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A Compact Independent Triple-band Bandpass Filter Using Mode Splitting

Dwi Astuti Cahyasiwi, *Member, IEEE*, Rahmat Alamsyah, Dian Widi Astuti, *Member, IEEE*, and Galih Adhi Yoga *Member, IEEE*

***Abstract*— In this paper, a compact tri-band bandpass filter (TBPF) is proposed. The proposed TBPF employs a multi-coupled-line structure to achieve an independence between the inter-passbands. In addition, the triple-band bandpass characteristics are generated separately and independently using two pairs of quarter-wavelength resonators with L- and U-shaped configurations. The two pair of resonators were set back-to-back creates a second order filter and coupling to the stub transmission lines. The pairs of U resonators create mode splitting results two resonances frequency at 1.87 GHz and 5.82 GHz while two pairs of L resonator create bandpass with a wide -3 dB bandwidth of 21.6% at 3.35 GHz centre frequency. The two of three passband frequencies can be set and designed independently. Consequently, the proposed TBPF achieves a 46.4% size reduction compared to the previously reported TBPF. To assess and validate its performance, the circuit was fabricated and experimentally characterized. The measured results are in close agreement with the simulations. Overall, the proposed TBPF exhibits compact dimensions and independently controlled inter-passband characteristics.**

***Index Terms*—A quarter wavelength resonator, mode splitting resonator, size reduction, triple bandpass filter.**

I. Introduction

The rapid expansion of modern wireless systems demands filters capable of simultaneously operating at multiple frequency bands to support diverse standards such as 5G, WLAN, and satellite communication. A tri-band bandpass filter (TBPF) offers a compact and efficient solution by integrating three distinct passbands into a single device, reducing circuit complexity and hardware footprint. This approach is particularly beneficial for portable and IoT devices, where space and power consumption are critical constraints. Moreover, tri-band BPFs enhance system performance by providing sharp selectivity and reduced interference across multiple services. Recent works highlight various design techniques, such as multi-mode resonators, coupled-line structures, and cavities resonators, to achieve compact tri-band filters for next-generation communication systems [1], [2], [3], [4], [5], [6], [7], [8].

Recent advances in multiband filtering have demonstrated that triband bandpass filters can be realized by employing triple-mode metal block resonators [9], in-line topologies based on star-like substrate integrated waveguide (SIW) resonators [6], and dual stepped-impedance resonators (SIRs) incorporating multiple open- and short-circuited stubs [2]. Another approach is the switchable microstrip BPF presented in [5], which achieves broadband, dual-band, and tri-band operations by controlling RF p-i-n diodes; however, the design lacks compactness since it employs six half-wavelength resonators, and neither the physical size nor the number of resonators is reduced by any miniaturization technique. The miniaturization is realized by reducing the effective cavity volume using quarter-mode SIW partitioning, while still employing three resonators, each corresponding to one of the passbands[7]. Multimode resonator consists of a half-wavelength resonator and a dual-mode stub loaded resonator were arranged to obtain multiband bandpass filter [10]. While in [4], TBPF was design using folded half wavelength resonator and step impedance resonator, though claim to have a compact design, using three pair resonators to induce three passband was not actually compact.

One of the simplest approaches to achieve a compact triple-band bandpass filter structure is to reduce the electrical length of the resonator and minimize the number of resonating elements. In [11], [12], [13] mode-splitting techniques were investigated to realize dual-mode resonators by introducing perturbations into symmetric structures, thereby eliminating the need for additional resonating elements to generate extra modes.

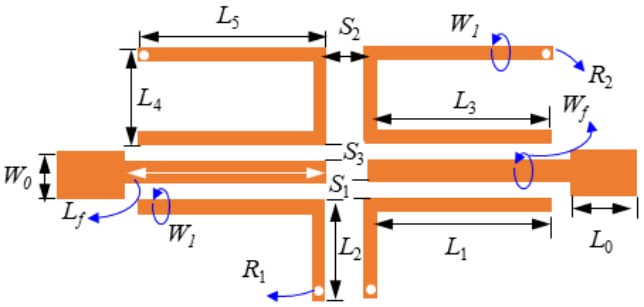


Fig. 1 Geometric structure of the triband bandpass filter

The authors would like to thank Research Center for Telecommunication, National Research and Innovation Agency for providing CST software.

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TABLE I
THE DIMENSION OF THE TBPF (UNIT IN MM)

L_0	L_f	$L1$	$L2$	$L3$	$L4$	$L5$	$S1$
7	2	11.5	6.5	12.5	8.5	12.5	0.5
$S2$=$S3$	W_0	W_f	W_1	W_2	W_3	W_4	W_5
0.5	4.86	2.86	1	1	1	1	1

Motivated by mode splitting techniques, in this work, a compact TBPF is realized using quarter-wavelength resonators with only two resonators. The L-shaped resonators with via holes, generate the middle passband, and U-shaped resonators with via holes, govern the other two bands. This work introduces a compact tri-band filter using two pairs of quarter-wavelength resonators. The key novelty lies in employing via-loaded U-shaped resonators to induce mode splitting, thereby generating two passbands from a single resonator pair, while the via-loaded L-shaped resonators independently realize the middle band. This configuration enables inter-passband independence and significantly reduces the physical size.

II. DESIGN METHOD

The geometry design of the structure is shown in Fig. 1 where the TBPF consists of two pairs of quarter wavelength resonators L and U resonators with a via through hole at the end of the arm resonator. The pairs of the resonator are set back-to-back creating a second order filter. Both resonators are feed with the stub feedline and the stub from the first port is coupled to the stub at the second port. The L-shaped resonator with length L_1 and L_2 defined the resonance frequency and coupling between the resonators, the via through hole at the arm of the resonator increased the electromagnetic coupling thus decreased the quality factor that make the improvement of bandwidth impedance. The U-shaped resonators with a via trough hole that are also a quarter wavelength resonator are set back-to-back symmetrically. This shaped is meant to create a mode splitting in the resonators. All the dimension of TBPF is shown in Table I. The wavelength of the microstrip line can be determined using the following expression,

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon r_{eff}}} \quad (1)$$

The diagram in Fig. 2(a) shows two port P_{in} and P_{out} connected trough a coupled stub. At the lower part of the coupled stub a pair of L-shaped resonators R_1 and R_2 with (red) is set back-to-back. At the upper part of the stub two U-shaped resonators R_3 and R_4 (blue) is also set back-to-back. Each resonator is loaded with a via-through hole, which converts it into a quarter-wavelength resonator (instead of a half- wavelength), reducing physical size. The combination of L and U resonators provides different resonant paths, each tuned to generate a distinct passband. Because the resonators are coupled to each other and to the feedline, their modes interact and split, producing three passbands. Fig. 2(b) shows the equivalent coupling scheme describing how the resonators interact where X and Y are the input and output coupling nodes. R_1 and R_2 (red) couple to input/output with couplings M_{11}, M_{12}, M_{22}. R_3 and R_4 couple

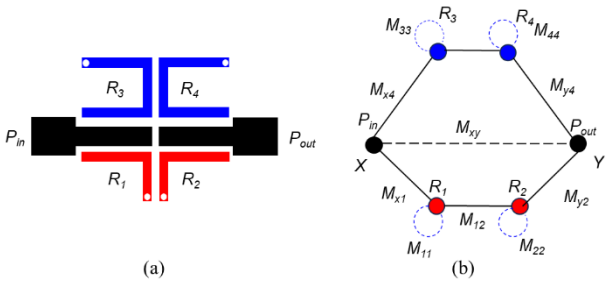


Fig. 2 (a) Physical Structure and (b) coupling topology of TBPF

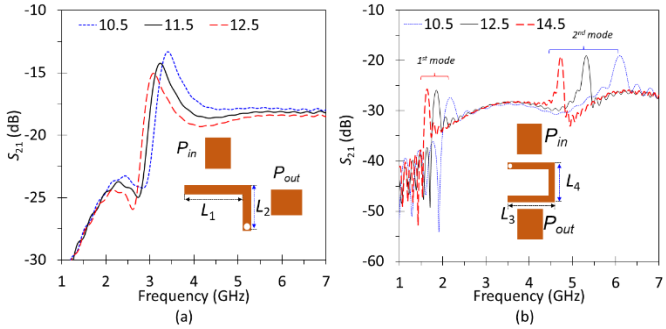


Fig. 3. The S_{21} responses over the frequency of the (a) L-shaped resonator with L_2 = 6.5 and various L_1 values and (b) U-shaped resonator with dual mode frequency under various L_3 with L_4 = 8.5. All unit in dimension in mm

with terms M_{33}, M_{44}. Cross-couplings M_{x1}, M_{y2}, M_{x4}, M_{y4}, are the port-to-resonator couplings that set external quality factor and bandwidth of each passband, while Mxy represent interactions source–load (port-to-port) cross-coupling. The cross-coupling coefficients and external quality factors are calculated for a second-order filter with a 0.1 dB ripple. The coupling matrix $M_{i,j}$ can be expressed as:

$$M_{i,j} = \begin{bmatrix} 0 & 0 & 0 & 0.299 & 0 & 0 \\ 0 & 0 & 0{,}0802 & 0 & 0 & 0 \\ 0 & 0{,}0802 & 0 & 0 & 0 & 0 \\ 0.299 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0{,}0497 \\ 0 & 0 & 0 & 0 & 0{,}0497 & 0 \end{bmatrix}.$$

The U-shaped resonator yields two cross-coupling coefficients and two external quality factors corresponding to its two resonant modes.

III. RESULTS AND DISCUSSION

In this work, a triple-band bandpass filter is implemented on a Rogers RT/Duroid 5880 substrate with a thickness of 1.575 mm, a dielectric constant of 2.2, and a loss tangent of 0.0009. The dimensions of both the U-shaped and L-shaped resonators are initially estimated using (1). Full-wave electromagnetic simulations are carried out using CST Microwave Studio. To achieve the second-band center frequency of 3.25 GHz, the length L_1 of the L-shaped resonator is adjusted, as illustrated in Fig. 3(a). The remaining two target frequencies, 1.8 GHz for the first band and 5.8 GHz for the third band are realized using the first and second resonant modes of the U-shaped resonator, respectively.

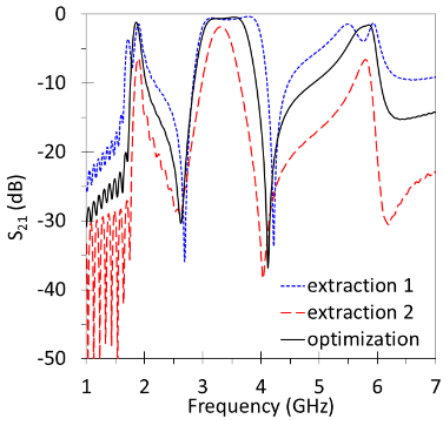


Fig. 4 Comparison of the initial design based on extraction 1, extraction 2 and the optimized design

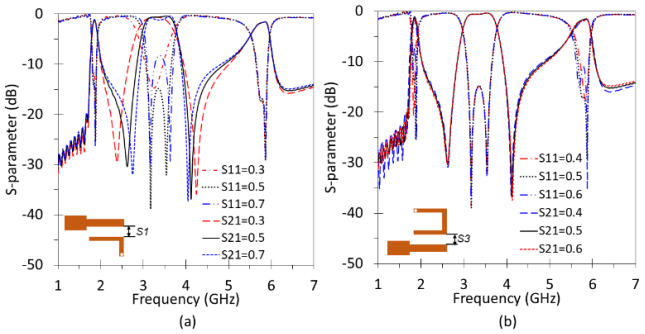


Fig. 5 Independently controlled features of the (a) second band (b) first band and third band variation of gap S_1 and S_3.

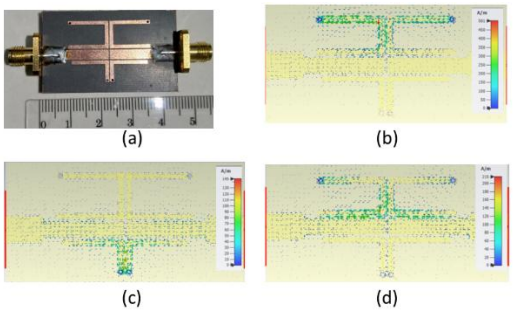


Fig. 6 (a) The fabricated and the surface current at (b) 1.87 GHz, (c) 3.25 GHz and (d) 5.87 GHz of TBPF

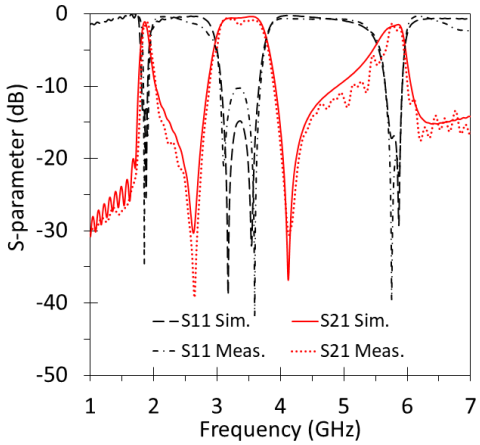


Fig. 7 The measurement and simulation result of TBPF

The variation of L_3 controls the resonant frequencies of these two modes, as shown in Fig. 3(b). Based on the required coupling coefficients and external quality factors, the gap between the L-shaped and U-shaped resonators (S_2) as well as the gaps between the resonators and the coupled stub (S_1 and S_3) are determined. A trade-off exists between the extraction of the first and third bands in order to achieve an optimized overall response, as depicted in Fig. 4. Extraction 1 represents the filter performance based on the coupling coefficient of the first mode, whereas Extraction 2 corresponds to the coupling condition of the second mode. Fig. 5(a) shows that the gap between the stub and the L resonator (S_1) controls the transmission of the band 2 (middle band), while the gap between the stub and the U resonator (S_3) governs the selectivity of the lower and upper bands as shown in Fig. 5(b), allowing independent tuning of the triple-band filter response.

Fig. 6(a) shows the fabricated design and the surface current at each bandpass where the lower and higher frequency are obtained from the U resonators. The electrical length of the first band flows along the smooth U resonator as shown in Fig. 6(b). The L- shaped resonator's surface current flow from the open circuit to the via

TABLE II
THE COMPARISON WITH THE PREVIOUS WORKS

Refs.	Freq (GHz)	Dimension in λ_g^3	−3 dB BW (%)	Insertion Loss (dB)	Method	Independent
[1]	2.90/5.60/11.00	0.0167	45.80/17.80/6.40	3, 3.1, 5.2	multi-mode spoof surface plasmon polaritons	Yes
[2]	2.20/ 7.90/14.10	0.0003	42.06/ 63.80/ 27.96	0.71, 0.87, 0.76	dual-step impedance resonator	No
[4]	1.75/2.55/ 3.55	0.0021	21.20/4.70/8.40	0.57, 1.36, 1.37	multi-coupled line stub-SIR	Yes
[8]	2.24/2.94/3.52	0.0048	2.70/4.80/1.70	0.49/0.36/0.73	dielectric waveguide	Yes
[9]	1.85/3.15/4.45	0.0167	5.40/3.10/2.24	0.40/0.35/1.00	metal block resonators	No
[14]	2.14/4.33	0,0003	6.72/5.45	0.8/1.3	dual-mode step impedance resonator	Yes
This work	1.87/3.25/5.87	0.0009	5.81/21.60/3.60	1.23/0.95/1.39	mode splitting	Yes

through hole as seen in Fig. 6(c) creates the middle band frequency. Meanwhile at the higher-order mode of U-shaped resonator, the structure splits into multiple effective resonant paths, near the short circuit arm and along the below couple arm and vertical side so the current looks fragmented or perturbed as shown in Fig. 6(d). The U-shaped resonator supports two symmetric current paths that naturally can oscillate at the same frequency. The introduction of a short-circuited stub imposes an inductive perturbation that disturbs this symmetry, as a result, revealing a second resonant mode [11], [12], [13]. Unlike U-shaped resonator, the split mode did not happen in the L-shaped resonator because the current flow smoothly along the electrical length at 1.87 GHz without any disturbance.

Fig. 7 presents the simulated and measured S-parameter responses of the proposed triband bandpass filter. The simulated results show three distinct passbands with insertion losses better than 1.39 dB at the resonant frequencies of 1.87, 3.25 and 5.87 GHz, accompanied by −3 dB FBWs of 5.81%, 21.60%, and 3.60%, respectively. The measured data exhibit good agreement with the simulations, with slight S_{21} ripple at the upper band attributed to discontinuities at connector launches, solder pads, or feedline transitions. Overall, the measured results validate the effectiveness of the design and confirm its suitability for compact multiband wireless applications.

TABLE II compares the proposed design with recently reported triple-band bandpass and dual-band bandpass filters in terms of operating frequencies, normalized dimensions, bandwidths, insertion losses, and design methods. Unlike several references that lack independent tuning [2], [9], and high profile [1], the proposed filter achieves independent passband control with a compact size of only 0.0009 λg^3, while maintaining competitive bandwidth and insertion loss. Furthermore, although [14] claims the use of a dual-mode step-impedance resonator, the reported filter employs two separate resonators to realize the dual-band bandpass response.

IV. CONCLUSION

In this paper, this paper describes the successful design and implementation of an independent and compact triple-band bandpass filter based on multi-coupled lines with a folded structure and via through hole addition. Triple-band bandpass filters are built with multi-coupled lines to produce independent inter-passbands. Additionally, triple-band bandpass filter performance is produced separately and independently using two sets of resonators. To miniature triple-band bandpass filter, a folded structure is also proposed. As a result, the proposed triple-band bandpass filter is very compact and reduces the size by 46.4%. The simulated and measured results of the triple-band bandpass filter show good agreement. Finally, our proposed triple-band bandpass filter structure has an independent inter-passband response and compact size.

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