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Evaluating the Impact of Geometric Dimensions of a Multi-Split Ring Resonator

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Abstract: In this paper, a metamaterial unit cell is designed and simulated based on the concept of multiple split-ring resonators (SRRs) in a compact size. The presented nested modified SRR resonator construct has the advantage of achieving more usable split gaps by increasing capacitance, resulting in a lower operational resonance frequency and improved sensitivity over typical SRR metamaterials. The impact of several split ring resonator geometric characteristics, such as the gap space, the width of the copper lines, the inner rings length, and the outer ring length on magnetic permeability and permittivity was analyzed. The modified metamaterial can be utilized for 5G mobile applications.

Keywords: Artificial Magnetic Materials (AMMs), Microstrip Patch Antenna, 5G Applications, SRR (Split Ring Resonator)

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1. INTRODUCTION

In recent decades, the interest of researchers has been increased toward the study of metamaterials, theoretically and empirically [1], [2]. Designers are entrusted with the challenge of producing more compact items as a result of these expectations.

Lately, artificially constructed materials, known as metamaterials, are used to exhibit electromagnetic capabilities that would be incompetent to obtain with traditional materials at the appropriate frequencies [3]. Metal structures are constructed on the interface of dielectric substrates in AMM, which is one of the newest materials. Consequently, the physical properties of metamaterials are defined further by their structures rather than the elements that constitute them [4]. Veselago, in 1968, was the first proficient at recognizing. that the constituent parameters permittivity (ε) and permeability (μ) were both regarded negatively at the same time when categorizing metamaterials. [4], [5]. Artificially structured materials are referred to in the literature as Double Negative (DNG), Epsilon Negative (ENG), negative (MNG), and Double Positive (DPS) based on their electromagnetic characteristics [6], [4].

The split-ring resonator (SRR) is a core part of metamaterials for achieving artificial magnetism at microwave frequencies, which is the main topic of this research. The SRRs electromagnetic characteristics and equivalent circuit model have been construed in [7], [8]. Using a basic equivalent circuit technique, the SRR of various geometrical shapes have been compared [9]. The effect of changing basic geometric parameters such as a single gap SRR metamaterial unit cell on its electromagnetic properties at 9.5 GHz has been analyzed [10]. However, it's still required to investigate the effect of increasing the number of SRR with dual split gaps and changing basic geometric parameters, which is achieved at sub- 6 GHz in this work.

Moreover, in a single SRR, the concentration of electric charges at the gap causes an electric dipole moment, which can diminish the idealized magnetic dipole moment [10]. Each ring's electric dipole moment cancels out the adjacent ring's electric dipole moment in twin SRRs. As a result, increasing the inserted concentric rings reduces the unit cell's electric polarizability.

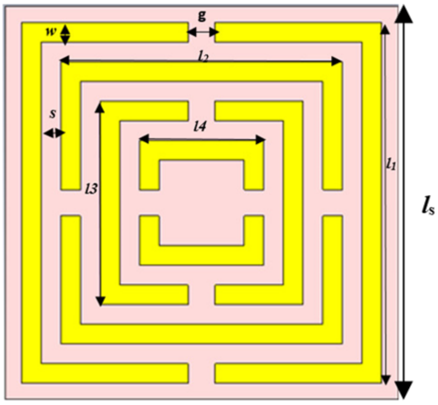
In this paper, Section 2, a quadruple metamaterial unit cell, was developed and simulated. SRR consists of four concentric square copper rings, each with two gaps. Then, Section 3 presents results and analysis considering the effect of various geometrical factors regarding several electromagnetic properties of the unit cell characteristics. The SRR effective permeability and permittivity were also acquired with various geometric characteristics in the 5G mid-band.

2. METAMATERIAL UNIT CELL GEOMETRIC DESIGN

Figure 1 (a) illustrates a perspective of the suggested multi-ring unit cell for the case of R = 4 (square copper section), with a 0.035 mm thickness. The dimensions of design parameters are chosen after a parametric study. The first square length (l_1) is chosen to reference the other three squares length (l_2,l_3,l_4). Furthermore, it is related to the other unicell parameters; the split gap (g), width (w), and space between the rings of all the proposed unit cell (s).

The SRR is attributed to a magnetic field, which results in negative permeability. Each ring's split gaps create a series capacitance that controls the resonant properties.

The proposed unit cell A ports (one for propagating signals and the other for receiving signals) are excited by an electromagnetic wave along the x-axis in the simulation setup. An electric boundary is launched on the y axis, while a properly magnetically conducted confine is placed on the z-axis. The unit cell's purpose is to achieve resonance within the frequency range of (0–6) GHz to execute the simulation.



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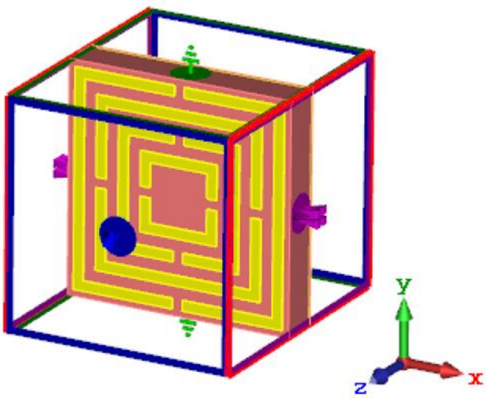

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Figure 1. (a) The proposed multi-ring unit cell, (b) Excitation setup for the SRR unit cell.

The equivalent capacitance and inductance of the split ring resonator's construction can be calculated using various approaches. In the subjected to a magnetic flux with frequency response, SRRs perform as an LC resonator, according to their electromagnetic characteristics [11]–[15] as in Equation (1).

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

The capacitance and inductance of the SRR are represented by the parameters C and L, respectively. Where, A is the split's region, ε_r is the relative permittivity, ε_0 is the free space permittivity, and d is the split width [16] as in Equation (2). Figure 2 illustrates the equivalent circuit of a four SRR.

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}(F) \qquad (2)$$

$$L = 0.00508l(2.303\log_{10}(4l)/(w) - \theta) \qquad (3)$$

$$l = (\lambda)/(R)\,, \quad \text{R= 4, 10, 20, ..., R-1} \qquad (4)$$

In which ε_e is the effective permittivity, c_0 is the speed of light, Z_0 is the impedance of the medium, and θ is the constant relay on the circuit topology. For SSRR θ is 2.853.

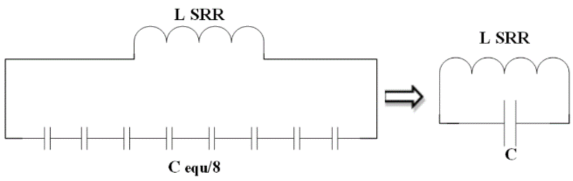


Figure 2. The equivalent circuit of the proposed multi-ring unit cell.

3. RESULTS AND ANALYSIS

3.1 The Geometrical Elements Variances

A parametric study on the impact of the SRRs geometric parameters on the operative magnetic parameters was separately demonstrated by simulating the proposed unit cell.

The gap (g) size exponentially increased from 0.15 to 0.5 mm to determine the influence of gap size on effective magnetic parameters as shown in Table 1. The other unit cell geometrical parameters are set as: w = 0.25 mm, l_1 = 7.5 mm, and s=0.2 mm. Figure 3 demonstrates the reflection coefficient and frequency resonance in terms of the gap variance.

Table 1. Gap variation effects

g (mm)	*f₁* (GHz)	*S₁₁* (dB)	*f₂* (GHz)	*S₁₁* (dB)
0.15	0.8	-76	4.48	-37.6
0.2	0.8	-75	4.5	-36.3
0.3	0.8	-74	4.6	-36.8
0.4	0.8	-73	4.62	-35
0.5	0.88	-73	4.75	-34

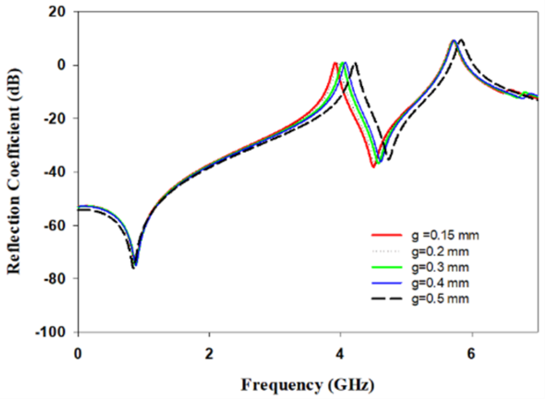


Figure 3. Reflection coefficient vs. frequency in terms of gap variation.

The impact of fluctuating the length (l_1) of the outer ring (which is related to other rings values was examined by changing the dimension from 5.5 to 7.5 mm as illustrated in Table 2. The other geometrical parameters are set as: w = 0.25 mm, g = 1.5 mm, and s= 0.2 mm, as shown in Figure 4.

Table 2. Length variation effects

l1 (mm)	*f_1 (GHz)*	*S_{11} (dB)*	*f_2 (GHz)*	*S_{11} (dB)*
5.5	1.1	-84.5	6.2	-40.5
6.5	0.82	-80.8	5.23	-41.5
7.5	0.72	-75.5	4.37	-39.8

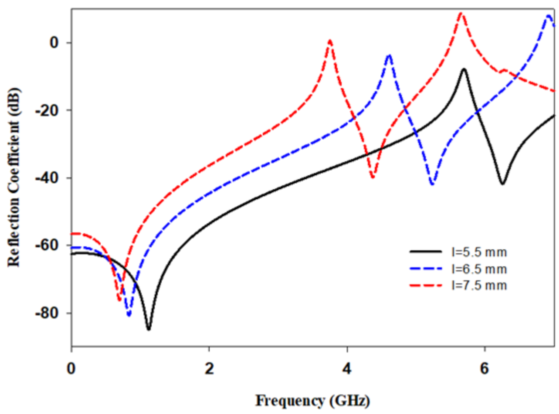


Figure 4. Reflection coefficient vs. frequency in terms of length variation.

The copper line rings width (w) was gradually increased from 0.1 to 0.4 mm to assess the influence of metallic width on effective magnetic parameters as shown in Table 3. The other geometrical parameters are set as: g = 0.1 mm, s = 0.2, and l_1 = 7.5 mm. The resonance frequency is proportional to the w- variants as is clear from Figure 5.

Table 3. Width variation effects

w(mm)	*f_1* (GHz)	*S_{11}* (dB)	*f_2* (GHz)	*S_{11}* (dB)
5.5	1.1	-84.5	6.2	-40.5
6.5	0.82	-80.8	5.23	-41.5
7.5	0.72	-75.5	4.37	-39.8

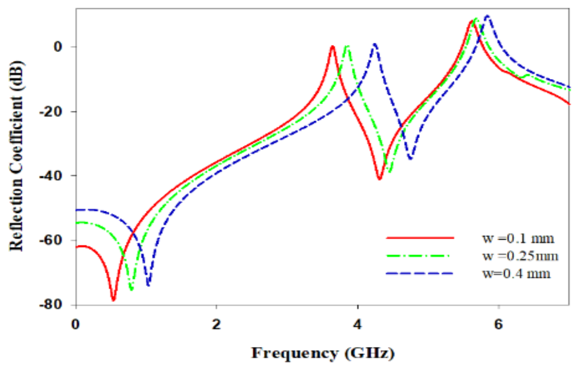


Figure 5. Reflection coefficient vs. frequency in terms of width variation.

Using the same method above the space (s) between the rings exponentially increased from 0.15 to 0.5 mm is referred to Table 4, while the other geometrical parameters are set as: w = 0.25 mm, g = 1.5 mm, and l_1=7.5 mm, as shown in Figure 6.

Table 4. Space variation effects

s (mm)	*f_1 (GHz)*	*S_{11} (dB)*	*f_2 (GHz)*	*S_{11} (dB)*
0.15	0.8	-76.4	4.3	-40.4
0.2	0.81	-75	4.5	-37
0.3	0.82	-74	4.8	-30.4
0.4	0.83	-73	5	-26
0.5	0.85	-72	5.2	-21.4

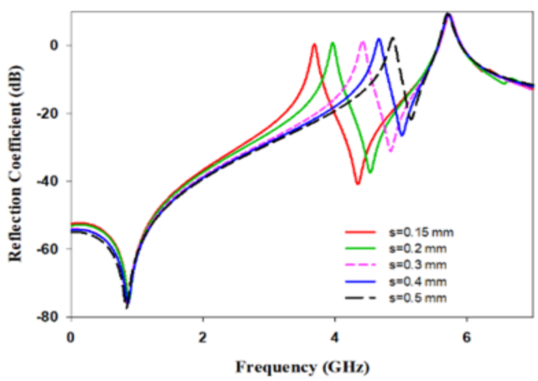


Figure 6. Reflection coefficient vs. frequency in terms of Space s variation.

To summarize the previous analysis results are a modest contribution to the ongoing discussions about the geometrical elements ***(l, w, g, s)*** variances effects; when the length l_1 dimension increases, the frequency of the resonance shifts to low frequency. At the same time, increasing the *w*, *g* and *s* values shifted the resonance frequency to high.

3.2 Permeability μ And Permittivity Ɛ

The medium's complex permittivity (ε) and permeability (μ) is extracted using Equations (5) through (8) from S-parameter amount [13].

$$z = \pm\left((1+S_{11})^2 - S_{21}^2\right)/\left((1-S_{11})^2 S_{21}^2\right)^{1/2} \quad (5)$$

$$n = \frac{1}{k_{0l}}\{[I\,m[l\,n(\exp[ink_0 l]) + 2m\pi] - iR\exp[[l\,n(\exp[ink_0 l])]]\} \quad (6)$$

$$exp[ink_0 l] = (S_{21})/(1 - S_{11}\ (z-1)/(z+1)) \quad (7)$$

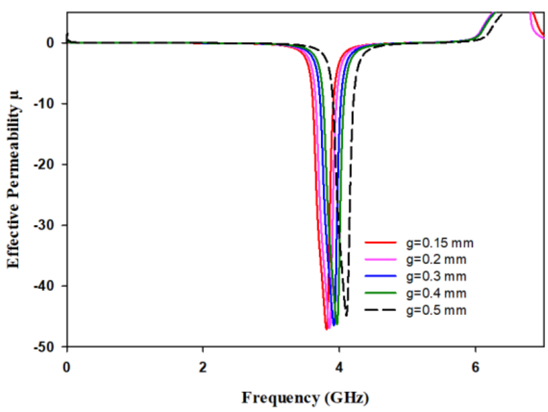
$$\varepsilon = n/z, \quad \mu = nz \quad (8)$$

where n is the refractive index, m is an integer in relation to n, and z is the normalized wave impedance, k_0 represents the wave number in free space.

The extracted permittivity (Ɛ) and permeability (μ) are plotted using the MATLAB code, as seen in Figures (7-10), respectively. From the results, Tables (5-8) and analysis graphs, it can be considered double-negative metamaterial (DNG) characteristics.

Table 5. Gap variation effects on μ and Ɛ.

g (mm)	*f*₀ (GHz)	*μ eff*	*ε eff*
0.15	3.8	-46.9	-9
0.2	3.84	-46.6	-10
0.3	3.9	-46	-8
0.4	3.96	-46.3	-7.6
0.5	4	-44.8	-8.9



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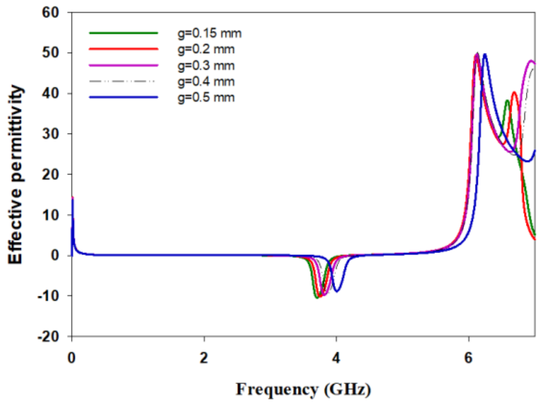

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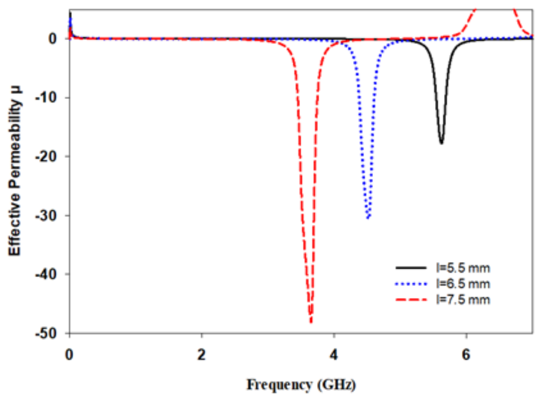
Figure 7. (a) Effective permeability, (b) effective permittivity vs. frequency in terms of gap variation.

Table 6. Length variation effects on μ and Ɛ

l(mm)	*f*₀ (GHz)	*μ eff*	*ε eff*
5.5	5.63	-84.5	-40.5
6.5	4.5	-80.8	-41.5
7.5	3.64	-75.5	-39.8



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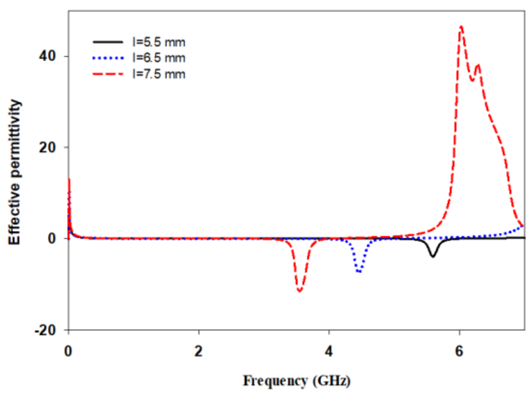

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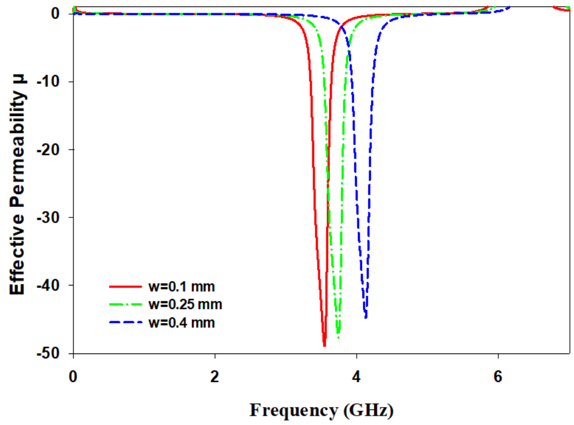
Figure 8. (a) Effective permeability, (b) effective permittivity vs. frequency in terms of length variation.

Table 7. Width variation effects on µ and Ɛ

w(mm)	f_0 *(GHz)*	μ_{eff}	ε_{eff}
0.1	3.5	-48.55	-11.53
0.25	3.75	-46.9	-10.45
0.4	4	-44.41	-8.13



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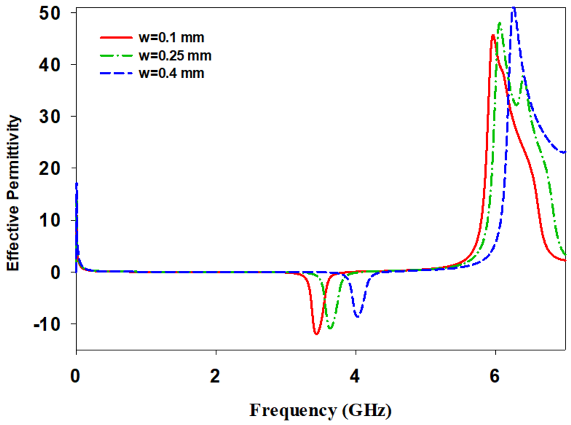
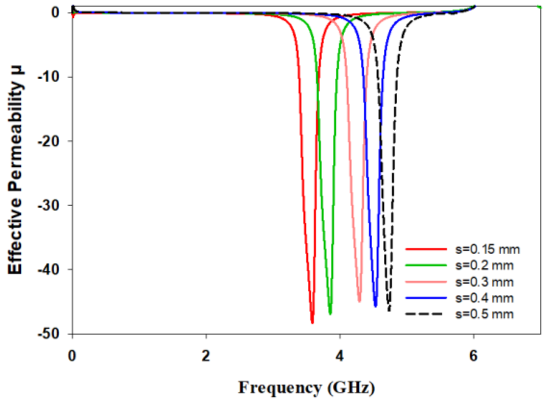


(b)

Figure 9. (a) Effective permeability, (b) effective permittivity vs. frequency in terms of width variation.

Table 8. Space variation effects on µ and Ɛ

s(mm)	f_0 *(GHz)*	μ_{eff}	ε_{eff}
0.15	3.57	-48	-11.24
0.2	3.8	-46.7	-9.73
0.3	4.2	-44.6	-7.5
0.4	4.4	-45.38	-5
0.5	4.7	-46.19	-3.45



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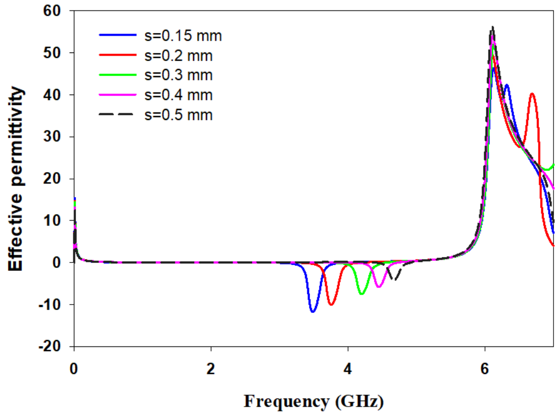

(b)

Figure 10. (a) Effective permeability, (b) effective permittivity vs. frequency in terms of space variation.

The analysis and simulation indicate that increasing the w, g, and s values shifted the resonance frequency to high and had the same impact on the effective permeability µ and permittivity ε.

4. CONCLUSION

A four split-ring metamaterial resonator has been constructed and proposed with double gaps on each ring for 5 G applications. Various geometric parameters determine the effective magnetic permeability and permittivity of SRR. From these outcomes have been carried conducted, it is possible to conclude that the influence of the gap's size and width of the unit cell copper resonator can adjust the inner and the outer ring's length. Moreover, the length of the outer unit cell ring has an impact on magnetic permeability. An essential contribution of these findings is that adding additional gaps results in more electric field density concentrated regions and higher sensitivity. As a result, these properties allow for a more flexible sensor design that can easily be expanded to terahertz frequency ranges, opening a new path for metamaterial applications to mobile applications.

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