The letter presents a triple-mode short-circuited circular patch resonator for bandpass filter (BPF) design. The resonator employs the TM_{010} mode as its dominant mode, the resonant frequency of which is lower than that of the TM_{110} mode. In addition, four radial slots are etched on the patch to extend the current paths of the TM_{110} and TM_{210} modes, shifting down the resonant frequencies of the two modes. The adjacent triple modes can be used to design wideband BPFs. Meanwhile, the centre frequency (CF) and bandwidth (BW) can be tuned by the length of the slots. Furthermore, the short-circuited vias are arranged in a circle by providing a tunable parameter to control the CF and BW as well. According to the symmetry of the geometry, the resonator can be bisected to realise half-mode resonance. Two cascaded half-mode semi-circular patch resonators are applied to design BPF with high selectivity. BPFs using the circular patch resonator and the semi-circular patch resonator are designed and measured for demonstration.

Introduction: Microstrip patch resonators with different structures for filter design are widely researched because of their low cost, light weight, small size, easy fabrication, and high integration [1–4]. Meanwhile, the patch resonators can excite multiple resonant modes for single- and dual-band bandpass filters (BPFs) design with compact size. The mostly used resonant modes are TM_{110} and TM_{210} modes, which are usually the first two modes of a patch resonator. Recently, the resonators with perturbations of metallic vias are extensively applied in BPF design for shifting the TM_{010} mode near to the TM_{110} and TM_{210} modes [5]. Such as in [1], the newly generated first mode by the grounded via and two degenerated TM_{110} modes are excited to design a wideband BPF. The theoretical analysis in [2, 3] is similar for designing a BPF with triple mode. In order to reduce the size, the perturbation of slot is etched on a resonator to lengthen the current path of the resonator, which is the most popular method for drawing down the resonant frequencies [1]. In addition, the half-mode, quarter-mode, even eighth-mode substrate-integrated waveguide (SIW) technology has developed for size compactness [6–8].

Here, a short-circuited circular patch resonator loaded with four radial slots is proposed to design a triple-mode BPF. The metallic vias are arranged in a circle at the centre of the patch, which brings down the resonant frequency of the TM_{010} mode lower than that of the TM_{110} mode. At the same time, the four radial slots move the resonant frequencies of the TM_{110} and TM_{210} modes near to that of the TM_{110} mode. Therefore, the proposed resonator can be used to design a triple-mode BPF with easily tuneable centre frequency and bandwidth. Meanwhile, the circular patch resonator can be bisected to realise half-mode BPF design, which can improve the selectivity and the stopband suppression. Finally, a triple-mode patch filter and a two semi-circular cascaded patch filter are designed, fabricated, and measured for illustration.

Proposed short-circuited patch resonator: Figure 1a shows the configuration of the proposed short-circuited circular patch resonator. Two 50-Ohm input/output feeding lines are directly connected to the resonator. The metallic vias are arranged in a circle with a radius r at the centre of the circular patch, which are similar to that of the SIW for easy fabrication. The four radial slots are etched on the patch with the same dispersive angle of 90 degrees. The width and the length of the slots are denoted by s and L. respectively. As shown in Figure 1b, the circular patch can be bisected into two semi-circular patches along the symmetric plane A-A'.

The excited resonant modes of the circular patch resonator in Figure 1a can be illustrated by the weak coupling between the two feeding lines and the resonator, which are shown in Figure 2. Figure 3 plots the electric distributions of the three resonant modes. The field distributions in Figure 3b,c near the slots are strengthened. Therefore, the four radial slots have no effect on the first resonant mode, but have great effect on the next two resonant modes. The corresponding current distributions of the three resonant modes are plotted in Figure 4. It can be seen from the electric field and current distributions that the first resonant mode is TM_{010} mode, the second resonant mode is TM_{110} mode, and the third resonant mode is TM_{210} mode.

As shown in Figure 3a and Figure 4a, the radial slots have no effect on the current distribution of TM_{010} mode, but they have a great effect on that of TM_{110} and TM_{210} modes. It can be deduced that the longer the length of the slot is, the longer the current paths of TM_{110} and TM_{210} modes are. As a result, the resonant frequencies of the two modes gets

Fig. 1 Proposed configurations of BPFs using short-circuited patch resonators. (a) Structure of triple-mode BPF based on circular patch resonator loaded with four radial slots. (b) Structure of BPF using two cascaded half-mode semi-circular patch resonators

Fig. 2 S-parameter of circular patch resonator under weak coupling

Fig. 3 Electric distributions of resonant modes under weak coupling. (a) TM_{010} mode. (b) TM_{110} mode. (c) TM_{210} mode

Fig. 4 Current distributions of resonant modes under weak coupling. (a) TM_{010} mode. (b) TM_{110} mode. (c) TM_{210} mode
Simulated $|S_{21}|$ against varied $s$

Simulated $|S_{21}|$ against varied parameters. (a) Variations with length of slots $L$. (b) Variations with inner radius $r$.

Fig. 5

Simulated $|S_{21}|$ against varied $s$

In addition, the inner metallic vias behave like an electric wall, which has a great effect on the TM$_{010}$ mode. The resonant frequency of TM$_{010}$ mode can be calculated by the characteristic equation in [9]. As shown in Figure 4a, the radius $r$ becomes larger, the current patch of TM$_{010}$ mode gets shorter, which results in the increase of the resonant frequency of TM$_{010}$ mode. It can also be observed from Figure 5b that the lower sideband frequency gets larger when the parameter $r$ increases. Meanwhile, the inner circle has less effect on the TM$_{210}$ mode. Therefore, the upper sideband frequency remains unchanged.

The width of the four identical slots also has effect on the resonant frequencies of the resonator. It can be observed in Figure 6 that the wider the width is, the lower the upper edge of the passband gets, because of the longer way the current goes, which results in an increase of the resonant frequency.

Through the modes analysis, the proposed resonator has two main parameters $r$ and $L$ to tune the centre frequency and the bandwidth independently. According to the symmetry of the resonator structure, the half-mode method for compactness can be applied in the proposed resonator. The symmetric plane A-A’ can be considered as a magnetic wall, the half-mode resonances keep the same resonant frequencies as that of the circular patch resonator with the symmetrical electric field distributions. The current distributions of the first three resonant modes are described in Figure 7, which are similar to that of the circular patch resonator shown in Figure 4.

Furthermore, the two semi-circular resonators can be cascaded to improve the performances and remain compact size as that of one circular resonator, which is shown in Figure 1b. Since the resonant frequency of each excited mode has a great difference to the centre frequency, the coupling topology of the cascaded resonators shown in Figure 1b can be described by the transversal coupling topology. The coupling topology of the two resonators is given in Figure 8. Due to the symmetry of the electromagnetic fields of the resonant modes, each resonator has three resonant modes and each mode couples to the same mode of the other resonator. Since more resonances are introduced in the BPF design, the selectivity and the upper stopband suppression performances can be improved.

Simulated and measured results: Based on the above theoretical analysis, a triple-mode BPF (BPF-I) using short-circuited circular patch resonator and a two semi-circular patch resonators cascaded BPF (BPF-II) are designed and fabricated on a substrate with a permittivity of 2.65, loss tangent of 0.003, and thickness of 1 mm. Filter-I is designed with centre frequency of 4.7 GHz and 3 dB fractional bandwidth (FBW) of 55%. The optimised parameters are $r = 1.5$, $R = 10$, $L = 6.5$, $s = 0.1$, $g = 0.1$ (all units: mm). BPF-II is designed with centre frequency of 4.3 GHz and FBW of 30%. All parameters of BPF-II are the same as that of Filter-I except $L = 8.2$ mm.

The photographs of the fabricated filters are given in Figure 9. Figure 10 plots the responses of the fabricated filters. The measured centre frequency (CF) $f_0$, insertion loss (IL) at the CF, minimum return loss (RL) in passband, and 3 dB FBW of BPF-I are 4.66 GHz, 1.6 dB, 10 dB, and 54.8%, respectively. While the measured CF, IL, RL, and FBW of BPF-II are 4.25 GHz, 0.6 dB, 25 dB, and 29.6%, respectively. The two filters have the same size of $0.41\lambda_g \times 0.41\lambda_g$, where $\lambda_g$ is the guided wavelength at $f_0$. The slight discrepancies between simulations and measurements are due to the fabrication errors, substrate losses, and the
Table 1. Comparison with reported patch filters

| Ref. | $f_0$ (GHz) | FBW (%) | IL (dB) | RL (dB) | Stopband (GHz-GHz) | Size ($\lambda_g \times \lambda_g$) |
|------|-------------|---------|--------|--------|-------------------|-------------------------------|
| [1]  | 6.89        | 110     | 0.9    | 17     | >11 dB, (12.8–15)  | 0.26 × 0.26                  |
| [2]  | 3.51        | 8.7     | 1.13   | 18.6   | >20 dB, (3.75–4.85)| 0.48 × 0.48                  |
| [3]  | 33.8        | 22.2    | 1.8    | 10     | >40 dB, (37.5–42.5)| 1.13 × 2.27                  |
| BPF-I| 4.66        | 54.8    | 1.6    | 10     | >20 dB, (6.72–10.9)| 0.41 × 0.41                  |
| BPF-II| 4.25       | 29.6    | 0.6    | 25     | >30 dB, (5.5–10.9)| 0.41 × 0.41                  |

radiation losses from the slots. Due to the feeding structure, it is not easy to adjust the coupling between the resonances and the feeding lines. Therefore, the number of the transmission poles are not relevant to that of the resonances. Table 1 gives the comparisons of the proposed filter with the reported multi-mode microstrip planar filters. It can be seen that the proposed filters have wide upper stopband with good compactness.

**Conclusion:** A triple-mode wideband BPF design based on short-circuited circular patch resonator is presented in this paper. The resonant frequencies of the proposed resonator can be tuned independently, which results in tuneable CF and BW as well. Meanwhile, a half-mode resonator is produced from the circular resonator to design cascaded BPF with high selectivity and compactness.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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