

Asymmetric Grounded Stub-Loaded Resonator and Its Application in Tri-Band Filter Design

Slobodan Birgermajer¹, Nikolina Janković², Vesna Crnojević-Bengin³

Abstract – A novel tri-mode asymmetric resonator that consists of a single-mode and a dual-mode resonator is presented. A detailed description and analysis of its behaviour is given and an analytical procedure for resonance positioning is provided. Using the proposed resonator two tri-band bandpass filters that operate at 2.4/3.5/5.2 and 1.8/2.4/3.5 GHz have been designed, fabricated and measured. The filters have good in-band and out-of-band characteristics as well as compact dimensions of only $0.24\lambda_g \times 0.115\lambda_g$ and $0.163\lambda_g \times 0.154\lambda_g$.

Keywords – Tri-band filter, tri-mode resonator, microstrip filters.

I. INTRODUCTION

An unprecedented growth of communication systems in last decade has brought about a great demand for low-cost, high-performance and compact passive devices. At the same time, devices are required to simultaneously operate at several non-harmonically related frequencies due to less and less available spectrum, i.e. multi-band devices. In order to incorporate multi-band requirements in single communication devices, miniature multi-band circuits are greatly needed. Beside simultaneous operation at several non-harmonically related frequencies, there is a need for narrow bandwidth, small insertion losses, high return losses, good quality factor, and good selectivity, which may be difficult to achieve if the design also requires a compact size.

Therefore, a considerable attention has recently been paid to the design of tri-band filters. Broadly speaking, there are four different methods of the design of tri-band filters, each of which can be divided into subgroups.

The first approach is based on classical filter design theory and synthesis of coupling matrices. Since the theory has been widely investigated and applied in single-band filter circuits, it has also been applied in multi-band filter design. So far, several classical-theory-based methods for multi-band filter design have been proposed.

Synthesis techniques applicable to all filter topologies which, at the same time, allow asymmetric passbands was proposed in [1]. The first analytical procedure for synthesizing both symmetric and asymmetric multi-band frequency responses including any number of passbands and stopbands was presented in [2-3]. Although being straightforward and efficient, the proposed methods have several drawbacks. Namely, the methods require optimization techniques in coupling matrix synthesis which reduce their efficiency whilst filtering circuits have large dimensions and passbands cannot be independently controlled.

The second approach to the tri-band filter design relies on introduction of transmission zeros in a single-band filter response and its main advantage lies in its simplicity. In [4-6] tri-band filters based on this method have been proposed and conventional and stepped-impedance stubs have been used in the proposed configurations to realize transmission zeros. Although it is considered to be the simplest of all methods for multi-band filter design, this method gives filters that are characterized by large size and the fact that performances of the passbands cannot be independently controlled.

The third approach is based on multi-mode resonators – structures that simultaneously support several non-harmonically-related resonances. There are three main types of multi-mode resonators - resonators with perturbation, stepped impedance and stub-loaded resonators. Although the positions of their resonant modes cannot be independently controlled to the full extent, the third approach allows more freedom in filter design in comparison with the previous methods.

Tri-band filter presented in [7] is comprised of a ring resonator with perturbations and it employs fundamental and higher order modes of the resonator to form multi-band response. However, this configuration is limited in terms of dimensions and passband control. The filters presented in [8-11] employ stepped-impedance resonators (SIR). Since they consist of several segments that differ in characteristic impedance and length they allow a great design freedom. However, these resonators do not enable a wide range of frequency ratios of fundamental and higher order modes. Stub-loaded resonators (SLR) are characterized by the fact that frequency positions of the even resonant modes are disturbed by the stub which have been used as a mechanism for independent control of the passbands in [12-15].

The fourth method of designing tri-band filters represents combination of dual-band and single-band filters. The filters designed by this method deploy different types of resonators - conventional $\lambda/2$ and $\lambda/4$ resonators as well as more complex resonators such as SIR, SLR, and dual-mode resonators with

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perturbation [16-20]. Since this method employ several distinct filters it gives designers the most freedom together with the third method.

In this paper, we propose tri-band bandpass filters based on the third method for tri-band filter design. Namely, the filters employ novel tri-mode asymmetric resonators which consist of one single-mode and one dual-mode resonator that share a common grounding via.

In Section II, the novel tri-mode resonator is presented and a detailed description of its behaviour is given. It is shown how different geometrical parameters influence three fundamental modes and an analytical procedure for resonance positioning is provided. In Section III, two tri-band bandpass filters that operate at 2.4/3.5/5.2 and 1.8/2.4/3.5 GHz are presented. A detailed design procedure is given and filters' characteristics are compared to those of other reported tri-band bandpass filters. A conclusion is presented in Section IV.

II. RESONATOR DESIGN

The proposed tri-mode resonator is shown in Fig. 1 where the most relevant geometrical parameters are indicated: w is the width of the microstrip line, d is the diameter of the grounding via, and l_1 , l_2 , l_3 , and l_4 are the lengths of the segments of the resonator. The resonator has been designed on 1.575 mm thick Rogers RT/Duroid 5880 substrate with $\epsilon_r=2.2$ and $\tan\delta=0.0009$.

The proposed resonating structure is comprised of one single-mode and one dual-mode resonator that are connected through common grounding via positioned between the segments l_1 and l_2 . The single-mode resonator consists of the segment l_1 long which is short-circuited on its right side and it represents a conventional quarter-wavelength resonator. Therefore, it exhibits a resonance at the frequency at which its electrical length is equal to $\pi/2$.

The structure that is comprised of the segments l_2 , l_3 , and l_4 and is short-circuited on its left side is a stub-loaded quarter-wavelength resonator which exhibits dual-mode behaviour. Namely, the stub perturbs the resonances of the conventional resonator, i.e. they are not harmonically related and in that manner dual-mode behaviour is obtained.

Fig. 2 shows the response of the proposed resonator whose geometrical parameters are: $l_1 = 14.4$ mm, $l_2 = 3$ mm, $l_3 = 17.7$ mm, and $l_4 = 6.5$ mm. The first and the third resonances originate from the dual-mode resonator, whilst the second one is provided by the single-mode resonator. Since the single-mode resonator is independent from the dual-mode one its resonance does not necessarily have to be positioned between those of the dual-mode resonator.

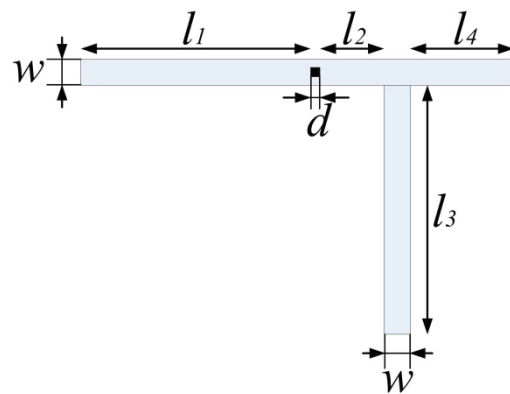


Fig. 1. The layout of the tri-mode asymmetric resonator

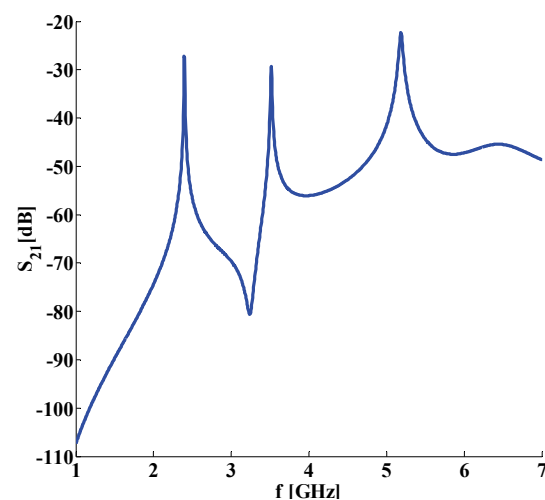


Fig. 2. The response of the tri-mode asymmetric resonator

Fig. 3 shows the current distribution in the resonator for each resonant mode. Fig. 3(b) confirms that the second resonant mode originates from the conventional quarter-wavelength resonator whose length is l_1 , i.e. that this resonance is not influenced by the dual-mode resonator.

On the other hand, the current distributions in Fig. 3(a) and Fig. 3(c) show that the first and the third resonances are not influenced by the segment l_1 long, whilst both resonances depend on the geometrical parameters l_2 , l_3 , and l_4 .

The previous statements are also proved by the responses shown in Fig. 4. It can be observed that the change of the parameter l_1 affects only the second resonance, whilst the resonances of the dual-mode resonator remains unaffected. Similarly, the parameters l_2 , l_3 , and l_4 influences both resonances of the dual-mode resonator whilst the resonance of the single-mode resonator remains unaffected.

The behaviour of the proposed resonator can also be analyzed using the input impedance of the resonator. Since the single-mode and dual-mode resonators are independent their input impedances can also be independently analyzed.

The single-mode resonator is a conventional quarter-wavelength resonator that exhibits the fundamental resonance at the frequency at which its electrical length is equal to $\pi/2$. Therefore, the analysis of its input impedance will be omitted.

Using notation from Fig. 5, the input impedance of the dual-mode resonator looking from the right end can be expressed as:

$$Z_{in2} = jZ_0 \frac{\tan \theta_2 + \tan \theta_4 (1 - \tan \theta_2 \tan \theta_3)}{1 - \tan \theta_2 (\tan \theta_3 + \tan \theta_4)} \quad (1)$$

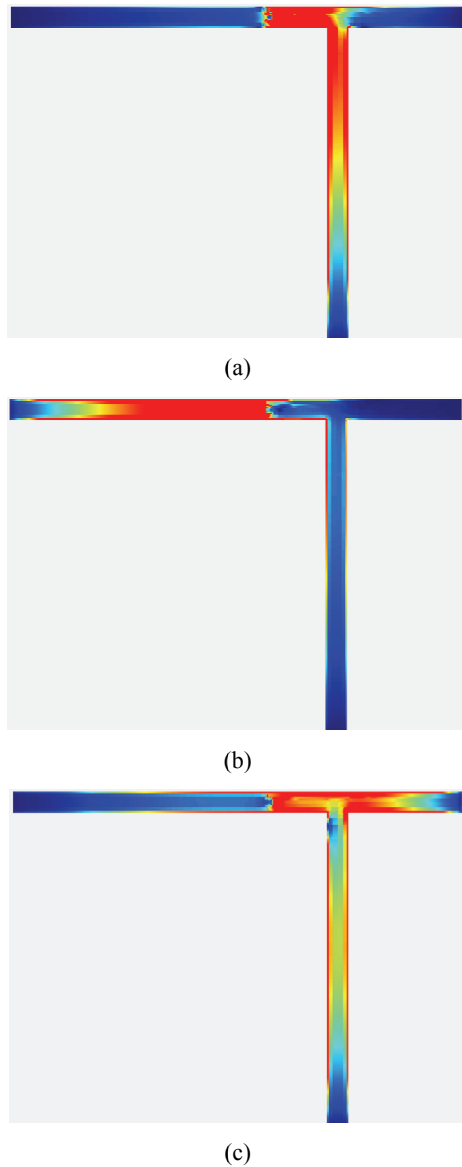


Fig. 3. Current distributions at the first (a), second (b), and third (c) resonant frequencies of proposed resonator

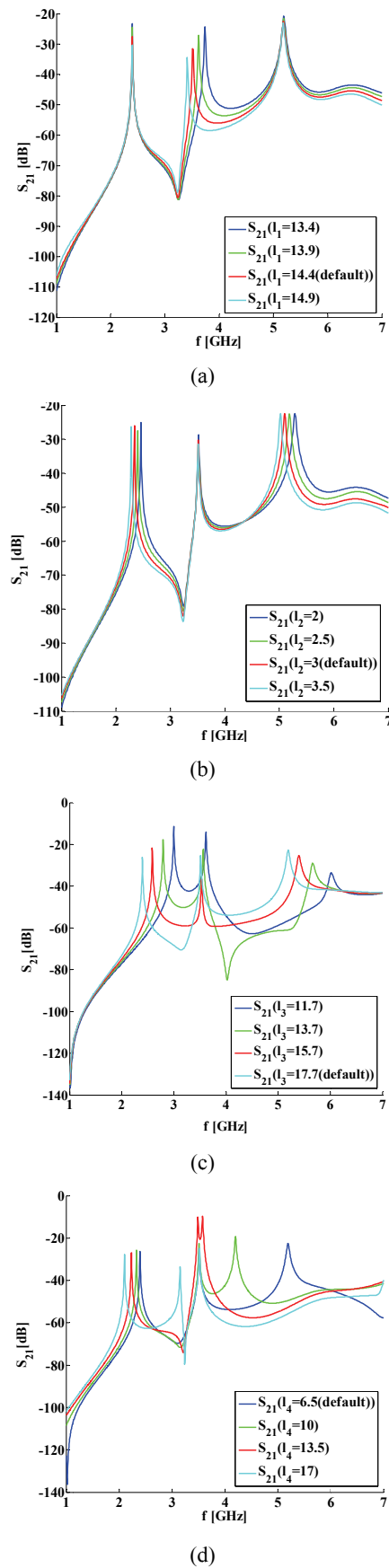


Fig. 4. The influence of the change of the segment lengths: (a) l_1 , (b) l_2 , (c) l_3 , and (d) l_4

For the sake of the simplicity the via is considered to be an ideal short circuit. The resonant condition $1/Z_{in}=0$ and (1) implies that the dual-mode resonator exhibits resonances when the following condition is satisfied:

$$1 - \tan \theta_2 (\tan \theta_3 + \tan \theta_4) = 0. \quad (2)$$

The previous equation can be rewritten in the following manner:

$$1 - \tan \theta_2 \left(\tan \frac{\theta_2}{\alpha_{23}} + \tan \frac{\theta_2}{\alpha_{24}} \right) = 0, \quad (3)$$

where

$$\alpha_{23} = \frac{\theta_2}{\theta_3}, \quad (4)$$

$$\alpha_{24} = \frac{\theta_2}{\theta_4}. \quad (5)$$

Using the electrical length ratios α_{23} and α_{24} , the ratio of the resonant frequencies of the two modes can be determined, Fig. 6. As it can be seen, the curves for different values of the parameter α_{23} have a hyperbolic shape, except for the point in which $\alpha_{23} = \alpha_{24}$ where they show extreme values.

In addition, the dual-mode resonator provides a transmission zero which occurs at the frequency at which the parameter θ_3 is equal to $\pi/2$.

III. TRI-BAND BANDPASS FILTERS BASED ON ASYMMETRIC RESONATOR

Using the proposed resonator, two tri-band bandpass filters that operate at 2.4/3.5/5.2 GHz and 1.8/2.4/3.5 GHz have been designed. The fundamental mode of the single-mode resonator is used to obtain the second passband whilst the two modes of the dual-mode resonator are used to obtain the first and the third passband of the filters.

In the case of the filter operating at 2.4/3.5/5.2 GHz, the first step in the filter design is to tune the resonance of the single-mode resonator to be positioned at 3.5 GHz. This is achieved by the proper choice of the length l_1 . In the following step, the parameters l_2 , l_3 , and l_4 need to be determined to obtain the resonances of the dual-mode resonator at 2.4 and 5.2 GHz. To that end, the ratio of the central frequencies of the first and third passbands and Fig. 6 are used.

Given that the frequency ratio is equal to 2.17 the ratios α_{23} and α_{24} are chosen to be 0.3 and 0.7, respectively. Since the stub in the dual-mode resonator provides a transmission zero when θ_3 is equal to $\pi/2$, the value of the parameter l_3 is chosen so as to obtain a transmission zero at the upper side of the first passband. Then, according to the expressions (4) and (5) the values of the parameters l_3 and l_4 are calculated.

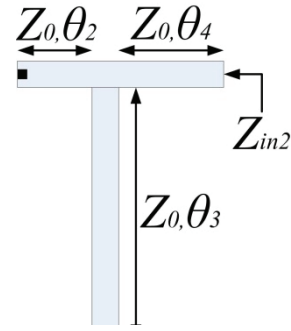


Fig. 5. Configuration of the dual-mode resonator

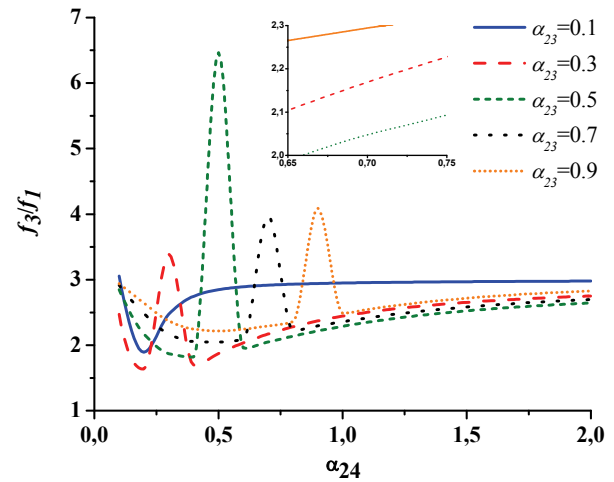


Fig. 6. Ratio of the resonant frequencies of the dual-mode resonator

Using the previous procedure the following values are obtained: $l_1 = 15.5$ mm, $l_2 = 5.1$ mm, $l_3 = 18$ mm, and $l_4 = 7.3$ mm.

Once the parameters are determined, two tri-mode resonators are coupled to form a tri-band filter. Each resonator is inductively coupled to the feed line and its segments folded to reduce the overall size of the circuit.

The layout of the final filter is shown in Fig. 7. Due to the folding of the segments, finite via impedance, limited precision of the data given in Fig. 6, and mutual influence between the single-mode and dual-mode resonators, the geometrical parameters of the filter have to be optimized to obtain passbands at the specified frequencies. Also, in order to improve characteristics of the filter tapered feeding lines are optimized.

The dimensions obtained after optimization are as follows $l_{11} = 10.5$ mm, $l_{12} = 5.9$ mm, $l_2 = 4.4$ mm, $l_{31} = 7.9$ mm, $l_{32} = 4.2$ mm, $l_{33} = 7.6$ mm, $l_{34} = 1.6$ mm, $l_{35} = 0.1$ mm and $l_4 = 5.8$ mm, $l_5 = 8.5$ mm, $l_6 = 3$ mm, $w = 1.2$ mm, $w_1 = 1$ mm, $w_2 = 4.8$ mm, $d = 0.4$ mm. The overall lengths of the folded segments of the asymmetric resonators are $l_1 = 15.2$ mm and $l_3 = 19$ mm.

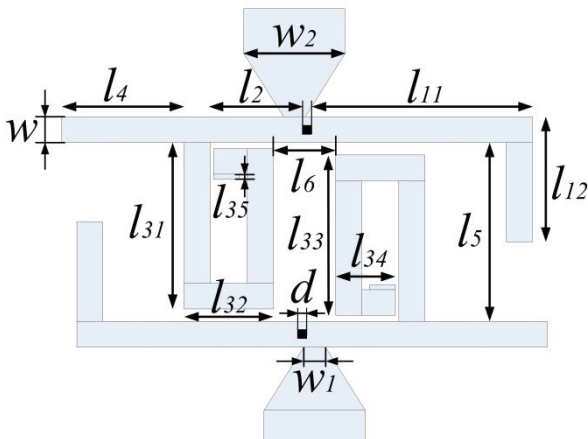


Fig. 7. Layout of the tri-band bandpass filter operating at 2.4/3.5/5.2 GHz

Fig. 8 shows the simulated response of the designed tri-band bandpass filter. It reveals that the filter exhibits three passbands with central frequencies of 2.4, 3.5, and 5.2 GHz. The insertion losses are 0.75, 0.99 and 1.02 dB, whilst 3-dB bandwidths are equal to 183, 168 and 249 MHz, respectively. Overall dimensions of the filter are 23 mm x 10.9 mm, i.e. $0.24\lambda_g \times 0.115\lambda_g$, where λ_g denotes guided wavelength at 2.4 GHz.

Beside good insertion- and return-loss characteristics, the filter shows a good selectivity provided by four transmission zeros located at 1.43, 2.66, 3.6 and 6.5 GHz. The lowest transmission zero occurs due to the presence of the vias in the structure, which act as coupled inductors, whilst the second transmission zero occurs due to the stub. As for the third and the fourth transmission zeros, they are a result of a specific position of the feeding lines with respect to the resonators. Namely, the tri-mode resonator is fed next to the position of

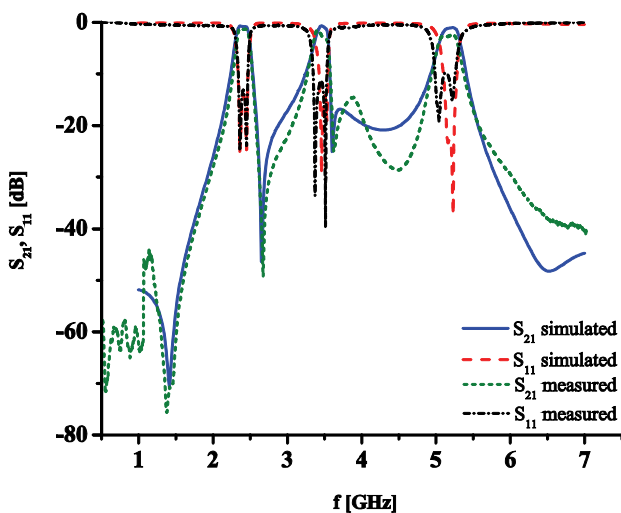


Fig. 8. Simulated and measured responses of the tri-band bandpass filter operating at 2.4/3.5/5.2 GHz

the grounding via and thus the input admittance of the tri-mode resonator Y_{in} can be obtained as a sum of input admittances of the single-mode and dual-mode resonators. When the condition $1/Y_{in}=0$ is met a transmission zero occurs.

To validate simulation results, the filter has been fabricated using a conventional PCB procedure. A photograph of the fabricated circuit is shown in Fig. 9. As can be seen from Fig. 8, the measurement results agree well with the simulated ones. The measured central frequencies are slightly shifted to 2.41 GHz, 3.45 GHz, and 5.14 GHz, while the corresponding insertion losses are 1.31 dB, 2.28 dB, and 2.67 dB. The slight shift of the central frequencies in the second and the third passband is due to fabrication tolerances of the vias.

To validate the applicability of the proposed design procedure, we have also designed a dual-band filter that operates at 1.8/2.4/3.5 GHz. The filter dimensions are as follows $l_{11} = 9.2$ mm, $l_{12} = 7.1$ mm, $l_{13} = 5$ mm, $l_{14} = 3$ mm, $l_2 = 5.4$ mm, $l_{31} = 7.2$ mm, $l_{32} = 5.6$ mm, $l_{33} = 7$ mm, $l_{34} = 4.4$ mm, $l_{35} = 1$ mm, $l_{41} = 3.6$ mm, $l_{42} = 7.7$ mm, $l_{43} = 1.1$ mm, $l_5 = 2.1$ mm.

The configuration of the filter is shown in Fig. 10 and its response in Fig. 11. The filter exhibits three passbands with central frequencies of 1.8, 2.4, and 3.5 GHz. The insertion losses are 1.17, 0.84, and 1.67 dB, whilst 3-dB fractional bandwidths are equal to 4.7%, 5.6%, and 3.4%, respectively. Overall dimensions of the filter are 19.8 mm x 18.7 mm, i.e. $0.163\lambda_g \times 0.154\lambda_g$, where λ_g denotes guided wavelength at 1.8 GHz.

Similar to the filter operating at 2.4/3.5/5.2 GHz, this filter also has a good selectivity owing to four transmission zeros. However, in this case the second and the third transmission zeros are not as emphasised as in the previous filter.

The characteristics of the proposed filters and previously reported tri-band configurations are compared in Table I where λ_g denotes guided wavelength at the first passband. The proposed filters are very compact solutions which, at the same time exhibit good selectivity and very good insertion- and return-loss characteristics.

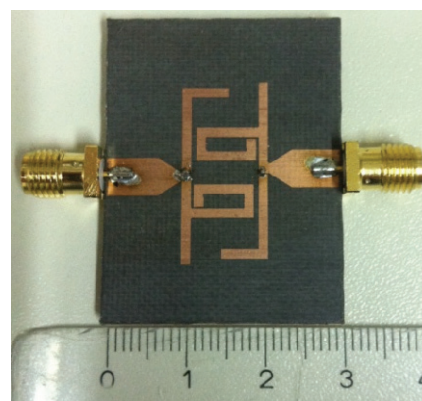


Fig. 9. Photograph of the fabricated circuit

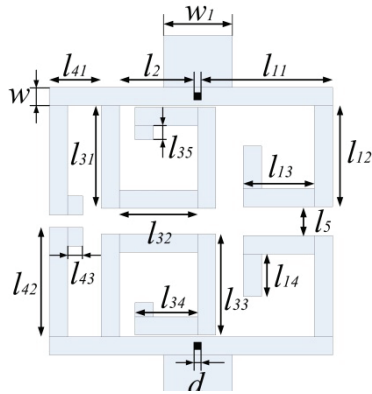


Fig. 10. Layout of the tri-band bandpass filter operating at 1.8/2.4/3.5 GHz

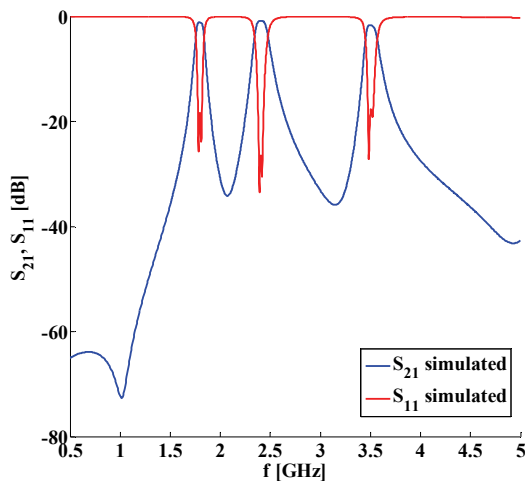


Fig. 11. Simulated response of the tri-band bandpass filter operating at 1.8/2.4/3.5 GHz

TABLE I
COMPARISON WITH REPORTED TRI-BAND BANDPASS FILTERS

	$f_1/f_2/f_3$ [GHz]	IL [dB]	RL [dB]	TZs	Dimen. [$\lambda_g \times \lambda_g$]	3 dB FBW [%]
Filter I	2.4/3.5 /5.2	1.31/2.28 /2.72	13/12 /10	4	0.24x 0.115	7.6/ 4.8/4.8
Filter II	1.8/2.4/ 3.5	1.17/0.84 /1.67	18/26 /17	4	0.163x 0.154	4.7/5.6 /3.4
[7]	2.4/4.8/ 7.2	1.7/0.9/ 0.7	15/23/ 18	5	0.37x 0.36	5.3/6.3 /8.7
[9]	1.5/2.4 /3.5	0.77/1.51 /1.8	31/29 /28	6	0.35x 0.25	12.5/8 /6
[13]	2.4/3.5 /5.25	1.2/1.1 /1.5	16.5/18 /14.5	6	0.27x 0.21	5/3.7 /4.2
[14]	2.4/3.5 /5.8	0.8/1.6 /1.8	18/16 /21	6	0.37x 0.297	7.59 /5.9/3.7
[15]	1.57/2.4 /3.5	1.6/1.5 /2.3	9/18.9 /13.5	5	0.39x 0.35	5.2/3.8/ 4.6
[16]	2.4/3.5 /5.25	2/2.4/1.7	18/16 /13	5	0.27x 0.25	2.5/1.7 /5
[17]	1.8/2.5 /3	0.9/1.6 /0.8	21/16 /17	5	0.27x 0.22	5.55/4. 17/6.67
[19]	2.4/3.5 /5.25	1.9/1.42 /1.51	14.3/15 /16.8	4	0.205x 0.117	6.2/12. 2/11.8

IV. CONCLUSION

In this paper, a novel tri-mode asymmetric grounded stub-loaded resonator has been proposed. A detailed description of its behaviour as well as an analytical procedure for resonance positioning are provided. Using the proposed resonator two filters that operate at 2.4/3.5/5.2 and 1.8/2.4/3.5 GHz have been designed and fabricated. The filters are characterized by good selectivity and very good insertion- and return-loss characteristics. At the same time, with the overall size of only $0.24\lambda_g \times 0.115\lambda_g$ and $0.163\lambda_g \times 0.154\lambda_g$, the filters present one of the most compact tri-band solutions published so far.

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