Compact Bandpass Filters Using Folded Quad-Mode Stub-Loaded Loop Resonators

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Abstract **─** Folded quad-mode stub-loaded loop resonators (QMSLLRs) are proposed for realizing both bandpass and dual-band bandpass filters with compact dimensions. The QMSLLR is a folded square loop loaded with four short stubs, providing structure symmetry in both transversal and longitudinal directions. Determined by the lengths of the loaded stubs, the four resonant frequencies as analyzed with even-odd mode method can be either distributed in one passband with equal space, or in two passbands with a guard band in between, for realizing a single-band bandpass filter or a dual-band bandpass filter, respectively. For both the input and output couplings, two perpendicular feeding lines are parallel coupled to the QMSLLR at one corner. The measure results prove that the structure is suitable for the design of a medium band or even narrow band bandpass filters with compact dimensions.

Index Terms **─** Dual-band bandpass filter, Quad-mode Stub-loaded Loop Resonator (QMSLLR), single-band bandpass filter.

I. INTRODUCTION

With the development of wireless communication systems, filters with better frequency selectivity, low insertion loss and compact size have attracted much research attention. The multi-mode resonator in microstrip form can bring good features like compact dimensions and higher out-of-band rejections [1-7]. Dual-mode loop resonator [1], stub-loaded T-shaped resonator [2], and triple-mode stub-loaded resonator [3] have been applied for realizing compact microstrip filters, but the out-of-band rejection are limited, as the filter orders are low. In [4-7], stepped-impedance multi-mode resonators and stub loaded multimode resonator were proposed for realizing UWB filter with compact dimensions, however it is not suitable for the design filter with medium or narrow bandwidth, because the modes are distributed in an ultra-wideband range. In [8] an inner and an outer dual-mode square loops are used for generating two passbands using corner dispersion coupling elements. To increase filter order, resonators realized with a DGS structure can be used for 4th order filter design [9]. In [10] and [11], quad-mode resonators with three loaded stubs are used to realize dual-band bandpass filters by allocating the 4 resonances into two passbands. Coupled-line Quad-mode resonators can also be used for dual-band bandpass filter realization in similar way [12].

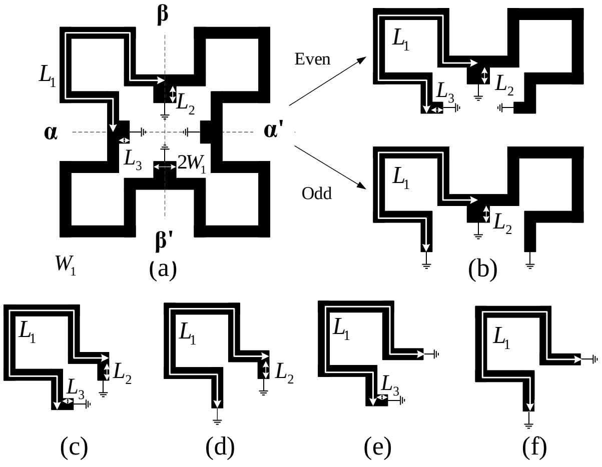

Fig. 1. QMSLLR and equivalent circuits of the resonant modes. (a) The circuit of QMSLLR; (b) even- and odd mode circuits; (c) even-even mode; (d) odd-even mode; (e) even-odd mode; (f) odd-odd mode.

In this paper, quad-mode folded stub-loaded loop resonators are proposed for realizing compact single-band and dual-band bandpass filters with medium bandwidths, taking the advantages that the resonances can be allocated to required frequency ranges. By folding the loop resonators, the dimensions can be further reduced.

II. QUAD-MODE RESONATOR

Figure 1 (a) shows the circuit of the proposed QMSLLR, which is basically a symmetric square loop with four short stubs loaded to the edge centers. Considering that the structure is symmetric in both

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transversal and longitudinal directions, four different modes can be obtained, called as even-even, odd-even, even-odd and odd-odd modes, with the circuits shown in Figs. 1 (c-f). All the four equivalent circuits are half wavelength resonators which are short-circuited at two ends, with different total lengths. By changing the values of L_1, L_2 and L_3, the distribution of the four resonant frequencies can be arranged as needed.

The formulas for calculating the four resonant frequencies can be written as:

$$f_{ee} = \frac{c}{2\sqrt{\varepsilon_{eff}}\,(L_1 + L_2 + L_3)}\ , \tag{1}$$

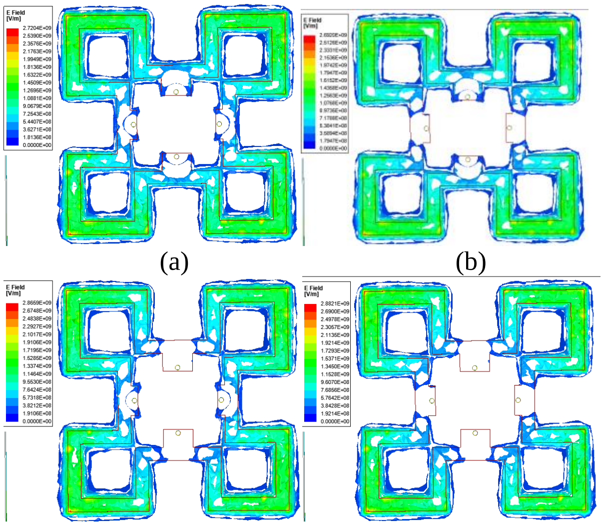
$$f_{oe} = \frac{c}{2\sqrt{\varepsilon_{eff}}\,(L_1 + L_2)}\ , \tag{2}$$

$$f_{eo} = \frac{c}{2\sqrt{\varepsilon_{eff}}\,(L_1 + L_3)}\ , \tag{3}$$

$$f_{oo} = \frac{c}{2\sqrt{\varepsilon_{eff}}\,L_1}\ , \tag{4}$$

Assuming the length of L_2 is larger than L_3, the order of the four resonant frequencies can be given as:

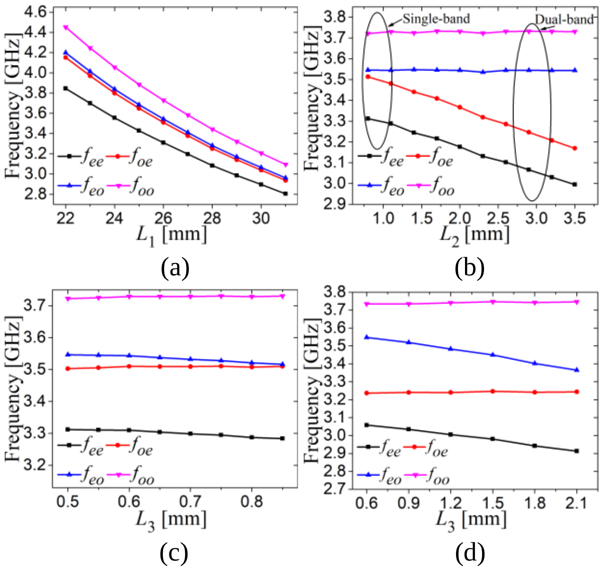
$$f_{ee} < f_{oe} < f_{eo} < f_{oo}. \tag{5}$$


(a) (b)

(c) (d)

Fig. 2. Electric field distributions of the resonating modes: (a) Even-even mode; (b) odd-even mode; (c) even-odd mode; (d) odd-odd mode.

Figure 2 shows the electric field distributions of the four resonant modes. In every mode, each quarter (a corner) of the QMSLLR has a field distribution as a half-wavelength resonator shorted at two ends, that, strong electric field can be found in the middle part and weak field is close to the shorted stubs. The electric field reaches zero at the grounding via holes and the odd-symmetric planes that are regarded as perfect electric planes. The results are achieved by using eigen-mode solver of ANSYS HFSS [13], which can find the resonant frequencies and fields of a given resonator structure in iterative passes. The simulation of the proposed quad-mode resonator can be finished in several minutes using a common laptop.



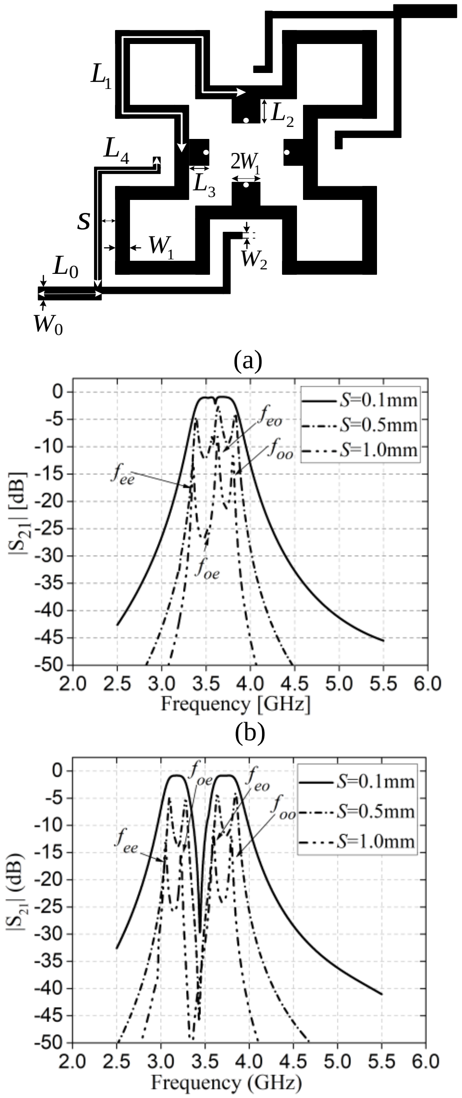
(a) (b)

(c) (d)

Fig. 3. Mode charts of the quad-mode resonator. (a) With varied L_1; (b) with varied L_2; (c) with varied L_3 (L_2 is larger than but close to L_3); (d) with varied L_3 (L_2 is much larger than L_3).

Figure 3 shows how the resonant frequencies vary with the parameters L_1, L_2 and L_3. When L_1 is increasing, all the four modes go lower, without changing the sequence, as shown in Fig. 3 (a). By varying L_2, f_{ee} and f_{oe} can be changed significantly, while f_{eo} and f_{oo} keep unchanged. Varying L_3 can change the frequency spaces between f_{ee} and f_{oe}, and between f_{eo} and f_{oo} as well. The observation tells that, by varying L_2 and L_3, the four modes can be arranged in one passband, or be divided into two passbands, and accordingly, single-band or dual-band bandpass filters can be realized respectively.

For quad-mode single-band bandpass filters design, the four resonances should be equally spaced within a specified passband, and the length L_2 should be about twice of L_3, according to Eqs. (1-4). In practical design, the resonances are also affected by the dimensions of the grounding via holes and by the loading effects of the input/output couplings, thus some tuning of L_2 and L_3 is needed. Proper input/output couplings as shown in Fig. 4 (a) are applied at the two corners of the QMSLLR, and each of them contains two perpendicular branches, which are parallel coupled to the edges of the QMSLLR. When the space S is decreased from 1mm to 0.1mm, the input/output couplings are enhanced, and the passband becomes much flatter, as shown in Fig. 4 (b). Increasing length L_4 in some extend can also introduce tighter input/output couplings.



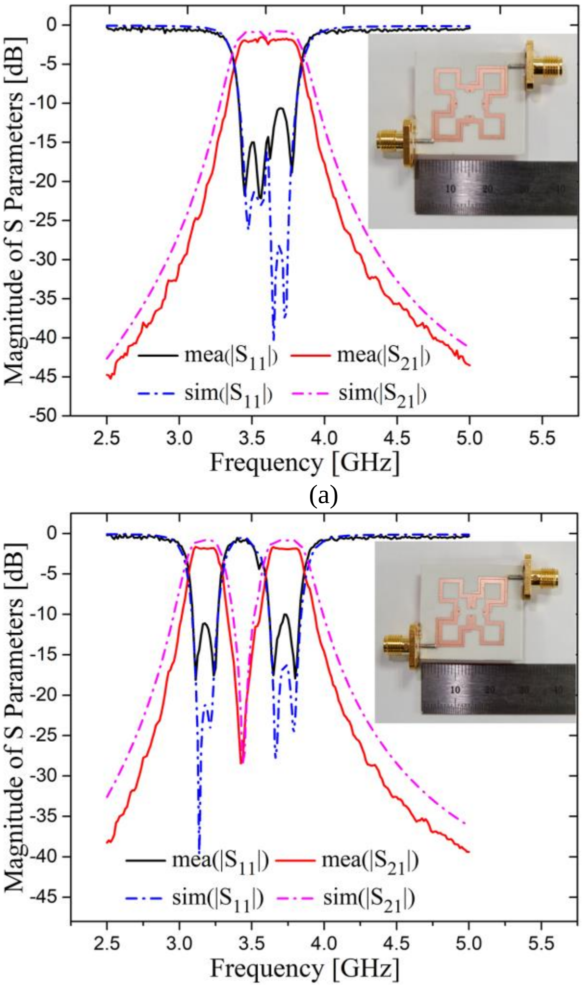
(c)

Fig. 4. Filter structure and simulated S parameters of the single- and dual-band filters: (a) the structure of the filter; (b) single-band bandpass filter; (c) dual-band bandpass filter.

For designing dual-band bandpass filters, the four resonances should be allocated into the upper passband (f_{eo} and f_{oo}) and the lower passband (f_{ee} and f_{oe}) with certain guard band in between. With this consideration, L_2 should be much larger than L_3, according to the equations, and the length L_3 determines the two bandwidths. Similar input/output coupling schemes as single-band filters can be applied, and we can observe the simulation results in Fig. 4 (c), that, by decreasing S from 1 mm to 0.1 mm, the input/output couplings are enhanced, generating two flat passbands. All the simulated results of the filters are achieved by using driven-modal solver of ANSYS HFSS [13], which is a frequency domain solver based on highly accurate finite element method (FEM), and suitable for calculating S parameters of passive components.

III. FILTER IMPLEMENTATION AND RESULTS

Based on the filter topology of Fig. 4 (a) and the design concepts, a single-band bandpass filter and a dual-band bandpass filter are designed using the QMSLLR, and both of the filters are implemented on a substrate with a dielectric constant of 3.55 and a thickness of 0.508mm, the diameters of the grounding vias are 0.4mm.



(b)

Fig. 5. Responses and photographs of proposed filters. (a) Single-band bandpass filter (L_0=4.1, W_0=1.1, L_1=26, W_1=1.1, L_2=0.84, W_2=0.6, L_3=0.6, L_4=13, S=0.1), (b) dual-band filter (L_0=4.1, W_0=1.1, L_1=26, W_1=1.1, L_2=3, W_2=0.6, L_3=0.6, L_4=13, S=0.1, all are in mm).

Figure 5 gives the simulation and measured S parameter results of the single-band filter and dual-band filter. Figure 5 (a) shows results of a single-band filter based on the QMSLLRs. The center frequency of passband is 3.6GHz and the fractional bandwidth is 12.4%. The insertion loss and return loss of the passband are 2.4dB and 10dB, respectively. Four transmission poles introduced by the four resonant modes can be clearly observed from the S_{11} plot. The results of the dual-band filter are shown in Fig. 5 (b), it has center frequencies of 3.18GHz and 3.73GHz, respectively. The 3dB fractional bandwidths are 6.9% and 7.2%, while the measured maximum insertion losses are 1.8dB and 2.0dB, and the measured return losses are better than 11dB and 10dB across the passbands. An isolation larger than 30dB is achieved between the two passbands.

The measured results agree well with the simulation results, and the small differences in return loss and insertion loss are mainly incurred by fabrication tolerances. The two filters are compact with dimensions of 27mm×27mm. ($0.3\lambda_g \times 0.3\lambda_g$, λ_g is the guided wavelength). Table 1 and Table 2 compare the performances of the designed filters and some published works.

Table 1: Comparison of the quad-mode single-passband filter with previous works

	FB (%)	Size ($\lambda_g \times \lambda_g$)	IL (dB)	RL (dB)
Ref. [3]	27	0.19×0.12	0.7	18
Ref. [8]	5.5	0.32×0.32	2.2	>10
Ref. [9]	32	N/A	1.98	>12
This work	12.4	0.3×0.3	2.3	>10

Table 2: Comparison of the proposed dual-mode dual-passband filter with previous works

	FB (%)	Size ($\lambda_g \times \lambda_g$)	IL (dB)	RL (dB)
Ref. [10]	14/10	0.15×0.12	0.8/0.9	25/20
Ref. [11]	3/9	0.3×0.11	1.5/0.9	15/13
Ref. [12]	9/8.5	0.09×0.12	1.3/2.4	17.5/23
This work	7/7.2	0.3×0.3	1.8/2	11/10

FB: Fractional bandwidth; IL: Insertion loss; RL: Return loss.

IV. CONCLUSION

A novel compact quad-mode resonator is proposed to design single-band and dual-band bandpass filters. The methods of controlling the resonant frequencies are described, enabling to design filters with single-passband and dual-passband responses with specified bandwidths. These filters are simple in circuit and compact in dimensions, and the center frequencies are easy to be controlled. Unlike multi-mode resonator filters with wide passbands, this technique is suitable for the design of filters with medium and narrow bandwidths.

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