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Research Article

The effects of geometrical parameters on resonance frequency of Inverted Split Ring Resonators (ISRRs)

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ABSTRACT

In this study, an inverted split ring resonator (ISRR) was designed and the effects of the design geometrical parameters on the resonance frequency presented by using an equivalent circuit approach. The width of the rings, *w*, the width of ring split, *s*, and the outer length of the resonator, l_{res} were chosen as geometrical parameters. The determined designs were implemented by making simulations with electromagnetic design software, and the numerically obtained results were compared with theoretically obtained results. A good agreement of simulation and theoretical results was achieved and presented.

1. Introduction

Metamaterials (MTMs) that are not found directly in nature are theoretically proposed artificial materials by Russian Physicist Victor Georgievich Veselego in the 1960s [1]. Since their discovery MTMs have been the subject of extensive investigations due to their unusual properties, negative dielectric constant (ε) and negative magnetic permeability (μ) [2], [3]. Negative dielectric constant (ε) and negative magnetic permeability (μ) means the medium must have a negative refractive index of (η). That's why MTMs are also called left-handed media (LHM), double negative (DNG) media or negative index materials (NIM) [4].

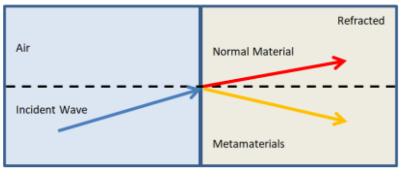

Figure 1. The behaviour of MTMs with the interaction of EM wave (negative refractive index, LHM)

The MTMs are increasingly demanded in different applications; super lens, invisibility cloaking, medicine, image processing, sensor technologies, defense industry, antenna, and microwave studies, etc. [3], [5]. Due to its unique features, different reactions are observed as a result of the interaction of the MTMs with electromagnetic waves. These properties result from designed artificial periodic structures on the material surface [6]. To illustrate how the MTMs interact with EM waves, a negative refraction medium example is shown in Figure 1.

The MTMs have been also successfully applied to the resonators, extensively to the split ring resonators (SRRs) [7], [8], [9]. SRRs were designed for the first time in 1999 by Pendry et all, exhibit a negative magnetic permeability in the resonance region [10],[11]. The SRRs are structurally composed of different numbers of metal rings etched on a dielectric substrate. There are slits etched on sides of these metal rings and rings can be in different shapes; square, circular, triangular, rhombic, pentagon, etc. [3], [12].

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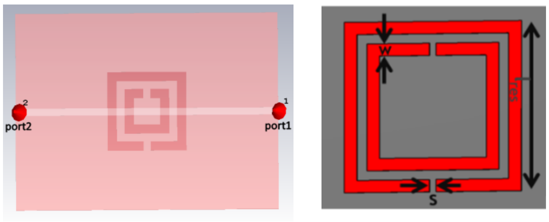
Basic parameters in resonators can be counted as resonance frequency, quality factor, bandwidth, loaded quality factor, damping coefficient, and coupling [13]. These parameters may be calculated with the equivalent circuit approach by using a suitable topology for the structure. Furthermore, the equivalent circuit of the system may be used to make the necessary interventions on the designed resonator and to understand the design theoretically [14]. By using the equivalent circuit approach, the complicated systems can be modeled with ideal simple circuit elements; resistors, inductors, capacitors, voltage, and current sources. SRRs have inductive and capacitive elements, so a single SRR cell structure can be modeled as an L-C circuit [15]. These capacitive and inductive effects are caused by the geometric structure of the resonator model and the parameters that make up the pattern [8]. In the literature, for SRR and ISRR structures, different equivalent circuit topologies have been discussed [16],[17],[18]. In the literature, studies comparing SRR with ISRR show that higher-quality factors were obtained in studies with ISRR [19].

MTMs are artificial periodic structures; however, due to having strong magnetic resonance even a single resonator unit cell exhibits a strong response with the interaction of EM waves [20], [21]. Thus, analyzes will be made over a single unit cell in the study.

In this study, to analyze the effect of geometrical parameters on the resonance frequency, an ISRR was designed. For the designed resonator, a simple equivalent circuit diagram model consisting of capacitors and inductors was proposed and the magnetic resonance of the system was calculated using this model. In the calculations, the influences of the geometric variables, forming the resonator pattern, on the resonance frequency were reported and compared with the results obtained by simulation studies. It was observed that the obtained results were compatible with each other and shift was occurred in magnetic resonance with the change in geometrical parameters (the width of the rings, *w*, the split widths, *s*, and the outer length of the resonator, l_{res}).



a) b)

Figure 2. Schematic drawing of a) designed ISRR, and b) front side and geometrical parameters of the ISRR.

2. Materials and Method

In order to analyze the effects of geometrical parameters on the resonance frequency, a square-shaped ISRR with two concentric rings was designed. The designed resonator consists of a pattern on the front side and a planar microstrip line on the backside. The pattern has etched square rings with slits on opposite sides. The slits were designed to be perpendicular to the planar microstrip line as shown in Figure 2.a. The studied geometrical parameters, the width of the rings, *w*, the split widths, *s*, and the outer length of the resonator, l_{res}, are shown in Figure 2.b and in Figure 3. Here *w* and *s* parameters equal for both the inner and the outer rings. The geometrical parameters *s*, *w*, l_{res} were increased from 0.3, 0.3, 4 mm to 0.5, 0.7, 6 mm in 0.05, 0.1, 0.5 mm increments, respectively. The effects of these parameters to the resonance frequency were investigated by changing only one parameter for each time. At the beginning the parameters were taken as s=0.4 mm, w=0.6 mm and l_{res}=5 mm. The distance between the rings (*g*), which is shown in Figure 3, can also be taken into consideration as another parameter to get definite results. However, in this study, it was kept constant (0.4 mm). The parameters arranged to preserve the shape of the pattern of the resonator and considering fabrication limitations.

The numerical analyses were observed between the frequency of 2.5 GHz and 5 GHz. The determined SRRs were also carried out by making simulations with electromagnetic design software (CST) for each time. The studied parameters are presented in Table 1.

Table 1. The selected geometrical parameters

Studied geometrical parameters (mm)		
l_{res}	*s*	*w*
4	0.3	0.3
4.5	0.35	0.4
5	0.4	0.5
5.5	0.45	0.6
6	0.5	0.7

The magnetic resonance of the system was determined using the equivalent circuit approach. In essence, there are two different equivalent circuits to be considered: that of the ISRR pattern and that of the microstrip line. Therefore, in the theoretical studies conducted to determine the resonance frequency of the system, the capacitive and inductive effect of the microstrip line and the resonator pattern were calculated separately. The proposed equivalent circuits of the planar microstrip line and the resonator pattern are discussed as in the Figure 3.

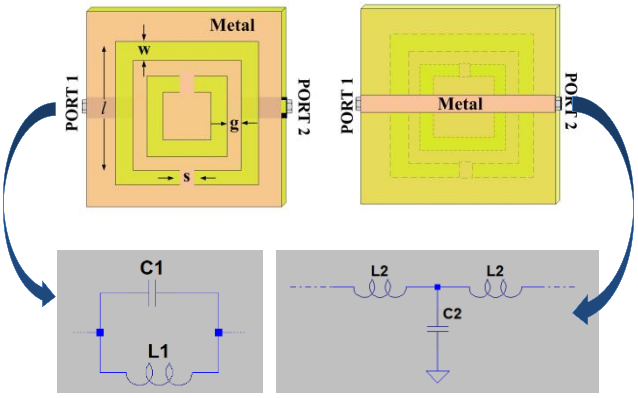


Figure 3. The equivalent circuit model for the ISRR pattern and planar microstrip line.

In essence, considering the equivalent circuit of the resonant ISRR structure, the behaviour of the system resembles a filter characteristic. The magnetic resonance of the structure can be given as Equation (1), where L represents the total equivalent inductance and C represents the total equivalent capacitance of the structure.

$$w = \frac{1}{\sqrt{LC}} \qquad (1)$$

In the study, the FR4 model substrate was chosen with dimensions of 15 mm x 20 mm x 1.6 mm, dissipation factor of 0.0025 at 10 GHz, thickness of copper cladding of 34 µm, and relative dielectric constant of 4,3.

3. Results

In order to understand the resonant structure more clearly and to make the desired interventions faster and in a more comfortable way a parametric study was carried out on the designed resonator. In this parametric study, besides the simulation studies, the equivalent circuit approach was also discussed. Firstly, an equivalent circuit for the ISRR system was proposed and the resonance frequency was calculated based on this model. Then, the determined ISRRs, with the same parameters, were carried out by making simulations with electromagnetic design software. The studies were done on 3 different parameters and each calculation was carried out by changing only one parameter at a time and keeping the other two parameters constant. The simulation results were compared with the theoretically obtained results.

Resonant S21 spectra simulated by CST for different l_{res} values given in Figure 4 shows that the resonance frequency of the ISRR decreases as the l_{res} increases. l_{res} parameter was varied with 0,5 mm steps between 4mm and 6mm. The results showed that the magnetic resonance is shifted by approximately 400 MHz when the l_{res} parameter has increased an increment, 0.5mm.

The simulation results for parameter *s* and *w* are shown in Figure 5 and in Figure 6, respectively. In the design of ISRR pattern, two concentric square rings were etched with the varying widths as 0.3, 0.4, 0.5, 0.6 and 0.7 mm. These etched rings have slits on them and the slits are perpendicular to the microstrip line. The dimension of the slits is increased from 0.3 to 0.5 in 0.05 increments. It was observed that there was a positive relationship between these two parameters and the resonance frequency. In these graphs, a general trend of increasing magnetic resonance can be seen. With the increasing value of the *s* and *w* parameters, there is an upward shift in the resonance frequency. While every 0.05 mm change in the *s* parameter causes a shift by approximately 25 MHz in the resonance frequency, the influence of *w* is approximately 240 MHz for each 0.1mm change.

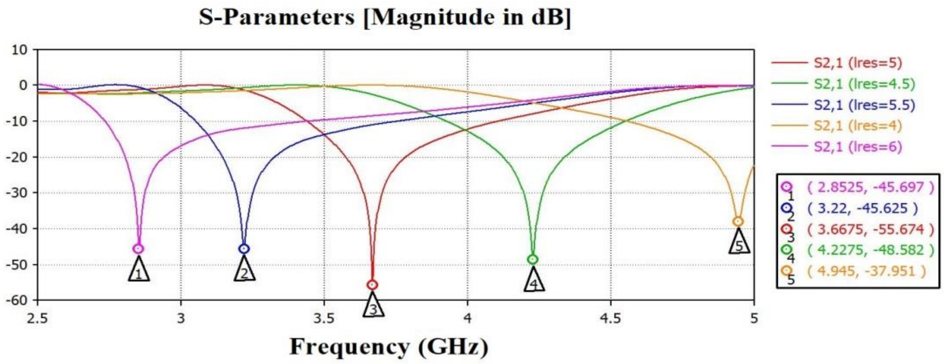


Figure 4. Resonant S_{21} spectra simulated by CST as the l_{res} geometric parameter is varied with 0.5 mm steps

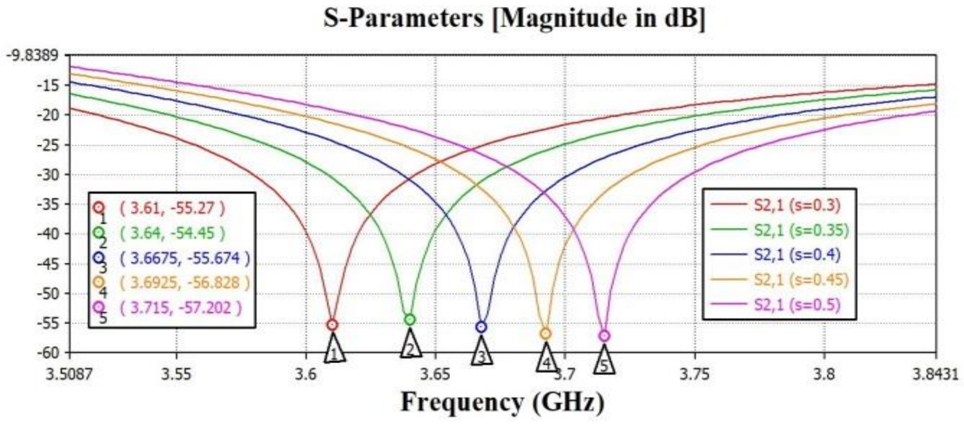


Figure 5. Resonant S_{21} spectra simulated by CST as the s geometric parameter is varied with 0,05mm steps

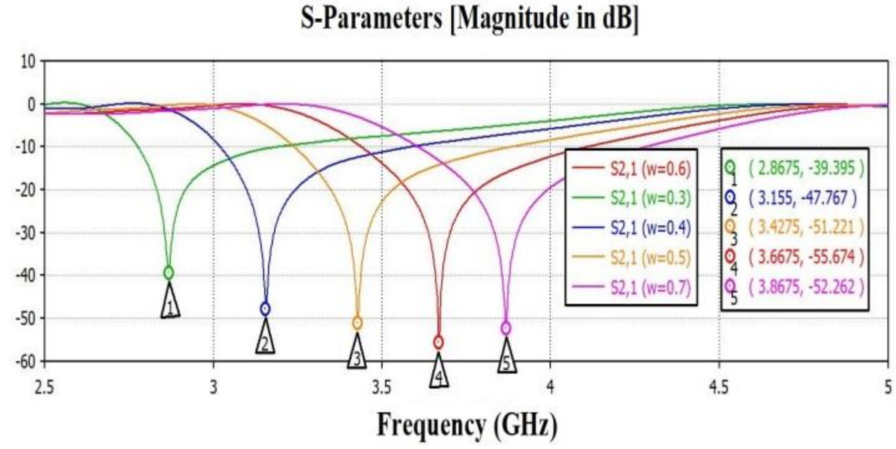


Figure 6. Resonant S_{21} spectra simulated by CST as the s geometric parameter is varied with 0,1mm steps

The simulation results were compared with the theoretical results. The obtained results for all parameters were shown in Figure 7 and in Figure 8. The results showed that the obtained results were in a good agreement with each other. The decrease of equivalent capacitances and inductances by the increase of the *s* and *w* parameters is expected to increase the resonance frequency in computational equivalent circuit model.

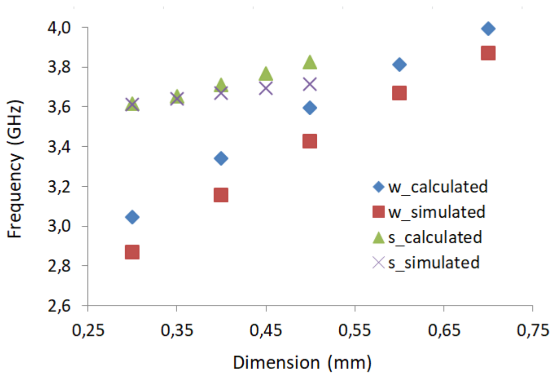


Figure 7. The simulation and theoretical results for geometrical parameters (*s* and *w)* versus resonance frequency

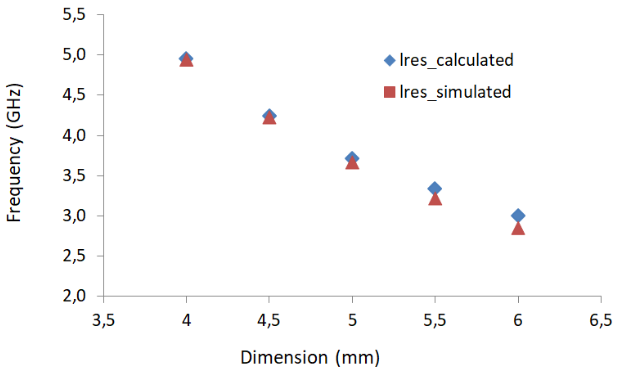


Figure 8. The simulation and theoretical results for geometrical parameter, l_{res}, versus resonance frequency

Moreover, the results reveal that the l_{res} parameter has an adverse effect on the total inductance and capacitance of the resonant structure. These reported numerical and theoretical results are also in good agreement with the results of the earlier studies [17], [22], [23].

The results showed that, in the resonator design studies, the desired resonant structure can be obtained by adjusting the frequency shifting with the changes made on the l_{res} variable where the size of structure is not very important. In studies where size is critical, it would be more logical to adjust the frequency by changing the w and s variables. In addition, small shifts in frequency are observed with the changes made in the s variable. This sensitivity in magnetic resonance may open up novel opportunities for the researchers to design more sensitive metamaterial-based RF devices.

4. Conclusions

We investigated the magnetic resonance of split ring resonators (SRR) and the effect of SRRs' geometrical parameters on the magnetic resonance frequency numerically and theoretically. As the studied parameters of the structure w, s and l_{res} were taken consideration, the obtained results illustrate that the calculated and simulated results are convenient to each other and for both results. While increasing the l_{res} decreases the resonance frequency of the ISRR, with the increasing of s and w parameters the resonance frequency shifts upward. The results obtained from this parametric study, which includes numerical and theoretical analysis, may provide a more comfortable path for researchers to design ISRRs.

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