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Compact frequency and bandwidth tunable stopband filters using split ring resonators and varactors coupled transmission line

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ABSTRACT

Two highly compact tunable stopband filters using microstrip transmission lines coupled with split ring resonators (SRRs) and varactor diodes are presented. Frequency or bandwidth tuning capability of each device is demonstrated. The frequency tunable filter, realized by a single stage, shows a wide tuning range of 19.8% with a maximum bandwidth of 5% and an insertion loss of approximately 20 dB at 4 GHz. The bandwidth tunable filter, realized by double stages, shows a 10-dB bandwidth of 19–34% with a biasing voltage of 0–10 V. The implemented frequency tuning and bandwidth tuning devices show a significant area reduction of 60.1% and 53.5%, respectively, in comparison with a similar frequency or bandwidth tunable structure presented by others. Equivalent circuit models are presented. The measured *S*-parameters are in good agreement with simulated ones.

1. Introduction

Microwave stopband filters are widely used for distortion reduction in transmitters due to their effective suppression of spurious signals. For the design of stopband filters, the split ring resonator (SRR) proposed by Pendry et al. [1] has been an attractive structure due to its negative magnetic permeability and small device size. After its experimental demonstration of SRR as a metamaterial unit [2], many new filter implementations using SRRs and complementary split ring resonators (CSRRs) have been introduced.

Baena et al. [3] used SRR and CSRR structures to implement waveguide and coplanar waveguide (CPW) stopband filters. Further, Radonic et al. [4] studied the effect of the orientation of the SRRs loaded on microstrip lines. These applications used *LC* resonance of the SRR, where a left-handed behavior was expected just above the resonant frequency of the SRR with a quite narrow rejection bandwidth. To improve the rejection bandwidth, Garcia-Garcia et al. [5] and Peng et al. [6] employed several SRRs with different lengths, resulting in an increased device size due to the large number of resonators used.

Another method to effectively improve the rejection bandwidth is to use tunable SRRs. Gil et al. introduced a varactor loaded SRR (VLSRR) filter [7], which could control the resonant frequency and improve the bandwidth by applying different bias voltages to the diodes [8]. Various structures for tunable stopband filters using varactor loaded SRRs [9,10] and CSRRs [11] are also suggested, while achieving only 2% fractional bandwidth with a third order tunable filter. Namely, those filters showed a relatively large size and a narrow bandwidth. Meantime, in the previous implementations of the filters with SRRs, a narrow gap between the transmission line and the SRRs was adopted, which imposed practical difficulties in fabrication and associated circuit modeling. Tunable stopband filters also could be designed using RF-MEMS switches and micro-electro mechanical deflectable cantilever type rings [12,13]. Although they realized stopband filters using microfabrication, the fabrication process is quite complex and expensive.

In this paper, two highly compact tunable stopband filters, where one has frequency tuning and the other does bandwidth tuning are presented. The filters consist of a microstrip transmission line, SRRs, and coupling varactors in the gap between the microstrip line and the SRRs. Different from other approaches, a relatively large gap between the microstrip transmission line and the SRRs is employed to alleviate fabrication difficulty and associated dimensional uncertainty and tolerance, which are commonly faced in the conventional narrow gap approaches [7–11]. Discrete coupling varactors placed in the enlarged gap facilitate effective tuning of resonant frequency and bandwidth. Also this approach does not require a large number of stages to achieve a large bandwidth, resulting in the reduction of overall device size.

2. Filter designs

The frequency and bandwidth tunable SRR stopband filters are shown in Fig. 1(a) and (b), respectively. The designed filters are implemented on an Arlon Copper Clad 250 substrate with a dielectric constant ε_r of 2.5 and a thickness of 0.508 mm. Filter design

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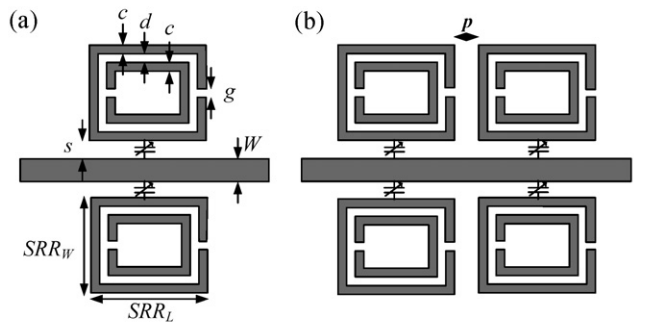

Fig. 1. Geometries of (a) a frequency tunable SRR stopband filter and (b) a bandwidth tunable SRR stopband filter.

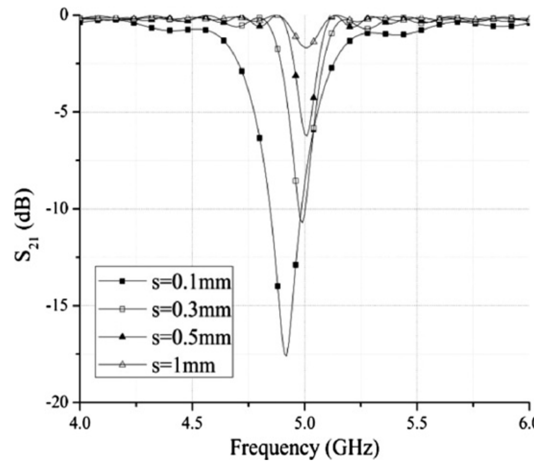

Fig. 2. Simulated S_{21} of a conventional SRR stopband filter as a function of *s*.

is assisted by a commercial EM simulator, CST Microwave Studio (MWS, CST, Inc.). The resonant frequency of the SRR structure behaving as an *LC* resonant circuit driven by an extended electromotive force is given by [14],

$$\omega_0 = \sqrt{\frac{2}{\pi r_0 \mathrm{LC}}} \tag{1}$$

where *L* is the total inductance of the SRR, *C* is the capacitance between the rings and r_0 is the average radius of the considered SRR. The optimized dimension of an SRR for 4 GHz is $c = d = g = 0.5$ mm, $\mathrm{SRR}_W = 5.25$ mm and $\mathrm{SRR}_L = 6.75$ mm (Fig. 1). The width of the transmission line *W* is 1.44 mm for a characteristic impedance of 50 Ω. To figure out the influence of the gap between the transmission line and resonators, we have changed its value from 0.1 mm to 1 mm. Fig. 2 shows the simulated insertion loss (*IL*) of a conventional SRR stopband filter as a function of gap *s*. The narrower gap, the better insertion loss performance for stopband could be obtained with a strong electromagnetic coupling between the transmission line and resonators. From the simulation results, the gap needs to be less than 0.3 mm to achieve a maximum *IL* of 10 dB and less than 0.1 mm for a maximum *IL* of 20 dB. Often, the implementation of a gap less than 0.1 mm is challenging to achieve by a conventional PCB milling machine patterning approach.

In this work, a gap of 1 mm is adopted, by which the inherent inductive and capacitive coupling between the transmission line and the SRRs is greatly suppressed, while the filter circuit can be effectively controlled by attached discrete varactors in the gap. This approach provides large frequency tuning. Also, the large gap facilitates easy fabrication.

Fig. 3(a) shows the electromagnetic (EM) simulation results of the frequency tunable SRR stopband filter with different capacitance values. When the capacitor values vary from 0.5 pF to 3 pF, the resonant frequencies are shifted from 4.17 GHz with a 10 dB-bandwidth of 3.6% to 3.73 GHz with a 10 dB-bandwidth of 14.4%. The maximum rejection level increases from 21 dB to 48 dB. This result shows that wide frequency tuning with wide bandwidth can be achieved by using only a pair of SRRs.

In order to further control the bandwidth of the filter, four SRRs and four discrete capacitors are used as shown in Fig. 1(b). The two capacitors of the first stage have the same capacitance value. The two capacitors of the second stage have the same capacitance value, but a different value from that of the first stage capacitors. Since a different coupling capacitance in each stage produces a different resonance frequency at each stage, the bandwidth of the filter can be conveniently controlled by choosing different resonant frequencies in those two stages. Also, note that the bandwidth can be affected by the coupling between two stages. For example, the geometrical parameters previously obtained are kept the same while the distance between two adjacent SRRs *p* has been increased from 1 mm. The bandwidth increases by increasing the distance *p*, but the improvement is not significant whereas the device size becomes bigger. So we keep the distance between two SRR stages as 1 mm and do not change it while we electrically tune the device with varactors.

Fig. 3(b) shows the EM simulation results of the bandwidth tunable SRR stopband filter with various capacitance values. The capacitance value connected to the first stage (the left SRR stage) is fixed at 0.5 pF, while the one connected to the second stage (the right SRR stage) is varied from 0.5 pF to 3 pF. When the capacitance values of both stages are the same, in this case 0.5 pF, the

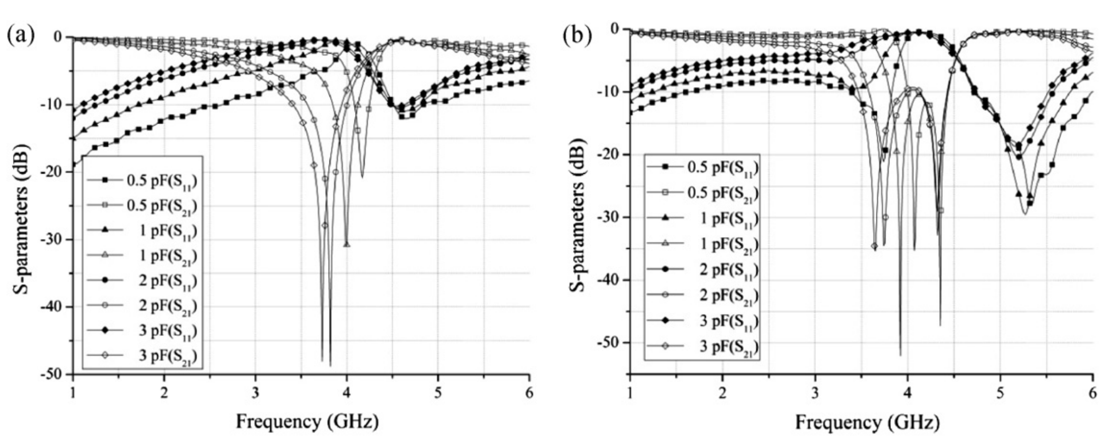

Fig. 3. Simulated *S*-parameters: (a) a frequency and (b) a bandwidth tunable SRR stopband filter with different capacitance values.