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NOVEL NESTED SPLIT-RING-RESONATOR (SRR) FOR COMPACT FILTER APPLICATION

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Abstract—In this paper, a novel miniaturized nested split-ring resonator (SRR) structure is proposed. The nested SRR structure incorporates multiple split-ring resonators in a compact nested structure, and has more split gaps than the conventional SRR structure. Compared with conventional SRR, this nested SRR has better performance on miniaturization and high-Q value. To verify good characteristics of the proposed resonator structure, a novel resonator-embedded band-pass filter (BPF), which is constructed by four nested resonators, is designed. This novel BPF is very compact and has good in- and out-band performances. The proposed nested SRR unit cell has size of $0.04\lambda_g \times 0.04\lambda_g$ (λ_g is the signal wavelength at the 2.4 GHz central frequency of the pass-band). Its stop-bands are extended $0.5 \sim 2$ GHz at lower band and $2.7 \sim 5.4$ GHz at upper band with a rejection level of higher than 20 dB, and its 1-dB pass-band is $2.2 \sim 2.55$ GHz with 1.8 dB optimized insertion loss. The measured and simulated results are well complied with each other.

1. INTRODUCTION

With the rapid development of wireless communication systems, compact size, low losses, high selectivity and low cost are the goals for modern applications. In recent years, the artificially structured metamaterials, have been proposed theoretically by Pendry et al. [1] and demonstrated experimentally by Smith et al. [2] have attracted much attention and grown exponentially. Split-ring resonator (SRR) structure is one of the metamaterial resonant particles, and it is small resonant element with high Q-factor at microwave frequencies. The

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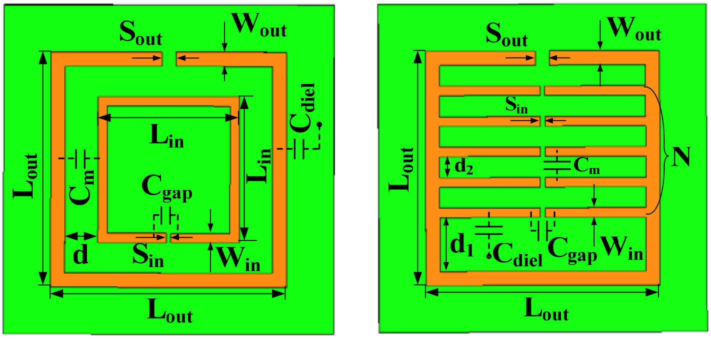
equivalent-circuit models for SRR structure, as well as its exciting through the planar transmission line, are studied in detail in the previous work [3]. Due to its peculiar electronmagnetic responses, SRR structure opens possibilities to form various structures with novel applications [4–9]. However, to high-level miniaturized applications the conventional SRR structure exhibits larger size and higher resonance frequencies, especially at low-frequencies. So such techniques would be restricted in these applications. In response to this need, a compact cross-coupled filter using improved SRR based on stepped impedance resonator was proposed, and the improved SRR unit cell only has size of $0.108\lambda_g \times 0.108\lambda_g$ [10].

In this paper, a novel SRR structure, which incorporates multiple split-ring resonators in a compact nested structure, is proposed. The nested SRR increases the split gaps of the SRR, and results in increasing the high-field region, improving the Q-factor and decreasing the resonance frequency. Compared with conventional SRR, the nested structure has better performance on miniaturization. The nested SRR unit cell has size of $0.04\lambda_g \times 0.04\lambda_g$ (λ_g is the signal wavelength at the resonance frequency). Moreover, a novel resonator-embedded bandpass filter, which is constructed by four proposed nested resonators, is designed and realized, and the good characteristics of the novel resonator structure have been verified by experiment results. It shows that the proposed nested SRR structure is very suited for compact filter applications using various resonator-embedded or cross-coupled filter techniques.

2. THE NESTED SPLIT-RING RESONATOR

The schematic illustration of the conventional and nested SRR structure proposed in this paper are shown in Figure 1. In the proposed structure, multiple split-ring resonators are incorporated in the compact nested structure, and share the same sides except where the gaps are located. The bottom line of the structure is connected, and it confers continuity in the nested design [11]. The SRR structure can be regarded equivalently as a LC resonator with a resonance frequency $f_0 = (2\pi\sqrt{LC})^{-1}$, where the inductance results from the current path on SRR structure and the capacitance depends on the gap dimensions of the SRR structure [3]. Therefore, changes in f_0 of SRR structure can be achieved by changing the capacitance or inductance. In the conventional SRR structure as shown in Figure 1(a), L_{out}, L_{in}, W_{out}, W_{in}, S_{out} and S_{in} represent the length, the width and the spacing across the gap of outer coil and inner coils, respectively. In the context of a design with fixed area size (L_{out} is constant), increasing



(a) (b)

Figure 1. Schematic illustration of the SRR structures. (a) Conventional SRR. (b) Proposed nested SRR.

L_{in} increases the capacitance between substrate and metal (C_{diel}), and increasing W_{in} and W_{out} increases the capacitance between gaps (C_{gap}), which decrease the resonance frequency. Besides, increasing S_{in} and S_{out} decreases C_{gap}, thus, increasing the resonance frequency. However, making L_{in} too much closer to L_{out} decreases Q-factor due to the increased parasitic capacitance. Moreover, the number of coils or gaps can only increase to some extent values in the limited area, resulting in a limited decrease of the resonance frequency.

The advantage of the proposed nested SRR structure is its ability to obtain more available split gaps to increase the capacitance, which results in a reduction of the resonance frequency and an improvement of the Q-factor. The design parameters of the nested SRR are shown in Figure 1(b), d_1 is the distance between the bottom line and the bottom comb, and d_2 is the distance between the nested combs. The width of the outer coil is W_{out} and the width of the nested comb is W_{in}. The spacing across the gap of the outer coil and that of the nested combs are S_{out} and S_{in}, respectively. L_{out} is the length of the outer coil. Similar to the conventional SRR structure, increasing W_{in} and W_{out} decreases the resonance frequency, and increasing S_{in} and S_{out} increases the resonance frequency.

Different from the conventional SRR structure, the proposed nested SRR structure, which exhibits excellent performances, depends dramatically on the numbers of the nested split gap N due to the realization of a larger C_{gap} in a compact area. Thus, N is the most important parameter for determining the resonance frequency of the nested SRR. Besides, to obtain the sufficient C_{diel}, which serves as the distributed capacitance, a dielectric substrate with high relative permittivity is also an important factor. In this paper, Taconic CER-10 substrate with a relative permittivity of 9.5 and a thickness of 0.635 mm is used.

The strong surface currents pass through the communal sides of the nested SRR structure, whereas no surface currents flow through the gaps [12]. This results in a build-up of charge across the gap with the energy stored as a capacitance (C_{gap}), consequently forming the concentrated areas of the electric field at the resonance frequency, as shown in Figure 2. Some performances of the nested SRR structure with constant L_{out} (5 mm) and different split gaps N are shown in Table 1.

It is obtained from Table 1 that as N increases, the resonance

Table 1. Performances of the nested SRR with constant L_{out} (5 mm) and different split gaps N.

N	W_{in} (mm)	d_1 (mm)	d_2 (mm)	Resonance frequency (GHz)	Q-factor
0	0.15	4.6	/	3.3	172
5	0.15	2.6	0.25	2.48	159
8	0.15	1.4	0.25	2.33	159
10	0.15	0.6	0.25	2.28	153
12	0.15	0.2	0.25	2.26	128
12	0.15	1	0.15	2.26	153
15	0.15	0.1	0.15	2.32	110

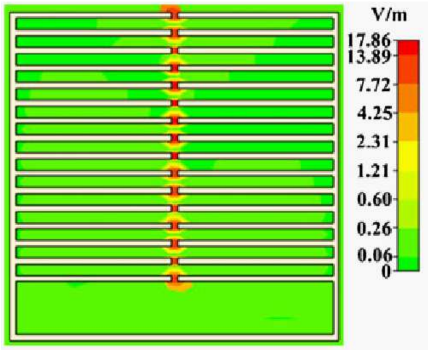


Figure 2. Electric field distribution of the proposed nested SRR structure.

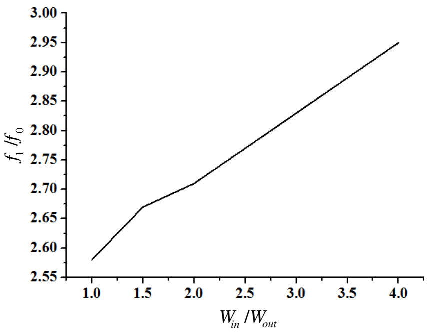


Figure 3. Performances of nested SRR with different impedance ratio (W_{in}/W_{out}).

frequency reduces from beginning, due to the increasing both C_{gap} and C_{diel}. But when N increases to a certain extent, the resonance frequency keeps intact or increases inversely, which indicates the N attains to a saturated state. It can be ascribed to the increase of parasitic capacitance effects. When N is small and the distance between the combs is large, the fringing effect does not occur. In this case, the total capacitance of the nested SRR is approximately equal to the shunt of all C_{gap} and C_{diel}, consequently resulting in the decrease of the resonance frequency as the increase of N. When the combs are close to each other, the fringing electric field exists between the combs. So resulting in that both C_{gap}, C_{diel} and mutual capacitances C_m between the combs increase as N increases, but the total capacitance is reduced due to the series between C_{gap} and C_m, which consequently results in the increase of the resonance frequency. Another important parameter is d_1. Decreasing d_1 as much as possible to decrease the resonance frequency, which is similar to the case of increasing N. If d_1 is decreased, then N is increased. But d_1 should be larger or equal to $2d_2 + W_{in}$ so that parasitic capacitance does not dominate to decrease Q-factor.

Furthermore, the proposed nested SRR structure inherits some excellent features of the stepped impedance resonator (SIR) structure due to the separate parameters W_{out} and W_{in}. The corresponding spurious frequency response can be adjusted by changing the impedance ratio of nested combs and outer coil. It adds a new degree of freedom for filter design. Figure 3 shows the performances of nested SRR with different impedance ratio (W_{in}/W_{out}), where f_0 and f_1 represent the central frequencies of the fundamental mode and the lowest spurious mode of the nested SRR structure. It is obtained from Figure 3 that increasing the ratio of W_{in}/W_{out} can increase the ratio of f_1/f_0.

3. COMPACT BAND-PASS FILTER BASED ON NESTED SRR

To verify good characteristics of the proposed nested SRR structure, a novel resonator-embedded band-pass filter, which is constructed by four proposed nested SRR unit cells, is designed as shown in Figure 4. The nested split gap number is 10 and the $50\,\Omega$ feed lines are terminated with standard SMA connectors to facilitate the measurement. Optimized parameters for the band-pass filter are listed in the Table 2. The coupling of resonator unit cells can be tuned by controlling parameter g_1, g_2 and B, and the external coupling can be tuned by parameter M, L and W_o.

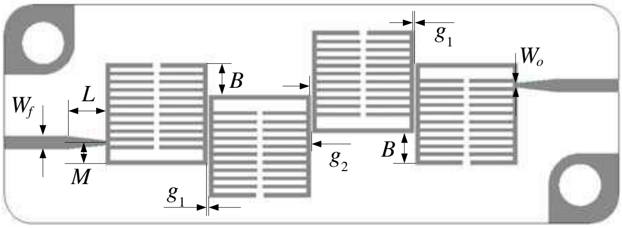


Figure 4. Proposed band-pass filter configuration.

Table 2. Optimized parameters for the proposed band-pass filter (units: mm).

L_{out}	W_{out}	W_{in}	S_{out}	S_{in}	d_1	d_2
5	0.2	0.15	0.4	0.3	0.6	0.25
W_f	W_o	L	M	g_1	g_2	B
0.62	0.2	2	1.1	0.1	0.1	1.6

The proposed nested SRR filter is fabricated as shown in Figure 5. Each nested SRR unit cell has size of $1/25\lambda_g$ and the total length of the proposed filter is about $1/5\lambda_g$ (λ_g is the signal wavelength at the central frequency of the filter). The filter is measured by an Agilent E8363B PNA network analyzer, and the measured results are plotted in Figure 6 together with the *HFSS* simulated results. The proposed band-pass filter has a measured central frequency at 2.4 GHz, and the 1-dB pass-band is 2.2 $\sim$ 2.55 GHz. The optimized pass-band insertion loss is about 1.8 dB including two SMA connectors, and the pass-band return loss is no less than 15 dB. The out-of-band rejection is better than 20 dB at the lower stop-band (0.5 $\sim$ 2 GHz) and the upper stop-band (2.7 $\sim$ 5.4 GHz). The good in- and out-band performances have been obtained and are in good agreement with the *HFSS* simulated results. The slight shift in frequency between simulation and measurement might be due to the unexpected tolerance of fabrication and substrate permittivity.

The proposed nested SRR band-pass filter has a lower central frequency and good performance on harmonic suppression. It can control spurious response by changing impedance ratio (W_{in}/W_{out}) of the nested SRR unit cells. Compared with conventional SRR, the first spurious-mode resonance frequency of the nested SRR shifts to the higher frequency. Therefore, as shown in Figure 6, the parasitic pass-band of the proposed band-pass filter is above 5.5 GHz. Table 3 compares the performance and size of some reported miniaturized SRR

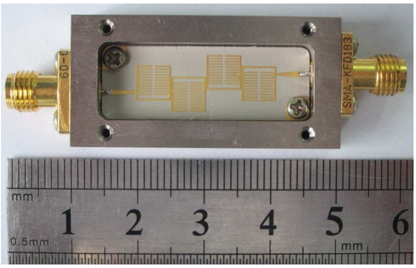


Figure 5. Photograph of the fabricated nested SRR band-pass filter.

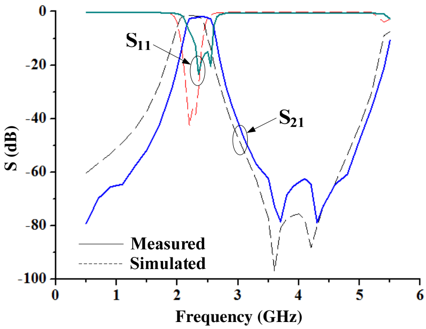


Figure 6. Simulated and measured results of the proposed nested SRR filter.

Table 3. Performance and size comparisons between various miniaturized SRR filters.

Ref.	Center frequency (GHz)	Fractional bandwidth (%)	Resonator unit cell	Resonator size
[10]	2.2	6.8	Stepped impedance SRR	$0.108\lambda_g \times 0.108\lambda_g$
[13]	2	5	Interdigital hairpin resonator	$0.066\lambda_g \times 0.071\lambda_g$
[14]	2.45	8	Open-loop SIR	$0.048\lambda_g \times 0.056\lambda_g$
This work	2.4	14.5	Nested SRR	$0.04\lambda_g \times 0.04\lambda_g$

filters. It is obtained that the proposed nested SRR structure has more compact size than other resonator unit cells in the Table 3, and it can achieve the miniature and high-frequency selectivity filters.

4. CONCLUSION

In this paper, a novel nested SRR structure is presented. Compared with conventional SRR, this nested SRR has better performance on miniaturization and high-Q value. This is largely due to the introduction of more gaps in the nested structure, resulting in larger capacitance and more electric field density concentrated regions, which finally contributes to the lower resonance frequency and higher Q-

factor. Moreover, the corresponding spurious frequency response can be adjusted by changing the impedance ratio of nested combs and outer coil of the nested SRR. A novel resonator-embedded band-pass filter based on the nested SRR is designed to verify the good characteristics. The band-pass filter shows good miniaturization and in- and out-band performances, such as high frequency selectivity and spurious response suppression. The combination of the novel nested SRR structure and various resonator-embedded or cross-coupled filter techniques can be applied to design novel miniaturized band-pass filters. In summary, the proposed nested SRR is found to be a very appropriate resonator structure for various miniaturized applications.

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