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COMPACT MICROSTRIP BANDPASS FILTERS USING TRIPLE-MODE RESONATOR

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Abstract—Step-by-step procedures for designing a third order bandpass filter and a sixth order bandpass filter using a triple-mode resonator are described in this paper. The triple-mode resonator is a square open-loop resonator with an open circuited stepped-impedance stub and a grounding via located at the symmetrical plane of the resonator. The equations for approximating the resonant frequencies of the resonator are obtained from odd and even mode analysis. To design a filter, first, the theoretical resonant frequencies for the filter are calculated. Then the basic dimensions of the resonator are approximated using the equations. The filter layouts are fine-tuned by simulation and verified by experiment to conclude the paper. The first spurious response occurs at about 3 times the center frequency of the first passband in both filters. The simulated and measured results are in good agreement.

1. INTRODUCTION

Compact bandpass microstrip filters are highly demanded in the telecommunication industries owing to their smaller size, lighter weight and ease in design and fabrication. Various resonator structures are studied and designed to obtain a more compact filter size [1]. O-ring resonator has a perimeter of one guided wavelength at its resonant frequency [2]. The perimeter of the O-ring resonator is halved by making the O-ring into an open loop resonator with the same resonant frequency [1]. The length of the open loop resonator can be further reduced into a quarter-wavelength to form a dual-mode resonator by placing a grounding via at the mid-point of the open-loop resonator [3].

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The advantage of the quarter-wavelength resonator is that the even harmonics of the resonator are suppressed. The physical length of the quarter-wavelength resonator can be shortened by using a stepped impedance line [4].

In this paper, a centrally loaded triple-mode resonator [5] is adapted to design a third order and a sixth order bandpass filters. The principle of operation and design of the resonator are described in Section 2. Sections 3 and 4 present the design procedure, as well as the discussion on the simulation and measurement results of these filters.

2. PRINCIPLE OPERATION OF TRIPLE-MODE RESONATOR

The triple mode resonator [5] is shown in Figure 1(a). It has a grounding via at the mid-point of the square loop which divides the microstrip line into two quarter-wavelength resonators. A stepped impedance line is also connected to the mid-point of the square loop. The actual length of this stepped impedance line should be less than $\lambda_g/8$ so that it can be fitted into a square open loop with a dimension of $\lambda_g/8 \times \lambda_g/8$, where λ_g is the guided wavelength at the center frequency. The odd and even mode analysis can be employed because the resonator is symmetrical along the central vertical line AB.

This triple-mode resonator has two even-mode resonances and one odd-mode resonance; they are labeled as f_1, f_3 and f_2, respectively.

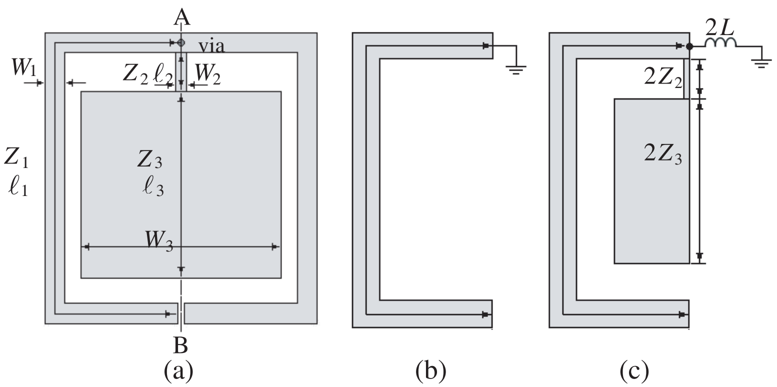


Figure 1. (a) Compact triple mode ring-like resonator. AB is the plane of symmetry. Equivalent circuit of the proposed triple-mode resonator: (b) odd mode and (c) even mode.

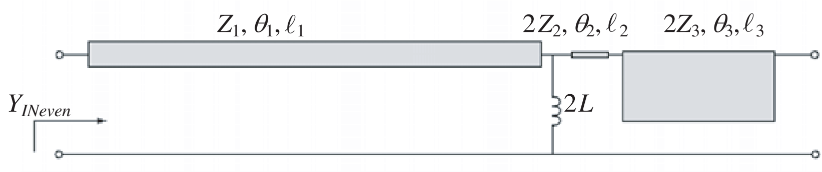


Figure 2. Even mode equivalent circuit of the triple-mode resonator.

Note that $f_1 < f_2 < f_3$. For the odd mode analysis, the symmetry plane is an electric wall which short circuits the central patch as shown in Figure 1(b). The boundary conditions are satisfied at the frequency f_2 (the center frequency) at which it is quarter wavelength long. Hence,

$$\ell_1 = \frac{c}{4f_2\sqrt{\varepsilon_1}} \tag{1}$$

where c is the velocity of light in free space and ε_1 the effective dielectric constant.

For the even mode analysis, the symmetry plane is a magnetic wall. The via inductance, L, is split into two parallel inductances, each of value $2L$. Each inductance couples to half the central patch to an outer arm. The even mode equivalent circuit is shown in Figures 1(c) and 2. The two even-mode resonant frequencies can be determined by matrix multiplication of the elements in the $ABCD$ matrices. When the 2-port network in Figure 2 is open-circuited on the right side of the network, the admittance of the network, $Y_{INeven} = C/A$, is equal to zero. The even mode resonant frequencies, f_1 and f_3, are the solutions for f in (2).

$$\begin{gathered}\left(\frac{1}{Z_1}\tan\theta_1 - \frac{1}{2\omega L}\right)\left(1 - \frac{Z_2}{Z_3}\tan\theta_2\tan\theta_3\right) + \frac{1}{2Z_2}\tan\theta_2 + \frac{1}{2Z_3}\tan\theta_3 = 0\\ \theta_1 = \frac{2\pi f\ell_1\sqrt{\varepsilon_1}}{c}, \theta_2 = \frac{2\pi f\ell_2\sqrt{\varepsilon_2}}{c}, \theta_3 = \frac{2\pi f\ell_3\sqrt{\varepsilon_3}}{c}, \omega = 2\pi f.\end{gathered} \tag{2}$$

Before applying (2), the characteristic impedance of two microstrip lines on the stepped impedance resonator must be selected. For the compactness of the resonator, the stepped impedance lines (see Figure 1(a)) should have an effective length of less than half of ℓ_1 to be effectively fitted into the square open loop. The stepped impedance line gives a ratio of the characteristic impedance for the two line segments as (3) if the higher characteristic impedance end is short-circuited to ground and the lower characteristic impedance end is open-circuited.

$$Z_3/Z_2 = R = \tan\theta_2\tan\theta_3 \tag{3}$$

Using (3), Figure 3 shows a plot of the total length $\ell_2 + \ell_3$ normalized to half of ℓ_1 against the electrical length of microstrip line ℓ_3, θ_3, for each given impedance ratio, R. This plot is used to determine Z_2, Z_3 and θ_3.

For the feed structure, the same coupling concept is applied as those in the asymmetrical coupling described in [1, 6, 7].

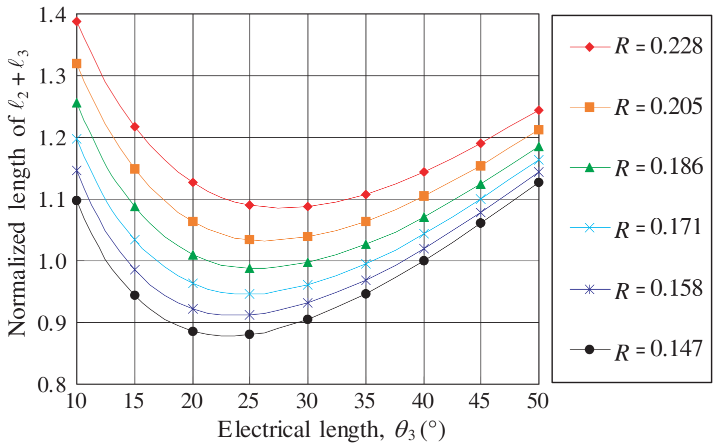


Figure 3. Ratio of Z_3/Z_2 varies with the normalized length $\ell_2 + \ell_3$, to determine the electrical length of the microstrip line ℓ_3, θ_3. Length of $\ell_2 + \ell_3$ is normalized to half of ℓ_1. R is the ratio of Z_3/Z_2.

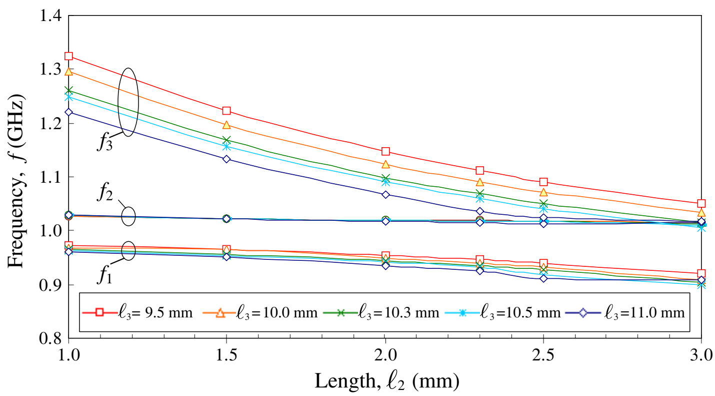


Figure 4. Resonant frequencies of the triple-mode resonator by varying ℓ_2 and ℓ_3. ℓ_2 and ℓ_3 are with the characteristic impedance of 70.44 Ω and 11.20 Ω, respectively. ℓ_1 is 29.00 mm.

3. THIRD ORDER BANDPASS FILTER

The triple mode resonator is used to design a third order filter with the following design specification: a passband ripple of 0.5 dB, a center frequency of 1.0 GHz, and a 3-dB fractional bandwidth of 15.0%. It is designed on a RT-Duroid 6010.2 which has a 1.27 mm thick dielectric substrate with a relative dielectric constant of 10.2. The design procedure is summarized as follows:

1) The three resonant frequencies of the resonator are distributed according to the pole frequencies. The three pole frequencies are calculated using the insertion loss function where the transmission poles [8] are given by

$$f_n = f_c \left(1 + x_n \times \frac{FBW}{2}\right) \tag{4}$$

$$x_n = \cos\left(\frac{2k+1-2n}{2k}\pi\right), \quad n = 1 \text{ to } k. \tag{5}$$

   where f_n is the pole frequency, f_c the center frequency of the passband, FBW the fractional bandwidth, and k the number of pole. For third order ($k = 3$) bandpass filter, the calculated frequencies f_1, f_2 and f_3 are 0.935 GHz, 1.0 GHz and 1.065 GHz, respectively.

2) The widths of the line ℓ_1 and ℓ_2 are chosen as $W_1 = 1.00$ mm and $W_2 = 0.50$ mm, respectively. The total length $\ell_2+\ell_3$ should be less than half of ℓ_1 so that they can be fitted into the open loop and hence the value of R is 0.159 as shown in Figure 3. $W_2 = 0.50$ mm gives a characteristic impedance, Z_2, of 70.44 Ω and hence Z_3 is 11.20 Ω for $W_3 = 10.90$ mm.

3) ℓ_1 is a quarter-wavelength at the center frequency of the passband, f_2, and it is determined using (1). ℓ_2 and ℓ_3 are determined from (2) to be 2.30 mm and 10.3 mm using the resonant frequencies, f_1 and f_3. ℓ_2 and ℓ_3 can also be determined from Figure 4. Figure 4 plots the resonant frequencies of the triple-mode resonator with varied ℓ_2 and ℓ_3. A grounding via with 0.52 mm in diameter introduces a small inductance L of 0.374 nH.

4) The resonator is coupled to the input and output signal feed structures with a gap size of 0.25 mm. The length of the feed structure is determined according to [1, 6, 7]. The coupling scheme of the proposed filter designed using the triple-mode resonator is as shown in Figure 5. The solid line is the direct coupling path. The layout in Figure 6(a) is simulated and optimized using Sonnet® simulator [9].

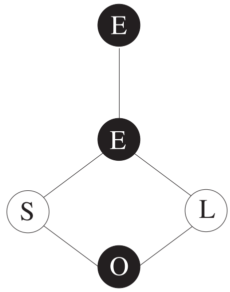
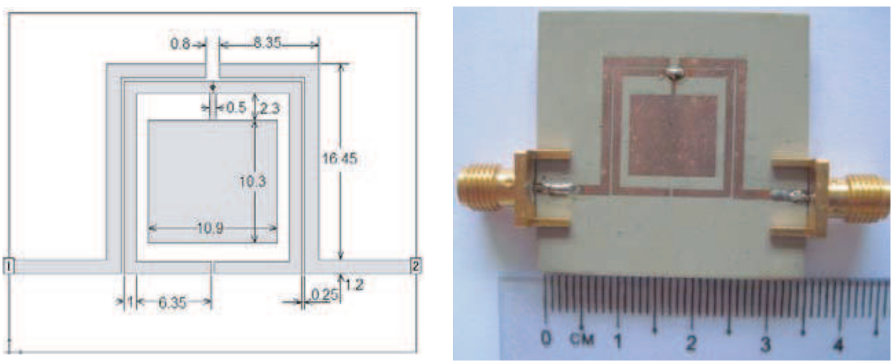


Figure 5. Coupling scheme of the third order passband filter. S is the source and L is the load. E is the even mode resonant frequency. O is the odd mode resonant frequency.



(a) (b)

Figure 6. (a) Layout of the third order bandpass filter (dimension in millimeters). (b) Photograph of the fabricated filter.

The resonator has a size of $15.00\,\mathrm{mm} \times 16.15\,\mathrm{mm}$. All the dimensions of the filter are shown in Figure 6(a), and a photograph of the fabricated filter is shown in Figure 6(b) after some small adjustments to improve the simulated response. All the simulations are simulated with copper and dielectric losses. Both the simulated and measured results are plotted in Figure 7. They show good agreement with each other. The measured passband insertion loss and return loss are 1.35 dB and 15.0 dB, respectively. The simulated and measured 3-dB fractional bandwidth of the passbands are 15% and 16%, respectively. The filter shows relatively high selectivity. The maximum variation of group delay within the passband is below 3.9 ns as shown in the inset of Figure 7. The first spurious occurs at 3 times the center frequency of the passband. The measured first spurious is less than -20 dB. This filter exhibits a good stopband performance.

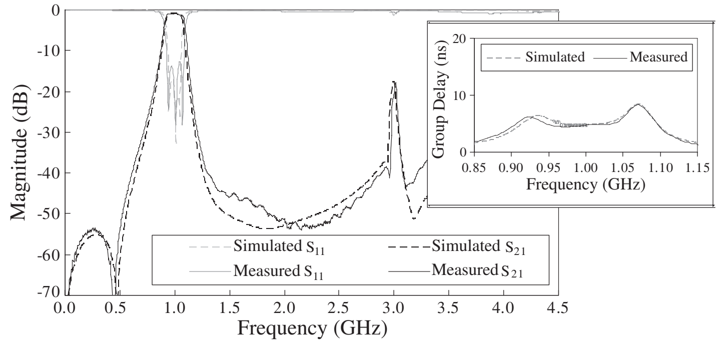


Figure 7. Broadband simulated results and measured results of the third order bandpass filter. Inset is the group delay for the first passband.

4. SIXTH ORDER BANDPASS FILTER

A sixth order bandpass filter, with the same design specification as the third order bandpass filter in Section 3, was designed and implemented using two identical triple-mode resonators. The following summarized the step-by-step design procedure of the sixth order passband filter.

1) The six pole frequencies, f_1, f_2, f_3, f_4, f_5, and f_6, are calculated using (5) and (6). They are 0.928 GHz, 0.947 GHz, 0.981 GHz, 1.019 GHz, 1.053 GHz and 1.072 GHz, respectively.
2) W_1, W_2, and W_3 have the same values as the resonator in Section 3. The value of R is the same as described in Section 3.
3) The two resonators are designed to have identical resonant frequencies. On coupling the two resonators, the three frequencies will split into six frequencies. For weak coupling, the original frequency lies approximately half way between the split frequencies. Hence for an approximate design, ℓ_1 is determined using (1) at $(f_3 + f_4)/2$. ℓ_2 and ℓ_3 are determined using (2) with ℓ_1 and the odd mode resonant frequencies at $(f_1 + f_2)/2$ and $(f_5 + f_6)/2$. The resonator is then simulated and adjusted using Sonnet® simulator to obtain the final dimension of the resonator.
4) The gap in between the two coupling resonators is adjusted so that all the six resonant frequencies are within the passband. Figure 8 shows the six resonant frequencies for each gap size. The chosen size of the gap is the one which the resonant frequencies match most of the six pole frequencies. In Figure 8, the gap size of 1.7 mm is the most suitable size for the gap. It has the resonant

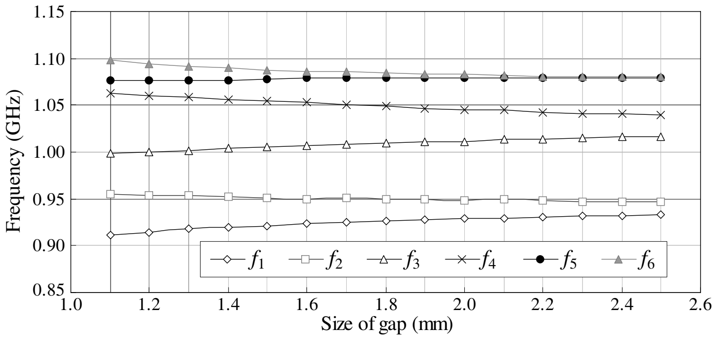


Figure 8. Resonant frequencies of the two coupling triple-mode resonators against the size of gap.

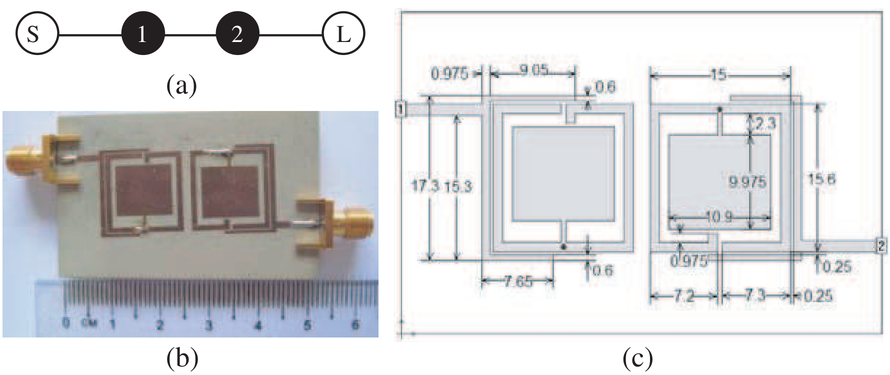


Figure 9. (a) Coupling scheme of the sixth order bandpass filter. Solid circle is the triple-mode resonator. The coupling of each triple-mode resonator is shown in Figure 5. S is the source and L is the load. (b) Photograph of the fabricated filter. (c) Layout of the sixth order bandpass filter designed using the proposed resonators (dimension in millimeters).

frequencies of 0.93 GHz, 0.95 GHz, 1.01 GHz, 1.05 GHz, 1.07 GHz and 1.08 GHz. The resonant frequency at 1.08 GHz merges with the resonant frequency at 1.07 GHz to form one resonance at 1.072 GHz.

5) The coupling feed structures are designed together with the two resonators. They are simulated and optimized using Sonnet® simulator to obtain the best passband. The coupling scheme of

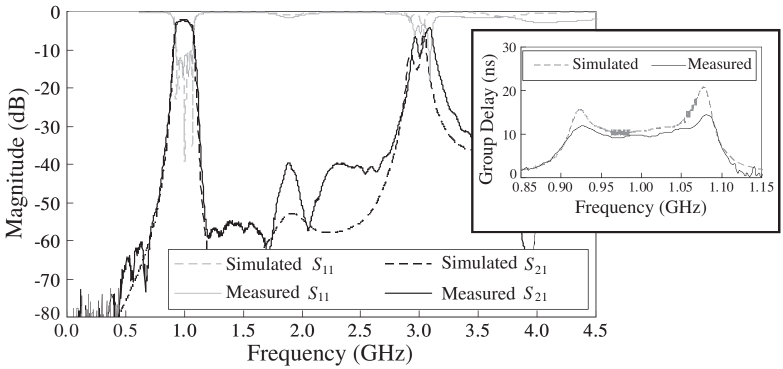


Figure 10. Broadband simulated results and measured results of the sixth order bandpass filter. Inset is the group delay for the first passband.

the bandpass filter is shown in Figure 9(a).

The layout of the filter designed in Figure 9(c) exhibits a sixth order bandpass passband. A photograph of the fabricated filter is shown in Figure 9(b). The measured and simulated (with copper loss and dielectric loss) results are plotted in Figure 10 for comparison. The measured passband insertion loss is about 2.6 dB and the return loss is 10.2 dB. The measured passband has a 3-dB fractional bandwidth of 14.8%. The maximum variation of group delay within the passband is below 5.1 ns as shown in the inset of Figure 10. The passband filter response shows the first spurious occurs at about 3 times the center frequency of the first passband. The sixth order bandpass filter shows better passband selectivity compared to the passband of the third order bandpass filter in Section 3.

5. CONCLUSION

A triple mode resonator is used to realize a third order bandpass filter and a sixth order bandpass filter. Approximate resonant frequency equations, obtained from odd and even mode analysis, are then used to determine the basic dimension of the resonator for the filter design. The filters are compact in structures. Furthermore, the first spurious response is observed at about three times the center frequency of the first passband. The measured results agree well with the simulated ones.

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