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ABSTRACT

There are a number of characteristics that make metamaterial has wide applications and has been researched at present, such as negative phase, negative index of refraction, super resolution, and reverse of Doppler's effects. This paper investigates a hexagonal metamaterial structure with a split and a double concentric rings so-called split ring resonator hexagonal (SRR-H) for frequency filtering application. SRR-H is designed structurally and operated computationally for frequency range of 1 to 120 GHz. The simulation results showed that SRR-H size will affect the resonant frequency significantly. The resonant frequency tends to shift the lower frequency when the size of the structure is enlarged. The properties of the structure SRR-H, such as permeability, permittivity and the refractive index have a similarity because it is dominated by the properties of permeability. Metamaterial SRR-H successfully responded to double negative and agreed with Lorentz's model. © 2017 Wiley Periodicals, Inc. Microwave Opt Technol Lett 59:1337–1340, 2017

GHz Frequency Filtering Source using Hexagonal Metamaterial Splitting Ring Resonators

T. SAKTIOTO[1], R.F. SYAHPUTRA[1], S. PUNTHAWANUNT[2], J. ALI[3, 4], P. YUPAPIN[5, 6*]

[1]Physics Department, FMIPA, Universitas Riau, Pekanbaru, Indonesia;
[2]Multidisciplinary Research Center, Faculty of Science and Technology, Kasem Bundit University, Bangkok 10520, Thailand;
[3]Laser Centre, IBNU SINA ISIR, Universiti Teknologi Malaysia 81310 Johor Bahru, Malaysia;
[4]Faculty of Science, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia;
[5]Department for Management of Science and Technology Development, Ton Duc Thang University, District 7, Ho Chi Minh City, Vietnam;
[6]Faculty of Electrical & Electronics Engineering, Ton Duc Thang University, District 7, Ho Chi Minh City, Vietnam;
*Corresponding author: <preecha.yupapin@tdt.edu.vn>

Abstract: There are a number of characteristics that make metamaterial has wide applications and has been researched at present, such as negative phase, negative index of refraction, super resolution, and reverse of Doppler's effects. This paper investigates a hexagonal metamaterial structure with a split and a double concentric rings so-called split ring resonator hexagonal (SRR-H) for frequency filtering application. SRR-H is designed structurally and operated computationally for frequency range of 1 GHz to 120 GHz. The simulation results showed that SRR-H size will affect the resonant frequency significantly. The resonant frequency tends to shift the lower frequency when the size of the structure is enlarged. The properties of the structure SRR-H, such as permeability, permittivity and the refractive index have a similarity because it is dominated by the properties of permeability. Metamaterial SRR-H successfully responded to double negative and agreed with Lorentz's model.

Keywords: Splitting ring resonator; Metamaterial, Lorentz's model; GHz frequency filtering

1. Introduction

A structure of split ring resonator (SRR) has a simple geometry and easy for implementing on metamaterial computationally, where this structure provides magnetic permeability response dominantly, so that it allows to obtain metamaterial with a negative index of refraction (Patel, 2008). The hypothesis of negative index of refraction reported firstly by Veselago [1]. He said that that if there is a medium which has a negative permittivity and permeability simultaneously, so that the medium will have a negative refractive index, which was called the medium as left-handed (LH) materials. The SRR structure has inspired by Smith and his colleges [2] to demonstrate the negative refractive index phenomena. Previously, Pendry et al. [3] has investigated SRR circular-shaped and arrangement of the wire to obtain a medium with a negative refractive index, where a few years later researchers have been investigating a number of structures are deliberately designed for the purpose of obtaining negative refractive index material or a single negative (only μ or ε has negative value). The SRR modification is most often studied by researchers, including circular and square SRR. Later, the hexagonal SRR also designed for the same purpose. The unit cell with hexagonal-shaped takes the space effectively and can use for broadband applications [4].

The important characteristic of optical metamaterial is negative index of refraction. This property influences all optical phenomena and generates new characteristics such as negative phase, negative index of refraction, super resolution, and reverse of Doppler's effect and so on. The metamaterial devices has a potential for broad applications, such as for imaging of sub-wavelength, as a component of electronic circuit and optical applications, antenna, absorber in solar cells, invisibility technology, detectors and biosensors [5]. Based on above studies, this paper proposes the structure of split ring resonator hexagonal shaped (SRR-H) as a follow-up investigation on SRR metamaterial structure. This structure is expected to enhance magnetic permeability of the structure. The frequency of application is varied from 1-120 GHz. These frequencies have noticed the requisite of optical metamaterial, where the SRR-H will be also observed for different size of the designed structure using commercial software, HFSS ™ which based on finite element method (FEM).

2. Theoretical Background

Metamaterial structures strongly influence the shape characteristics, instead of its constituent materials. This type is called optical metamaterial [6]. The optical metamaterial structure size is smaller than half the wavelength applications for avoiding diffraction effects [7].

The electromagnetic (EM) characteristics, such as permittivity, permeability or susceptibility of materials found in nature are not completely linear. Magnitudes tend to show the nature of dependence on electromagnetic wave frequency [8], from which the materials that have these properties are known as dispersive material. There are several models that can describe the characteristics of dispersive materials, one of which is the Lorentz model. The general equation of relative permittivity dependent $\varepsilon_r(\omega)$ to frequency (ω) in Lorentz's models for n dipole is given by

$$\varepsilon_r(\omega) = \varepsilon_\infty + \sum_{n=1}^{n} \frac{\Delta\varepsilon_n \omega_n^2}{\omega_n^2 + i\omega\gamma_n - \omega^2} \tag{1}$$

where ε_∞ is relative permittivity at infinite frequency, $\Delta\varepsilon_n = \varepsilon_{s,n} - \varepsilon_{\infty,n}$ is the relative permittivity changes caused by the dipole Lorentz, $\varepsilon_{s,n}$, which is the relative permittivity at zero frequency on *n*th dipole, $\varepsilon_{\infty,n}$ the relative permittivity at infinite frequency on nth dipole, ω_n is a resonant frequency of *n*-dipole and damping constants γ_n to the *n*-dipole [9].

Modification on Nicolson-Ross-Weir (NRW) method has been done by Ziolkowski [10], where it explicitly used for rectangular waveguide [7]. The NRW equations are used widely to calculate the complex permittivity and permeability of a waveguide by measuring the S-parameters (scattering parameters). When the waves propagate to the boundary of air-material, the partially reflected and transmitted waves pass through the material. If the waveguide length is t_m, then the expression for S-parameters, S_{21} and S_{11}, are as follows

$$S_{11} = \frac{\Gamma_1(1 - z^2)}{1 - \Gamma_1^2 z^2} \tag{2}$$

$$S_{21} = \frac{z(1 - \Gamma_1^2)}{1 - \Gamma_1^2 z^2} \tag{3}$$

where $\Gamma_1 = (z - 1)/(z + 1)$, $z = \exp(-i\theta)$ is the complex transmission coefficient and $\theta = kt_m$ is wave phase. Then, the sum and difference of the parameters S_{21} and S_{11} are expressed by,

$$V_1 = S_{21} + S_{11} \tag{4}$$

$$V_2 = S_{21} - S_{11} \tag{5}$$

Consider $|\Gamma_1| \leq 1$, then it is obtained,

$$\mu_r = \frac{2}{jk_0 t_m} \frac{1 - V_2}{1 + V_2} \tag{6}$$

$$\varepsilon_r = \mu_r + j\frac{2S_{11}}{k_0 t_m} \tag{7}$$

$$n = \sqrt{\varepsilon_r}\sqrt{\mu_r} \tag{8}$$

where $k_0 = 2\pi f/c$, *f* is the applied frequency and c is speed of light (3×10^8 m/s). Eq. 8 ensures the refractive index will be positive if ε_r and μ_r are positive respectively, and negative if ε_r and μ_r are negative respectively.

3. Structural Design

The structure is designed by using HFSS™. SRR-H unit cell consists of two rings of metallic inclusions placed concentrically with the radius of the inner ring R_1 and outer ring R_2 as shown on Table 1 by using aluminium as metallic inclusion. The rings are layout on the substrate FR-4 epoxy. The structure will be observed in the frequency range of 1 GHz to 120 GHz for investigating frequency filter. The symmetrical PMC (front and back of Figure 1) and PEC (upper and bottom of Figure 1) boundary are applied. The SRR-H structure is designed in the order of 1 mm smaller to fit the dimensions of the metamaterial optical terms, smaller than $\lambda_{observing}/2$ [7]. The SRR-H is expected to provide a structure resonant as DNG metamaterial properties. The structure designed in this study is shown in Figure 1. The radius of the inner ring R_1 and the radius of the outer ring of R_2 are varied. Ring radius measured from the centre point to one of the outer corners of the hexagon. Table 1 shows the variant and size of SRR-H, where the substrate has the dimensions of a × b with thickness t_s = 0:07 mm. The gap c_1 and c_2 are made constants of 0.03 mm and 0.05 mm, respectively. Trace width l and thickness t_c of each the ring are fixed at 0.1 mm and 0.03 mm, respectively. The distance between outer side of the outer ring and substrate side is fixed at 0.02 mm.

Table 1. Structure Size variation SRR

Variant	R_1 (mm)	R_2 (mm)	a (mm)	b (mm)
r_1	0.20	0.35	0.66	0.74
r_2	0.25	0.40	0.74	0.84
r_3	0.30	0.45	0.84	0.94
r_4	0.35	0.50	0.92	1.04
r_5	0.40	0.55	1.02	1.14
r^6	0.45	0.60	1.10	1.24
r_7	0.50	0.65	1.20	1.34

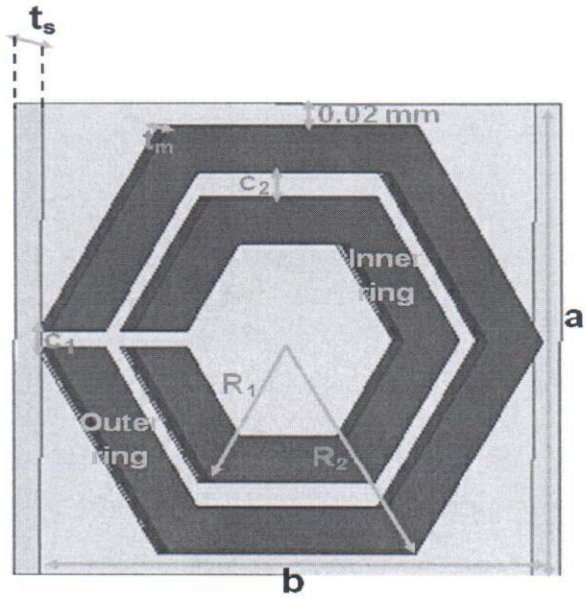


Figure 1. The dimensional structure of SRR-H

4. Results and Discussion

The dimensional structure changes will cause a shift in the resonance frequency up and down, where Figure 2 depicts the S-parameters variant *r4*. The resonant frequency tends to shift down to the increased dimensions of the structure, for instance, in variant *r2*, where the resonance downwards in line with the growing size of the structure, in which the upper and lower resonant frequency tend to be lower for larger dimensions. As described in Figure 2, the red line, S21 is the transmission line and the black line, S11 is the reflection line. The value of S11 goes down slightly along the frequency change and sharply for one point as a filter. Similarly for S21 but the peak one occurs at high frequency compared to S11. The transmission wave can keep maintaining the high value while the reflection tends to decrease. The sum of S11 and S21 value are not constant due to the effect of absorption and medium of structure.

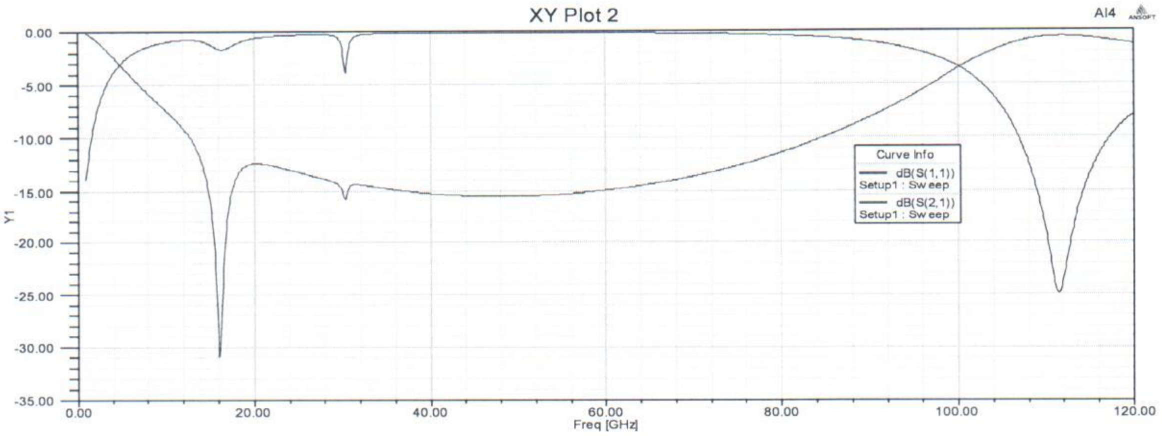
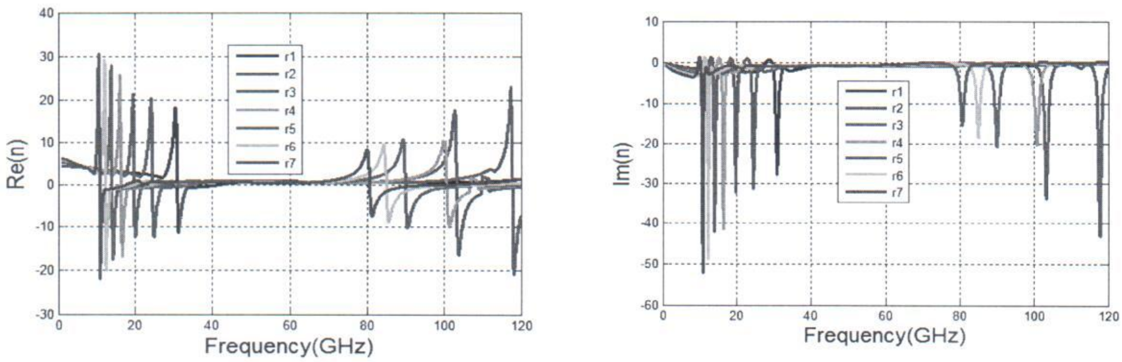


Figure 2. S-parameters of PCP-H aluminium as a function of frequency, where the ring radius is 0.35 mm (variant r_4).

Table 2. The resonant frequency of SRR-H

Variant	f_{01} (GHz)	Im(n)	f_{02} (GHz)	Im(n)	Δf_0 (GHz)
r_1	30.8	-28.108	-	-	-
r_2	24.5	-31.340	117.8	-43.280	93.3
r_3	19.8	-32.292	103.2	-33.881	83.4
r_4	16.4	-41.392	100.7	-20.182	84.3
r_5	14.1	-42.166	89.9	-20.768	75.8
r_6	12.3	-48.993	84.9	-18.339	72.6
r_7	10.8	-52.226	80.6	-15.446	69.8



(a) (b)

Figure 3. Effect of variation SRR-H dimensional structures to the resonance frequency. (a) Real part of refractive index and (b) Imaginary part of refractive index.

However, the distance both resonance frequency is decrease, so that varying the structure size shows the broadband negative index of refraction which is useful for broadband filter application, stealth technology and other EM applications. More results are as shown in Figure 3 and Table 2, where both real and imaginary parts of Figure 3(a) and 3(b) show that the lower variant has the lower peak and *vice versa* for fewer frequency function. On the other hand, the higher variant has the lower peak and *vice versa* for higher frequency function, where the outer ring increases it will produce a slightly lower frequency resulted, but the discrepancy of r_{01} and r_{02} is about $\Delta f = 60$ GHz in Figure 4, which explains that r_{02} can maintain the high frequency.

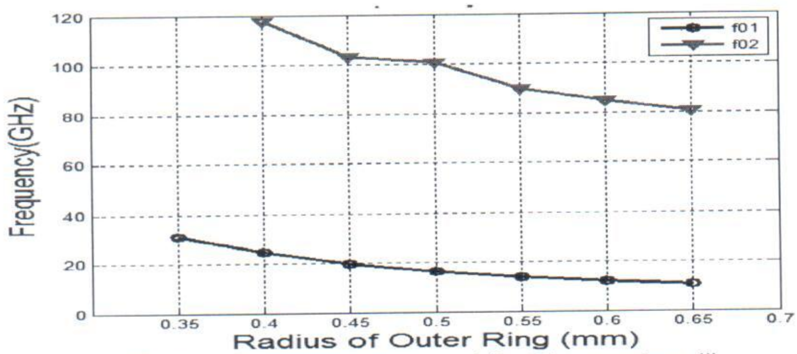


Figure 4. The resonant frequency shift of the outer ring radii

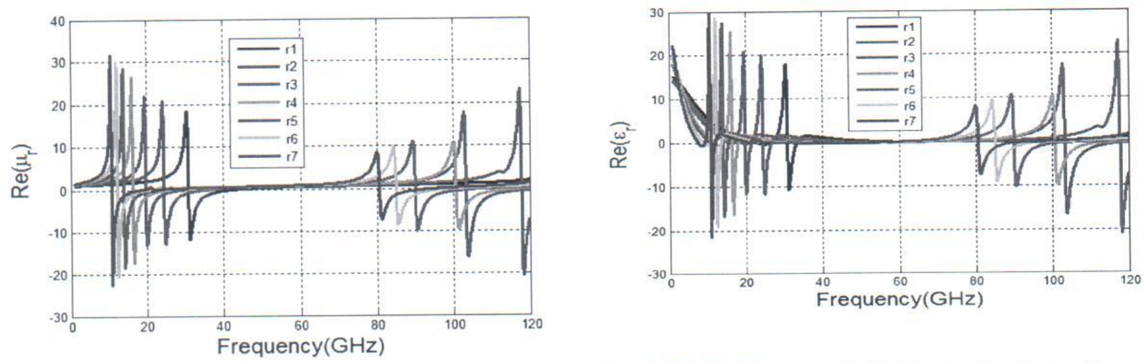


Figure 5. The relative permittivity, where (a) permeability, (b) of SRR-H. There are similarities to the chart patterns of refractive index due to their dominance of magnetic permeability of the structure

The relative permittivity, relative permeability and refractive index have a same pattern, as shown in Figure 3 and Figure 5 for SRR-H. This is due to the structural properties of SRR-H is more dominated by the properties of the magnetic permeability. In addition, the intrinsic properties of the NRW models which have been modified by Ziolkowski [10], which prefers the permeability than the permittivity in order to obtain a response metamaterial with a negative refractive index.

The data resonance frequency can be used to generate Lorentz's model for dispersive materials. In addition, the other variables are required to complete the calculation such $\varepsilon_\infty, \Delta\varepsilon$, and γ, where the value of ε_∞ is the relative permittivity when frequency towards the infinity, generally the value is 1. The value of $\Delta\varepsilon$ determines the resonant frequency bandwidth, while the value of γ determines the value of permittivity [9]. Here the other used parameters are $\Delta\varepsilon_1 = 1$, $\Delta\varepsilon_2 = 0{,}3$, $\gamma_1 = 0{,}35$ GHz and $\gamma_2 = 0{,}4$ GHz for each resonance frequencies. From Figure 6, the obtained data SRR-H has shown the good agreement with the Lorentz's models, from which each resonant frequency are f_{01} = 24.5 GHz and f_{02} = 117.8 GHz. It is clear that the imaginary part of permittivity is equal to the resonance frequency, in which at this point the structure of relative permittivity is the lowest value.

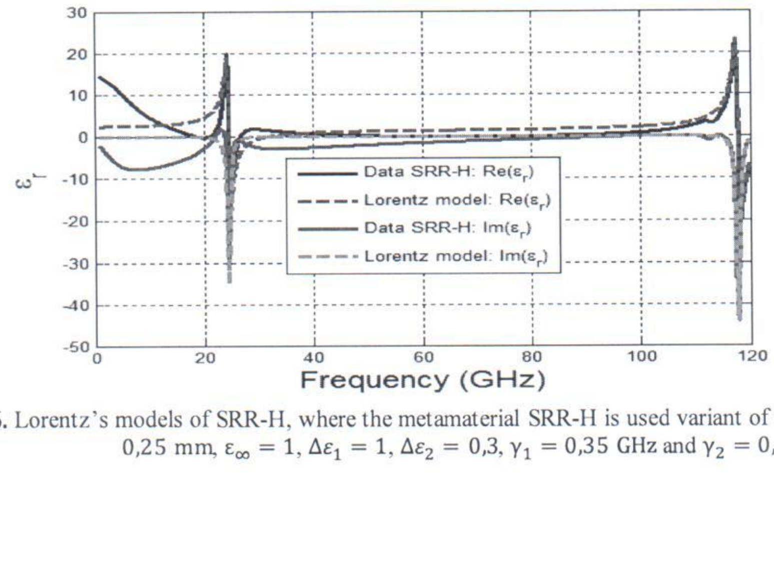


Figure 6. Lorentz's models of SRR-H, where the metamaterial SRR-H is used variant of r_2 with R_1 = 0,25 mm, $\varepsilon_\infty = 1$, $\Delta\varepsilon_1 = 1$, $\Delta\varepsilon_2 = 0{,}3$, $\gamma_1 = 0{,}35$ GHz and $\gamma_2 = 0{,}4$ GHz.

5. Conclusion

The split ring resonator metamaterial-hexagonal (SRR-H) is a hexagonal ring-shaped metamaterial structures comprising concentric inner ring and outer ring. There are two points on the resonance frequency of SRR-H in the interval of 1-120 GHz frequency, i.e. the resonance frequency below, f_{01} the resonant frequency above, f_{02}. SRR-H metamaterial size significantly influences to the resonance frequency, in which the resonance frequency tends to decrease the structure size is enlarged. The refractive index of the metamaterial SRR-H is an effective response of the structure. The refractive index value is more dominated by the structure permeability, which has shown the good agreement with the Lorentz's model.

Acknowledgment

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GHz FREQUENCY FILTERING SOURCE USING HEXAGONAL METAMATERIAL SPLITTING RING RESONATORS

T. Saktioto,[1] R.F. Syahputra,[1] S. Punthawanunt,[2] J. Ali,[3,4] and P. Yupapin[5,6]
[1] Physics Department, FMIPA, Universitas Riau, Pekanbaru, Indonesia
[2] Multidisciplinary Research Center, Faculty of Science and Technology, Kasem Bundit University, Bangkok, 10520, Thailand
[3] Laser Centre, IBNU SINA ISIR, Universiti Teknologi Malaysia 81310 Johor Bahru, Malaysia
[4] Faculty of Science, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia
[5] Department for Management of Science and Technology Development, Ton Duc Thang University, District 7, Ho Chi Minh City, Vietnam
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1. INTRODUCTION

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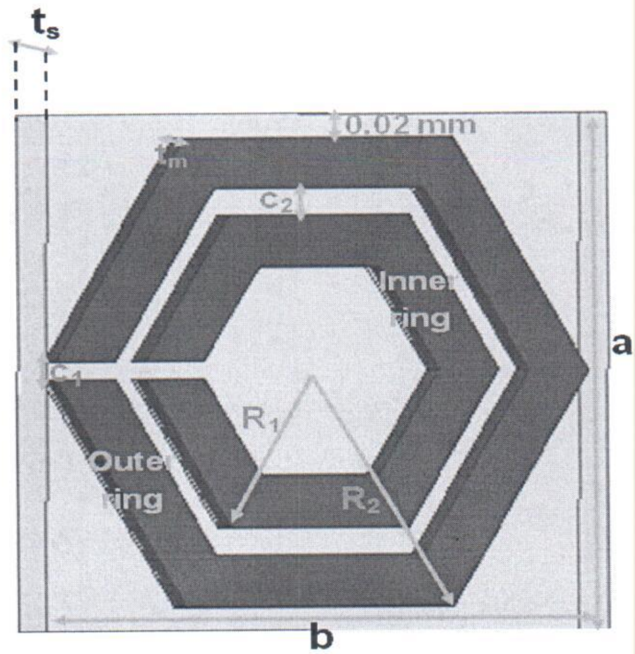

Figure 1 The dimensional structure of SRR-H. [Color figure can be viewed at wileyonlinelibrary.com]

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where $k_0=2\pi f/c$, f is the applied frequency and c is speed of light (3×10^8 m/s). Eq. (8) ensures the refractive index will be positive if ε_r and μ_r are positive respectively, and negative if ε_r and μ_r are negative respectively.

3. STRUCTURAL DESIGN

The structure is designed by using HFSS™. SRR-H unit cell consists of two rings of metallic inclusions placed concentrically with the radius of the inner ring R_1 and outer ring R_2 as shown on Table 1 by using aluminium as metallic inclusion. The rings are layout on the substrate FR-4 epoxy. The structure will be observed in the frequency range of 1 GHz to 120 GHz for investigating frequency filter. The symmetrical PMC (front and back of Fig. 1) and PEC (upper and bottom of Fig. 1) boundary are applied. The SRR-H structure is designed in the order of 1 mm smaller to fit the dimensions of the metamaterial optical terms, smaller than $\lambda_{\text{observing}}/2$ [7]. The SRR-H is expected to provide a structure resonant as DNG metamaterial properties. The structure designed in this study is shown in Figure 1. The radius of the inner ring R_1 and the radius of the outer ring of R_2 are varied. Ring radius measured from the centre point to one of the outer corners of the hexagon. Table 1 shows the variant and size of SRR-H, where the substrate has the dimensions of a × b with thickness t_s = 0:07 mm. The gap c_1 and c_2 are made constants of 0.03 mm and 0.05 mm, respectively. Trace width l and thickness t_c of each the ring are fixed at 0.1 mm and 0.03 mm, respectively. The distance between outer side of the outer ring and substrate side is fixed at 0.02 mm.

TABLE 1 Structure Size variation SRR

Variant	R_1 (mm)	R_2 (mm)	a (mm)	b (mm)
r_1	0.20	0.35	0.66	0.74
r_2	0.25	0.40	0.74	0.84
r_3	0.30	0.45	0.84	0.94
r_4	0.35	0.50	0.92	1.04
r_5	0.40	0.55	1.02	1.14
r_6	0.45	0.60	1.10	1.24
r_7	0.50	0.65	1.20	1.34

4. RESULTS AND DISCUSSION

The dimensional structure changes will cause a shift in the resonance frequency up and down, where Figure 2 depicts the S-parameters variant r_4. The resonant frequency tends to shift down to the increased dimensions of the structure, for instance, in variant r_2, where the resonance downwards in line with the

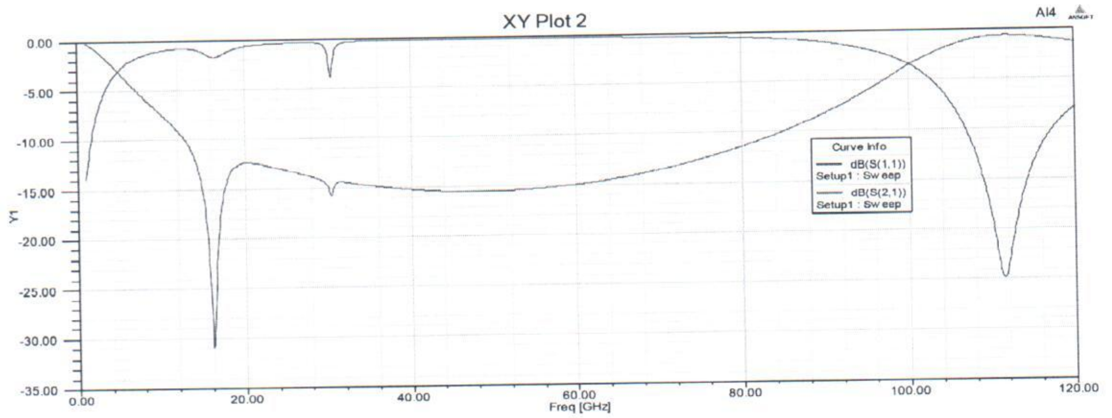

Figure 2 S-parameters of PCP-H aluminium as a function of frequency, where the ring radius is 0.35 mm (variant r_4). [Color figure can be viewed at wileyonlinelibrary.com]

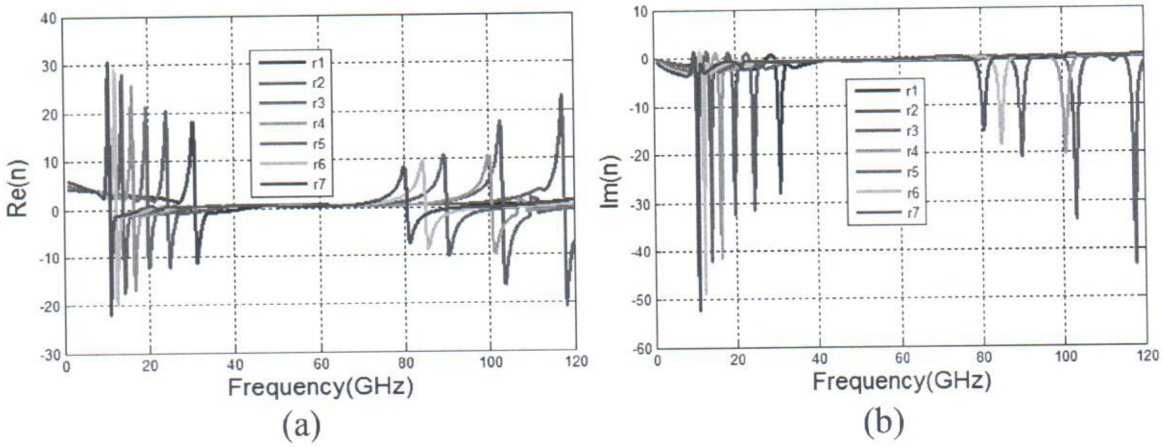

Figure 3 Effect of variation SRR-H dimensional structures to the resonance frequency. (a) Real part of refractive index and (b) Imaginary part of refractive index. [Color figure can be viewed at wileyonlinelibrary.com]

growing size of the structure, in which the upper and lower resonant frequency tend to be lower for larger dimensions. As described in Figure 2, the red line, S_{21} is the transmission line and the black line, S_{11} is the reflection line. The value of S_{11} goes down slightly along the frequency change and sharply for one point as a filter. Similarly for S_{21} but the peak one occurs at high frequency compared to S_{11}. The transmission wave can keep maintaining the high value while the reflection tends to decrease. The sum of S_{11} and S_{21} value are not constant due to the effect of absorption and medium of structure.

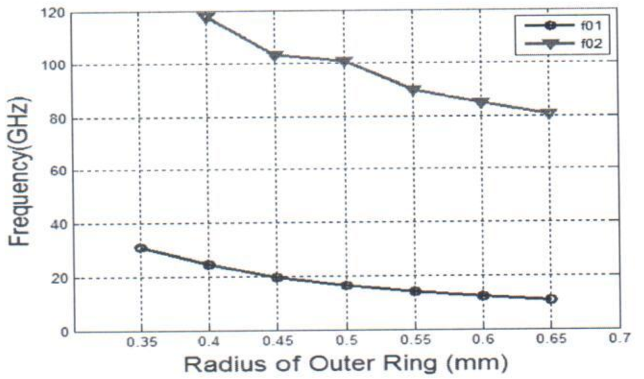

Figure 4 The resonant frequency shift of the outer ring radii. [Color figure can be viewed at wileyonlinelibrary.com]

However, the distance both resonance frequency is decrease, so that varying the structure size shows the broadband negative index of refraction which is useful for broadband filter application, stealth technology and other EM applications. More results are as shown in Figure 3 and Table 2, where both real and imaginary parts of Figures 3(a) and 3(b) show that the lower variant has the lower peak and *vice versa* for fewer frequency function. Conversely, the higher variant has the lower peak and *vice versa* for higher frequency function, where the outer ring increases it will produce a slightly lower frequency resulted, but the discrepancy of r_{01} and r_{02} is about $\Delta f = 60$ GHz in Figure 4, which explains that r_{02} can maintain the high frequency.

TABLE 2 The Resonant Frequency of SRR-H

Variant	f_{01} (GHz)	Im (n)	f_{02} (GHz)	Im (n)	Δf_0 (GHz)
r_1	30.8	−28.108	-	-	-
r_2	24.5	−31.340	117.8	−43.280	93.3
r_3	19.8	−32.292	103.2	−33.881	83.4
r_4	16.4	−41.392	100.7	−20.182	84.3
r_5	14.1	−42.166	89.9	−20.768	75.8
r_6	12.3	−48.993	84.9	−18.339	72.6

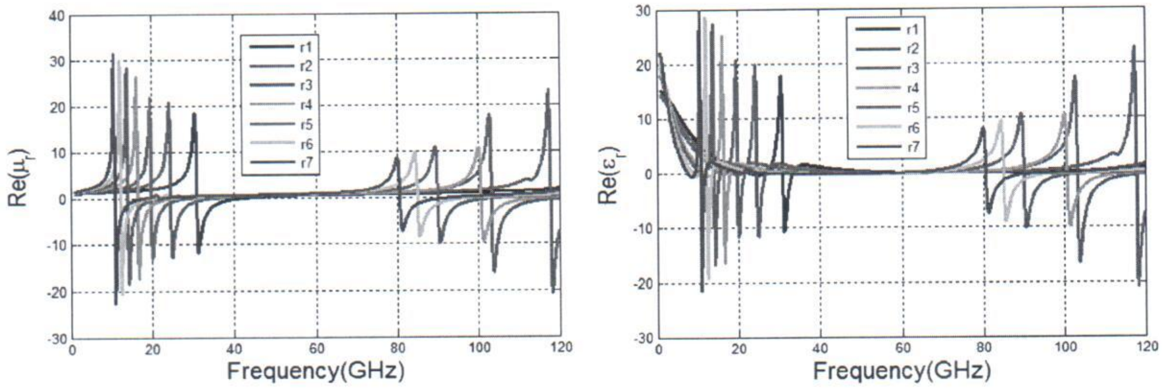

Figure 5 The relative permittivity, where (a) permeability, (b) of SRR-H. There are similarities to the chart patterns of refractive index due to their dominance of magnetic permeability of the structure. [Color figure can be viewed at wileyonlinelibrary.com]

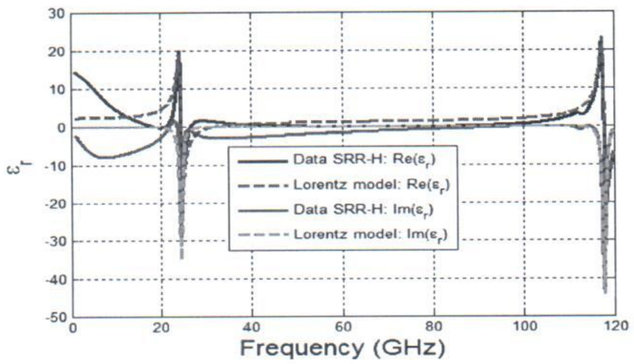

Figure 6 Lorentz's models of SRR-H, where the metamaterial SRR-H is used variant of r_2 with $R_1=0,25$ mm, $\varepsilon_\infty=1$, $\Delta\varepsilon_1=1$, $\Delta\varepsilon_2=0,3$, $\gamma_1=0,35$ GHz and $\gamma_2=0,4$ GHz. [Color figure can be viewed at wileyonlinelibrary.com]

The relative permittivity, relative permeability and refractive index have a same pattern, as shown in Figures 3 and 5 for SRR-H. This is due to the structural properties of SRR-H is more dominated by the properties of the magnetic permeability. In addition, the intrinsic properties of the NRW models which have been modified by Ziolkowski [10], which prefers the permeability than the permittivity to obtain a response metamaterial with a negative refractive index.

The data resonance frequency can be used to generate Lorentz's model for dispersive materials. In addition, the other variables are required to complete the calculation such ε_∞, $\Delta\varepsilon$, and γ, where the value of ε_∞ is the relative permittivity when frequency towards the infinity, generally the value is 1. The value of $\Delta\varepsilon$ determines the resonant frequency bandwidth, while the value of γ determines the value of permittivity [9]. Here the other used parameters are $\Delta\varepsilon_1=1$, $\Delta\varepsilon_2=0,3$, $\gamma_1=0,35$ GHz and $\gamma_2=0,4$ GHz for each resonance frequencies. From Figure 6, the obtained data SRR-H has shown the good agreement with the Lorentz's models, from which each resonant frequency are $f_{01}=24.5$ GHz and $f_{02}=117.8$ GHz. It is clear that the imaginary part of permittivity is equal to the resonance frequency, in which at this point the structure of relative permittivity is the lowest value.

5. CONCLUSION

The split ring resonator metamaterial-hexagonal (SRR-H) is a hexagonal ring-shaped metamaterial structures comprising concentric inner ring and outer ring. There are two points on the resonance frequency of SRR-H in the interval of 1–120 GHz frequency, i.e. the resonance frequency below, f_{01} the resonant frequency above, f_{02}. SRR-H metamaterial size significantly influences to the resonance frequency, in which the resonance frequency tends to decrease the structure size is enlarged. The refractive index of the metamaterial SRR-H is an effective response of the structure. The refractive index value is more dominated by the structure permeability, which has shown the good agreement with the Lorentz's model.

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