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ANALYSIS AND APPLICATION OF SHUNT OPEN STUBS BASED ON ASYMMETRIC HALF-WAVELENGTH RESONATORS STRUCTURE

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Abstract—In this paper, the applications of shunt open stubs are reported based on asymmetric half-wavelength resonators structure. To demonstrate the design ideas, the analysis methods of *ABCD* matrix and equivalent circuit are used. The multi-band bandpass, miniaturization and harmonic suppression by application of the shunt open stubs are demonstrated. The measured insertion loss of the dual-band filter with the center frequency of 1.9 and 5.8 GHz is less than 2.7 dB. The insertion loss of the tri-band filter with the center frequency of 1.5, 4 and 6.3 GHz is less than 2.7 dB. Furthermore, a compact bandpass filter with size around 12.3 mm∗11.5 mm is designed and fabricated. The bandwidth of the filter is 120 MHz with the center frequency of 2.4 GHz and the insertion loss is less than −3 dB. Especially, the insertion loss is less than −20 dB from 2.8 GHz to 7 GHz. For the filters above, the simulated results and the measured results agree well.

1. INTRODUCTION

The development in wireless communication and radar systems has presented new challenges to design and produce high-quality miniature and multi-band operation components. Thus, the characteristics of high-quality miniature and multi-band operation for modern microwave filters are highly required.

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Recently, microstrip bandpass filters have been proposed, using asymmetric half-wavelength resonators structure to obtain two transmission zeros lying on either side of the passband [1]. The asymmetric half-wavelength resonators were also used in designing miniature and multi-band filter [2, 3]. The method of loading grounded coupled lines with shunt capacitors was introduced in [4, 5] for miniaturization. Shunt stubs were introduced for adding passbands [6, 7], harmonic suppression [8, 11], and realization of compact filters with harmonic suppression [9, 10, 13–17].

In this paper, a dual-band filter is designed based on the asymmetric half-wavelength resonators structure. The insertion loss of the dual-band filter with the center frequency of 1.9 and 5.8 GHz is less than 2.7 dB. Then, a tri-band filter is designed with insertion loss less than 2.7 dB at the center frequencies of 1.5, 4 and 6.3 GHz. Finally, a compact bandpass filter with harmonic suppression is designed. The center frequency of the filter is 2.4 GHz and the bandwidth 120 MHz with the size around 12.3 mm $*$ 11.5 mm. The harmonic is suppressed less -20 dB from 2.8 GHz to 7 GHz.

This paper is organized as follows. In Section 2, the structure of asymmetric half-wavelength resonators structure with shunt open stubs is analyzed. In Section 3, the applications of the shunt open stubs are proposed, and the conclusion is given in Section 4.

2. ANALYSIS THE HALF-WAVELENGTH RESONATORS WITH SHUNT OPEN STUBS

2.1. Analysis of Transmission Zeros

In order to facilitate the analysis, the asymmetric half-wavelength resonators coupling structure with shunt open stubs is designed, as shown in Figure 1. The total length of the resonator is $2l_3 + l_2 + l_1 = \lambda_g/2$, where λ_g is the guided wavelength at fundamental resonance. The l_4 connected to the resonator is the shunt open stub. The coupling between the two open ends of the resonators is simply expressed by the gap capacitance C_S [12].

Inspecting Figure 1, the whole circuit represents a shunt circuit, as shown by the dotted boxes, which consists of upper and lower sections. Each section is composed of l_1, l_2, l_3, l_4 and C_S. The $ABCD$ matrices for the upper and lower sections of the lossless shunt circuit are [3, 18]

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{upper} = M_1 M_4 M_3 M_C M_3 M_4 M_2 \tag{1a}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{lower} = M_2 M_4 M_3 M_C M_3 M_4 M_1 \tag{1b}$$

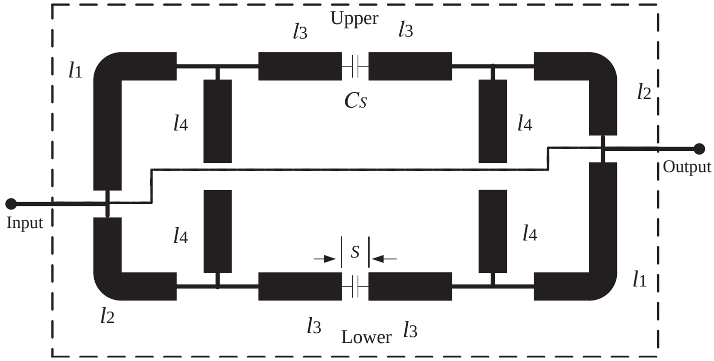

Figure 1. Configuration of asymmetric half-wavelength resonators coupling structure with shunt open stubs ($l_1 > l_2$).

with

$$M_n = \begin{bmatrix} \cos\beta l_n & jZ_0 \sin\beta l_n \\ jY_0 \sin\beta l_n & \cos\beta l_n \end{bmatrix} \quad (n = 1, 2, 3)$$

$$M_C = \begin{bmatrix} 1 & \frac{1}{j\omega C_S} \\ 0 & 1 \end{bmatrix} M_4 = \begin{bmatrix} 1 & 0 \\ jY_0 \tan\beta l_4 & 1 \end{bmatrix}$$

where β is the propagation constant, Z_0 the characteristic impedance of the resonator, ω the angular frequency, and $Y_0 = 1/Z_0$. The Y-parameters for this circuit can be obtained by adding the upper and lower section Y-parameters, which follow from (1a) and (1b), respectively. When the load is matched, S_{21} of the circuit can then be calculated from the total Y-parameters, as shown in (2). In order to obtain the transmission zeros, for a small C_S, an approximate equation can be obtained as:

$$\cos\beta(l_2+l_3)\cos\beta(l_1+l_3)-\cos\beta(l_2+l_3)\sin\beta l_1\cos\beta l_3\tan\beta l_4$$
$$-\cos\beta(l_1+l_3)\sin\beta l_2\cos\beta l_3\tan\beta l_4+\sin\beta l_1\sin\beta l_2\cos\beta l_3^2\tan\beta l_4^2=0 \quad (2)$$

In general, we assume $l_1<\lambda_g/4$, $l_2<\lambda_g/4$, $l_3<\lambda_g/4$, $l_4<\lambda_g/4$, where λ_g is the guided wavelength at fundamental resonance. Thus, we can obtain $\sin\beta l_1\cos\beta l_3\tan\beta l_4>0$ and $\sin\beta l_2\cos\beta l_3\tan\beta l_4>0$. In addition, we assume $\sin\beta l_1\cos\beta l_3\tan\beta l_4<1$ and $\sin\beta l_2\cos\beta l_3\tan\beta l_4<1$. The four transmission zeros, f_1, f_2, f_3 and f_4, can be obtained as:

$$f_1 = \frac{c \times n \times \cos^{-1}(\sin\beta l_1 \cos\beta l_3 \tan\beta l_4)}{2\pi\sqrt{\varepsilon_{eff}}\,(l_1 + l_3)} \quad (3a)$$

$$f_2 = \frac{c \times n \times \cos^{-1}(\sin\beta l_2 \cos\beta l_3 \tan\beta l_4)}{2\pi\sqrt{\varepsilon_{eff}}\,(l_2 + l_3)} \quad (3b)$$

$$f_3 = \frac{c \times n \times \cos^{-1}\left(-\cos\beta l_2 \sin\beta l_3 \sin\beta l_4\right)}{2\pi\sqrt{\varepsilon_{eff}}\left(l_1 + l_3 + l_4\right)} \tag{4a}$$

$$f_4 = \frac{c \times n \times \cos^{-1}\left(-\cos\beta l_1 \sin\beta l_3 \sin\beta l_4\right)}{2\pi\sqrt{\varepsilon_{eff}}\left(l_2 + l_3 + l_4\right)} \tag{4b}$$

where ε_{eff} is the effective dielectric constant, n the mode number, and c the speed of light in free space.

According to [3], the two transmission zeros, f_1' and f_2', in the case of without the shunt open stubs, can be obtained as:

$$f_1' = \frac{c \times n}{4(l_1 + l_3)\sqrt{\varepsilon_{eff}}} \tag{5a}$$

$$f_2' = \frac{c \times n}{4(l_2 + l_3)\sqrt{\varepsilon_{eff}}} \tag{5b}$$

Comparing Equations (3), (4) and (5), the extra passband can be obtained by the shunt open stubs.

For the first passband, the center frequency f_{center} can be obtained as:

$$f_{center} \approx \frac{f_1 + f_2}{2}$$

According to Equation (5), the center frequency $f_{center'}$, in the case of without the shunt open stubs, can be obtained as:

$$f'_{center} \approx \frac{f_1' + f_2'}{2}$$

Obviously

$$f_{center} < f'_{center}$$

From the analysis above, the center frequency of the filter can be shifted to low frequency by shunt open stubs. Therefore, the shunt open stubs can be used to implement the miniaturization of the half-wavelength resonators filter. However, the bandwidth will also be reduced after miniaturization. In the asymmetric half-wavelength resonators structure, the reduced bandwidth can be compensated to increase the distance of the two transmission zeros on the two sides of the passband.

2.2. Analysis the Resonance Frequency of Asymmetric Half-wavelength Resonators Structure with Shunt Open Stubs by the Method of Equivalent Circuit

Equivalent circuit model is frequently used in microwave devices analysis [19–22]. The equivalent circuit of the asymmetric half-wavelength resonators coupling structure with shunt open stubs is established, as shown in Figure 2.

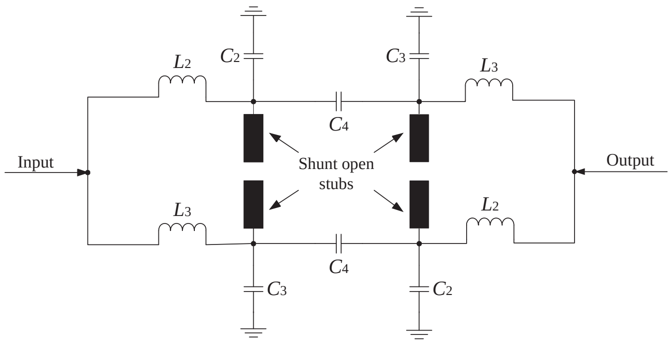

Figure 2. Equivalent circuit of the asymmetric half-wavelength resonators coupling structure with shunt open stubs.

As shown in Figure 2, the resonator is modeled by L_2, C_2 and L_3, C_3. The gap between two half-wavelength resonators is presented by C_4. According to correspondence between the equivalent circuit and Figure 1, we can obtain the relationship

$$f_1' = \frac{1}{2\pi\sqrt{L_2 C_2}} \tag{6a}$$

$$f_2' = \frac{1}{2\pi\sqrt{L_3 C_3}} \tag{6b}$$

The resonance frequency of the half-wavelength resonators is f'_{center}, which can be presented as:

$$f'_{center} = \frac{1}{2\pi\sqrt{(L_3 + L_2)(C_3 + C_2)}} \tag{7}$$

When the length of the shunt open stub is less than quarter wavelength, it is equivalent to capacitance and can be assumed to be C_5. The resonance frequency of the half-wavelength resonators with shunt open stubs is f_{center}, which can be presented as:

$$f_{center} = \frac{1}{2\pi\sqrt{(L_3 + L_2)(C_3 + C_2 + 2C_5)}} \tag{8}$$

Obviously, we can obtain $f'_{center} > f_{center}$. The resonance frequency of the half-wavelength resonator is shifted downward by shunt open stubs.

Comparing Equations (3), (4) and (8) with (5) and (7), we can see that the first passband can be shifted toward low frequency by shunt open stubs, and the second passband can be obtained by shunt open stubs.

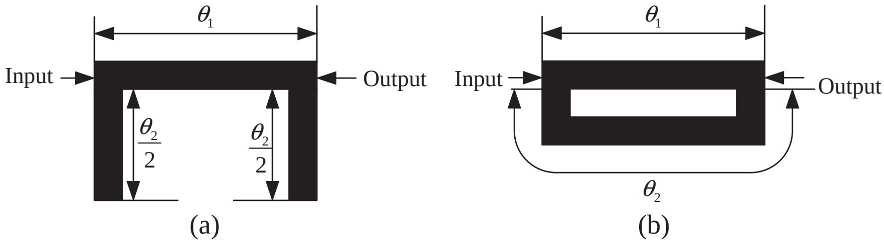

Figure 3. The layout of (a) shunt open stubs and (b) the connected shunt open stubs.

2.3. Harmonic Suppression by Adding Shunt Open Stubs

In this part, in order to suppress harmonic, the resonance frequency of transmission line with shunt open stubs is discussed.

As shown in Figure 3(a), it is a transmission line with length θ_1 and two shunt open stubs with length $\theta_2/2$. The input admittance of the resonator from the open end is

$$Y_{in} = \frac{4\sin(\theta_1 + \theta_2)}{\cos(\theta_1 + \theta_2) + 1} \tag{9}$$

If we let $\theta_1 + \theta_2 = 2\pi$, $Y_{in} = 0$. The transmission line in Figure 3(a) is a resonator with resonance frequency of f_1.

After we connect the two shunt open stubs in Figure 3(a), its structure is shown in Figure 3(b). Figure 3(b) is composed of two shunt transmission lines with the lengths θ_1 and θ_2, respectively. The input admittance of the resonator from the open end is

$$Y_{in} = j\tan\theta_1 + j\tan\theta_2 = j\frac{\sin(\theta_1 + \theta_2)}{\cos\theta_1\cos\theta_2} \tag{10}$$

If we let $\theta_1 + \theta_2 = \pi$, the transmission line shown in Figure 3(b) is a half-wavelength resonator with resonance frequency of f_2.

Then we obtain:

$$f_1 = 2f_2$$

3. APPLICATION

Based on the analysis above, the dual-band and tri-band passband filters are fabricated. The Agilent Technologies' Advanced Design System (*ADS*) is used for filters design. A commercial *TLX-0* dielectric substrate of *TACONIC* with a relative dielectric constant of 2.45 and thickness of 0.79 mm is chosen to fabricate the filters, and Agilent's

N5071c network analyzer is used for measurement. The photograph and responses of initial asymmetric half-wavelength filter are shown in Figure 4 and Figure 5.

3.1. Dual-band Filter Design to Suppress the Harmonic by Shunt Open Stubs

According to Equations (3), (4) and (5), the passband can be obtained by the shunt open stubs, thus, the dual-band filter can be designed by adding shunt open stubs to the resonators. However, the second passband may be interfered by the harmonic. The shunt open stubs can also be used to suppress harmonic.

Firstly, in order to obtain the dual-band filter, the filter with four shunt open stubs is designed, as shown in Figure 6.

As shown in Figure 6, the asymmetric half-wavelength resonators filter with four shunt open stubs is illustrated. The responses of

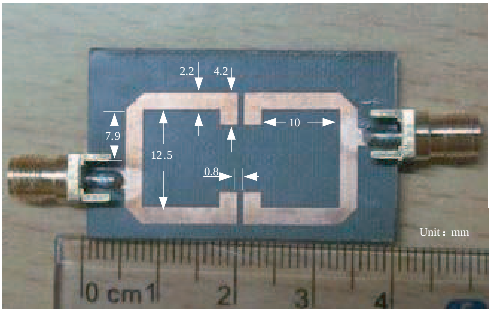

Figure 4. The photograph and size of the asymmetric half-wavelength filter.

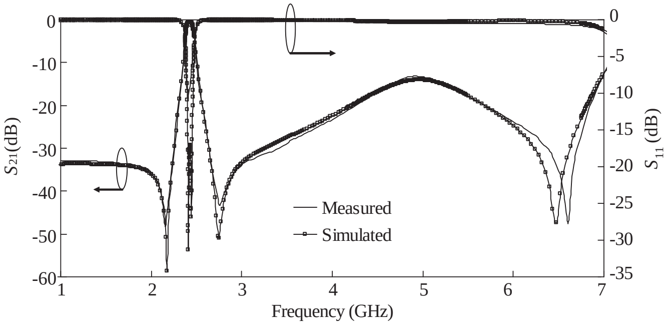

Figure 5. The responses of the asymmetric half-wavelength filter.

the asymmetric half-wavelength resonators filter with four shunt open stubs and without shunt open stubs are illustrated in Figure 7.

From Figure 7, we can see that the second passband is obtained by shunt open stubs, and the first passband is shifted toward low frequency. However, the performance of the second passband is poor. These problems can be overcome by adding another four shunt open stubs, as shown in Figure 8.

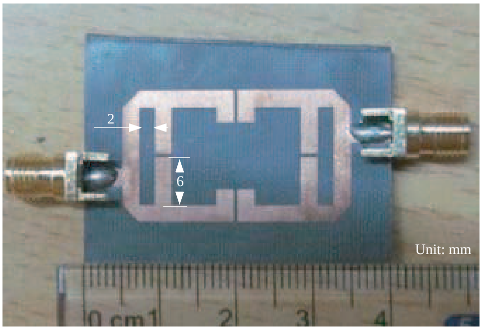

Figure 6. The photograph and size of the asymmetric half-wavelength filter with four shunt open stubs.

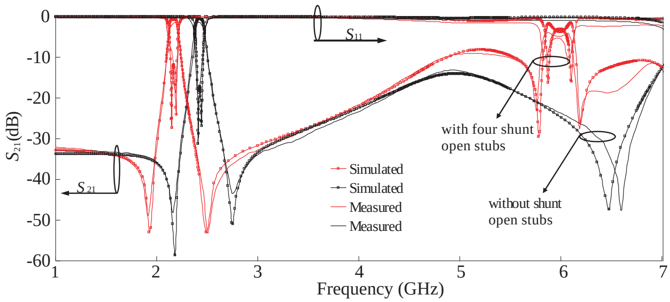

Figure 7. The comparison of the asymmetric half-wavelength resonators filter performance without and with four shunt open stubs.

The responses of the filter with eight shunt open stubs are illustrated in Figure 9. By adding another four shunt open stubs, the harmonic is suppressed, and the second passband is obtained with better performance. As shown in Figure 9, the center frequencies of the dual-band filter are 1.9 GHz and 5.8 GHz with the bandwidths of 40 MHz and 100 MHz, respectively, and the insertion loss is not more than 2.7 dB.

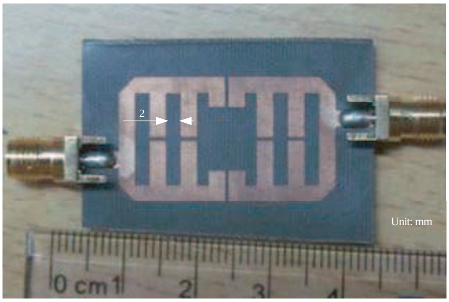

Figure 8. The photograph of the filter with eight shunt open stubs.

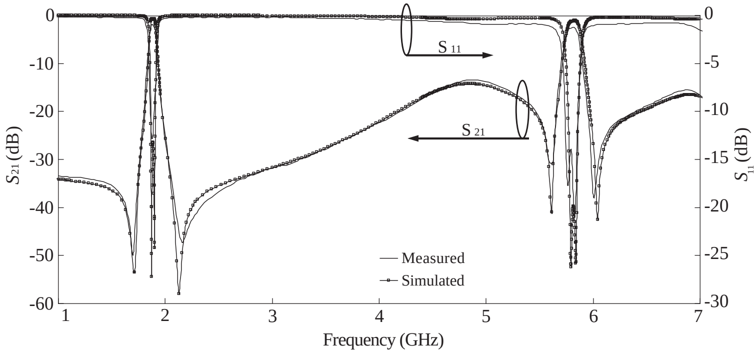

Figure 9. The responses of the filter with eight shunt open stubs.

From the comparison of the first passband of the filters without, with four and with eight shunt open stubs in Figure10, we can see that the first passand is shifted toward low-frequency when the number of the shunt open stubs is increased.

3.2. Tri-band Filter Design

According to Equations (3), (4) and (5), the extra passband can be obtained by adding shunt open stubs. Based on it, the tri-band filter is designed in this section.

Based on the dual-band filter in Figure 8, another four shunt open stubs are added to the filter. The photograph and size of the tri-band bandpass filter is shown in Figure 11. In order to save space, the four extra shunt open stubs are folded, and the responses of the tri-band filter are illustrated in Figure 12.

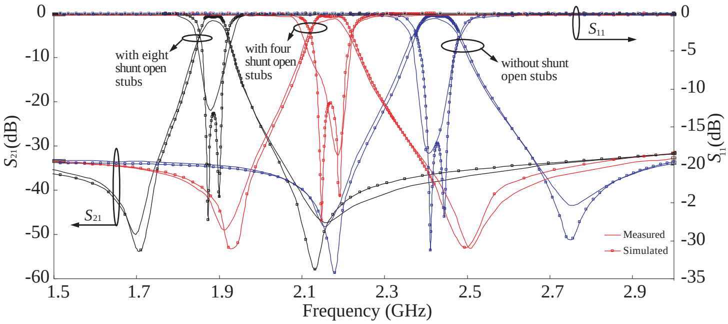

Figure 10. The first passband responses of the filters without with four and with eight shunt open stubs.

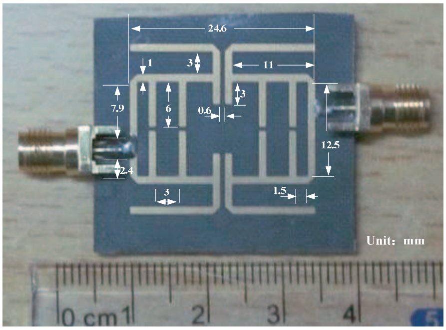

Figure 11. The photograph and size of the tri-band filters.

From Figure 12, we can see that the measured -3dB frequency ranges (fractional bandwidths) for the three passbands centered at 1.51, 4, and 6.26 GHz are 1.484–1.546 GHz (4.1%), 3.9–4.0 GHz (3.4%) and 6.19–6.34 GHz (2.3%), respectively. The measured minimum insertion losses are -2.5, -1.6, and -2.5 dB, and the measured transmission zeros are 1.385 and 1.685 GHz for the first passband, 3.810 and 4.224 GHz for the second band, and 6.104 and 6.481 GHz for the third band, respectively.

3.3. The Compact Filter with Harmonic Suppression

From the analysis in Section 2, the miniature filter can be designed by the shunt open stubs, and Figure 10 also illustrates that the passband can be shifted toward the low-frequency. In short, the asymmetric

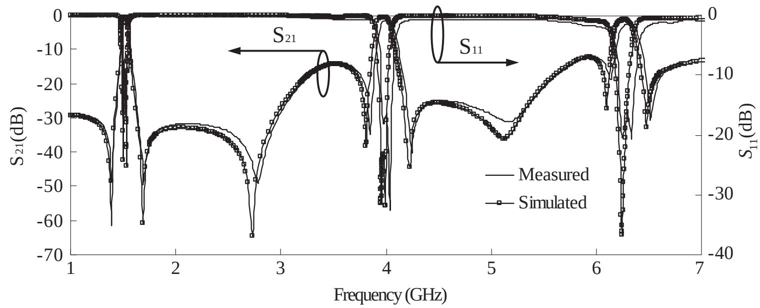

Figure 12. The responses of the tri-band filter.

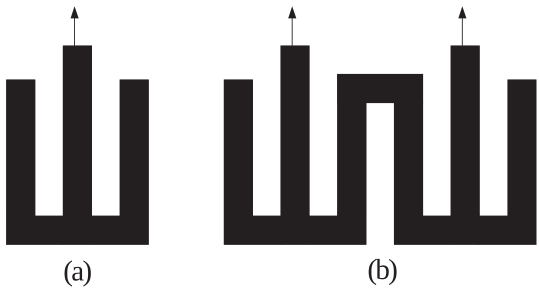

Figure 13. (a) The layout of the T shunt open stub. (b) The layout of the T shunt open stub with harmonic suppression feature.

half-wavelength resonators filter can be miniaturized by the shunt open stubs.

In order to effectively miniaturize the filter, the T shunt open stub is designed, as shown in Figure 13(a). The T shunt open stub can make full use of space. Based on the T shunt open stub, the miniature filter is designed. The layout and size of the filter are shown in Figure 14, and the responses of the filter are shown in Figure 15.

As shown in Figure 15, the center frequency of the filter is 2.4 GHz, and the bandwidth of the filter is 120 MHz. However, there is the harmonic at 4.8 GHz.

Based on the method introduced in Section 2.3, the T shunt open stubs are connected in order to suppress the harmonic, as shown in Figure 13(b). The fabricated filter and its response are shown in Figure 16, and Figure 17, respectively.

Comparing Figure 17 with Figure 15, we can see that the harmonic at 4.8 GHz is suppressed. The center frequency of the filter is 2.4 GHz,

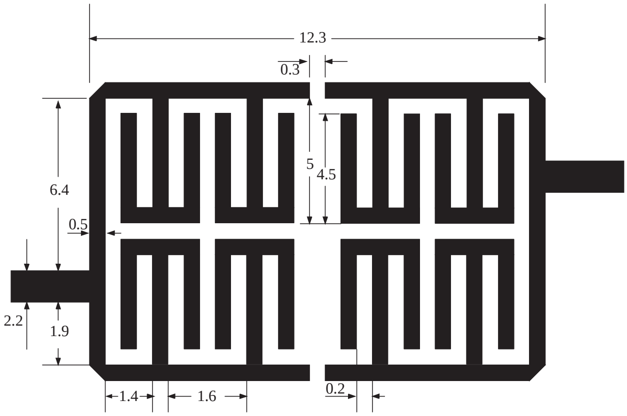

Figure 14. The layout and size of the miniature filter without suppress harmonic (Unit:mm).

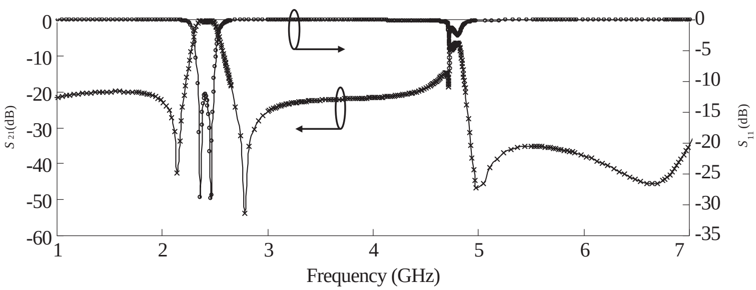

Figure 15. The simulated responses of the compact filter without harmonic suppression.

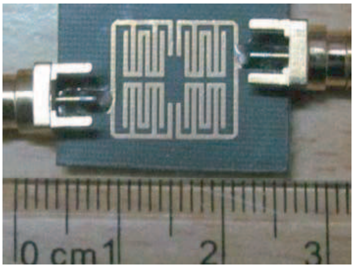

Figure 16. The photograph of the miniature filter with suppress harmonic.

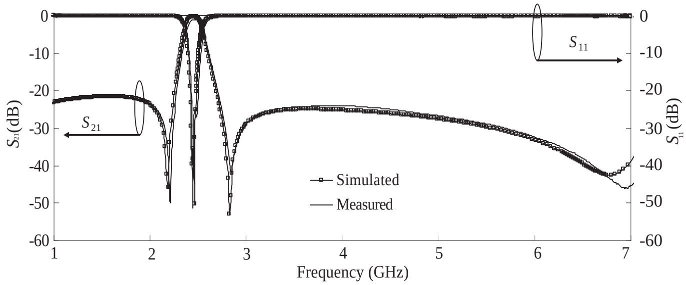

Figure 17. The performance of the filter with harmonic suppress.

the bandwidth of the filter 120 MHz, the insertion loss less than -3 dB, and S_{21} less than -20 dB from 2.8 GHz to 7 GHz. The simulated and measured results agree well.

4. CONCLUSION

The structure of asymmetric half-wavelength resonators with shunt open stubs structure is analyzed by the method of $ABCD$ matrix and equivalent circuit. The multi-band filter can be designed by adding the shunt open stubs. The miniature filter can also be designed by adjusting the length of the shunt open stubs. Finally, the method to suppress harmonic is obtained by designing the structure of the shunt open stubs.

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