 3.55 and loss tangent of 0.0027 is used as the lower substrate. It should be noted that the antenna has two individual channels/ports (P_1, P_2).

To better understand the mechanism of the dual-band dual-sense CP duplexing antenna, a topology based on

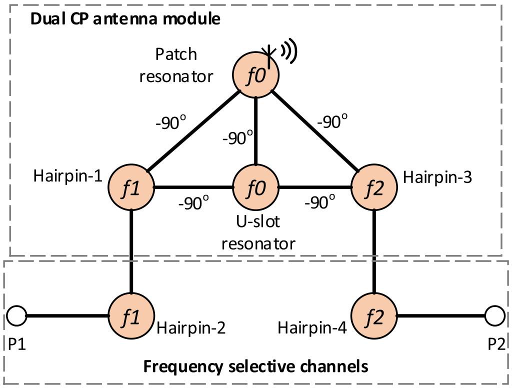


FIGURE 2. Topology of the proposed dual-band dual-CP duplexing antenna.

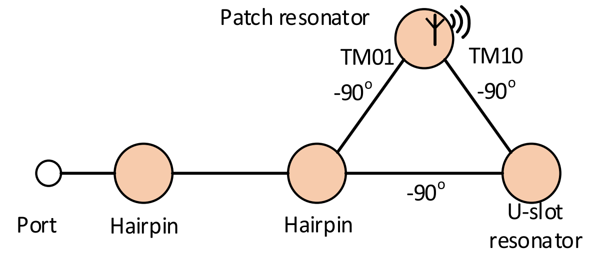


FIGURE 3. The in-half topology of a single operation channel.

coupled resonators is shown in Fig. 2. The circles represent single-mode resonators, and the solid lines represent the couplings among them. The U-shaped slot is deliberately inserted to serve not only the coupling structure but also a single-mode resonator, which has the same resonant frequency of f_0 as the circular patch resonator (radiation element). For traditional patch antenna fed directly, $f_0 \approx 5.0$ GHz is determined by the radius $R = 12$mm based on cavity theory of patch antenna, and only one resonant frequency can be produced. However, for our design, the U-slot and circular patch are stacked, and the intensive coupling between the ground plane and the radiation patch can be utilized to excited the circular radiation patch by the slot coupling feed. That can help to improve the impedance matching of the proposed antenna greatly and get a low-profile, an additional resonance (zero reactance) can be obtained [25], and thus a dual-resonance excitation can be achieved. In this meaning, we can consider that the fundamental mode f_0 of the patch split into two modes, denoted as f_1 and f_2. These two modes are then respectively coupled to the two groups of hairpin resonators with different resonant frequencies, generating two frequency separate channels/inputs. Simultaneously, the two resonators (Hairpin-1 and 3) at the both sides of the U-slot couple to the circular patch directly via the straight slots. Such a coupling structure is intentionally constituted for introducing the cross couplings to generate two orthogonal CPs. This will be detailed in the next part. It is also noted that the two resonators attached to the feeds (Hairpin-2 and 4) function as two frequency selective channels, which are used to select out the desired signals while providing the isolation between the channels/ports.

B. GENNERATION OF ORTHOGONAL CPS

One of the most important contributions of this work is to realize LHCP and RHCP characteristics at two different bands using only a single patch. The generation of the dual-sense CP can be explained using a coupled-resonator topology, as shown in Fig. 3. This topology is obtained by splitting the topology in Fig. 2 in-half. As can be seen, the 2nd hairpin resonator, U-slot and the patch resonator form a cross coupling network, so there are two paths available for the input signal to couple to the patch resonator (terminal) to stimulate TM01-mode and TM10-mode, respectively. Owing to the couplings between the resonators can be modeled by an admittance inverters J with $-90°$ phase delay [26], an inherent 90° phase difference can be achieved between the two coupling paths. Thus, two orthogonal modes (TM01-mode and TM10-mode) of the patch can be obtained by each operation band. By adjusting the coupling strength of the two paths, the magnitudes of the TM01 and TM10 modes can be balanced. As a result, CP characteristics of the dual-band antenna are realized. Moreover, this structure for achieving CP is not relevant to the frequency, and therefore CP characteristics at two operation bands can be achieved simultaneously.

The most outstanding advantage of our work is that the CP characteristics at the low- and high-band are orthogonal, and this characteristic are realized by combing the electrical characteristics and physical configuration of the proposed antenna. As we have already noticed, the low- and high-band channels have a common transmission path (U-slot) and opposite straight coupling slots (Up vs Down, as shown in Fig.1), and that leads to an 180° phase difference between the two TM01 modes of the low- and high-band operations. Therefore, the phase difference between the two orthogonal modes (TM01-mode and TM10-mode) at the low-band is 90°, but at high-band is changed to $-90°$, as shown in Fig. 4. At the low-band, the TM01-mode is delayed by 90° as compared with the TM10-mode, resulting in LHCP. At the high-band, however, the TM10-mode is delayed by 90° as compared with the TM01-mode, so the RHCP is achieved. Fig. 5(a)-(d) show the simulated current distribution on the patch at $t = 0$ and

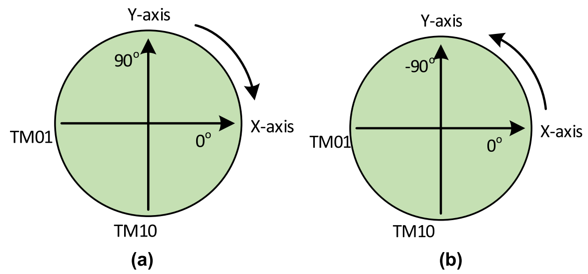


FIGURE 4. Schematics of mode and phase characteristics on the patch: (a) low-band, LHCP, (b) high-band, RHCP.

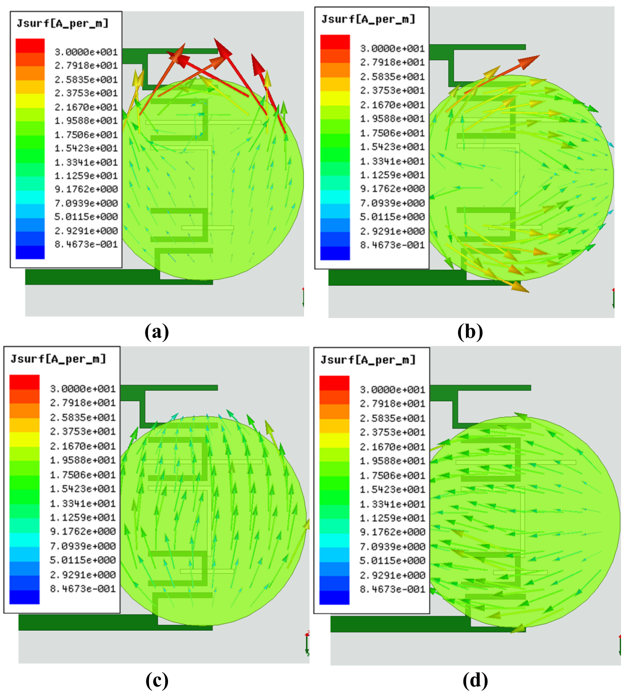


FIGURE 5. Simulated current distribution on the patch: (a)P_1 excitation, f = 4.5 GHz, t= 0; (b) P_1 excitation, f = 4.5 GHz, t =T/4; (c) P_2 excitation, f = 5.6 GHz, t = 0; (d) P_2 excitation, f= 5.6 GHz, t = T/4.

T/4 when the antenna works at 4.5 GHz (P_1 excited) and 5.6 GHz (P_2 excited), respectively. As expected, the current on the patch exhibits the LHCP characteristics when the antenna works at 4.5 GHz, but the RHCP characteristics at 5.6 GHz.

C. IMPLEMENTATION OF DUPLEXING AND FILTERING FUNCTION

The other main contribution of this work is that the antenna has independent channel/port for the low- and the high-band operation, respectively. To better illustrate the duplexing function, the topology shown in Fig. 2 is modified and presented in Fig. 6. The circular patch and the U-slot are combined and equivalent to a dual-mode resonator (f_1 and f_2), and then both the two modes are respectively coupled to their corresponding filtering channels, forming a dual-port duplexing antenna.

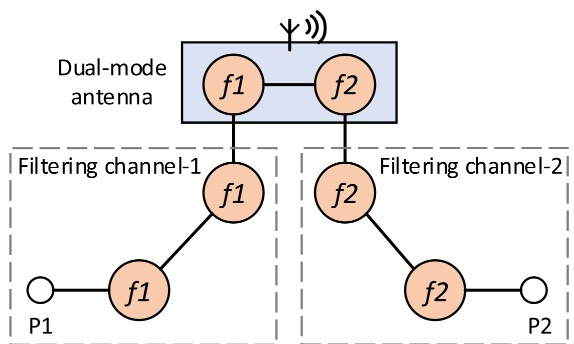


FIGURE 6. Modified topology of the proposed duplexing antenna.

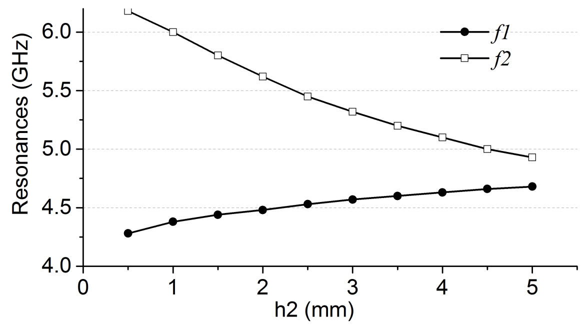


FIGURE 7. Resonant frequencies of the U-slot coupled patch with different h_2.

Due to the two operation modes are produced by splitting the patch's fundamental mode, it is worthwhile to understand how to control these modes. The coupling strength between the patch and the U-slot is related to the thickness h_2 of the spacer, so the two modes can be controlled by changing h_2. Fig. 7 shows the extracted resonant frequencies f_1 and f_2 as a function of h_2. As h_2 decreases, the 1st resonant frequency f_1 move to the lower frequency, while the 2nd frequency f_2 towards the higher frequency, leading to a larger frequency ratio. As a proof-of-concept, f_1 = 4.5 GHz and f_2 = 5.6 GHz are chosen in the design, and h_2 = 2 mm.

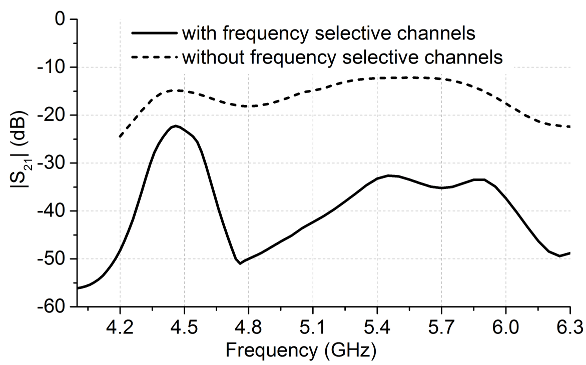


FIGURE 8. Comparison of the channel isolations for the proposed antenna.

One of the important requirements for the duplexing antenna is the high channel isolation. In our design, the hairpin resonators (Hairpin-2 and 4) attached to the feeds are served as the frequency selective devices for enhancing the channel isolation, as indicated in Fig. 2. The antennas with or without the frequency selective devices are studied, and the comparison of simulated $|S_{21}|$ for the two cases is shown in Fig. 8. The channel isolation is significantly improved by more than 8 and 20 dB at the low- and high-band, respectively, when the frequency selective devices are integrated in the design.

III. RESULTS AND DISCUSSION

The proposed dual-band dual-sense CP duplexing antenna has been prototyped and measured. Fig. 9 shows the

(a) (b)

FIGURE 9. Prototype of the proposed antenna: (a) front view, (b) back view.

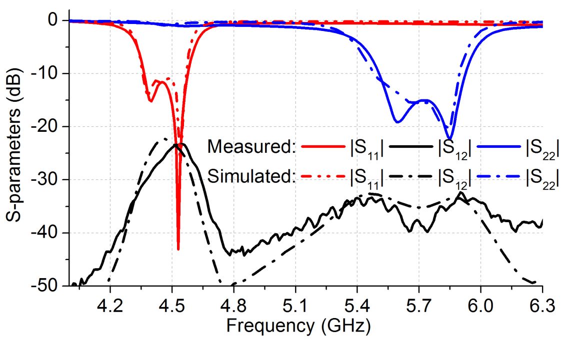


FIGURE 10. Simulated and measured S-parameters of the proposed antenna.

front and back views of the prototype. The measured reflection coefficients and the channel isolation are shown in Fig. 10. Very good agreements between the measurements and simulations are achieved. For port 1, a frequency band from 4.37 to 4.58 GHz (FBW = 4.7%) is achieved for the low-band operation; for port 2, another band from 5.5 to 5.92 GHz (FBW = 7.3%) is obtained for the high-band operation. The measured $|S_{21}|$ are lower than -24 dB and -35 dB for the low-and high-band operation, respectively.

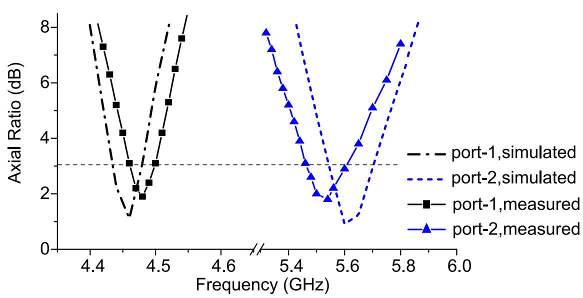


FIGURE 11. Simulated and measured AR of the proposed antenna.

Fig. 11 shows the simulated and measured ARs of the proposed dual-band dual-CP antenna. When port 1(low-band operation) is excited, the antenna achieves a 3-dBc AR bandwidth from 4.45 to 4.5 GHz (FBW = 1.1%). Compared with the simulated one, the measured AR bandwidth is shift to high frequency about 25 MHz. The minor discrepancy is attributed to the fabrication tolerance. When port 2 is excited (high-band operation), the measured 3-dB AR bandwidth is 5.45-5.62 GHz (FBW = 3.1%), which moves towards low frequency about 80 MHz comparing with the simulated one. It is also noted that the two AR bandwidths are situated in their corresponding impedance bandwidths, respectively. The simulated and measured realized gains of the proposed antenna are shown in Fig. 12. When the antenna works at the low-band, a flat gain of 6 dBi from 4.4 to 4.6 GHz is achieved. When the antenna works at the high-band, a flat gain of 8 dBi is achieved for 5.5-5.9 GHz. The realized gain rapidly drops by more than 10 dB as the frequency shifts out of the two operation bands. Results shown in Figs.10 and 12 reveal that the dual-CP duplexing antenna has filtering feature with excellent frequency selectivity, out-of-band rejection, and out-of-band radiation suppression.

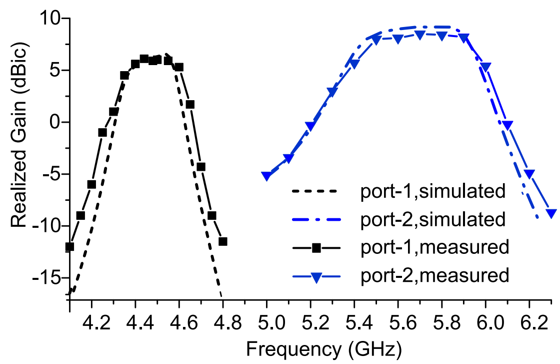


FIGURE 12. Simulated and measured realized gains of the proposed antenna.

The normalized radiation patterns of the proposed antenna at 4.48 GHz (port 1 excited) and at 5.6 GHz (port 2 excited) are presented in Fig. 13. At 4.48GHz, the antenna exhibits LHCP characteristics with the maximum radiation in the broadside direction, whereas, RHCP radiation characteristics are obtained at 5.6GHz. The measured and simulated patterns in the forward agree very well with each other. The disagreement of the backward radiation patterns is caused by the blockage of the installation devices in the measurement.

Table 1 compares the proposed dual-band dual-CP duplexing patch antenna with the other four reported dual-band CP antennas [9], [10], [21], and [24]. The comparison focuses on the number of antenna radiators, the channels of the two bands, the polarizations for the two bands, filtering characteristics, feed method, antenna profile and systematic integration level. This comparison shows that just the proposed antenna and the antenna [24] employ a single radiation element but achieve the dual-band operation with the orthogonal CP polarization characteristics. Furthermore, the two antenna have the separate channels for the dual-band operation and integrated filtering functions. However, the proposed design in this paper excites the patch by slot coupling feed, which can reduce the antenna profile and is favorable for integrated

TABLE 1. Comparison with other dual-band CP antennas.

Antenna	Radiator number	Dual-band Channels	Polarization property	Filtering feature	Feed method	Antenna profile	Systematic integration
[9]	2	separate	same	no	slot feed	$0.014\lambda_o$	low
[10]	2	combined	same	no	slot feed	$0.063\lambda_o$	low
[21]	2	separate	same	no	slot feed	$0.082\lambda_o$	low
[24]	1	separate	different	yes	probe feed	$0.091\lambda_o$	fair
This work	1	separate	different	yes	slot feed	$0.044\lambda_o$	high

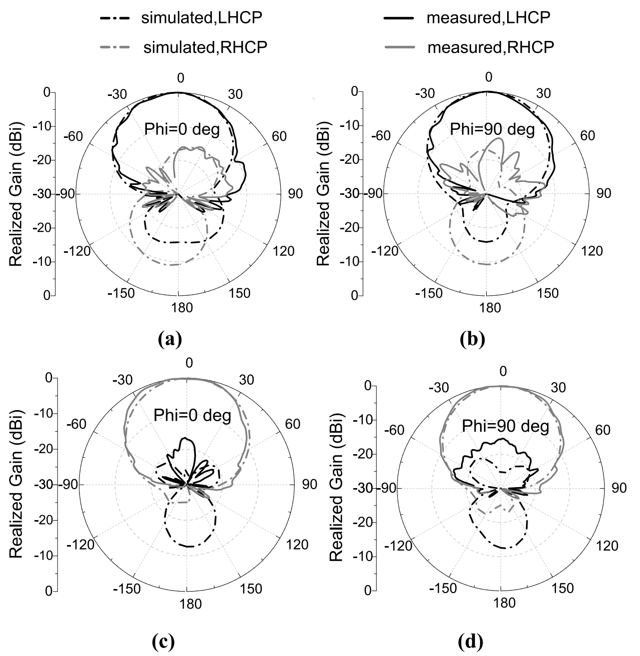


FIGURE 13. Radiation patterns of the proposed antenna: (a) $\varphi = 0°$, 4.48 GHz, port-1 excited; (b) $\varphi = 90°$, 4.48 GHz, port-1 excited; (c) $\varphi = 0°$, 5.6 GHz, port-2 excited; (d) $\varphi = 90°$, 5.6 GHz, port-2 excited.

process, and thus the proposed antenna has a higher level of systematic integration than the antenna [24]. In Table 1, λ_o is the wavelength in vacuum at the lowest frequency of the operation band.

IV. CONCLUSION

A novel low-profile dual-band dual-sense CP patch antenna with integrated duplexing and filtering performance are proposed. By employing the co-design approach, dual operation bands with the orthogonal CPs characteristics are been achieved by a single circular patch. The approaches of achieving duplexing and good channel isolation are investigated based on the resonator-based topologies.

REFERENCES

[1] S. Gao, Q. Luo, and F. Zhu, *Circularly Polarized Antennas*. Hoboken, NJ, USA: Wiley, 2013.

[2] L. Liu, Y. Li, Z. Zhang, and Z. Feng, "Circularly Polarized Patch-Helix Hybrid Antenna With Small Ground," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, no. , pp. 361–364, 2014.

[3] Q. Zhu, K.-B. Ng, and C. H. Chan, "Printed circularly polarized spiral antenna array for millimeter-wave applications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 636–643, Feb. 2017.

[4] X. Fang, K. W. Leung, and E. H. Lim, "Singly-fed dual-band circularly polarized dielectric resonator antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 995–998, 2014.

[5] Nasimuddin, Z. N. Chen, and X. Qing, "Symmetric-aperture antenna for broadband circular polarization," *IEEE Trans. Antennas Propag.*, vol. 59, no. 10, pp. 3932–3936, Oct. 2011.

[6] S. H. Yeung, K. F. Man, and W. S. Chan, "A bandwidth improved circular polarized slot antenna using a slot composed of multiple circular sectors," *IEEE Trans. Antennas Propag.*, vol. 59, no. 8, pp. 3065–3070, Aug. 2011.

[7] L. Bernard, G. Chertier, and R. Sauleau, "Wideband circularly polarized patch antennas on reactive impedance substrates," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1015–1018, 2011.

[8] H. Nawaz and I. Tekin, "Dual-polarized, differential fed microstrip patch antennas with very high interport isolation for full-duplex communication," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 7355–7360, Dec. 2017.

[9] F. Ferrero, C. Luxey, G. Jacquemod, and R. Staraj, "Dual-band circularly polarized microstrip antenna for satellite applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 4, pp. 13–16, 2005.

[10] C. Deng, Y. Li, Z. Zhang, G. Pan, and Z. Feng, "Dual-band circularly polarized rotated patch antenna with a parasitic circular patch loading," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 492–495, 2013.

[11] X. L. Bao and M. J. Ammann, "Dual-frequency circularly-polarized patch antenna with compact size and small frequency ratio," *IEEE Trans. Antennas Propag.*, vol. 55, no. 7, pp. 2104–2107, Jul. 2007.

[12] C. H. Chen and E. K. N. Yung, "A novel unidirectional dual-band circularly-polarized patch antenna," *IEEE Trans. Antennas Propag.*, vol. 59, no. 8, pp. 3052–3057, Aug. 2011.

[13] C.-X. Mao, S. Gao, Y. Wang, Q. Luo, and Q.-X. Chu, "A shared-aperture dual-band dual-polarized filtering-antenna-array with improved frequency response," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 1836–1844, Apr. 2017.

[14] C.-X. Mao *et al.*, "Integrated dual-band filtering/duplexing antennas," *IEEE Access*, vol. 6, pp. 8403–8411, 2018.

[15] C.-X. Mao, S. Gao, Y. Wang, F. Qin, and Q.-X. Chu, "Multimode resonator-fed dual-polarized antenna array with enhanced bandwidth and selectivity," *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5492–5499, Dec. 2015.

[16] C.-X. Mao *et al.*, "An integrated filtering antenna array with high selectivity and harmonics suppression," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 6, pp. 1798–1805, Jun. 2016.

[17] C. X. Mao, S. Gao, Y. Wang, F. Qin, and Q.-X. Chu, "Compact highly integrated planar duplex antenna for wireless communications," *IEEE Trans. Microw. Theory Tech.*, vol. 64, no. 7, Jul. 2016.

[18] P. Cheong, K.-F. Chang, W.-W. Choi, and K.-W. Tam, "A highly integrated antenna-triplexer with simultaneous three-port isolations based on multi-mode excitation," *IEEE Trans. Antennas Propag.*, vol. 63, no. 1, pp. 363–368, Jan. 2015.

[19] P. F. Hu, Y. M. Pan, X. Y. Zhang, and S. Y. Zheng, "A compact filtering dielectric resonator antenna with wide bandwidth and high gain," *IEEE Trans. Antennas Propag.*, vol. 64, no. 8, pp. 3645–3651, Aug. 2016.

[20] X. Y. Zhang, Y. Zhang, Y.-M. Pan, and W. Duan, "Low-profile dual-band filtering patch antenna and its application to LTE MIMO system," *IEEE Trans. Antennas Propag.*, vol. 65, no. 1, pp. 103–113, Jan. 2017.

[21] C. X. Mao, S. Gao, Y. Wang, Q. X. Chu, and X. X. Yang, "Dual-band circularly polarized shared-aperture array for *C*-/*X*-band satellite communications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 10, pp. 5171–5178, Oct. 2017.

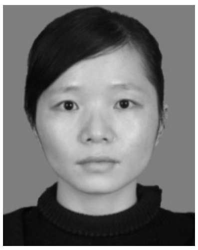
[22] M. Barbuto, F. Trotta, F. Bilotti, and A. Toscano, "Design and experimental validation of dual-band circularly polarised horn filtenna," *Electron. Lett.*, vol. 53, no. 10, pp. 641–642, 2017.

[23] X. Ma, C. Huang, W. Pan, B. Zhao, J. Cui, and X. Luo, "A dual circularly polarized horn antenna in Ku-band based on chiral metamaterial," *IEEE Trans. Antennas Propag.*, vol. 62, no. 4, pp. 2307–2311, Apr. 2014.

[24] Y.-L. Lu, Y. Wang, S. Gao, C. Hua, and T. Liu, "A single-aperture duplex antenna with dual circular polarizations," *Microw Opt Technol. Lett.*, vol. 59, pp. 3031–3036, Dec. 2017.

[25] C. H. Chang and K. L. Wong, "Internal Coupled-Fed Shorted Monopole Antenna for GSM850/900/1800/1900/UMTS Operation in the Laptop Computer," *IEEE Trans. Antennas Propag.*, vol. 56, no. 11, pp. 3600–3604, Nov. 2008.

[26] J.-S. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*. New York, NY, USA: Wiley, 2001.



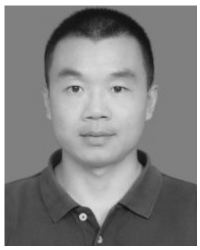
JIAN-FENG LI was born in Maoming, Gangdong, China. She received the Ph.D. degree from the South China University of Technology, Guangzhou, Guangdong, China, in 2013. She is currently a Teacher with the Guangdong University of Technology, Guangzhou. Her research interests include phone antenna, multiband antenna, MIMO antenna, filtering antenna, UWB antenna, and base station antenna. She is serves as a Reviewer for several journals, including the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, and the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS.

DUO-LONG WU (S'87–M'95–SM'98) was born in Tongcheng, Anhui, China. He received the B.S., M.S., and Ph.D. degrees from the University of Electronic Science and Technology of China, Chengdu, China, in 1987, 1995, and 1998, respectively. From 1998 to 2000, he was a Postdoctoral Fellow with Changhong Electric Co., Ltd., Mianyang, China, and the University of Electronic Science and Technology of China, Chengdu, China. From 2002 to 2003, he was a Research Fellow with the Nanyang Technological University, Singapore. From 2015 to 2016, he was a Visiting Scholar with Linköping University, Norrköping, Sweden. He is currently with the Guangdong University of Technology. His current research interests include RF and antennas.

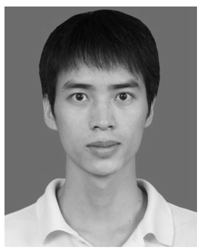
GARY ZHANG (M'96–SM'08) received the B.S. and M.S. degrees in electromagnetic field and microwave technology from Southeast University, China, in 1985 and 1988, respectively, and the Ph.D. degree in microelectronics from the University of Leeds, U.K., in 1996.

From 1996 to 2003, he was a Senior Engineer with Epsilon-Lambda Electronics Corporation and a Principal Engineer with California Amplifier, Inc., USA, respectively. From 2004 to 2008, he was a Senior Manager of new product development with Skyworks Solutions, Inc., USA. Since 2012, he has been with the Guangdong University of Technology, Guangzhou, China, where he is currently a Professor with the School of Information Engineering. He has issued 29 US patents and published more than 30 papers in international journals and conferences. He has organized and/or chaired more than ten international conferences and forums.

Dr. Zhang was a recipient of the Innovation Ward for Load Insensitive Power Amplifier Technologies in Skyworks Solutions, Inc., in 2008. He was included in the 2010 edition of *Who's Who in America*.



YAN-JIE WU received the B.S. and M.S. degrees from Central South University, Changsha, China, in 2003 and 2006, respectively, and the Ph.D. degree from Sun Yat-sen University, Guangzhou, China, in 2015. He is currently with the Guangdong University of Technology, Guangzhou, China. His current research interests include UWB antennas, MIMO antennas, and base station antennas and propagation, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, and the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS.



CHUN-XU MAO was born in Hezhou, Guangxi, China. He received the M.S. degree in RF and microwave engineering from the South China University of Technology, in 2013, and the Ph.D. degree from the University of Kent, U.K., in 2017. He is currently with the Computational Electromagnetics and Antennas Research Lab, Department of Electrical Engineering, Pennsylvania State University, USA, as a Postdoctoral Research Associate. He has authored or co-authored more than 30 papers in peer reviewed international journals and conference proceedings. His research interests include filtering antenna integration, UWB antenna, circularly polarized satellite antenna array, multiband synthetic aperture radar antenna array, multifunctional RF frontend, and wearable antenna. He received the Outstanding Master Thesis Award of Guangdong Province, China, in 2014. He also serves as a Reviewer for several journals, including the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, the IEEE ACCESS, IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, and *IET Microwaves, Antennas & Propagation*.