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A Dual-mode Resonator-Fed Gap Coupled Filtering Antenna with Improved Selectivity and Bandwidth

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Abstract—A novel dual-mode resonator-fed filtering patch antenna with improved selectivity and bandwidth is proposed in this paper. Unlike well-known cascaded-resonator structure, the proposed filtering antenna shows five poles in the reflection coefficient response utilizing only one resonator. The gap-coupled radiating part introduces two gain zeros along each side of the gain response. Meanwhile, the dual-mode resonator feeding structure of the antenna will also produce another two gain zeros. All these four gain zeros highly improve the selectivity of the filtering antenna without increasing the number of coupling resonators. In addition, the bandwidth of the antenna is also considerably extended using this feeding structure. For validation, a prototype is designed, fabricated, and measured. The measured results agree well with the simulated ones.

1. INTRODUCTION

Antenna, a component in signal transmitting and receiving, plays an indispensable role in modern communication systems. In a wireless system, the signal communication between devices all relies on antennas, of course, together with other RF devices such as filter and amplifier. Recently, with the rapid development of wireless communication, antenna design faces new challenges.

One of these challenges is improving the conventional bulky structure of an RF system, as the space for these RF circuits and antennas is becoming more and more limited. To solve this problem, new design theories such as filtering antenna and filtering amplifier are put forward. For the design of a filtering antenna, most commonly used methods make an antenna work as a resonator in the whole design procedure [1]. Based on the bandpass filter synthesis theory, the antenna is modeled as an RLC circuit and replace the last stage of the conventional bandpass filter. The specific synthesis procedure is already presented by researchers in literature [1, 2]. In [3], a filtering power divider fed structure is presented based on the filtering antenna synthesis method. The cascaded resonators are replaced by several multi-mode resonators, and the coupling strength between each two resonators dominates the power distribution ratio. Different power distribution ratios are studied in [3] to reduce the sidelobe level. In [4], a dual-mode resonator is used as the feeding structure of a dual-band antenna to get a filtering response. The stub of the resonator introduces a gain zero between the two operating bands. Since only one resonator is used in this design, the selectivity shown in [4] is not so satisfying.

Obviously, the cascaded structure method simultaneously tells a truth that sharper roll-off rate means more cascaded resonators and higher insertion loss. To overcome this drawback, another method is considered by researchers to serve the same purpose [5]. Different from the cascaded-resonator structure, the filtering function of this design is realized by introducing multiple attenuation poles in the gain response, which will be called as gain zeros in this letter for easy reference. The required gain zeros can be introduced by either feeding structures [5–7], loading elements [8–11], or specially

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designed coupling topology [12–14]. In [14], the authors present a gap coupled multi-patch structure. Different combinations of the patches lead to different gain responses. The gain zeros resulting from the canceling of the radiation of different patches make a good roll-off ratio in the gain response.

Based on the structure presented in [14], a stub-loaded resonator-fed structure is designed to improve the selectivity and bandwidth of the antenna. The stub-loaded resonator is a dual-mode resonator, which can be used to extend the bandwidth of the filtering antenna. The radiating part is a gap coupled patch antenna consisting of three patches. The loading stub will introduce a transmission zero at the frequency where the stub length is about a quarter wavelength. There are five reflection zeros in passband and two pairs of gain zeros at each side of the gain response. All these gain zeros considerably improve the selectivity of the proposed antenna. To the authors' knowledge, it is the first time that a filtering antenna with such two pairs of gain zeros is presented. For validation, a prototype is designed, fabricated, and measured. Extended bandwidth and high selectivity can be observed from the measured results of the proposed filtering antenna.

2. ANTENNA DESIGN

It has been outlined in our previous work [14] that the parasitic patches introduce two gain zeros in the gain response. However, the suppression level is not very good because perfect canceling only occurs at a very narrow frequency range. To further improve the filtering performance of the proposed broadband antenna, a stub loaded resonator similar to the feeding structure in [15] is utilized to introduce another two gain zeros.

The geometry of the proposed dual-mode resonator-fed gap coupled broadband antenna is shown in Fig. 1. The antenna consists of two dielectric substrates with a dielectric constant of 2.55, thickness of 0.8 mm, and loss tangent of 0.0029. An air gap between the two substrates is used to increase the impedance bandwidth and radiation efficiency of the antenna [16]. The larger the air gap is, the lower the effective dielectric constant is, resulting in decreased quality factor of the antenna.

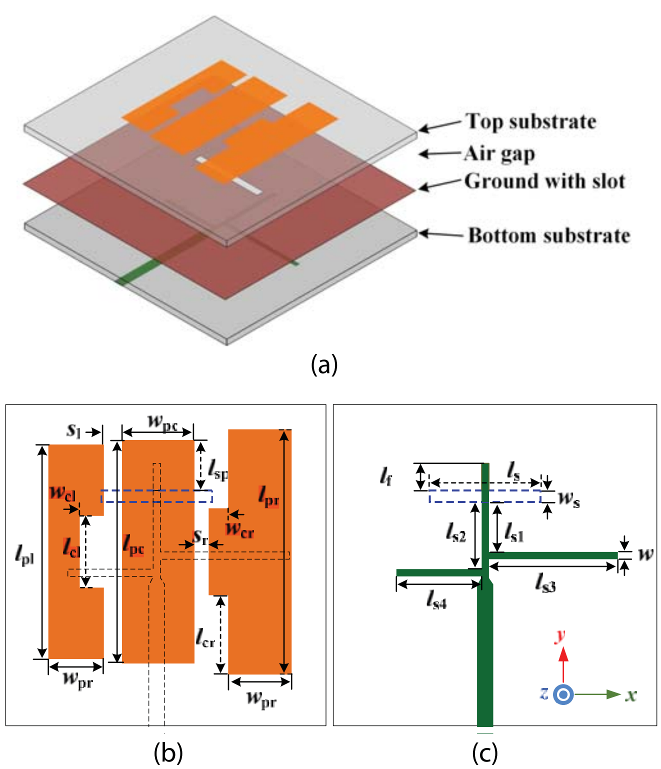

Figure 1. Structure of the proposed broadband filtering antenna. (a) Exploded view. (b) Top view. (c) Bottom view.

On the top substrate, there are three radiating patches, and one of them is a rectangular central patch whereas the other two parasitic patches are both particularly modified as shown in Fig. 1. One of the parasitic patches is modified into a concave patch while the other is a convex one. A stub-loaded resonator located at the bottom layer of the bottom substrate is used to excite the radiating patches through the aperture in the ground. The ground plane is placed at the top layer of the bottom substrate.

The tapped-line coupled structure is used in this design, as shown in Fig. 1(c). The stub loaded resonator is a dual mode resonator and can introduce inherent transmission zeros (or gain zero) when the length of the stub is quarter-wavelength. The total length indicated by $(l_{s4}+l_{s2}+l_f+w_s)$ is about half-wavelength at 3.5 GHz. The length of the loading stub is optimized to properly locate the second resonance frequency of the resonator. Referring to the analysis in [14], the coupling topology of the proposed filtering antenna is shown in Fig. 2. P is the input port, and P_r is the equivalent radiation resistance. Resonators R_1, R_2, and R_3 represent the central patch, left patch, and right patch, while R_A and R_B represent the dual-mode stub-loaded resonators. From the coupling topology, five reflection zeros can be obtained. According to [14], two gain zeros can be introduced by the three patches. Another gain zero occurs when the length of the open-circuit stub (l_{s3}) is equal to one quarter guide wavelength, while the forth transmission zero arises when l_{s4} is about a quarter wavelength. Ultimately, all these results in the appearance of two pairs of gain zeros at the finite frequencies are just like a cascaded quadruplet (CQ) filter.

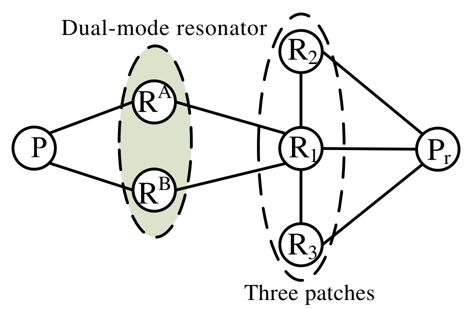

Figure 2. Coupling topologies of the proposed filtering antennas.

The dimensions of the patches can be obtained following the procedure presented in [14]. The central patch is about a half wavelength at the center frequency of the antenna. The width of each patch is about $\lambda_g/6$, where λ_g is the guide wavelength. The total size of the proposed patch antenna is approximately $0.5\lambda_g^2$, which is comparable to the conventional single patch one. The topologies of the antenna with fifth-order filtering performance are shown in Fig. 1. As can be seen, the structure using the design method presented in [1] asks for four resonators except for the radiating component. However, using the method proposed in this work there are only one dual-mode resonator is needed to serve the same purpose. The dual-mode resonator is excited by a simple tapped 50-Ω microstrip line and then coupled to the radiating patches through slot. Three patches provide three resonances in the passband, respectively.

The optimized dimensions of the antenna are given in Table 1. The simulated and measured

Table 1. Parameters of the Proposed Tri-band Antenna (unit: mm).

Parameters	l_{p1}	l_{c1}	l_f	l_s	l_{cr}	l_{pr}	l_{pc}	w_{pl}
Value (mm)	31.7	11.4	3.95	15.3	11.55	32	31.2	9
Parameters	w_{c1}	w_s	w_{pc}	w_{cr}	w_{pr}	s_l	s_r	h
Value (mm)	3.5	1.1	14.4	3.1	11	1.8	3.1	4
Parameters	l_{sp}	l_{s1}	l_{s2}	l_{s3}	l_{s4}	w		
Value (mm)	9.35	7.4	9.3	17.2	11.9	0.5		

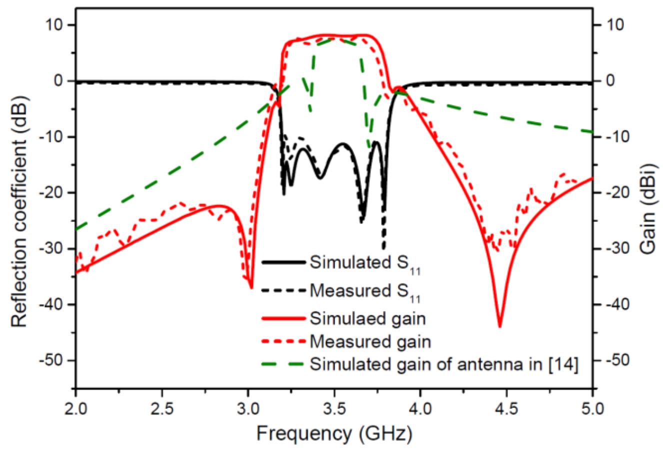

Figure 3. Simulated and measured reflection coefficients and gains of the proposed filtering antenna.

reflection coefficients and gains are plotted in Fig. 3. The impedance bandwidth is measured to be 3.19–3.8 GHz (17%). This would be about only 2%–5% for a conventional rectangular patch antenna. Compared to the filtering antenna in [14], the bandwidth is also highly improved from 8.3% to 17%. Besides, the stub loaded resonator not only introduces two gain zeros, but also serves as a broadband impedance matching network. The bandwidth of the antenna can be adjusted by varying the coupling between the feed structure and patches.

The measured peak in-band realized gain of the antenna is about 7.67 dBi. The out-of-band rejection is considerably improved by the two pairs of gain zeros as shown in Fig. 3. The first pair of gain zeros near the operating band is introduced by the antenna portion whereas the second pair of gain zeros is controlled by the length of the stubs of the feed structure. The current distributions at the frequencies of the first pair of gain zeros (near the passband) are shown in Fig. 4(a). Taking the gain zero located at 3.2 GHz as an example, the current mainly concentrates on the concave patch and central rectangular patch, whereas the current on the parasitic convex patch is much weaker. This means that the radiation at this frequency point is dominated by the concave and central patch. However, the currents on these two patches are out-of-phase. As a consequence, the radiation is suppressed at this frequency (3.2 GHz), so as the second gain zero at 3.8 GHz as shown in Fig. 4(b).

Figure 5 shows the radiation pattern in two planes. It can be observed that the antenna obtains a considerably low cross polarization level and good broadside radiation pattern in the passband. The low

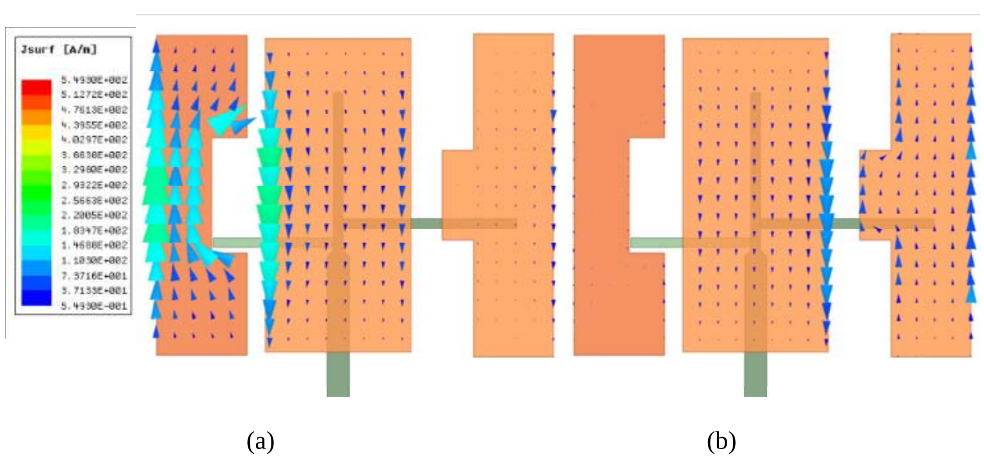

Figure 4. Current distributions at the frequencies of the first pair of gain zeros. (a) 3.2 GHz. (b) 3.8 GHz.

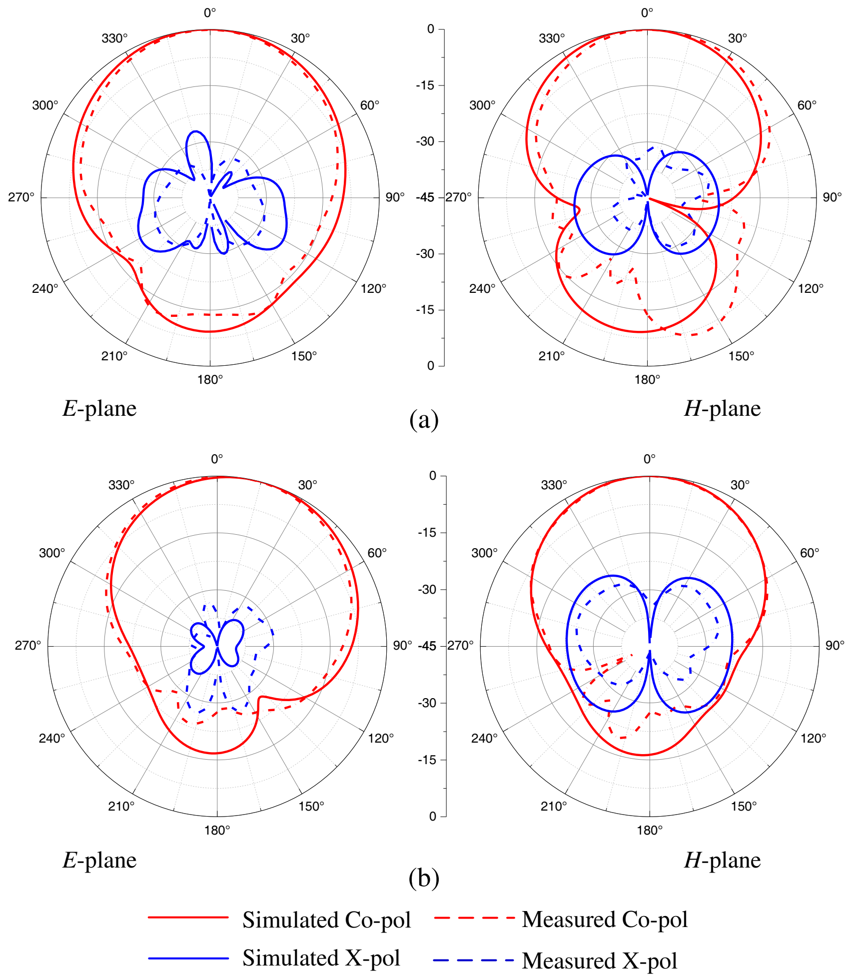

Figure 5. Normalized simulated and measured radiation patterns of the proposed filtering antenna at (a) 3.4 GHz. (b) 3.6 GHz.

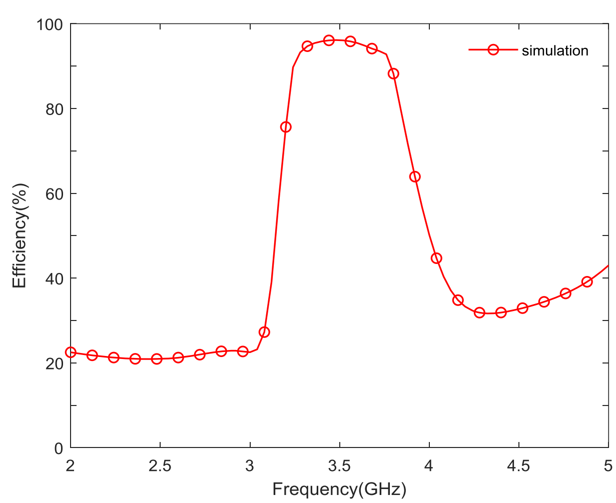

Figure 6. Simulated radiation efficiency of the proposed filtering antenna.

Figure 7. Photography of the proposed broadband filtering antenna.

cross polarization level is mainly because of the weak current along the Y-axis, which can be observed in Fig. 4. The measured radiation pattern and gain response of the antenna indicate that the drawback of frequency-sensitive radiation pattern in conventional gap-coupled patch antenna designs is avoided in this design. The simulated radiation efficiency is given in Fig. 6. The efficiency at center frequency is about 92%, thus the proposed antenna can be used to realize an array antenna with high efficiency [17].

Figure 7 shows a photograph of the fabricated antenna. Six insulative spacers with height of 4 mm are placed and fixed by seven nylon screws between the two substrates to realize the supposed air gap.

3. CONCLUSION

In this paper, a dual-mode resonator-fed gap-coupled filtering antenna is presented. The antenna is composed of a dual-mode resonator and a gap-coupled broadband patch antenna. The dual-mode resonator works as the feed structure of the antenna, helping increase the bandwidth of the antenna. Two pairs of radiation nulls along each side of the passband introduced by the antenna portion and the feed structure make a satisfying selectivity. The radiation pattern across the operating band is very stable. The proposed broadband filtering antenna has the advantages of low profile, light weight, and easy fabrication, which is promising in modern communication systems

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REFERENCES

1. Chuang, C.-T. and S.-J. Chung, "Synthesis and design of a new printed filtering antenna," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 4, 1036–1042, Mar. 2011
2. Lin, C.-K. and S.-J. Chung, "A filtering microstrip antenna array," *IEEE Trans. Microw. Theory Techn.*, Vol. 59, No. 11, 2856–2863, Nov. 2011.
3. Chen, F.-C., H.-T. Hu, R.-S. Li, Q.-X. Chu, and M. J. Lancaster, "Design of filtering microstrip antenna array with reduced sidelobe level," *IEEE Trans. Antennas Propag.*, Vol. 65, No. 2, 903–908, Feb. 2017.
4. Mao, C.-X., et al., "Dual-band patch antenna with filtering performance and harmonic suppression," *IEEE Trans. Antennas Propag.*, Vol. 64, No. 9, 4074–4077, Sep. 2016.

5. Zhang, X.-Y., W. Duan, and Y.-M. Pan, "High-gain filtering patch antenna without extra circuit," *IEEE Trans. Antennas Propag.*, Vol. 63, No. 12, 5883–5888, Dec. 2015.
6. Lin, C. K. and S. J. Chung, "A compact filtering microstrip antenna with quasi-elliptic broadside antenna gain response," *IEEE Antennas Wireless Propag. Lett.*, Vol. 10, 381–384, 2011.
7. Duan, W., X. Y. Zhang, Y.-M. Pan, J.-X. Xu, and Q. Xue, "Dual-polarized filtering antenna with high selectivity and low cross polarization," *IEEE Trans. Antennas Propag.*, Vol. 64, No. 10, 4188–4196, Oct. 2016.
8. Wu, J., Z. Zhao, Z. Nie, and Q.-H. Liu, "A printed unidirectional antenna with improved upper band-edge selectivity using a parasitic loop," *IEEE Trans. Antennas Propag.*, Vol. 63, No. 4, 1832–1837, Apr. 2015.
9. Zhang, Y., X.-Y. Zhang, L.-H. Ye, and Y.-M. Pan, "Dual-band base station array using filtering antenna elements for mutual coupling suppression," *IEEE Trans. Antennas Propag.*, Vol. 64, No. 8, 3423–3430, Aug. 2016.
10. Tang, M.-C., Y. Chen, and R. W. Ziolkowski, "Experimentally validated, planar, wideband, electrically small, monopole filtennas based on capacitively loaded loop resonators," *IEEE Trans. Antennas Propag.*, Vol. 64, No. 8, 3353–3360, Aug. 2016.
11. Jin, J.-Y., S.-W. Liao, Q. Xue, "Design of filtering-radiating patch antennas with tunable radiation nulls for high selectivity," *IEEE Trans. Antennas Propag.*, Vol. 66, No. 4, 2125–2130, Feb. 2018.
12. Zhang, B. H. and Q. Xue, "Filtering antenna with high selectivity using multiple coupling paths from source/load to resonators," *IEEE Trans. Antennas Propag.*, Vol. 66, No. 8, 4320–4325, May 2018.
13. Mao, C.-X., et al., "An integrated filtering antenna array with high selectivity and harmonics suppression," *IEEE Trans. Microw. Theory Techn.*, Vol. 64, No. 6, 1798–1805, Jun. 2016.
14. Qian, J.-F., F.-C. Chen, Q.-X. Chu, Q. Xue, and M. J. Lancaster, "A novel electric and magnetic gap coupled broadband patch antenna with improved selectivity and its application in MIMO system," *IEEE Trans. Antennas Propag.*, Vol. 66, No. 10, 5625–5629, Jul. 2018.
15. Hu, H. T., F. C. Chen, and Q. X. Chu, "Novel broadband filtering slotline antennas excited by multi-mode resonators," *IEEE Antennas Wireless Propag. Lett.*, Vol. 16, 489–492, 2017.
16. Lee, K. F., K. Y. Ho, and J. S. Dahele, "Circular-disk microstrip antenna with an air gap," *IEEE Trans. Antennas Propag.*, Vol. 32, No. 8, 880–884, Aug. 1984.
17. Morabito, A. F., "Synthesis of maximum-efficiency beam arrays via convex programming and compressive sensing," *IEEE Antennas Wireless Propag. Lett.*, Vol. 16, 2404–2407, 2017.