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Design of Triband Bandstop Filter Using an Asymmetrical Cross-Shaped Microstrip Resonator

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Abstract—An asymmetrical cross-shaped microstrip resonator is proposed. It is analyzed on its characteristic impedance and resonant conditions. A first order triband bandstop filter (BSF) and a second order triband BSF are designed using this resonator. Both filters are simulated on Sonnet Suite software. Simulation results show that both filters generate three attenuation poles at 2.0, 3.0, and 4.5 GHz. The second order BSF is also fabricated and measured using a microwave network analyzer. Simulation and measurement results on the second order BSF agree well.

1. INTRODUCTION

Microstrip bandstop filters are being widely used in local oscillators, mixers, duplexers, switches, and other microwave subsystems. Various techniques have been developed to synthesize and design BSFs [1]. Tri-band bandstop filters are highly desired for their three separate stopbands. Conventionally, a tri-band BSF can be obtained by cascading three different BSFs. The side effect of this technique is an increase in circuit size and high passband insertion loss. Size reduction of BSFs is an important research topic.

Triband microstrip BSFs have not been widely investigated. Only a few papers on triband BSFs are found [2–11]. In [2], a pair of coupled lines and a modified spurline are used to generate three stopbands, but the insertion losses in passbands are high. In [3], a T-shaped defected microstrip structure is used to generate three stopbands. However, the third stopband is not investigated in details. In [4], a dual-band BSF and a well-known DGS are combined to generate three stopbands. The third stopband is generated by that DGS. In [5], three pairs of folded fingers similar to three open stubs are used, and the resultant passband insertion losses are high. In [6], a Hilbert-Fork resonator is proposed and used to design a compact triband BSF having excellent performance. However, no design formula is given, and the resonator and filter have to be tuned manually. In [7], stub-loaded resonators and a phase shift section on the main transmission line are used to generate three stopbands. However, the given formulae are too rough to be used in filter design. In [8], three fractal based open ring resonators with three different electrical lengths are used. This method is similar to that using three different BSFs. In [9], two meandered slot defected microstrip structures on the main transmission line and six simplified spiral microstrip resonators are used. Three deep stopbands are generated around 2.37, 3.54, and 5.01 GHz. In [10], three cascaded C-ring resonators are used to generate three wide and deep stopbands. In [11], two folded trisection stepped impedance resonators are used to generate three deep stopbands.

In this research, an asymmetrical cross-shaped microstrip resonator is proposed. Its characteristic impedance is derived, and its resonant conditions are found. A Matlab program is made to calculate the four electrical lengths of the four arms in the resonator. A first order triband BSF and a second order triband BSF are designed using this resonator. Both filters are simulated on Sonnet Suite software. The second order BSF is fabricated and measured using a microwave network analyzer.

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2. THEORETICAL ANALYSIS OF THE RESONATOR

The proposed asymmetrical cross-shaped microstrip resonator is shown in Figure 1. The characteristic impedance of all the microstrips is Z. The electrical lengths of the bottom and top vertical arms are θ_1 and θ_2, and the electrical lengths of the right and left arms are θ_3 and θ_4. Since the cross is not symmetrical, θ_3 is not equal to θ_4. Also θ_1 is shorter than θ_2.

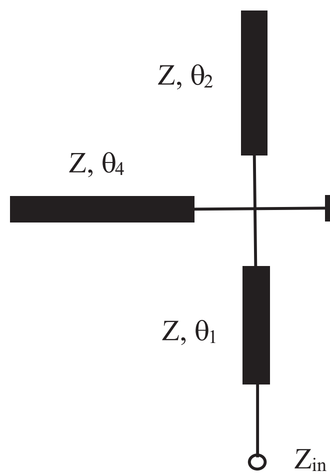

Figure 1. The structure of the proposed asymmetrical cross-shaped resonator.

Based on transmission line theory [12], the impedance at the input of the cross-shaped resonator or the lower end of the bottom arm can be calculated as

$$Z_{in} = Z\frac{Z_L + jZ\tan\theta_1}{Z + jZ_L\tan\theta_1} = jZ\frac{\tan\theta_1\left(\tan\theta_2 + \tan\theta_3 + \tan\theta_4\right) - 1}{\tan\theta_1 + \tan\theta_2 + \tan\theta_3 + \tan\theta_4} \tag{1}$$

where Z_L is the total impedance of θ_2, θ_3, and θ_4 arms seen from the center of the resonator.

In resonance condition, Z_{in} should be zero. Hence, the following equations can be obtained as

$$\tan\theta_1\left(\tan\theta_2 + \tan\theta_3 + \tan\theta_4\right) - 1 = 0 \tag{2a}$$
$$\tan n_1\theta_1\left(\tan n_1\theta_2 + \tan n_1\theta_3 + \tan n_1\theta_4\right) - 1 = 0 \tag{2b}$$
$$\tan n_2\theta_1\left(\tan n_2\theta_2 + \tan n_2\theta_3 + \tan n_2\theta_4\right) - 1 = 0 \tag{2c}$$

The four electrical lengths θ_1, θ_2, θ_3, and θ_4 are designed at the lowest resonant frequency f_1. The two frequency ratios n_1 and n_2 are f_2 to f_1 and f_3 to f_1, and f_2 and f_3 are the two higher resonant frequencies.

3. DESIGN OF TRIBAND BANDSTOP FILTERS

First, three factors are defined as

$$k_1 = \frac{\theta_1}{\theta_1 + \theta_2} \tag{3a}$$
$$k_2 = \frac{\theta_3}{\theta_1 + \theta_2} \tag{3b}$$
$$k_3 = \frac{\theta_4}{\theta_1 + \theta_2} \tag{3c}$$

These three factors are used to express the relations between the four electrical lengths. Next, a triband bandstop filter with three stopbands at 2.0, 3.0, and 4.5 GHz is designed. Apparently, n_1 is 1.5, and n_2 is 2.25. The factor k_1 is chosen as 0.1. The other two factors k_2 and k_3 are chosen temporally as n_1 or 1.5, and n_2 or 2.25. Then k_2 and k_3 can be tuned to the right values using Equation (2). A MatLab program is made to calculate the three roots of this equation. The first root is always 1. The other two roots are found as 1.418 and 2.085. When k_1 increases, the second and third roots also increase. When k_2 increases, the third root increases, and the second does not change much. The two factors k_2 and k_3 are tuned until the second and third roots are equal to n_1 and n_2. The two factors k_2 and k_3 are easily finalized as 1.65 and 2.5, and at the same time θ_1 is calculated as 0.1508. Next θ_2, θ_3, and θ_4 are calculated as 1.3572, 0.9139, and 0.6032.

The filter is made on a Rogers AD1000 substrate with a relative dielectric constant of 10.6 and loss tangent of 0.0023. The thickness of the substrate is 1.27 mm. The back of the substrate is the ground plane. A microstrip with a width of 1.14 mm on the top layer can yield a characteristic impedance of 50 Ohm [1]. The line width of the crossed-shaped resonator is chosen as 0.2 mm. At 2.0 GHz, the wavelength is calculated as 59.07 mm [1]. Then θ_1, θ_2, θ_3, and θ_4 are calculated as 1.42 mm, 12.76 mm, 8.59 mm, and 5.67 mm.

The layout of the first order triband BSF is shown in Figure 2. Dimensional parameters are: $W_1 = 0.20$ mm, $W_2 = 1.14$ mm, $L_1 = 1.32$ mm, $L_2 = 12.66$ mm, $L_3 = 8.59$ mm, $L_4 = 5.67$ mm. This filter is simulated on Sonnet Suite 14.52. The simulation results are shown in Figure 3. The three attenuation poles are at 2.02, 3.14, and 4.5 GHz. The first two attenuation poles are close to 2.0, 3.0 GHz, and the third attenuation pole is already at 4.50 GHz.

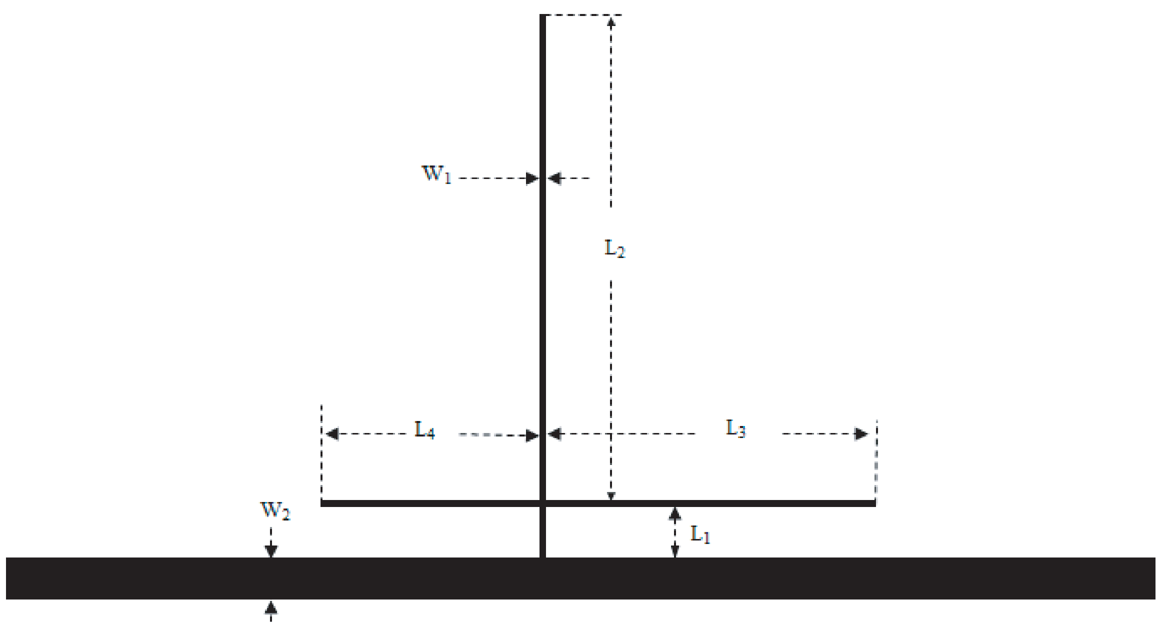

Figure 2. Layout of the first order triband BSF.

Then the lengths of the four arms need to be slightly tuned to move the three attenuation poles to the three desired values. Simulations show that the lengths of the four arms have different effects on the three center frequencies. The total length of the two vertical arms has main influences on the first attenuation pole but almost no influence on the other two. The length of the long horizontal arm has main influence on the second attenuation pole. The length of short horizontal arm has main influence on the third attenuation pole. The lengths of the four arms are slightly tuned. New dimensional parameters are: $L_1 = 1.32$ mm, $L_2 = 12.86$ mm, $L_3 = 9.14$ mm, and $L_4 = 5.60$ mm. The filter is simulated again on Sonnet suite 14.52. The simulation results are shown in Figure 4. The three attenuation poles are at 2.0, 3.0, and 4.5 GHz. The three attenuation depths at these three frequencies are -46 dB, -28 dB, and -31 dB.

Additional simulations are run to show how the lengths of L_1 to L_4 influence the three attenuation poles. If the length of L_1 is increased by 0.5 mm, the three attenuation poles will be shifted to 1.90, 2.92, and 4.36 GHz. If the length of L_2 is increased by 0.5 mm, the three attenuation poles will be shifted to

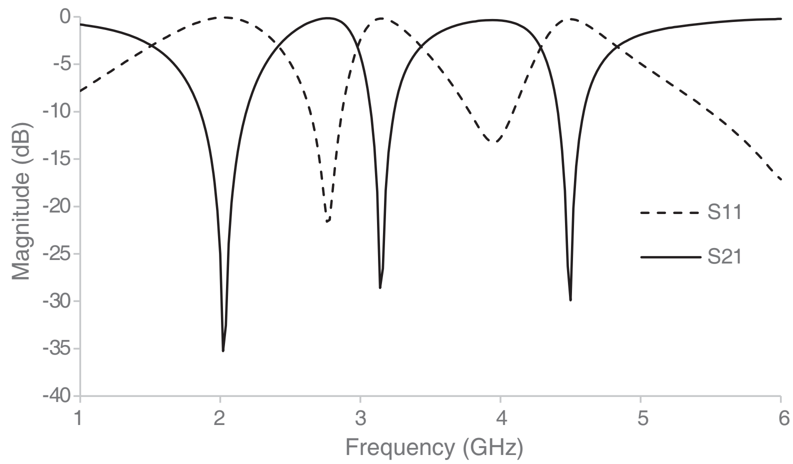

Figure 3. Simulation results of the first order triband BSF.

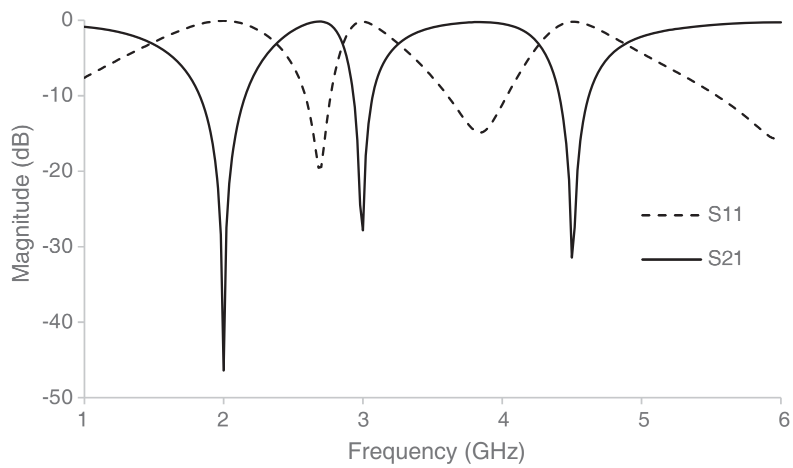

Figure 4. Simulation results of the tuned first order triband BSF.

1.94, 2.98, and 4.50 GHz. If the length of L_3 is increased by 0.5 mm, the three attenuation poles will be shifted to 2.0, 2.86, and 4.50 GHz. If the length of L_4 is increased by 0.5 mm, the three attenuation poles will be shifted to 2.0, 2.98, and 4.24 GHz. The length of L_3 influences only the second attenuation pole, while the length of L_4 mainly influences the third attenuation pole. The length of L_2 influences the first and second attenuation poles. The length of L_1 influences all the three attenuation poles.

Next, a second order triband BSF using this asymmetrical cross-shaped resonator is designed. Its layout is shown in Figure 5. Three arms are bent in both resonators to reduce the circuit size. The lengths of the arms are slightly tuned. To reduce the passband insertion loss, the distance between the two resonators is chosen at 8.65 mm, and the width of the connecting line is optimized at 0.73 mm. The main dimensional parameters are: $L_1 = 1.32$ mm, $L_{2a} = 10.00$ mm, $L_{2b} = 2.00$ mm, $L_{2c} = 2.81$ mm, $L_{3a} = 2.00$ mm, $L_{3b} = 7.56$ mm, $L_{4a} = 2.00$ mm, $L_{4b} = 3.98$ mm, $S = 8.65$ mm, and $W_3 = 0.73$ mm. This second order triband BSF is also simulated on Sonnet Suite 14.52, and simulation results are shown in Figure 6. The three attenuation poles are at 2.0, 3.0, and 4.5 GHz, and the attenuation depths are -37, -37, and -52 dB at these three frequencies.

The second order triband BSF is also fabricated (Figure 7). The circuit substrate is 1.27 mm thick AD1000 board made by Rogers. The finished metal lines are covered with a thin layer of gold. Then this filter is measured with a microwave network analyzer after two-port calibration. The measured results are shown in Figure 8. The three attenuation poles are at 2.04, 3.06, and 4.54 GHz, and the attenuation depths are -35, -40, and -49 dB at these three frequencies. The simulated and measured results are

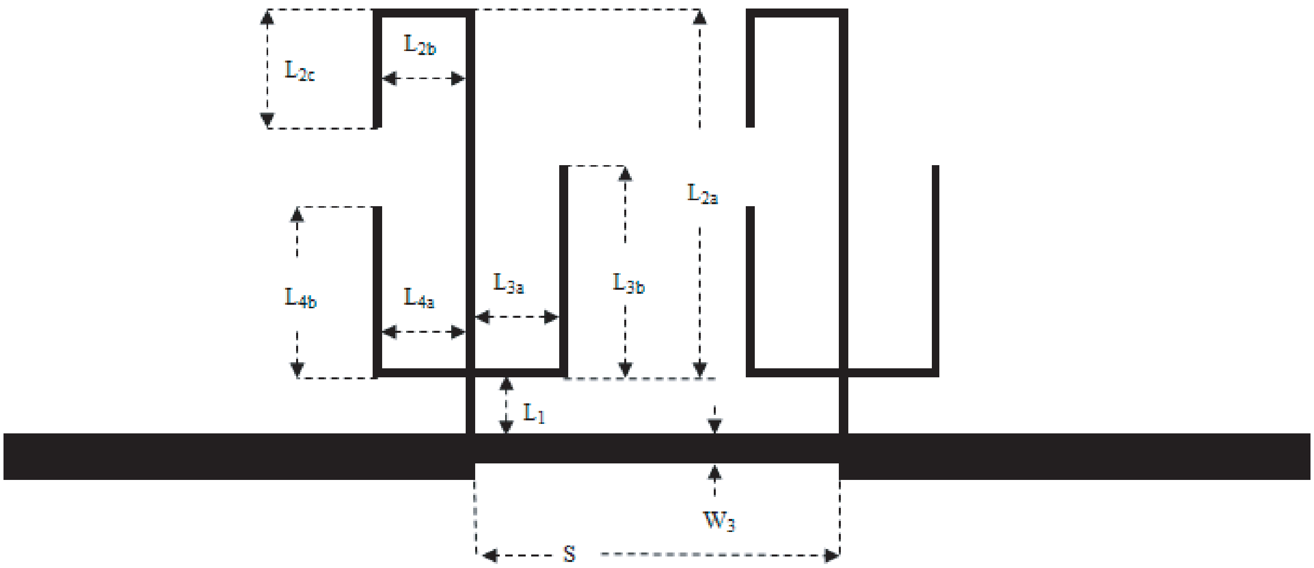

Figure 5. Layout of the tuned second order triband BSF.

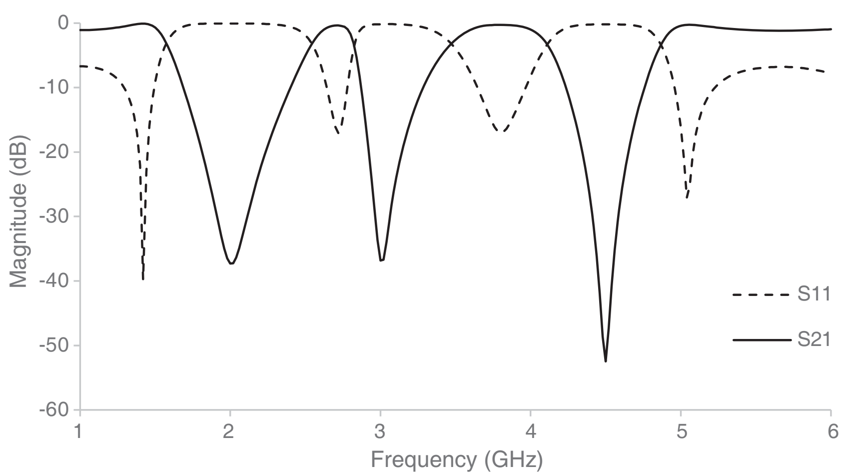

Figure 6. Simulation results of the second order BSF.

shown together in Figure 9 and Figure 10 for comparison. The simulated and measured results are close to each other. The measured insertion loss is shifted slightly to higher frequencies from the simulated result (Figure 9). There are also some small fluctuations in the measured results. The differences between measured and simulated results should be caused mainly by PCB fabrication process tolerance and substrate material property variations. Based on the measurement, the three attenuation poles of the 2nd order BSF are still very close to 2.0 GHz, 3.0 GHz, and 4.5 GHz, respectively. The measured insertion loss is about 3 dB from 5.0 to 6.0 GHz. The loss tangent of the PCB material AD1000 increases with frequency. This effect is not included in the simulation process.

Certain procedures must be followed to design triband BSFs using the proposed resonator. The first step is to choose k_1 factor (such as 0.1 or 0.05). The second step is to find k_2 and k_3 using Equations (2a), (2b), and (2c). This is a key step through programming. Only about 30 lines of MatLab code are needed. The third step is to calculate θ_1, θ_2, θ_3, and θ_4. The forth step is to find physical dimensions of the resonator using routine formulae. The fifth step is to simulate and tune the filter. The rest steps are the layout, fabrication, and testing.

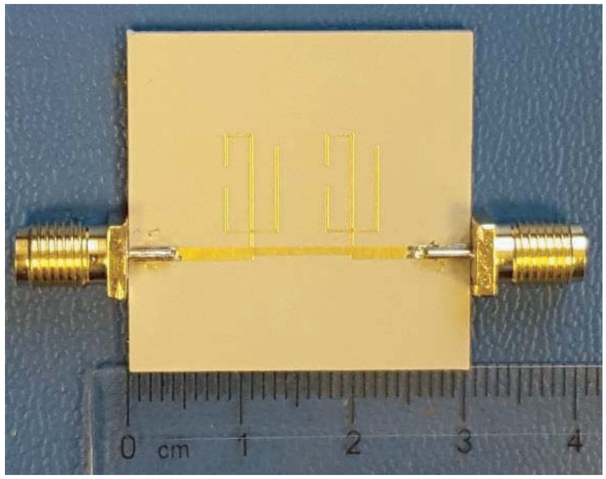

Figure 7. Fabricated 2nd order triband BSF.

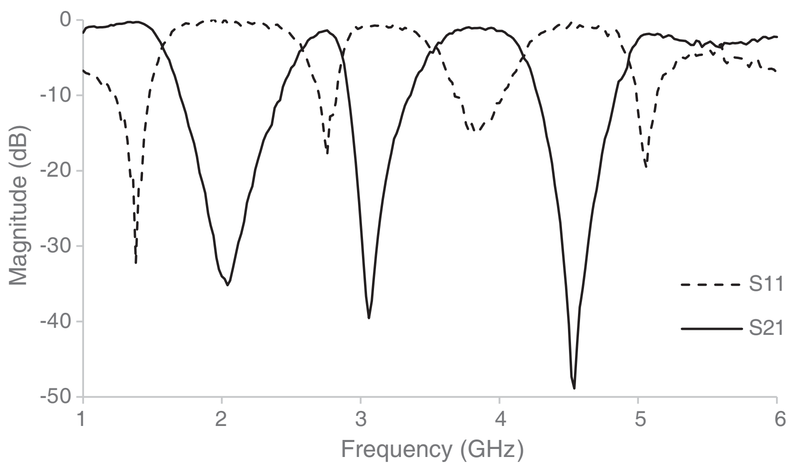

Figure 8. 2nd order triband BSF measurement results.

In Table 1, four reported triband BSFs having outstanding performance are compared with this work. The wavelength refers to the guided wavelength at the lowest resonant frequency. The proposed filter is more compact than those in [9] and [10]. It has deeper rejection levels than those in [6], [9], and [10]. The filter in [11] has the deepest rejection levels and smallest size.

Table 1. Performance comparison of reported triband BSFs.

Reference	Frequencies (GHz)	Rejection (dB)	Circuit Size (wavelength^2)
[6]	2.36, 3.48, 5.19	−14, −26, −35	0.21×0.11
[9]	2.37, 3.54, 5.01	−31, −31, −41	0.44×0.18
[10]	4, 6, 8	−30, −30, −30	0.37×0.25
[11]	1.98, 3.63, 5.50	−55, −56, −39	0.19×0.15
This work	2.04, 3.06, 4.54	−35, −40, −49	0.24×0.20

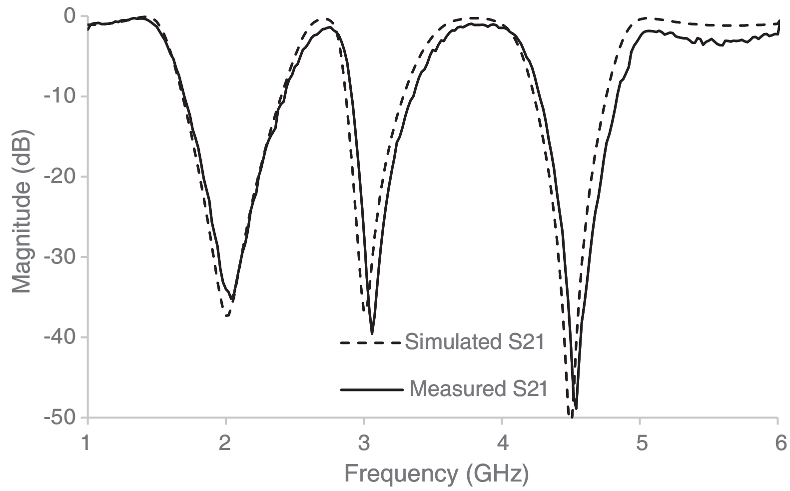

Figure 9. Simulated and measured S_{21}.

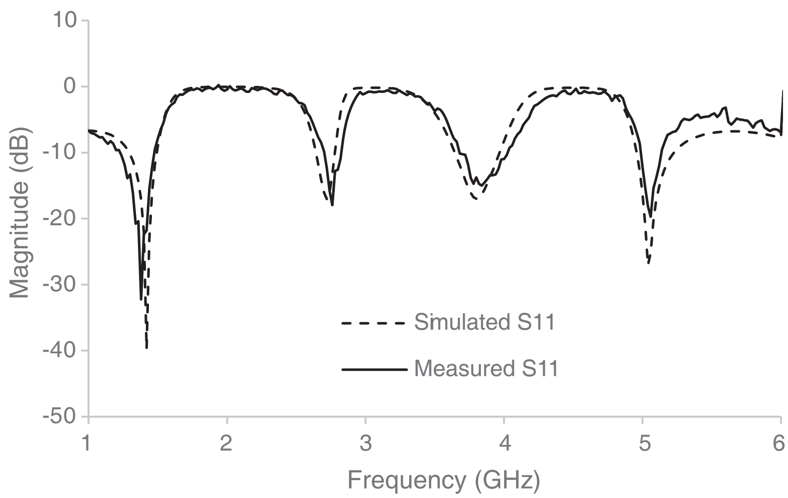

Figure 10. Simulated and measured S_{11}.

4. SUMMARY

In this letter, a new approach to design a triband BSF using an asymmetrical cross-shaped resonator is proposed. First, the asymmetrical cross-shaped resonator is analyzed. Secondly, a first order triband BSF is designed and simulated. Simulation results show that three attenuation poles are generated at 2.0, 3.0, and 4.5 GHz. Next, a second order triband BSF is designed, fabricated, and measured. Simulation and measurement results on the second order filter agree, verifying the presented theory and approach.

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