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A Wideband Filtering Dielectric Patch Antenna With Reconfigurable Bandwidth Using Dual-Slot Feeding Scheme

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ABSTRACT A wideband filtering dielectric patch (DP) antenna with reconfigurable bandwidth is investigated in this paper. Adjusting the aspect ratio of the DP resonator can make the high-order TE_{121} mode close to the dominate TM_{101} mode to facilitate the design of wideband filtering DP antenna. Meanwhile, the high-order TM_{111} mode is adjacent to the TE_{121} mode and then used as a non-excitation and non-radiation mode for producing an upper band-edge radiation null. On this basis, two slots with different sizes in parallel are introduced into the ground plane to excite the DP resonator, resulting in a lower band-edge radiation null, which sharpens the lower band-edge roll off. A pair of slits between the two coupling slots are incorporated and the varactor diodes are loaded on the slits to tune the electrical distance of the coupling slots, thereby electrically controlling the frequency of the lower band-edge radiation null. In this way, the fractional bandwidth (FBW) of the resultant filtering antenna can be flexibly tuned from 21% to 15.3%. A prototype has been designed, fabricated, and measured. Reasonable agreement was obtained between the simulated and measured results.

INDEX TERMS Wideband filtering antenna, dielectric patch (DP) antenna, bandwidth-reconfigurable and low profile.

I. INTRODUCTION

In order to meet the development requirements of wireless communication systems, multifunctional antennas have been extensively studied in recent years. Among them, reconfigurable antennas and filtering antennas have become two research hotspots due to their excellent properties. Reconfigurable antennas have superior characteristics such as small size, flexible functions and they can replace multiple antennas [1]–[20]. This kind of antennas can be achieved through the introduction of tunable elements, such as using p-i-n diodes to switch among multiple, discrete states [1]–[4], or loading varactor diodes to tune the operating state continuously [5], [6]. Reconfigurable performance can also be achieved by employing liquid metal [7], [8] or radio frequency micro electromechanical systems (MEMS) [9].

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On the other hand, to meet the development requirements, various filtering antennas have been developed in recent years, which can effectively eliminate the interconnection and matching network [24], [33]. In order to combine the advantages of reconfigurable antennas and filtering antennas, the concept of reconfigurable filtering antenna is proposed.

Normally, the method to achieve reconfigurable filtering antenna is to integrate the antenna with the reconfigurable filter directly [10]–[13]. In the past decades, reconfigurable filters have been extensively studied and mainly focused on frequency or bandwidth reconfigurability. Both of them play a key role in current reconfigurable communication systems and usually integrate with wideband antenna, acting as frequency-selective function [22], [23]. However, this method mentioned above belongs to cascading designs, requiring multiple resonators. At present, there are few methods to solve these problems. In [14], the method of implanting the reconfigurable filtering structure into the feeding circuits of

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the antenna is reported. The fractional bandwidth (FBW) can be continuously tuning by embedding varactors in an F-type feeding probes. It can be found that the antenna can achieve tunable FBW without adding any additional circuits, avoiding the introduction of extra loss effectively. However, these designs mentioned above are based on metal, whose conductor loss is more serious especially in high frequency, leading to a significant reduction of radiation efficiency.

To solve this problematic issue, the filtering dielectric resonator (DR) antennas [26]–[33] and reconfigurable DR antennas [15]–[21] have been widely developed in the past few years due to its relatively high radiation efficiency. In order to address the shortcomings of high profile and low gain of traditional DR antennas, a quasi-planar dielectric patch (DP) antenna has been developed in 2013 [34], which is an ideal compromise between traditional microstrip patch antenna and DR antenna in terms of profile, efficiency and gain. In addition, since the DP resonator inherits the multi-mode nature of the DR, its high-order modes can be applied to expand the bandwidth of the DP antenna [35]–[37], or be used to generate a natural radiation null in the designs of the filtering DP antenna [38], [39]. To the best of our knowledge, there is no design of reconfigurable filtering antenna based on DP resonator.

In this paper, a dual-slot coupled wideband filtering DP antenna with reconfigurable bandwidth is proposed for the first time. Benefiting from the multi-mode property of the DP resonator, the proposed antenna can be designed to operate at the dominate TM_{101} mode and the high-order TE_{121} mode by adjusting the aspect ratio of the DP resonator to achieve the bandwidth expansion. At the same time, the high-order TM_{111} mode is just adjacent the TE_{121} mode and then used as a non-excitation and non-radiation mode for producing a natural upper band-edge radiation null. Two slots of different sizes are used to excite the DP resonator to directly generate a radiation null at lower band edge. In order to achieve reconfigurability, two varactor diodes are introduced into the feeding circuits, which has achieved the electrical tunability of the FBW.

II. WIDEBAND FILTERING DIELECTRIC PATCH ANTENNA

A. ANTENNA CONFIGURATION

Fig. 1 illustrates the configuration of the proposed filtering DP antenna with x-axis linear polarization, which consists of a thin rectangular DP and two layers of substrates. The DP is with a dielectric constant $\varepsilon_{r1} = 45$, a loss tangent $\tan\delta = 1.9 \times 10^{-4}$ and a volume of $l_d \times w_d \times h_d$. The employed substrate ($L_g \times W_g$) is Rogers *RO4003* with $\varepsilon_{r2} = 3.38$, $\tan\delta = 2.7 \times 10^{-3}$, and the heights of the upper and lower substrates are h_1 and h_2, respectively. The ground plane is placed between the substrates 1 and 2, two slots with different sizes are etched on it, marked as slot 1 ($w_{s1} \times l_{s1}$) and slot 2 ($w_{s2} \times l_{s2}$), for aperture coupling between the DP resonator and microstrip feeding line on the bottom surface of the substrate 2. The distance between two slots is S. The detailed dimensions are listed in Table 1.

TABLE 1. The detailed dimensions of the proposed antenna.

Parameters	L_g	W_g	h_1	h_2	l_d	w_d
Values/mm	60	56	1.524	0.813	38	25
Parameters	h_d	S	l_{s1}	w_{s1}	l_{s2}	w_{s2}
Values/mm	1.0	4.2	8.6	2.0	21.5	1.0

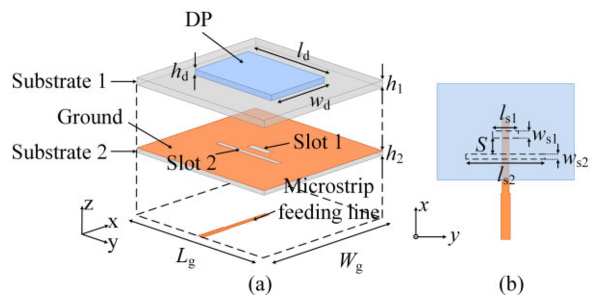

FIGURE 1. The configuration of the filtering DP antenna. (a) 3-D view. (b) Top view.

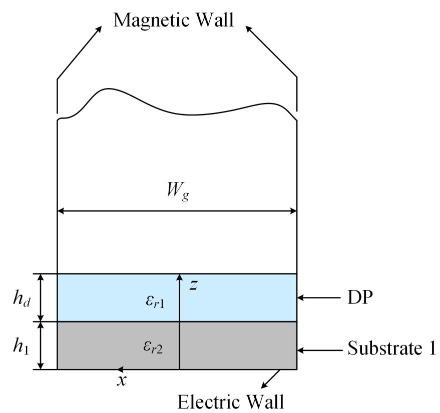

FIGURE 2. The theoretical model of the DP antenna for analysis.

B. THEORETICAL EVOLUTION AND DESIGN CONSIDERATION

Fig. 2 shows the analysis model of the DP resonator, where both four side planes of the model along z-axis direction and the top plane of the DP resonator are treated as magnetic walls, and the bottom ground is considered as an electrical wall. The remaining field components of the DP and the substrate are obtained by the following formula,

$$\begin{cases} E_x = \dfrac{1}{k_c^2}\dfrac{\partial^2 E_z}{\partial_x \partial_z}, & E_y = \dfrac{1}{k_c^2}\dfrac{\partial^2 E_z}{\partial_y \partial_z} \\ H_x = \dfrac{j\omega\varepsilon}{k_c^2}\dfrac{\partial E_z}{\partial_y}, & H_y = -\dfrac{j\omega\varepsilon}{k_c^2}\dfrac{\partial E_z}{\partial_x} \end{cases} \tag{1}$$

In order to realize a wideband filtering DP antenna, it is necessary to conduct an intensive study on the modes of the DP resonator in this section. Thanks to the multi-mode characteristic of the DP resonator, the dominant TM_{101} mode, the high-order TE_{121} and TM_{111} modes that can be applied to the subsequent design are found through the eigenmode

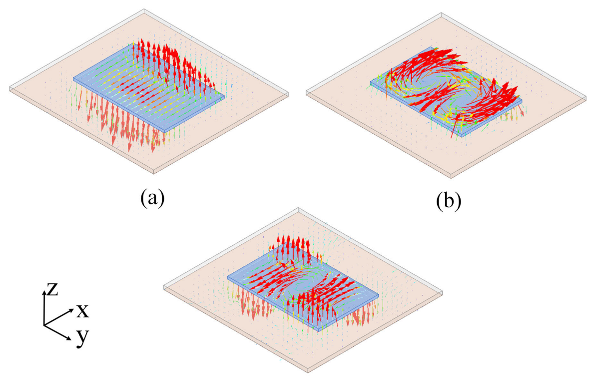

FIGURE 3. The E-field distributions. (a) TM_{101} mode. (b) TE_{121} mode. (c) TM_{111} mode.

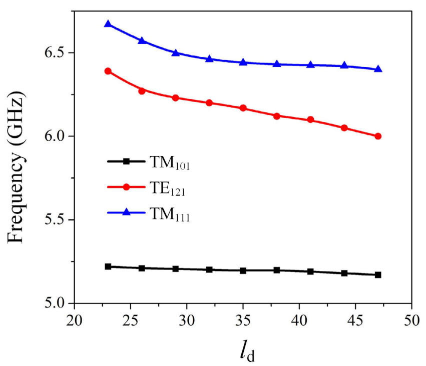

FIGURE 4. Simulated results of DP resonator with different length l_d of DP while other parameters keep unchanged as in Table 1.

simulation, as shown in Fig. 3. Among them, the dominate mode of the DP is TM_{101} mode, whose *E*-filed distribution shown in Fig. 3(a) is similar to that of microstrip patch [34]. According to [34], the dominate TM_{101} mode frequency of the DP without slot is close to that of the microstrip patch counterpart when the ε_r of the employed DP is high enough (>70). The dominate TM_{101} mode and high-order TE_{121} mode can be used as the radiation mode of the filtering DP antenna simultaneously, thereby achieving the bandwidth expansion. Since the TM_{111} mode *E*-field distributes in anti-phase along *y*-axis, as shown in Fig. 3(c), it acts as a non-radiation mode, meanwhile, it cannot be excited well as the *E*-fields of both coupling slots in Fig. 1 are in-phase along *y*-axis [38]. Therefore, a natural radiation null can be generated at the upper band to achieve filtering performance.

In order to facilitate the design of subsequent wideband filtering DP antenna, it is necessary to adjust the aspect ratio of DP to make the high-order TE_{121} mode close to the dominate TM_{101} mode. As shown in Fig. 4, when the width w_d of DP remains unchanged, as its length l_d increases, the frequency of the high-order TE_{121} mode gradually decreases and approaches the dominant TM_{101} mode. Meanwhile, the high-order TM_{111} mode is also decreased due to the same effect, and it varies hand in hand with the TE_{121} mode. After comprehensive consideration, $w_d = 25$ mm and $l_d = 38$ mm are selected as the final physical parameters of the DP.

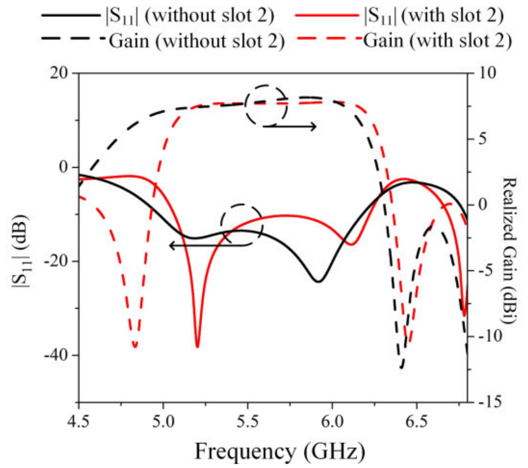

FIGURE 5. The simulated |S11| and gain of the DP antenna without/with slot 2.

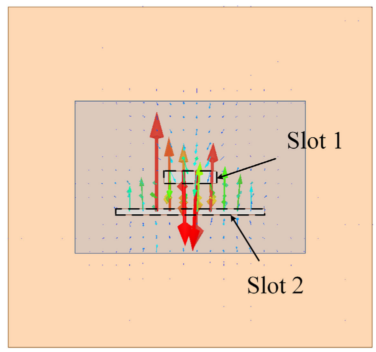

FIGURE 6. The *E*-field distribution of the lower band-edge radiation null at 4.84 GHz.

C. THE PROPOSED FILTERING DP ANTENNA

To analyze the filtering characteristics of the proposed antenna, a traditional microstrip aperture coupling (only slot 1) is firstly used to centrally excite the proposed DP resonator for antenna design. As can be seen from Fig. 5 that when the DP resonator is only excited by slot 1 (without slot 2), there is only a natural upper band-edge radiation null at 6.4 GHz resulting from the non-excitation and non-radiation high-order TM_{111} mode. In order to sharpen the lower band-edge roll off for good filtering performance, the slot 2 is introduced into the ground plane to participate in the excitation of the DP resonator, as shown in Fig. 1. It can be found from Fig. 5 that after the introduction of slot 2, a lower band-edge radiation null is generated at 4.84 GHz in the gain curve, resulting in a high selectivity and a sharp band skirt. Meanwhile, the operating frequency of the antenna moves up slightly and the radiation performance keeps almost unchanged. The proposed antenna produces a wide FBW of 20.4% (5.07 GHz-6.22 GHz) with a stable antenna gain of about 7.9 dBi. Fig. 6 shows the E-field distribution of the lower band-edge radiation null at 4.84 GHz. It can be found that the E- fields at slot 1 and slot 2 have nearly the same amplitudes but opposite directions, which leads to a deep lower band-edge radiation null in the gain

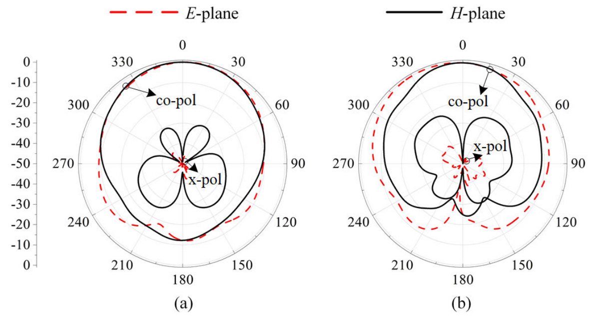

FIGURE 7. The simulated radiation patterns. (a) 5.2 GHz. (b) 6.14 GHz.

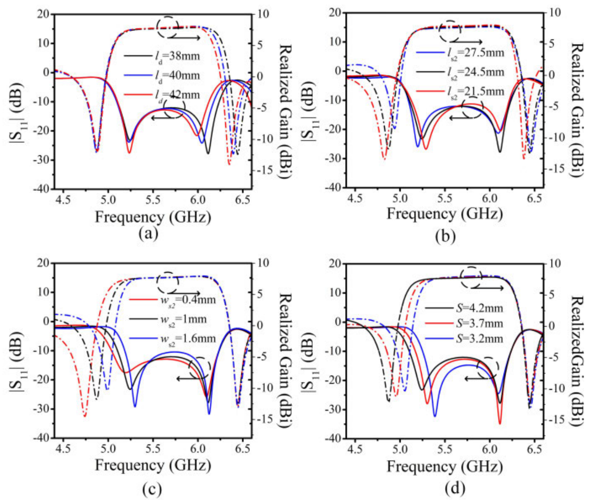

FIGURE 8. Simulated results for different parameters. (a) Length l_d of the dielectric patch. (b) Length l_{s2} of the slot 2. (c) Width w_{s2} of the slot 2. (d) Distance S between the two slots.

curve. Therefore, two radiation nulls can be generated at both sides of the passband, realizing filtering performance in the DP antenna. The E-plane and H-plane radiation patterns at 5.2 GHz and 6.14 GHz are shown in Fig. 7(a) and (b), respectively. The cross polarization is at least 20 dB lower than the co-polarization.

D. PARAMETRIC STUDIES

The introduction of slot 2 in the ground plane is a key technique in the proposed design. In order to fully display the characteristic of the proposed filtering DP antenna, a series of parametric studies are conducted, as shown in Fig. 8 where one parameter is changed while other parameters shown in Fig. 1 are fixed.

Fig. 8(a) exhibits that the effect of the length l_d of the DP on the filtering performance. It can be seen that the frequencies of both upper band-edge radiation null and TE_{121} mode are influenced by l_d. When l_d increases from 38 mm to 42 mm, both of them move down. Meanwhile, the TM_{101} mode and lower band-edge radiation null remain unchanged. It can be found from these results that the upper band-edge radiation null can be independently adjusted by l_d.

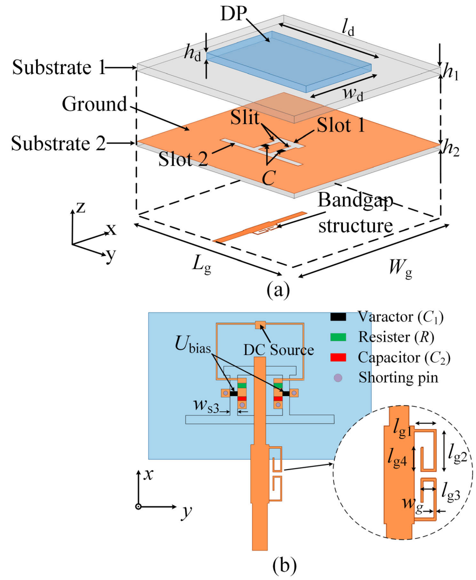

FIGURE 9. The configuration of the bandwidth reconfigurable filtering DP antenna. (a) 3-D view. (b) Implementation sketch of the variable capacitance C and the bandgap structure in the bottom layer, l_{g1} = 1.4 mm, l_{g2} = 2.8 mm, l_{g3} = 1 mm, l_{g4} = 1.85 mm, w_g = 0.15 mm.

Fig. 8(b)-(d) show the simulated $|S_{11}|$ and gain of the proposed filtering DP antenna under different slot length l_{s2}, slot width w_{s2} and the distance S between slots 1 and 2. The frequencies of both TM_{101} mode and lower band-edge radiation null are sensitive to the variation of l_{s2}, w_{s2} and S. When l_{s2} and w_{s2} decrease or S increases, they shift down while the upper resonant frequency (TE_{121} mode) and upper band-edge radiation null keep almost unchanged. It indicates the lower band-edge radiation null can be independently tuned by l_{s2}, w_{s2} and S.

Based on the above discussion, it can be concluded that the two radiation nulls are independently controllable so that the FBW can be easily adjustable, exhibiting a simple design procedure. After comprehensive consideration, l_{s2} = 21.5 mm, w_{s2} = 1 mm, S = 4.2 mm and l_d = 38 mm are chosen as the final physical parameters.

III. RECONFIGURABLE FILTERING ANTENNA

A. THE PROPOSED RECONFIGURABLE FILTERING ANTENNA

As can be seen from the simulated results of Fig. 8(d) in Section-II, the frequency of the lower band-edge radiation null is sensitive to the variation of the distance S between the slot 1 and slot 2. On this basis, a bandwidth reconfigurable filtering DP antenna is proposed and investigated in this section. In order to tune the FBW electrically, a pair of slits (with a width of w_{s3} = 0.8 mm) between the two coupling slots are incorporated and the varactor diodes are loaded on the slits to tune the electrical distance of the coupling slots, as shown in Fig. 9. Besides, a simple bandgap structure composed of a pair of spiral stubs is embedded in the feeding line which will be explained in the following paragraph. Fig. 9(b) shows

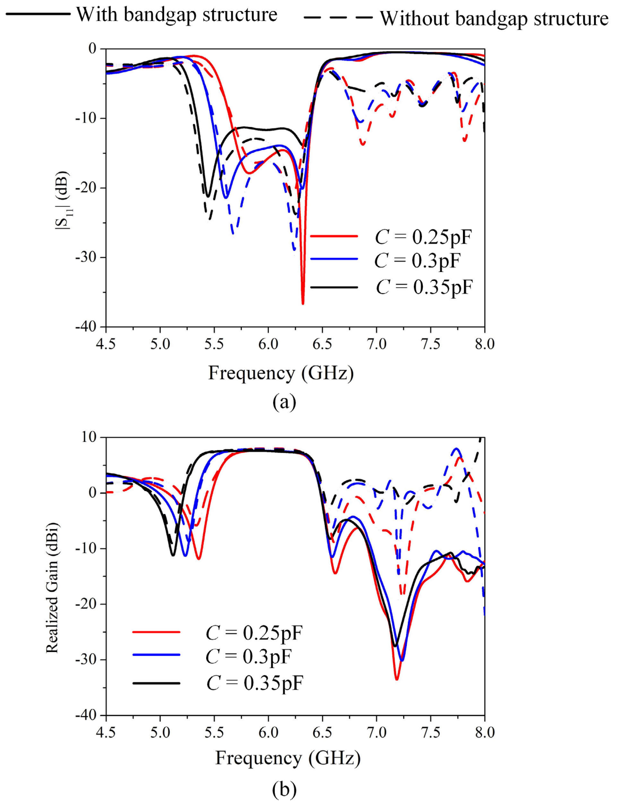

FIGURE 10. The simulated results of the bandwidth-reconfigurable filtering DP antenna without/with bandgap structure. (a) $|S_{11}|$. (b) Gain.

the implementation sketch of the variable capacitance C and the bandgap structure in the bottom layer. C is realized by a lumped capacitor $C_2 = 0.5$ pF (DC block) and a varactor C_1 in series, respectively. As a result, $C = C_1C_2 / (C_1 + C_2)$ varies from 0.25 pF to 0.35 pF. R means the radio frequency choke realized by a resistor with 51 kΩ. Fig. 10 shows the simulated reflection coefficients ($|S_{11}|$) and gains of the bandwidth reconfigurable filtering DP antenna without/with bandgap structure.

As mentioned before, the DP resonator inherits the multi-mode nature of DR whose high-order mode can be applied to expand the bandwidth of the DP antenna. However, the cluttered high-order harmonics will inevitably degrade the filtering performance of the filtering DP antenna. We have investigated that the bandwidth reconfigurability is derived from the changing of the lower band-edge radiation null and the lower resonant frequency. Meanwhile, the upper band-edge radiation null and other high-order harmonics of the antenna without bandgap structure keep almost unchanged which can be seen in Fig. 10. In this case, a simple bandgap structure can be embedded in the feeding line to suppress the unwanted harmonics and improve the suppression level in the upper stopband without increasing the antenna size.

In Fig. 10, the FBW of the antenna with bandgap structure can be continuously tuned from 12.4% (5.65-6.4 GHz) to 18.1% (5.34-6.4 GHz). As can be seen from Fig. 11(a),

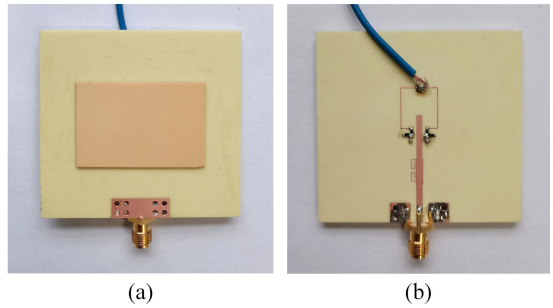

FIGURE 11. Photograph of the fabricated prototype. (a) Top view. (b) Bottom view.

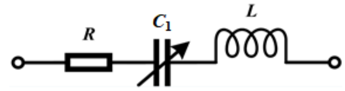

FIGURE 12. The equivalent circuit of the varactor, including the parasitic resistance R of 0.8 Ω and parasitic inductance L of 0.7 nH.

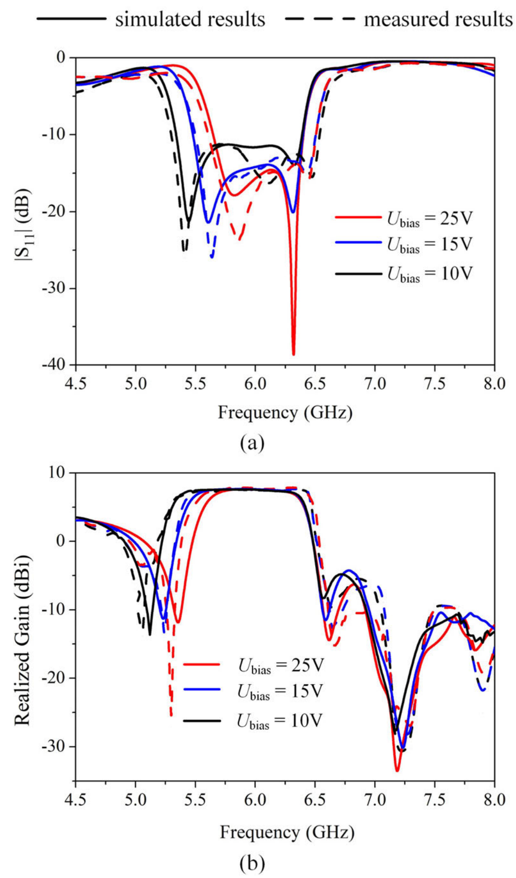

FIGURE 13. The simulated and measured results of the proposed reconfigurable filtering DP antenna. (a) $|S_{11}|$. (b) Gain.

the simulated reflection coefficients ($|S_{11}|$) in the upper stopband of the antenna with bandgap structure are close to 0 dB under different C. Meanwhile, another radiation null in Fig. 10(b) is generated at about 7.2 GHz, resulting in a high suppression of the upper stopband, and the out-of-band suppression level is improved more than 8 dB.

TABLE 2. Performance comparison with the previous filtering antennas using DR or DP resonators.

Ref	Resonator	f_0 (GHz)	FBW (%)	Profile (λ_0)	Peak Gain (dBi)	ξ (dB/GHz)	Reconfigurability
[29]	DR	8.15	6.13	0.11	5.30	21.14	N
[30]	DR	11.0	7.00	0.15	6.45	12.1	N
[31]	DR	1.97	21.9	0.12	5.10	267.5	N
[32]	DR	5.00	20.4	0.1	5.0	100.1	N
[33]	DR	2.49	7.20	0.15	5.80	377.8	N
[38]	DPR	4.17	< 1%	0.026	4.80	253	N
[39]	DPR	3.5	12.3	0.154	9.2	49.2	N
This work	DPR	5.7	21	0.063	7.9	143.6	Y

λ_0 means the free-space wavelength at the center frequency f_0, DPR means dielectric patch resonator.
Gain roll-off ξ is defined as:

$$\xi = \frac{G_{3dB} - G_{null}}{|f_{3dB} - f_{null}|} \text{ (dB/GHz)}$$

where $G_{3dB} = G_{max}$-3dB (G_{max} is the peak gain in the passband) and G_{null} is the gain value of the radiation null, while f_{3dB} represents the 3dB cutoff frequency of the gain passband and f_{null} is the frequency of the radiation null.

B. MEASUREMENT VERIFICATION

To verify the proposed idea, a prototype of the reconfigurable filtering DP antenna is fabricated and measured. The photograph of the implement antenna prototype is exhibited in Fig. 11. The varactor diodes are JDV2S71E from Toshiba, which possess the capacitance range of 0.6-7 pF and have a parasitic resistance R of 0.8 Ω and a parasitic inductance L of 0.7 nH, as shown in Fig. 12. Fig. 13(a) and (b) show the simulated and measured reflection coefficients ($|S_{11}|$) and gains of the proposed antenna under different reverse bias voltages. The measured FBW ($|S_{11}| < -10$ dB) can be continuously tuned from 15.3% (5.6-6.53 GHz) to 21% (5.29-6.53 GHz) and the peak gains in these three states are 7.8 (10V), 7.9 (15V) and 7.9 (25V) dBi, respectively. During the whole tuning process, three radiation nulls can be observed in the measured gain curve as expected. It can be found that the continuous tunable states can be obtained while maintaining stable in-band gain and filtering characteristics. Fig. 14 and Fig. 15 depicts the simulated and measured radiation patterns of the E- and H- plane at the reverse bias voltages 25 V and 10 V, respectively. The measured cross polarization is at least 20 dB lower than the co-polarization. The small discrepancy can be attributed to the implementation error.

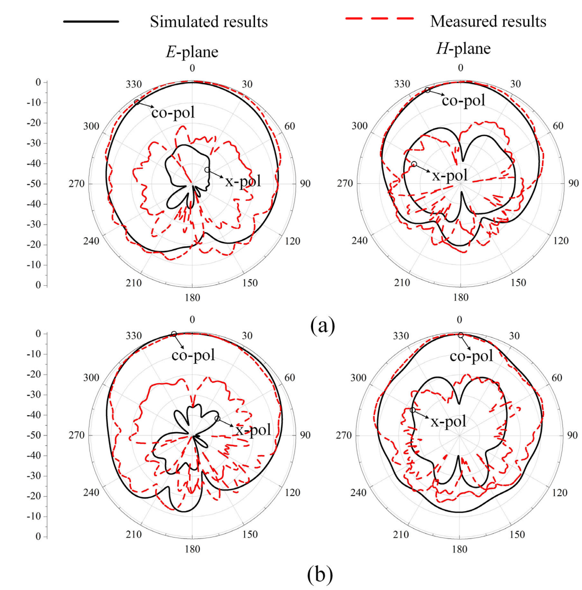

FIGURE 14. The simulated and measured radiation patterns at 25 V. (a) 5.88 GHz. (b) 6.42 GHz.

C. COMPARISON AND DISCUSSION

Since there has been no existing design of DR or DP antenna possessing reconfigurable characteristic and filtering response simultaneously, this antenna will be compared with the previously reported filtering antennas and reconfigurable antennas using DR or DP resonators respectively as summarized in Table 2 and 3. It can be found that benefiting from the adoption of the DP resonator, the proposed antenna owns lower profile and higher gain than the DR antennas in [17]–[21], [29]–[33]. Furthermore, due to the application

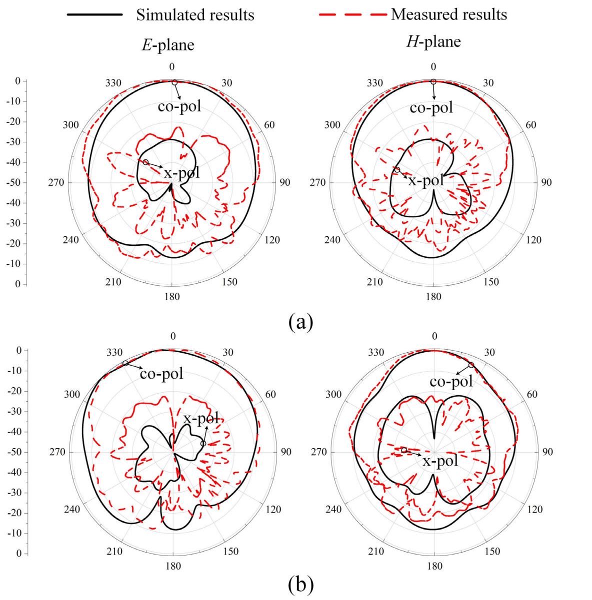

FIGURE 15. The simulated and measured radiation patterns at 10 V. (a) 5.44 GHz. (b) 6.44 GHz.

TABLE 3. Performance comparison with the previous reconfigurable DR antennas.

Ref	Freq/BW agility	FBW (%)	Filtering Response	Peak Gain (dBi)	Profile (λ_0)
[17]	Freq	~2	N	6.7	0.12
[18]	Freq	~6	N	4.5	0.09
[19]	Freq	~2	N	4	0.25
[20]	BW	6.9-8.8	N	-	0.13
[21]	BW	4.4-16.4	N	6	0.15
This work	BW	15.3-21	Y	7.9	0.063

Freq means frequency, BW means bandwidth.

of the modified DP resonator with a specific aspect ratio, the proposed antenna obtains a wider bandwidth. The gain roll-off of the proposed antenna is comparable to the DR design in [32] and is much higher than designs in [29], [30], and [39]. Although the gain roll-off of the antennas without reconfigurability in [31], [33], and [38] is high, however, they are generally limited due to some deficiencies like higher profile, narrow bandwidth or lower gain. In summary, compared with the previous designs, the proposed antenna is compact in size, diverse in function and has great filtering characteristics.

IV. CONCLUSION

In this communication, a novel kind of wideband filtering DP antenna with reconfigurable bandwidth operating at the dominate TM_{101} mode and high-order TE_{121} mode has been presented. Meanwhile, the non-excitation and non-radiation high-order TM_{111} mode produces a natural upper band-edge radiation null. By using two slots with different sizes to excite the DP resonator, a radiation null can be generated at the lower band edge, resulting in a sharp band skirt without any additional circuits. Continuously tunable states with different FBW ranging from 15.3% to 21% have been achieved by changing the reverse bias voltages applied to the varactor diodes. The proposed reconfigurable filtering antenna owns several advantages such as controllable bandwidth, lower profile, simple structure and design procedure, which would make the antenna attractive in future wireless communication.

REFERENCES

[1] F. D. Dahalan, S. K. A. Rahim, M. R. Hamid, M. A. Rahman, M. Z. M. Nor, M. S. A. Rani, and P. S. Hall, ''Frequency-reconfigurable archimedean spiral antenna,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1504–1507, Nov. 2013.

[2] B. P. Chacko, G. Augustin, and T. A. Denidni, ''Electronically reconfigurable uniplanar antenna with polarization diversity for cognitive radio applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 213–216, Feb. 2015.

[3] Y. Yang, R. B. V. B. Simorangkir, X. Zhu, K. Esselle, and Q. Xue, ''A novel boresight and conical pattern reconfigurable antenna with the diversity of 360° polarization scanning,'' *IEEE Trans. Antennas Propag.*, vol. 65, no. 11, pp. 5747–5756, Nov. 2017.

[4] W.-W. Yang, X.-Y. Dong, W.-J. Sun, and J.-X. Chen, ''Polarization reconfigurable broadband dielectric resonator antenna with a lattice structure,'' *IEEE Access*, vol. 6, pp. 21212–21219, May 2018.

[5] E. Erfani, J. Nourinia, C. Ghobadi, M. Niroo-Jazi, and T. A. Denidni, ''Design and implementation of an integrated UWB/reconfigurable-slot antenna for cognitive radio applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 77–80, Mar. 2012.

[6] P.-Y. Qin, F. Wei, and Y. J. Guo, ''A wideband-to-narrowband tunable antenna using a reconfigurable filter,'' *IEEE Trans. Antennas Propag.*, vol. 63, no. 5, pp. 2282–2285, May 2015.

[7] N. Biyikli, Y. Damgaci, and B. A. Cetiner, ''Low-voltage small-size double-arm MEMS actuator,'' *Electron. Lett.*, vol. 45, no. 7, pp. 354–356, Mar. 2009.

[8] C. Wang, J. C. Yeo, H. Chu, C. T. Lim, and Y.-X. Guo, ''Design of a reconfigurable patch antenna using the movement of liquid metal,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 6, pp. 974–977, Jun. 2018.

[9] Z. Chen, H. Wong, and J. Kelly, ''A polarization-reconfigurable glass dielectric resonator antenna using liquid metal,'' *IEEE Trans. Antennas Propag.*, vol. 67, no. 5, pp. 3427–3432, May 2019.

[10] J. Deng, S. Hou, L. Zhao, and L. Guo, ''Wideband-to-narrowband tunable monopole antenna with integrated bandpass filters for UWB/WLAN applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2734–2737, Oct. 2017.

[11] M. M. Fakharian, P. Rezaei, A. A. Orouji, and M. Soltanpur, ''A wideband and reconfigurable filtering slot antenna,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1610–1613, Sep. 2016.

[12] R. E. Lovato, T. Li, and X. Gong, ''Tunable filter/antenna integration with bandwidth control,'' *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 10, pp. 4196–4205, Oct. 2019.

[13] M.-C. Tang, Z. Wen, H. Wang, M. Li, and R. W. Ziolkowski, ''Compact, frequency-reconfigurable filtenna with sharply defined wideband and continuously tunable narrowband states,'' *IEEE Trans. Antennas Propag.*, vol. 65, no. 10, pp. 5026–5034, Oct. 2017.

[14] P. F. Hu, Y. M. Pan, X. Y. Zhang, and B.-J. Hu, ''A filtering patch antenna with reconfigurable frequency and bandwidth using F-Shaped probe,'' *IEEE Trans. Antennas Propag.*, vol. 67, no. 1, pp. 121–130, Jan. 2019.

[15] A. Altaf, J.-W. Jung, Y. Yang, K.-Y. Lee, and K. C. Hwang, ''Reconfigurable dual-/triple-band circularly polarized dielectric resonator antenna,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 19, no. 3, pp. 443–447, Mar. 2020.

[16] B.-J. Liu, J.-H. Qiu, S.-C. Lan, and G.-Q. Li, ''A wideband-to-narrowband rectangular dielectric resonator antenna integrated with tunable bandpass filter,'' *IEEE Access*, vol. 7, pp. 61251–61258, Mar. 2019.

[17] C. X. Hao, B. Li, K. W. Leung, and X. Q. Sheng, "Frequency-tunable differentially fed rectangular dielectric resonator antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 884–887, 2011.

[18] J. Desjardins, D. A. McNamara, S. Thirakoune, and A. Petosa, "Electronically frequency-reconfigurable rectangular dielectric resonator antennas," *IEEE Trans. Antennas Propag.*, vol. 60, no. 6, pp. 2997–3002, Jun. 2012.

[19] S. Keerthipriya and C. Saha, "Tunable multifunctional reconfigurable step profiled dielectric resonator antenna for cognitive radio applications," in *Proc. TEQIP III Sponsored Int. Conf. Microw. Integr. Circuits, Photon. Wireless Netw. (IMICPW)*, Tiruchirappalli, India, May 2019, pp. 440–442.

[20] R. D. Gupta and M. S. Parihar, "Bandwidth reconfigurable dielectric resonator antenna," in *Proc. Loughborough Antennas Propag. Conf. (LAPC)*, Nov. 2014, pp. 473–475.

[21] B. Liu, J. Qiu, S. Lan, N. Wang, and H. Liu, "Bandwidth reconfigurable cylindrical dielectric resonator antenna excited by double-ring slot," in *Proc. IEEE Int. Symp. Antennas Propag USNC/URSI Nat. Radio Sci. Meeting*, Boston, MA, USA, Jul. 2018, pp. 2097–2098.

[22] J. Lee, E. J. Naglich, and W. J. Chappell, "Frequency response control in frequency-tunable bandstop filters," *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 12, pp. 669–671, Dec. 2010.

[23] B. Gowrish and R. R. Mansour, "A novel bandwidth reconfigurable waveguide filter for aerospace applications," *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 6, pp. 577–580, Jun. 2020.

[24] M. Tang, C. Li, and Y. Chen, "Electrically small, planar, wideband filtering antenna with dual ring patches," *Electron. Lett.*, vol. 56, no. 2, pp. 61–62, Jan. 2020.

[25] W. Yang, S. Chen, Q. Xue, W. Che, G. Shen, and W. Feng, "Novel filtering method based on metasurface antenna and its application for wideband high-gain filtering antenna with low profile," *IEEE Trans. Antennas Propag.*, vol. 67, no. 3, pp. 1535–1544, Mar. 2019.

[26] H. Tang, C. Tong, and J.-X. Chen, "Differential dual-polarized filtering dielectric resonator antenna," *IEEE Trans. Antennas Propag.*, vol. 66, no. 8, pp. 4298–4302, Aug. 2018.

[27] H. Tang, C. Tong, and J.-X. Chen, "Multifunction applications of substrate integrated waveguide cavity in dielectric resonator antennas and reconfigurable circuits," *IEEE Trans. Antennas Propag.*, vol. 67, no. 8, pp. 5700–5704, Aug. 2019.

[28] P. F. Hu, Y. M. Pan, X. Y. Zhang, and S. Y. Zheng, "Broadband filtering dielectric resonator antenna with wide stopband," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 2079–2084, Apr. 2017.

[29] A. K. Sahoo, R. D. Gupta, and M. S. Parihar, "Circularly polarised filtering dielectric resonator antenna for X-band applications," *IET Microw., Antennas Propag.*, vol. 12, no. 9, pp. 1514–1518, Apr. 2018.

[30] H. Chu, H. Hong, X. Zhu, P. Li, and Y.-X. Guo, "Implementation of synthetic material in dielectric resonator-based filtering antennas," *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3690–3695, Jul. 2018.

[31] Y. M. Pan, P. F. Hu, K. W. Leung, and X. Y. Zhang, "Compact single-/dual-polarized filtering dielectric resonator antennas," *IEEE Trans. Antennas Propag.*, vol. 66, no. 9, pp. 4474–4484, Sep. 2018.

[32] 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.

[33] Y.-T. Liu, K. W. Leung, J. Ren, and Y.-X. Sun, "Linearly and circularly polarized filtering dielectric resonator antennas," *IEEE Trans. Antennas Propag.*, vol. 67, no. 6, pp. 3629–3640, Jun. 2019.

[34] H. W. Lai, K.-M. Luk, and K. W. Leung, "Dense dielectric patch antenna—A new kind of low-profile antenna element for wireless communications," *IEEE Trans. Antennas Propag.*, vol. 61, no. 8, pp. 4239–4245, Aug. 2013.

[35] X.-Y. Wang, S.-C. Tang, L.-L. Yang, and J.-X. Chen, "Differential-fed dual-polarized dielectric patch antenna with gain enhancement based on higher order modes," *IEEE Antennas Wireless Propag. Lett.*, vol. 19, no. 3, pp. 502–506, Mar. 2020.

[36] S.-C. Tang, X.-Y. Wang, W.-W. Yang, and J.-X. Chen, "Wideband low-profile dielectric patch antenna and array with anisotropic property," *IEEE Trans. Antennas Propag.*, vol. 68, no. 5, pp. 4091–4096, May 2020.

[37] Y. M. Pan and S. Y. Zheng, "A low-profile stacked dielectric resonator antenna with high-gain and wide bandwidth," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 68–71, Feb. 2016.

[38] X.-Y. Wang, S.-C. Tang, X.-F. Shi, and J.-X. Chen, "A low-profile filtering antenna using slotted dense dielectric patch," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 3, pp. 502–506, Mar. 2019.

[39] K. Xu and J. Shi, "High-efficiency circular dense dielectric patch antenna with frequency selectivity," *Electron. Lett.*, vol. 54, no. 14, pp. 861–862, Jul. 2018.

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