Design of a Multilayer Dual-Band Balanced Bandpass Filter on a Circular Patch Resonator

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This letter presents a novel multilayer dual-band balanced bandpass filter (BPF) design by using two perturbed circular patch resonators. The TM11 mode and TM21 mode of the resonator with odd-symmetric field distributions are explored to realize the desired differential-mode (DM) transmission and common-mode (CM) suppression. Two circular patches are properly coupled in the back-to-back form to realize a dual-passband balanced response by virtue of coupling apertures etched on the ground. In addition to the internal coupling, the above apertures are also further utilized for the undesired degenerate mode harmonic suppression. Besides, slot perturbations on the patch are introduced to perturb the TM21 resonant mode to independently adjust the center frequency of the higher passband, while the lower passband remains almost unchanged. Thus, two passbands can be flexibly controlled by simultaneously tuning the above slots and size of the patch. For validation, a dual-band balanced BPF prototype is implemented. The results indicate 18 and 26% wide fractional bandwidths centered at 5.5 and 7.5 GHz with return loss higher than 20 dB under DM operation and CM suppression higher than 40 dB over an ultra-wide frequency band.

Keywords: dual-band, balanced, filter, multilayer, circular patch

INTRODUCTION

Balanced filters play key roles in modern wireless communication systems, attributing to their superior immunity to the electromagnetic interference and environmental noise [1]. In the meantime, great development of modern wireless communication systems brings out an increased requirement for dual-band operations. To the end, dual-band balanced bandpass filters (BPFs) are desired.

Accordingly, much efforts have been made to explore a variety of high-performance dual-band balanced BPFs by using different transmission line structures, such as planar microstrip transmission line resonators [2–5], substrate-integrated waveguide (SIW) resonators [6–9], and dielectric resonators (DRs) [10]. On the contrary, the patch-type resonators are attracting much attention in balanced BPF designs due to their superior advantages of higher power handling capability and lower loss over the transmission line–based resonators and simpler and more straightforward analysis and design compared with the SIW and DR forms. However, to the best of our knowledge, only limited works have been carried out on design of single-band balanced BPFs, e.g., square patch resonator–based balanced BPFs [11–13] and triangular patch resonator–based balanced BPFs [14–16]. How to design a dual-band patch balanced BPF is still rarely reported and remains challenging.
This letter is aimed at presenting a new dual-band balanced BPF design on a circular patch resonator. For this purpose, the TM\textsubscript{11} mode and TM\textsubscript{21} mode resonant properties of a circular patch are carefully analyzed and investigated with both differential-mode (DM) excitation and common-mode (CM) excitation. Two vertically coupled circular patches, via proper coupling apertures etched on the common ground, are explored to realize two passbands under DM operation. Furthermore, slot perturbations on the patch are designed to adjust the frequency ratio of the two passbands and attain high CM suppression. In order to demonstrate the design concept, a circular patch dual-band balanced filter prototype was designed, manufactured, and tested. Measured and simulated results well coincide with each other.

**DESIGN AND ANALYSIS OF THE PROPOSED DUAL-BAND BALANCED FILTER**

Figures 1A–E describe the configuration of the proposed dual-band balanced BPF. Two layers of RO4003C substrates ($\varepsilon_r = 3.55$, $h = 0.508$ mm, and $\tan\delta = 0.0027$) are used. Two differential input ports (Ports 1 and 1') are placed at the top layer, while two output ports (Ports 2 and 2') are at the bottom layer. Two coupling apertures of length $l_2$ and width $w_2$ are arranged along the main diagonal line (A–B) on the square common ground of Figure 1D. Besides, two perturbation slots with length $l_1$ and width $w_1$ are placed along the diagonal line (C–D) of a circular patch with radius $r$ as shown in Figures 1C,E. The dual-band response of the proposed balanced BPF is realized by the utilization of two diagonal modes: TM\textsubscript{11} mode (Mode 1) and TM\textsubscript{21} mode (Mode 3), in the patch resonator. In this context, the first DM passband is made up of a pair of TM\textsubscript{11} modes (Mode 1), while the second DM passband is formed by two TM\textsubscript{21} modes (Mode 3) from the two top- and bottom-layer patches, respectively. Detailed working mechanisms are illustrated as follows.

Figure 2 and Figure 3 indicate simulated electrical and magnetic fields of the first three resonant modes in the circular patch: a pair of degenerate TM\textsubscript{11} modes (Mode 1 and Mode 2) and TM\textsubscript{21} mode (Mode 3), respectively. As observed in Figure 2, the electrical-field patterns of these modes are odd-symmetric inside the patch. In other words, almost same intensity and opposite direction can be found with respect to the corresponding symmetric plane. Therefore, when input ports 1 and 1' are injected with DM signals, the fields of the TM\textsubscript{11} mode (Mode 1) and TM\textsubscript{21} mode (Mode 3) can be simultaneously excited in the top-layer patch. Meanwhile, the magnetic-field...
intensity around regions (Area 1 and Area 3) in Figure 3 is high for both the TM_{11} mode (Mode 1) and the TM_{21} mode (Mode 3).

Two coupling apertures placed in the above regions are utilized for the internal coupling of both passbands in a vertically stacked form. Accordingly, the field patterns from the TM_{11} mode (Mode 1) and TM_{21} mode (Mode 3) on the bottom-layer patch will be excited. When the feeding output ports are chosen to place at two sides of the symmetrical plane as Ports 2 and 2', balanced outputs can be attained for both the TM_{11} mode (Mode 1) and the TM_{21} mode (Mode 3) in the bottom-layer patch.

It should be mentioned that, under CM excitation, the TM_{11} mode (Mode 1) and TM_{21} mode (Mode 3) cannot be supported on the patches, while the TM_{11} mode (Mode 2) can be activated. Thanks to the fields of Mode 2 that are weak around coupling apertures as shown in Figure 3, the CM signals can hardly be coupled to the bottom-layer resonator. Therefore, the CM suppression will be obtained with this structure.

Based on the above analysis, the corresponding coupling scheme is depicted for the dual-band balanced filter, as shown in Figure 4. In the scheme, 1^A and 2^A represent the coupled TM_{11} modes (Mode 1) of the top and bottom patch resonators for the second passband. As is known, for the intact circular patch, the resonant frequency (f_{nm}) of each mode (TM_{nm}) is determined by the radius r of the circular patch, and the formula is provided as follows [17]:

\[ f_{nm} = \frac{c x_{nm}}{2 \pi a \sqrt{\varepsilon_r}} \]  

\[ x_{11} = 1.841184, x_{21} = 3.054237, \]  

\[ a = r \left( 1 + \frac{2h}{\pi r \varepsilon_r} \left( \ln \frac{\pi r}{2h} + 1.7726 \right)^\frac{3}{2} \right), \]  

where c is the speed of light.

According to Eqs. 1–3, the two resonant frequencies of the interested modes for the dual-band balanced BPF are simultaneously changed with various radii r. Therefore, it is impossible to independently control two passbands by just changing the radius r. To further improve the flexibility of the design, two slot perturbations on the patch are carefully introduced in the patches as shown in Figure 1 to perturb the

FIGURE 3 | Simulated H-fields of the resonant modes in the circular patch. (A) TM_{11} mode (Mode 1), (B) TM_{11} mode (Mode 2), and (C) TM_{21} mode (Mode 3).

FIGURE 4 | Coupling scheme for the dual-band balanced filter.

FIGURE 5 | Simulated S_{21} of the filter against varied h_1.
TM21 (Mode 3) resonant mode while seldom influencing the TM11 mode (Mode 1), according to the magnetic-field distributions. The corresponding design parameters are calculated: the center frequencies of the passbands, BW of the first passband and BW of the second passband. Thirdly, the final parameters of the feedline (lF), slots (w1), and internal coupling apertures (w2 and l2) are optimized to achieve a compromise for calculated external quality factors (Qext) and internal coupling coefficients (Mij) of both passbands. Herein, it is worth mentioning that as the internal coupling is obtained using the same coupling apertures for both passbands, the two passband bandwidths will not be able to be independently controlled.

**MEASUREMENT AND DISCUSSIONS**

Based on the given specifications and design procedures discussed above, the size of the proposed dual-band balanced filter can be determined as follows: r = 8.0, l1 = 6.0, l2 = 4.9, lF = 5, w1 = 0.3, and w2 = 0.68 (unit: mm). A dual-band balanced filter is designed and manufactured. Simulation and measurement results are shown in Figure 7. The measured results show that the CFs are 5.5 and 7.5 GHz and the 3 dB BWs are 1.0 GHz (18%) and 2.0 GHz (26%). In the two passbands, the measured insertion loss is both less than 1.4 dB and the return loss is both higher than 22 dB. Common-mode inhibition is higher than 40 dB.

Table 1 compares the proposed dual-band balanced filter with other state-of-the-art designs. The present work not only exhibits a new effective design method for a dual-band balanced patch filter but also achieves nice operation performance in terms of much wider bandwidths, independently controllable center frequencies, better return loss, competitive common-mode suppression, compact size, etc.

**CONCLUSION**

A new dual-band balanced patch filter has been designed and implemented in this letter. The resonant modes of circular patch TM11 mode and TM21 mode are explored to design the dual-band balanced filter. By wisely etching coupling apertures on the ground and introducing slots on the patch, a nice controllable...
dual-band response and improved CM suppression are attained in the design. Measured results coincide well with simulated ones, verifying the proposed design concept. It is our belief that this design has a prospect of broad application in the application of wireless communication systems.

### DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, and further inquiries can be directed to the corresponding author.

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### TABLE 1 | Comparison with other previous works.

| Refs. | CF (GHz) | BW (%) | Size (λg×λg) | CMS (dB) | RL (dB) | IL (dB) |
|-------|----------|--------|--------------|----------|---------|---------|
| [6]   | 9.5 and 9.9 | 11 and 4.0 | 2.67 × 2.95 | > 30     | 11      | 1.9     |
| [7]   | 3.5 and 5.2 | 2.8 and 3.8 | 1.23 × 1.23 | > 50     | 14      | 1.6     |
| [8]   | 9.2 and 14   | 2.8 and 5.5 | 2.70 × 1.75 | > 40     | 10      | 2.7     |
| [9]   | 9.5 and 15   | 2.7 and 5.3 | 0.98 × 0.98 | > 60     | 17      | 2.7     |
| [10]  | 2.1 and 2.4  | 8.5 and 0.9 | 0.47 × 0.47 | > 10     | 9       | 1.3     |
| This work | 5.5 and 7.5  | 18 and 26  | 0.50 × 0.50 | > 40     | 22      | 1.4     |

CMS, common-mode suppression; RL, return loss; IL, insertion loss; λg, guided wavelength at its first center frequency.

### AUTHOR CONTRIBUTIONS

YX conducted extensive analysis and wrote this paper. ZL gave assistance in the measurement. SW and TC revised this paper. JC contributed to the funding support.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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