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A Novel Triple-Mode Bandpass Filter Using Half-Wavelength-Resonator-Coupled Square-Loop Resonator

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Abstract—A novel triple-mode bandpass filter (BPF) using half-wavelength-resonator-coupled square-loop resonator is developed in this letter. The half wavelength resonator is applied to add an additional path, which increases a pole in the passband and a transmission zero in the stopband. Furthermore, the coupling scheme is used to accurately predict its desired performance. Compared to the conventional square-loop dual-mode filter, higher frequency selectivity and wider bandwidth are achieved. Finally, this filter is designed, fabricated and measured. Good agreement is achieved among the theoretical, simulated and measured results. All of these results validate our design idea.

1. INTRODUCTION

Multimode microwave filters with compact sizes, high performance and ease of design are now required. So far, microstrip dual-mode resonators have been the subject of intensive research. The concept of microstrip dual-mode bandpass filter was firstly presented in 1972 [1]. Then, several types of dual-mode resonator have been introduced, including square-loop resonator [2], stub-loaded resonator [3] and slotline resonator [4]. Recently, there are several triple-mode resonators reported in the literature to design integrated BPFs [5–16]. In [5], a compact microstrip filter using a triple-mode stepped impedance resonator (TSIR) is proposed in order to suppress the first spurious passband. In [6], a triple-mode bandpass filter uses an original triple-mode circular patch resonator with etched radial slots, which split the $\mathrm{TM}_{Z1,1,0}$ degenerate fundamental modes and also perturb the $\mathrm{TM}_{Z2,1,0}$ modes. In [7], a triple-mode resonator is evolved from a microstrip square-loop dual-mode resonator by adding a diagonal trace, without increasing the size. Two triple-mode microstrip BPFs using slotted-patch loaded cross resonator are proposed in [8]. In [9], a triple-mode resonator consists of a square open-loop resonator with an open circuited stepped-impedance stub and a grounding via located at the symmetrical plane of the resonator. In [10], a triple-mode wideband BPF based on a single slotline ring resonator with two unequal-length slot stubs attached is presented. A triple-mode wideband BPF with a very broad stopband is proposed in [12]. A triple-mode hexagon BPF with meander line and central-loaded stub is proposed in [14]. A low-frequency filter with the characteristic of wide passband and wide stopband using a triple-mode resonator is applied to achieving superconducting wideband BPF in [16].

This letter presents a novel design of a microstrip triple-mode bandpass filter, which is developed from a traditional dual-mode square-loop resonator with loading square-patch perturbation at the corner [2]. The proposed filter is realized by adding an additional path to a square-loop dual-mode resonator. The additional path is achieved by coupling a half wavelength resonator to the opposite corners of the host square loop, without increasing circuit size. The square-loop resonator is coupled by feeding lines, which are separated spatially at 90°.

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2. RESONATOR ANALYSIS

Figure 1(a) shows layout of the traditional dual-mode square-loop resonator with loading square-patch perturbation at the corner. The equivalent circuits of odd-mode and even-mode are depicted in Figures 1(b) and (c), respectively. The resonant conditions can be derived as

$$\text{the odd mode resonance condition: } Y_{\text{inodd}} = \frac{1}{jZ_1 \tan\theta_1} = \infty \tag{1}$$

$$\text{from Equation (1), it can be deduced as: } Z_1 \tan\theta_1 = 0 \tag{2}$$

$$\text{the even mode resonance condition: } Y_{\text{ineven}} = \frac{1 + \dfrac{Z_p}{Z_1 \tan\left(\dfrac{\theta_p}{2}\right)} \tan\theta_1}{\dfrac{Z_p}{j\tan\left(\dfrac{\theta_p}{2}\right)} + jZ_1 \tan\theta_1} = 0 \tag{3}$$

$$\text{from Equation (3), it can be deduced as: } \frac{Z_p}{Z_1}\tan(\theta_1) + \tan\left(\frac{\theta_p}{2}\right) = 0 \tag{4}$$

Equations (2) and (4) illustrate that the patch physical size p influences only the even mode but has no effect on the odd mode. So the resonant frequency of odd mode can be decided by Z_1 and θ_1, and the resonant frequency of even mode can be determined by Z_p and θ_p. Figure 1(d) shows layout of the proposed triple-mode resonator. In addition, the whole half wavelength resonator is placed in the inner loop so that this structure does not increase the size of the original resonator. After the bent half wavelength resonator is loaded in the dual-mode resonator, a new resonant mode is added. The resonant frequency of the new mode can be decided by the total length of the bent half wavelength resonator.

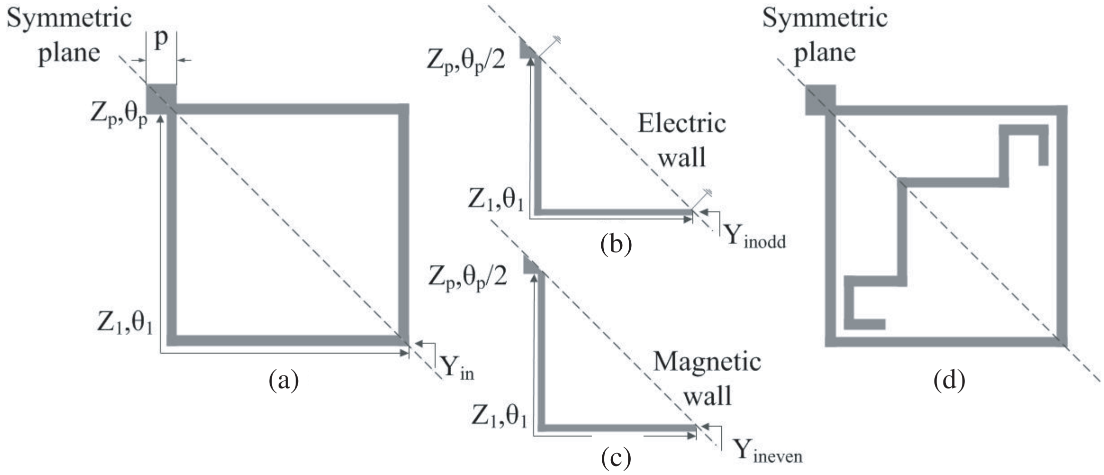


Figure 1. (a) Layout of the traditional dual-mode square-loop resonator with loading square-patch perturbation at the corner. (b) Odd-mode equivalent circuit. (c) Even-mode equivalent circuit. (d) Layout of the proposed triple-mode resonator.

3. FILTER DESIGN

The layout of the proposed triple-mode bandpass filter is illustrated in Figure 2, which consists of a proposed triple-mode resonator and a pair of orthogonal microstrip feeding lines. The proposed triple-mode resonator is fed by two feeding lines.

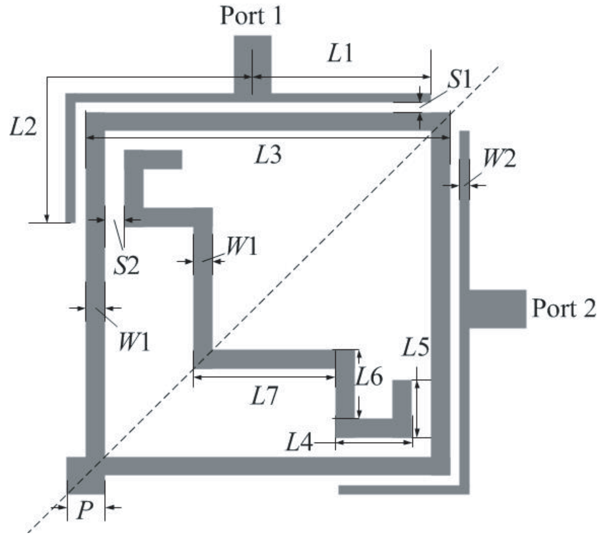


Figure 2. Layout of the proposed triple-mode bandpass filter (Substrate: $\varepsilon_r = 2.55$, $h = 0.8\,\mathrm{mm}$, $W1 = 0.8\,\mathrm{mm}$, $W2 = 0.4\,\mathrm{mm}$, $S1 = 0.22\,\mathrm{mm}$, $S2 = 0.5\,\mathrm{mm}$, $P = 1.92\,\mathrm{mm}$,$L1 = 14\,\mathrm{mm}$, $L2 = 23.6\,\mathrm{mm}$, $L3 = 31.2\,\mathrm{mm}$, $L4 = 5.2\,\mathrm{mm}$, $L5 = 4.4\,\mathrm{mm}$, $L6 = 6.6\,\mathrm{mm}$).

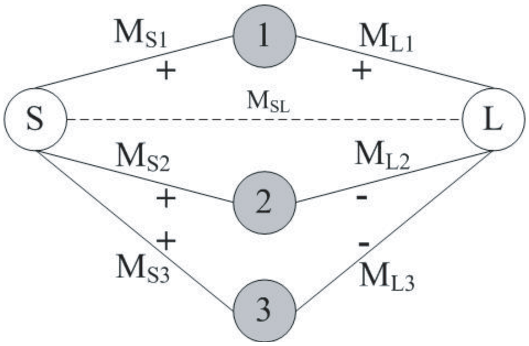


Figure 3. Coupling scheme of the proposed triple-mode BPF.

The coupling scheme of the triple-mode filter is shown in Figure 3. The shaded circles (marked 1, 2 and 3) represent the three resonance modes, i.e., even mode (mode 1) and odd mode (mode 2) of square-loop resonator and odd mode of half-wavelength resonator (mode 3). The source and load, shown as the white circles, are coupled to the three modes by admittance inverters, which are represented by the solid lines. In addition, the source and load are weakly coupled, denoted by the dashed line. In our design, the three modes are not coupled to each other.

The corresponding coupling matrix M is given by [17]

$$M = \begin{bmatrix} 0 & M_{S1} & M_{S2} & M_{S3} & M_{SL} \\ M_{S1} & M_{11} & 0 & 0 & M_{L1} \\ M_{S2} & 0 & M_{22} & 0 & M_{L2} \\ M_{S3} & 0 & 0 & M_{33} & M_{L3} \\ M_{SL} & M_{L1} & M_{L2} & M_{L3} & 0 \end{bmatrix}$$

Since our proposed triple-mode filter is diagonal symmetrical in geometry, the coupling coefficients satisfy $M_{S1} = M_{L1}$, $M_{S2} = -M_{L2}$, $M_{S3} = -M_{L3}$. The negative sign means capacitive coupling between source and load. M_{ii} and M_{Si} in the coupling matrix are calculated by:

$$Q_e = \frac{\pi f_0 T d_1}{2} \tag{5}$$

$$M_{Si} = \sqrt{1/FBW * Q_e} \tag{6}$$

$$M_{ii} = \frac{f_0^2 - f_i^2}{\Delta f * f_i} \tag{7}$$

where parameters f_0 and Δf are the central frequency and bandwidth of the filter, respectively, and T_{d1} and Q_e are the extracted group delay and external quality factor of the three modes, respectively. FBW is the 3 dB fractional bandwidth, and f_i is the resonant frequency of the ith resonator.

The application of the synthesis technique with these specifications yields the following coupling matrix:

$$M = \begin{bmatrix} 0 & -0.638 & -0.359 & -0.435 & -0.03 \\ -0.638 & 0.205 & 0 & 0 & -0.638 \\ 0.349 & 0 & 1.148 & 0 & 0.359 \\ -0.7 & 0 & 0 & -1.124 & 0.435 \\ -0.03 & -0.638 & 0.359 & 0.435 & 0 \end{bmatrix}$$

Figure 4 provides comparisons of the synthesized response based on this coupling matrix and the EM

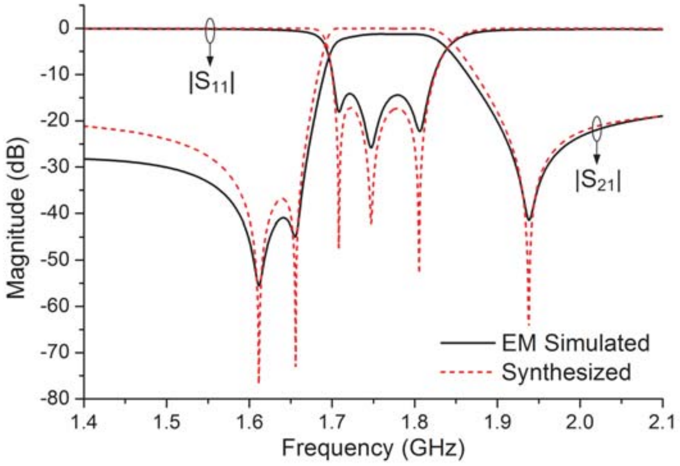


Figure 4. Comparisons of EM simulated response (solid line) and synthesized (dashed line) response of the proposed triple-mode BPF.

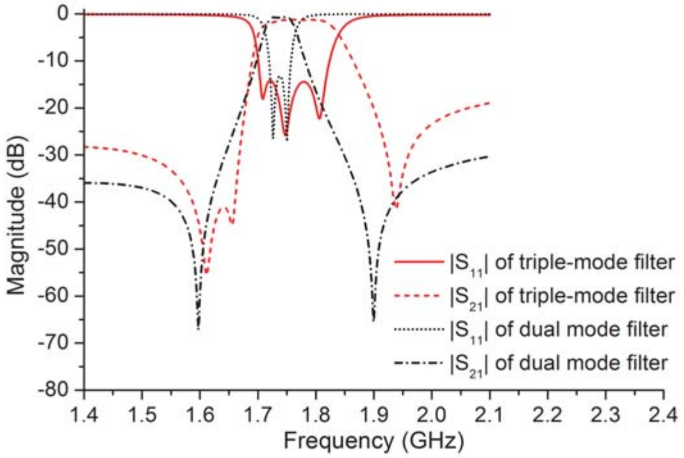


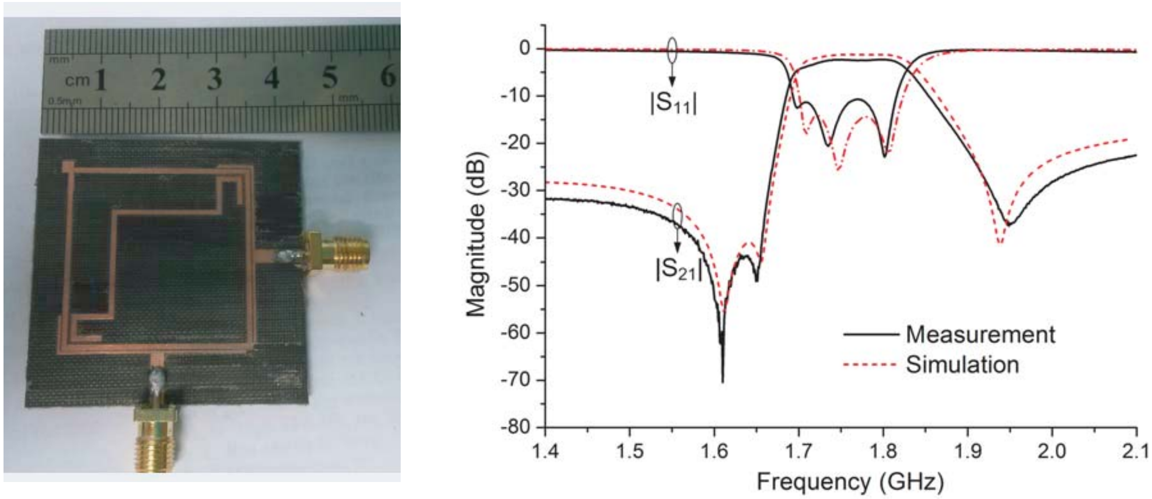
Figure 5. Comparisons of simulated response of the proposed triple-mode filter and the traditional dual-mode filter with the same perturbation p.

simulated response (using commercial MoM simulator SONNET) of the proposed triple-mode BPF. A good agreement between the two results is achieved.

Comparisons of simulated response of the proposed triple-mode filter and the traditional dual-mode filter with the same perturbation p are depicted in Figure 5. It is clearly seen that a pole in the passband and a transmission zero in the stopband are added in the proposed triple-mode filter. Furthermore, compared to traditional dual-mode filter, higher frequency selectivity and wider bandwidth are achieved.

4. RESULTS AND DISCUSSION

Based on the above analysis, the proposed triple-mode BPF was designed and fabricated on a substrate 0.8 mm in thickness with a relative dielectric constant of 2.55 in Figure 6(a). The overall size for the proposed BPF is about $44 \times 44\,\text{mm}^2$ ($0.32\lambda_g \times 0.32\lambda_g$, λ_g is the guided wavelength). The other physical parameters are optimized as follows: $W1 = 0.8$ mm, $W2 = 0.4$ mm, $S1 = 0.22$ mm, $S2 = 0.5$ mm, $P = 1.92$ mm, $L1 = 14$ mm, $L2 = 23.6$ mm, $L3 = 31.2$ mm, $L4 = 5.2$ mm, $L5 = 4.4$ mm, $L6 = 6.6$ mm. Simulated and measured frequency responses are compared in Figure 6(b). Results show that the proposed filter has a fractional bandwidth of 7.97% at central frequency of 1.76 GHz, and its insertion loss in passband is less than 2.5 dB. There are three transmission zeros on the sides of the passband. Rejection levels are −70.4, −49 and −37.5 dB at frequencies of 1.61, 1.66 and 1.94 GHz, respectively. They are close to the passband edges and can greatly improve the selectivity. Measured results agree well



(a) (b)

Figure 6. (a) Photograph of the proposed filter. (b) Measured and simulated response of the proposed filter.

Table 1. Comparisons the proposed filter with several reported square-loop multimode filers.

Ref.	Substrare Height/ε_r	3 dB FBW	Center Frequency	Number of Modes	Insertion Loss	Return Loss	Size ($\lambda_g * \lambda_g$)
[2]	1.27 mm/10.8	2.3%	1.6 GHz	2	3.1 dB	17 dB	0.3 × 0.3
[4]	4.5 mm/10.8	4.6%	1.3 GHz	2	2 dB	15 dB	0.22 × 0.22
[7]	0.83 mm/3.38	6%	5 GHz	3	2.2 dB	10 dB	0.32 × 0.32
[13]	0.8 mm/2.55	5%	1.8 GHz	4	2.2 dB	10 dB	0.32 × 0.32
This work	**0.8 mm/2.55**	**7.97%**	**1.8 GHz**	**3**	**2.5 dB**	**12 dB**	**0.32 × 0.32**

with the simulated ones and prove the validity of the introduced design principles. Some discrepancy can be attributed to the inaccuracy in fabrication and implementation. Finally, Table 1 compares the proposed filter with several reported square-loop multimode filers, where it illustrates the merits of this work about good passband performance and wide bandwidth.

5. CONCLUSION

A novel triple-mode bandpass filter using half-wavelength resonator-coupled square-loop resonator is proposed. The half-wavelength resonator is coupled to the opposite corners of the square loop so that an additional path is added. Compared to the conventional dual-mode filter, higher frequency selectivity and wider bandwidth are achieved. Finally, it is compact and easy to fabricate. Good agreement between the simulated and measured results demonstrates the validity of the proposed filter design.

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