Tunable Bandstop Filter Based on Split Ring Resonators Loaded Coplanar Waveguide

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Abstract **─** In this paper, a novel electrical tunable bandstop filter based on coplanar waveguide (CPW) loaded with split ring resonators (SRRs) is proposed. The unit cell of the bandstop filter is formed by etching single SRR on the CPW back substrate side, and the SRRs can be excited by the CPW slot's magnetic field. Lumped equivalent circuit models are developed to analyze the frequency responses, and it shows that by loading the common cathode varactor diodes at the split region of the SRR outer ring, the resonant frequency of the bandstop filter can be electronically adjusted by tuning the reverse voltage of the varactor diodes. The prototype with overall size of 26.6 mm × 50 mm × 0.508 mm was designed and fabricated to validate the proposed structure. The measured tunable resonant frequency of the fabricated bandstop filter is from 2.19 GHz to 2.31 GHz while a reverse bias voltage is varying from 0 V to 30 V. It also shows that the -10 dB bandwidth is less than 45 MHz.

Index Terms **─** Coplanar waveguide, tunable bandstop filter, and varactor loaded split ring resonators.

I. INTRODUCTION

Recently, it is very popular to add tuning ability to conventional microwave components to realize electrical tunable/reconfigurable microwave components [1-9], which can well satisfy the requirements of modern multi-mode and programmable wireless systems. Bandstop filter is one of the most important microwave components to filter out the unwanted signals or nearby huge power signals, and avoid frequency aliasing in the intermediate frequency [8-11]. Therefore, tunable bandstop filters will play a key role in the future wireless systems. Split ring resonators (SRRs) are small resonant elements with a high quality factor at microwave frequency. Since SRRs can be easily implemented by planar technology, several compact microwave components using SRRs and complementary split ring resonators (CSRRs) have been proposed based on microstrip technology and coplanar waveguide (CPW) technology, i.e., lowpass and bandpass filter [12], metamateral devices [13-15], and bandstop filters [16].

In this work, a novel tunable bandstop filter based on CPW loaded with SRRs is presented. The unit cell of the bandstop filter is formed by etching a single SRR on the CPW back substrate side. By loading the common cathode varactor diodes at the split region of the resonator's outer ring, the resonant frequency of the bandstop filter can be electronically adjusted by tuning the reverse voltage of the varactor diodes.

II. FILTER DESIGN

Figure 1 shows the structure of the proposed bandstop filter with two unit cells, and a single SRR is etched in the CPW central back substrate for each unit. As a single SRR is etched in the central back substrate for each unit, it provides an opportunity for acquiring low resonant frequency by modifying the dimensions of the SRR, while the working frequency range of the conventional CPW metamaterial transmission line unit cell with a pair of SRRs is limited by the CPW strip layout [16]. To analyze the performances of this structure, Rogers 5880 substrate with a relative permittivity of 2.2, a loss tangent of 0.0009 and

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thickness of 0.508 mm is chosen for our designs. Since SRR is a planar magnetic resonator, which can be excited by an axial magnetic field [17]. Therefore, the strong magnetic coupling between the CPW and the SRRs is expected in the vicinity of resonance, thereby, a stopband is generated in the frequency response. Since SRR is a sub-wavelength resonator, lumped circuit model can be used to study the characters of the filter. The proposed lumped-element equivalent circuit model for the bandstop filter is depicted in Fig. 2 (a). In this model, the SRR is modeled as the average inductance L_r, the loss resistance R_r and the average capacitance C_r. The average capacitance C_r can be approximately obtained usin equation (1); [1, 18],

$$C_r = \frac{C_g}{4} + \frac{C_o + 0.4C_i}{2\pi} \tag{1}$$

where C_g is the capacitance due to the gap of the outer and inner rings, C_o and C_i are the capacitance of the outer ring split region and the inner ring split region, respectively. The CPW is modeled as a low pass network that contains the inductance L_{sin}, L_s, and L_g, and the capacitance C_{sin} and C_s. The magnetic coupling effect is denoted by M.

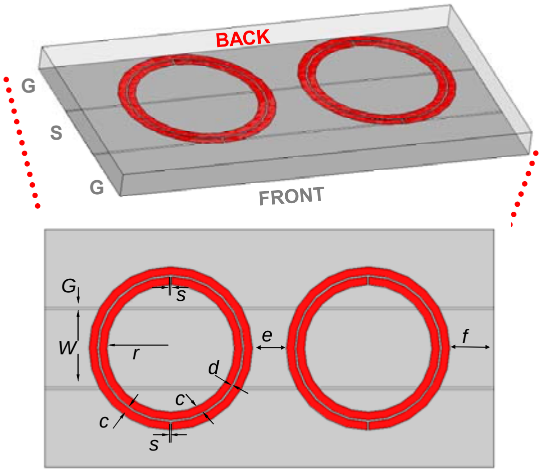
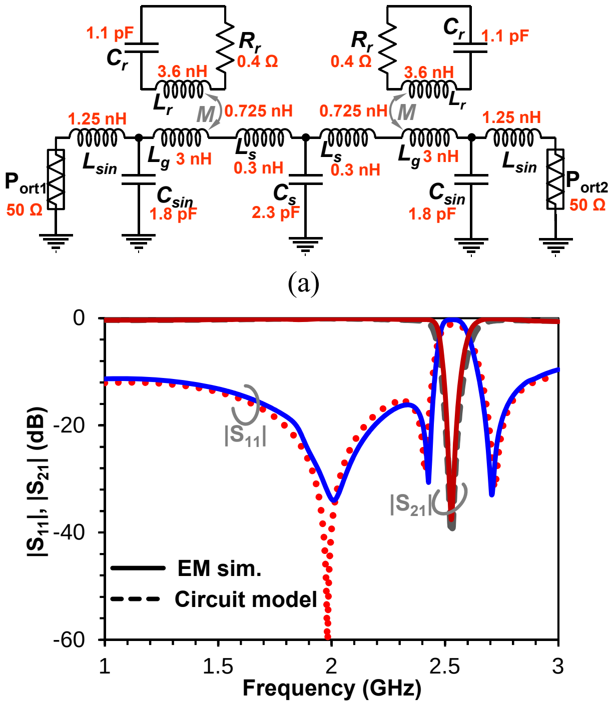


Fig. 1. Configuration of the bandstop filter. (The width of the CPW signal strip W = 8.7 mm, the gap of the CPW signal strip G = 0.2 mm, the width of the SRR strip c = 0.9 mm, the gap between the SRR inner and outer rings d = 0.2 mm, the radius of the inner ring r = 7.1 mm, the split of the SRR rings s = 0.2 mm, the distance between the SRR edge e = 3.8 mm, the distance between the SRR edge, and the CPW terminal f = 4.9 mm).

The transmission responses of the proposed bandstop filter in Fig. 1 are simulated and investigated by full-wave electromagnetics (EM) simulation software (Ansoft's HFSS10) using finite-element method and the resonant characteristics of the filter are presented in Fig. 2 (b). The simulated resonance frequency is 2.53 GHz, and a frequency bandgap is obtained profiting from the resonant of the SRRs. By using the curve-fitting technology we have extracted the parameters from the equivalent circuit model network as shown in Fig. 2 (a). The circuit model simulated results are shown as the dash curve in Fig. 2 (b), which match the EM simulated results very well. Therefore, we can conclude that the equivalent circuit model is basically correct and is fully capable of explaining the transmission characteristics of the structure. In view of this model, the lowest resonant frequency (f_r) of the bandstop filter can be written as,

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}}. \tag{2}$$



(a)

(b)

Fig. 2. EM simulated and lumped circuit model calculated results of the bandstop filter: (a) the lumped circuit model of the bandstop filter, and (b) the lumped circuit model calculated results and the EM simulated results.

Generally, the split capacitances of the SRR are ignored since they are relatively small and only the gap capacitance is taken into account when modeling the SRR. However, when a capacitor is loaded in the split region, the effect of the split capacitance gets stronger on the resonant frequency [1], and the capacitance of the SRR loaded with varactor should be written as,

$$C_{rt} = C_r + \frac{C_{\mathrm{var}}}{2\pi} \tag{3}$$

where C_{var} is the varactor capacitance.

Figure 3 (a) shows the lumped circuit model of the tunable bandstop filter based on the SRR loaded with varactor, and the resonant frequency (f_{rt}) of the tunable bandstop filter, which can be obtained using equation (4),

$$f_{rt} = \frac{1}{2\pi\sqrt{L_r C_{rt}}} = \frac{1}{2\pi\sqrt{L_r\left(C_r + \frac{C_{\mathrm{var}}}{2\pi}\right)}} \ . \tag{4}$$

Therefore, the frequency tuning radio of the circuit can be expressed as,

$$R = \frac{f_{rt(\max)}}{f_{rt(\min)}} = \sqrt{\frac{2\pi C_r + C_{\mathrm{var(max)}}}{2\pi C_r + C_{\mathrm{var(min)}}}} \ , \tag{5}$$

where $f_{\mathrm{rt(max)}}$ is the maximum central frequency under the minimum varactor capacitance $C_{var(min)}$, and $f_{rt(min)}$ is the minimum central frequency under the maximum varactor capacitance $C_{var(max)}$.

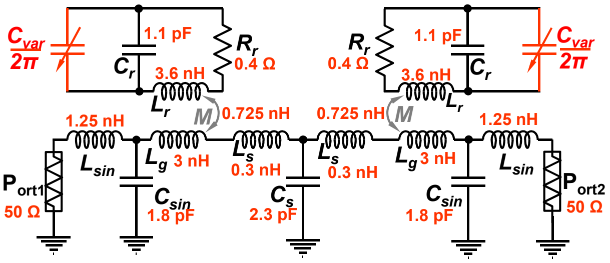
It can be seen from equation (5) that the tuning ratio of the central frequency of the bandstop filter is reduced by C_r. However, for a constant central frequency, small C_r will increase the requirement of the inductance L_r, therefore leading to a large area of SRR layout. Fig. 3 (b) shows the circuit model calculated transmission characters under different value of C_{var} (0.315 pF ~ 1.335 pF), and a 158 MHz (2.316 GHz ~ 2.474 GHz) resonant frequency tunable range is obtained. It can be seen from equation (4) and Fig. 3 (b) that the frequency performance of the bandstop filter can be tuned by placing the varactor at the split region of the SRR outer ring. Figure 3 (c) shows the configuration of the proposed tunable bandstop filter loaded with semiconductor varactor diodes. Since single varactor diode can be DC shorted by the outer ring, and a DC disconnected capacitor may reduce the tune radio of the varactor. In this work, the common cathode connection of the varactor diodes is adopted to deal with this problem. A tunable reverse bias voltage source with inductor choke is connected between the cathode and anode of the varactor diodes. The resonant frequency of the proposed bandstop filter can be adjusted by tuning the reverse bias voltage.

To electronically tune the stop-band of the bandstop filter, SMV-1405 varactor diode from SKYWORKS in SC-70 package has been adopted as a tuning element, and common cathode diode connection is used to avoid DC straightforward of the circuit. The single varactor capacitance is 0.63 pF and 2.67 pF at 30 V and 0 V reverse bias voltage, respectively, and the relative capacitance change is less than 5 % while the temperature ranging from -40° C to 85° C. Figure 3 (d) shows the simulated performance of the proposed filter under different reverse bias voltages from 0 V to 30 V. The simulated tunable resonant frequency of the bandstop filter is from 2.28 GHz to 2.425 GHz.

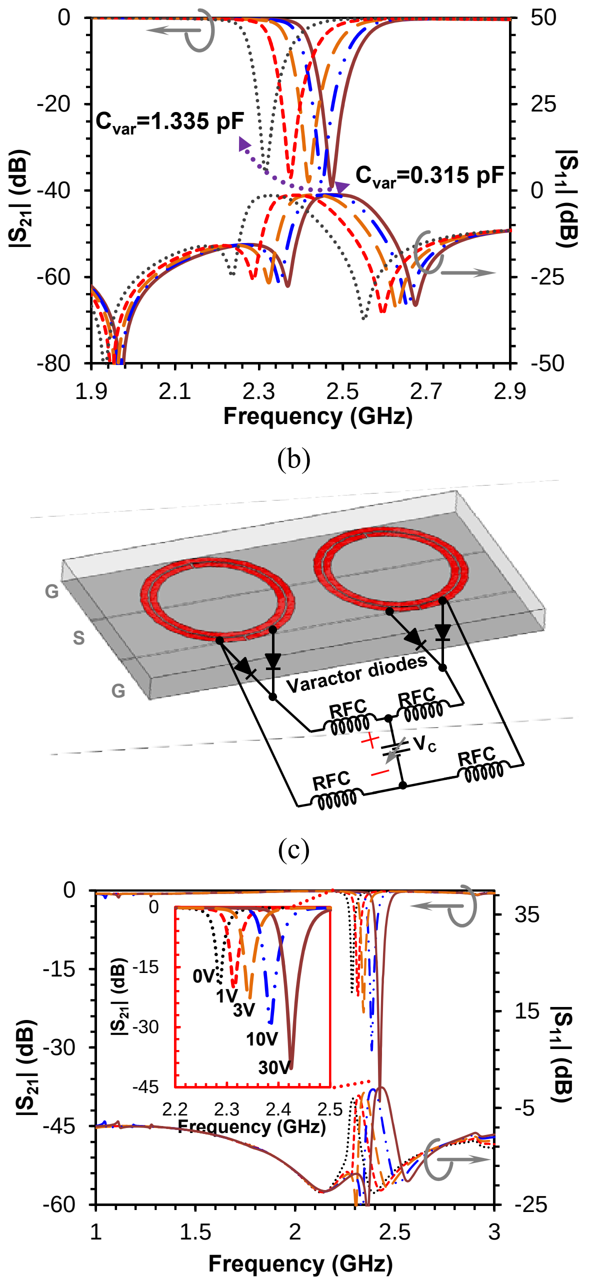
III. MEASUREMENT

To confirm and demonstrate the tuning characteristics of the stop-band, the structure shown in Fig. 3 (c) is fabricated on a *Rogers* 5880 substrate. The photograph of the fabricated filter is proposed in Fig. 4. The overall size of the prototype is 26.6 mm × 50 mm × 0.508 mm. The measurement is accomplished with *Agilent* E5071C network analyzer and *Agilent* E3634A tunable DC power supply.

Figure 5 (a) shows the simulated and measured *S*-parameters of the bandstop filter without loading the varactors. It can be observed that the stop-band insertion loss is better than 40 dB, the central frequency is 2.458 GHz, and the retern loss of the pass-band is better than 10 dB. There is a 100 MHz frequency shift between the simulated and measured results in Fig. 5 (a) due to the inaccuracy in fabrication and implementation, and the parameters leading to skew values.



(a)



(b)

(c)

(d)

Fig. 3. Configuration and frequency responses of the tunable bandstop filter: (a) the circuit model, (b) the circuit model calculated tunable results, (c) the configuration of the tunable bandstop filter, and (d) the simulated *S*-parameters of the filter loaded with SMV1405 varactor diode under different reverse voltages.

Figure 5 (b) and (c) show the measured *S*-parameters of the fabricated tunable bandstop filter. The measured tunable resonant frequency of the bandstop filter is from 2.19 GHz to 2.31 GHz with a -10 dB bandwidth less than 45 MHz. The results show that the rejection of the stop-band is reduced when the reverse bias decreases. From equation (6), it can be seen that this is because the large capacitance or the small inductance of the SRR, which can result in a low quality value (*Q*) due to the parasitic resistance R_r of the SRR,

$$Q = \frac{1}{2\pi R_r}\sqrt{\frac{L_r}{C_r + C_{\mathrm{var}}/2\pi}}\ . \tag{6}$$

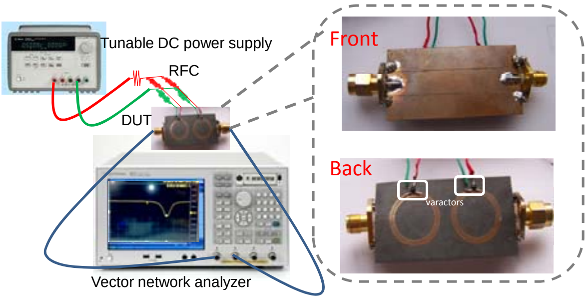
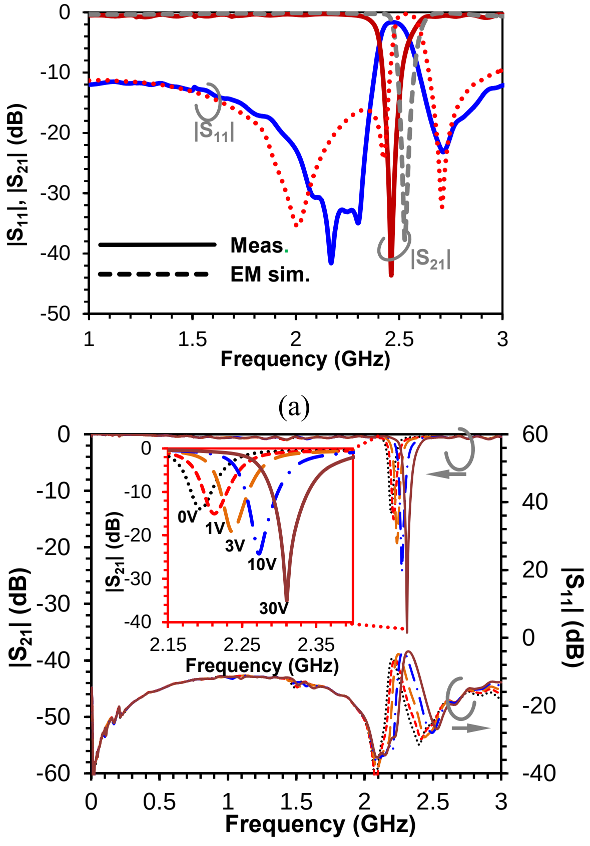
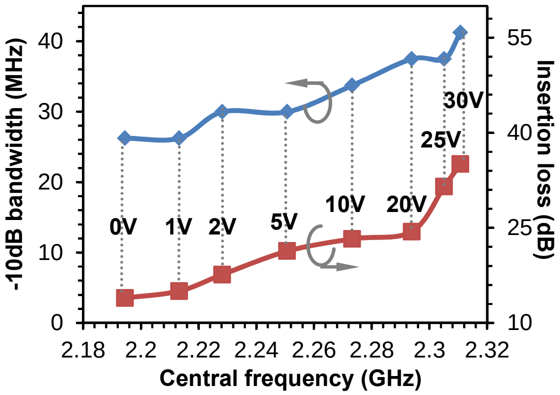


Fig. 4. The Photograph of the fabricated tunable bandstop filter.



(a)

(b)



(c)

Fig. 5. The *S*-parameters of the fabricated filter: (a) the simulated and measured *S*-parameters of the bandstop filter without loading the varactors, (b) the measured *S*-parameters of the tunable bandstop filter under different reverse voltages, and (c) the -10 dB bandwidth, resonant frequency and insertion loss of the tunable stop-band under different reverse voltages.

IV. CONCLUSION

A novel tunable bandstop filter based on coplanar waveguide (CPW) loaded with split ring resonators (SRRs) is proposed, and lumped equivalent circuit analysis models are developed. The unit cell of the bandstop filter is formed by etching a single SRR on the CPW back substrate side. Comparing with the conventional CPW metamaterial transmission line unit cell with a pair of SRRs whose resonant frequency is limited by the CPW strip layout, the proposed structure provides an opportunity for acquiring low resonant frequency by modifying the dimensions. By loading common cathode varactor diodes at the split region of the SRR outer ring, the resonant frequency of the bandstop filter can be electronically tuned by adjusting the reverse voltage of the varactor diodes. The prototype with overall size of 26.6 mm × 50 mm × 0.508 mm was designed and fabricated. The tunable bandstop filter with a measured tunable resonant frequency from 2.19 GHz to 2.31 GHz under a bias voltage of 0 V to 30 V has been presented and the -10 dB bandwidth is less than 45 MHz.

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