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Design and Analysis of a New Double Negative Metamaterial

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Abstract: This paper presents a new double negative metamaterial unit cell structure which is designed on a Rogers RT 6010 substrate. The proposed structure exhibits resonant frequency within the C-band of microwave spectra and shows a negative permeability and permittivity at that resonant frequency. The commercially available simulation software CST Microwave Studio has been used to get the reflection and transmission parameters of the unit cell. The simulated result shows good conformity with the experimental result. In addition, an analysis has been done with the same design by replacing the substrate with popular FR-4 and then it behaves as a single negative metamaterial at the same frequency band.

Keywords: DNG, Metamaterials, SNG

Načrtovanje in analiza novega dvojno negativne meta material

Izvleček: Članek opisuje novo strukturo osnovne celice dvojno negativnega meta materiala, ki je načrtovana na Roger RT 6010 substratu. Predlagana struktura izkazuje resonančno frekvenco v C pasu mikrovalovnega spektra in izkazuje negativno permeabilnost in permitivnost pri resonančni frekvenci. Za določitev refleksijskih in transmisijskih parametrov je bil uporabljen komercialna programska oprema CST Microwave Studio. Simulacijski rezultati se dobro ujemajo s poskusi. Opravljena je bila tudi analiza strukture na popularnem FR-4 substratuu, kjer struktura deluje kot enojno negativen meta material v enakem frekvenčnem pasu.

Ključne besede: DNG, meta material, SNG

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1 Introduction

Metamaterials are artificially constructed materials which may exhibit some exotic electromagnetic property and not naturally found. It may exhibit negative value of permittivity and permeability simultaneously at a specific frequency range. Metamaterials with simultaneous negative permeability (ε) and permittivity (μ) are called double negative (DNG) metamaterials. Materials of this type of negative characteristics are also called left handed materials (LHM), negative-refractive index materials, and backward wave media. The metamaterials with either of the permittivity or permeability negative is called single negative metamaterial. In 1968, Victor Veselago first explained and theoretically showed that materials with simultaneous negative permeability (μ<0) and permittivity (ε<0) had some different properties as compared to ordinary materials that are found in nature [1] but until 1999 this topic was not much interesting to the researchers due to lack of available such natural materials. Although there are some materials that show the property of effective negative permittivity but materials with effective negative permeability was still a challenging issue. In 2000 Smith at et al. successfully showed a new artificial material of such double negative property (i.e both μ and ε are negative) where, Snell's law, Cherenkov radiation, Doppler Effect are inverted [2]. Due to these exotic electromagnetic properties of these materials, it can be used in many important applications like, antenna design, electromagnetic cloaking, SAR reduction etc [3-6]. There are varieties of metamaterial structures have been proposed according to the applications like U-shape, V-shape, S-shape, Triangular etc. and very few of them are applicable for C-band microwave spectra [7-12]. In this paper we are introducing a new metamaterial unit cell structure that contains two split ring resonators with a metal stripe between them and shows resonant frequency in the C-band (4-8 GHz) [13] of microwave spectra and it also shows double negative properties (both permittivity and permeability are simultaneously negative) at that frequency.

2 Design of the Unit Cell

The design parameter and the schematic view of the proposed double negative unit cell structure are given in Fig. 1(a). The structure has been designed with two split ring resonators (SRR) of copper and a metal strip of copper between them with all of them having thickness of 0.035mm. Each ring has inner radius 3mm and outer radius 4mm and gap width of 1mm. In between the rings there is a metal strip of copper with a length of 14mm and width of 1.6mm. The gap between each ring and the metal is 0.33mm. The structure is printed over a square shaped Rogers RT 6010 substrate with dielectric constant of 10.2, dielectric loss-tangent of 0.002, side length and width of 30mm and thickness of 1.6 mm. The unit cell parameters are seen in the Table 1.

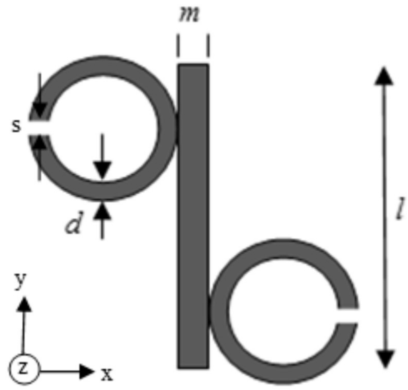
Afterwards for further investigation, the popular FR-4 Substrate has been replaced by the Rogers RT 6010 substrate of the proposed design structure which has dielectric constant of 4.5, dielectric loss-tangent of 0.002, side length and width of 30mm and thickness of 1.6 mm.

Table 1: Design specifications of the unit structure

Unit Cell Parameters	Value (mm)
d	1
l	14
m	1.6
s	1

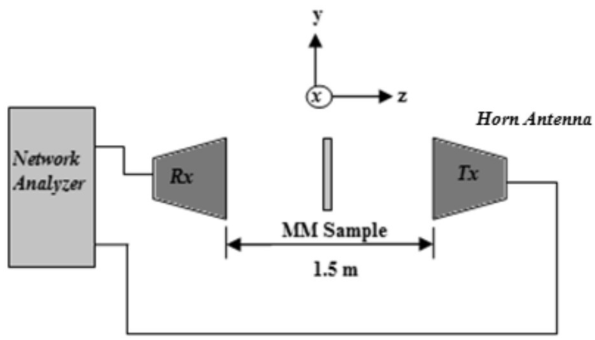
3 Methodology

The commercially available Simulation software CST Microwave Studio has been used to compute complex scattering parameters and also to monitor the resonance frequencies of the proposed unit cell structure. These parameters are used for the retrieval of effective permeability (μ) and permittivity (ε) for the proposed unit cell structure.



(a)

(b)



(c)

Figure 1: (a) The proposed unit cell structure (b) Fabricated metamaterial prototype for measurement on Rogers RT 6010 substrate material (c) Measurement setup (top view)

The structure has been placed between two waveguide ports of positive and negative of z- axis and excited by the transverse electromagnetic (TEM) wave. The perfect electric conductor (PEC) boundary has been defined in the x-plane and the perfect magnetic conductor (PMC) boundary has been defined in the y-plane. Frequency domain solver has been used for simulation. The normalized impedance has been set to 50 ohm. Simulation is done for the frequency range of 4-7 GHz.

However, further simulation is done after replacing the substrate with a FR-4 substrate and the same methodology has been used to get the values of S-Parameters and effective medium parameters.

A 160×160 mm^2 prototype of 4×4 unit cell is fabricated for measurement, as shown in Fig. 1(b). The prototype is then placed between two horn antennas which are 1.5m apart in the same plane. The measurement arrangement is being displayed in Fig. 1(c). An Agilent E8363D vector network analyzer is used to calculate the transmission co-efficient. For calibration purpose, measurement without metamaterial and with metamaterial is done.

There are many methods exist for effective parameter extraction of metamaterial like-TR Method, Lossy-Drude Method, Nicolson-Ross-Weir method etc. The effective medium parameters permeability and permittivity are extracted from the simulated complex S_{21} and S_{11} parameters using method mentioned in [14]. The simplified formulae have been given bellow,

$$V_1=S_{21}+S_{11} \quad (1)$$

$$V_2=S_{21}-S_{11} \quad (2)$$

$$\mu_r \approx \frac{2}{jk_0 d}\frac{1-V_2}{1+V_2} \quad (3)$$

$$\varepsilon_r \approx \frac{2}{jk_0 d}\frac{1-V_1}{1+V_1} \quad (4)$$

$$\eta = \sqrt{\varepsilon_r \mu_r} \quad (5)$$

where, ε_r is the effective permittivity, μ_r is the effective permeability, 'd' is the thickness of the substrate, k_0 is the wave number and η is the refractive index.

4 Results and Discussion

The simulated result of transmission coefficient (S_{21}) for the proposed unit cell structure is given in Fig-2(a) and the experimental results for the unit cell are seen in Fig. 2(b) and 2(c). Here the simulated spectra of the transmission coefficient (S_{21}) shows the maximum resonance at 5.09 GHz which is in the range of C-band microwave spectra and the experimental result of the transmission coefficient that is seen in the Fig. 2(c), agrees well with the simulated result. Unlike the SRR rings the currents flows in the opposite direction of the two rings and these two opposite currents also create opposite currents in the two sides of the metal strip and Fig-3 shows the currents distribution at frequency 5.09 GHz in the unit cell structure.

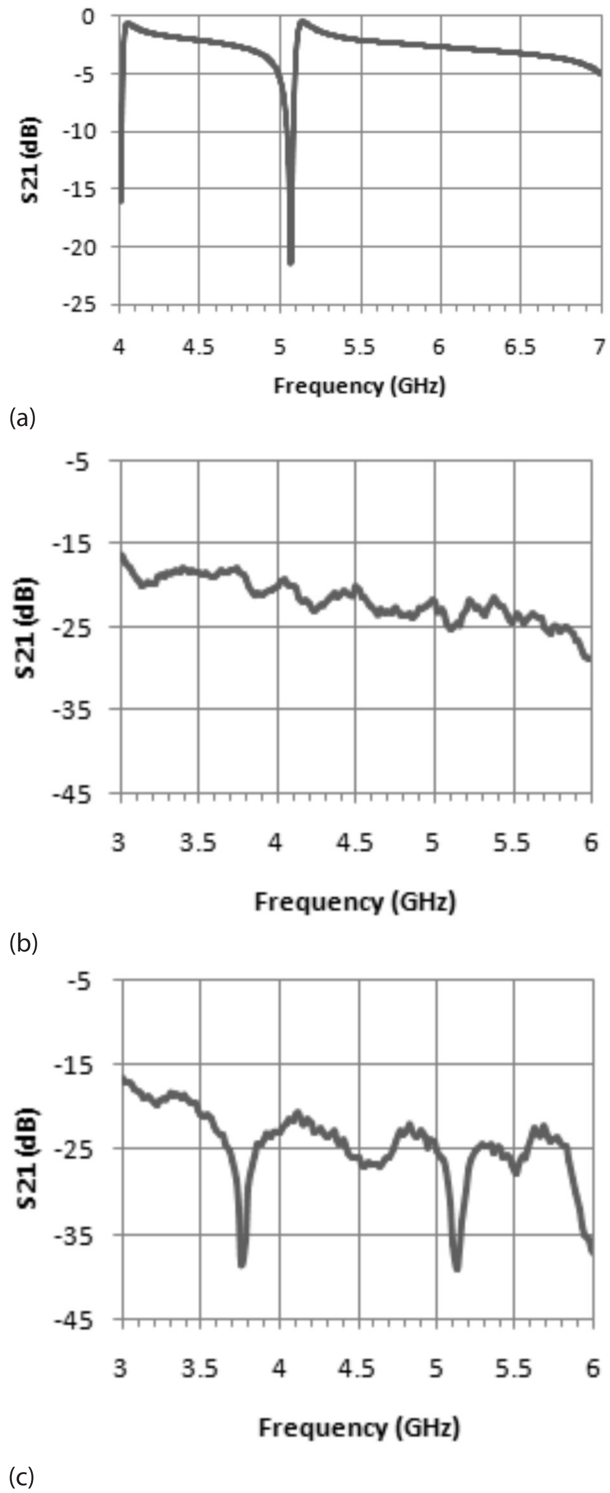


Figure 2: (a) Simulated transmission coefficient (S_{21}) in dB (b) Measured value of S_{21} in dB without metamaterial (c) Measured value of S_{21} in dB with metamaterial sample

The two metal rings are responsible for creating the inductance and by increasing the side length of the rings the inductance can be increased which leads to decrease the LC resonance frequency. On the other hand

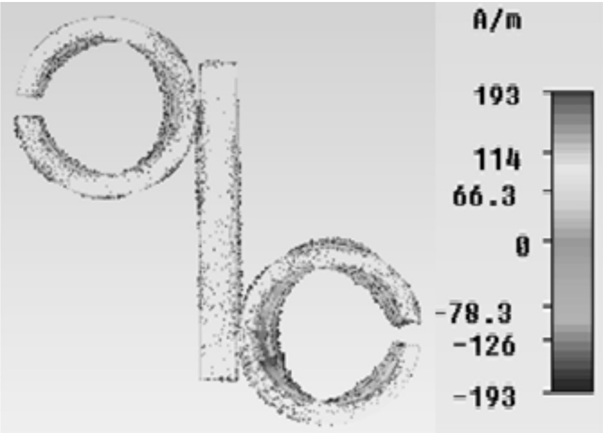


Figure 3: Current distribution in the unit cell structure

as the split of the rings are responsible for creating the capacitance for the design, by increasing the gap the capacitance can be reduced which leads to increase the LC resonant frequency.

These results are given in Fig-4(a) and Fig-4(b) where the effective permeability is shown in Fig-4(a) and effective permittivity is shown in Fig-4(b) against frequency. In Fig-4(a) and 4(b), we see that at the maximum point of resonance frequency of 5.09 GHz, the both curve of permeability and permittivity show negative value and they are ε= -13.93 (Real) and μ= -11.92 (Real) . So, the structure can be said a double negative (DNG) metamaterial. Normally a charge builds up in the gap of a split ring resonator and creates capacitance if it is kept in a changing magnetic field. At low frequency the current of the oscillator remain in phase of the driving field but in higher frequency the current starts lagging which produces negative permeability at that frequency.

The DNG material are also called negative refractive index materials, backward media, and left handed materials (LHM). In case of negative refractive index material, the light rays are refracted in the same side of its entrance. Actually in a double negative media the phase and the energy flow of the wave moves in the opposite direction which makes the wave to flow in the backward direction. Accordingly in Fig-5 the real part of refractive index curve is seen against the frequency where at frequency 5.09 GHz the refractive index is also negative and that is η= -19.09 . So, realization of negative permeability over that frequency bands may also be useful in long distance communication applications. The simulated result also depicts the double negative characteristics for the unit cell at the frequency of 4.03GHz which is in the range of S-band (2-4GHz) microwave spectra. However, the measured result has bit displaced from the simulated result in this case. This difference most likely happens because of fabrication error.

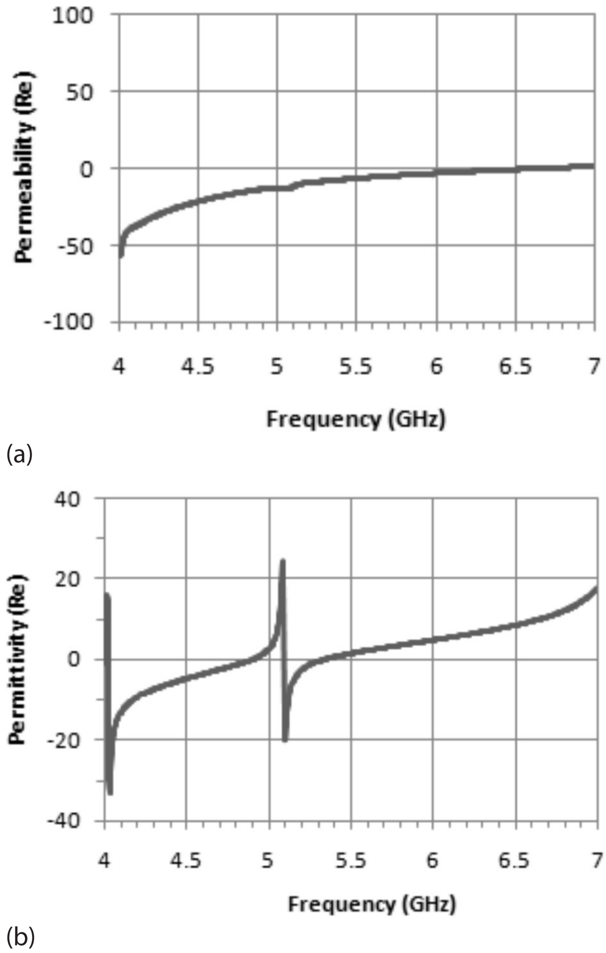


Figure 4: (a) Real value of effective permeability (μ) versus frequency (b) Real value of effective permittivity (ε) versus frequency

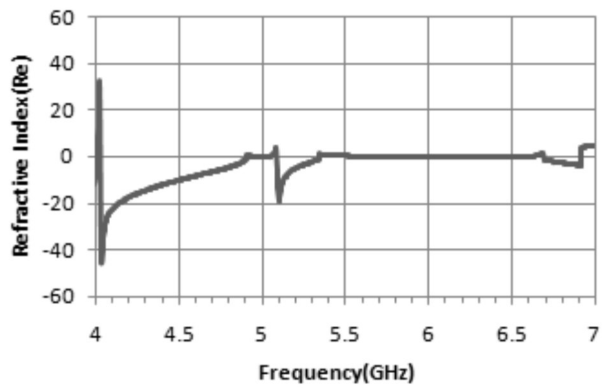
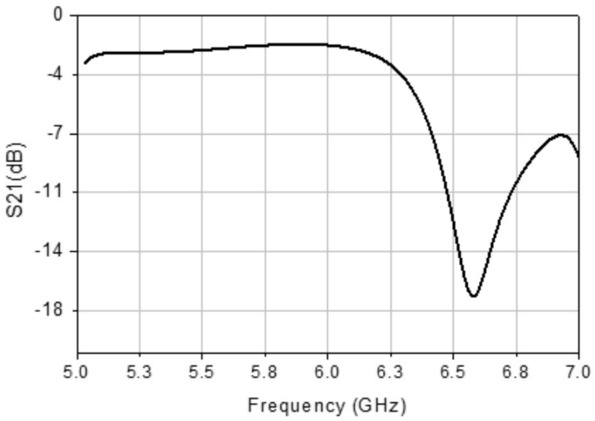
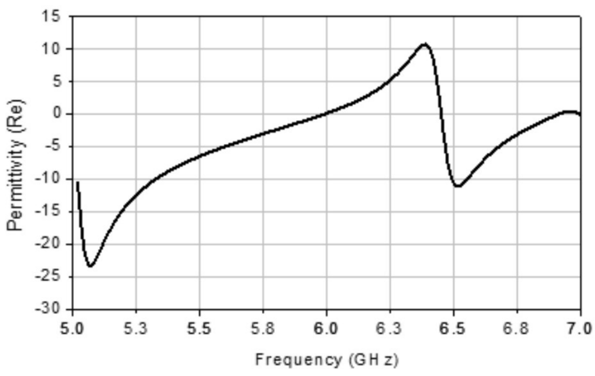


Figure-5: Real value of Refractive Index versus frequency.

After using the FR-4 substrate for the same design structure it is seen in Fig-6 (a), that the S-Parameter spectra has changed a bit. Previously we found that transmission spectra at 5.09 GHz for the design on Rogers RT 6010 substrate and we had sharp resonance below -25dB whereas for substrate FR-4 we have got the resonance at the frequency of 6.65 GHz but this time the resonance is seen very close to -18dB. Actually this difference in the transmission coefficients of Fig. 2(a) and Fig. 6(a) has occurred due to the difference of dielectric constants in the two substrate materials, where the Rogers RT 6010 has dielectric constants of 12.2 and FR-4 has 4.2. The dielectric constant of a material depends on the material internal structure. When electromagnetic waves propagated through a material it's electric and magnetic fields oscillate as sinusoidal pattern and its velocity depends upon the electrical conductivity of the material which actually depends on the internal structure of the material. The relative speed of electrical signal that travel through the material varies according to the type of interaction with its internal structure and this variation caused the different results in the transmission characteristics. In Fig. 6(b), the frequency versus permittivity curve for FR-4 substrate depicts that permittivity is still negative and its real value is ε= -4.77 which was -1.03 for Rogers RT 6010 based design. However the Fig. 7(a) reveals that the permeability for the FR-4 substrate for the same design does not show negativity and the real value is μ= 8.33 which was previously -4.48 for Rogers RT 6010 substrate. So, now it is clear that the design based on FR-4 substrate does not show double negative characteristics and accordingly the real value of refractive index in Fig-7(b) reveals the positive value of η= 0.92. So, for FR-4 substrate the material can be characterized as single negative (SNG) metamaterial. The overall comparative results are presented in Table 2.

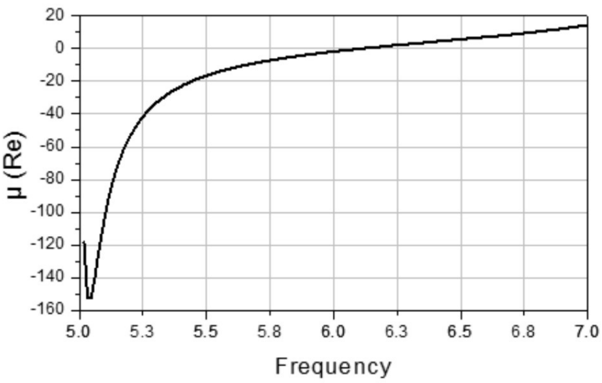


(a)

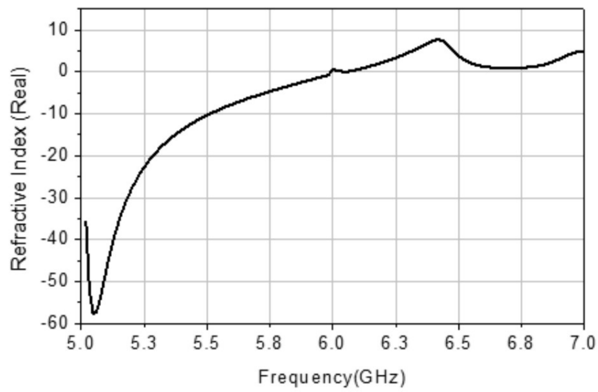


(b)

Figure 6: (a)Transmission coefficient for FR-4 substrate material (b) Real magnitude of permittivity (ε) for FR-4 substrate material



(a)



(b)

Figure 7: (a) Real magnitude of permeability (μ) for FR-4 substrate material (b) Real magnitude of refractive Index (η) for FR-4 substrate material

Table 2: Effective parameters comparisons for two popular substrate materials

Substrate	Dielectric Constant	Frequency (GHz)	Permittivity(ε)	Permeability(μ)	Refractive Index (η)	Metamaterial Type
Rogers RT 6010	10.2	5.09 GHz	-13.93	-11.92	-19.09	DNG
FR-4	4.2	6.65 GHz	-4.77	8.33	0.92	SNG

5 Conclusion

In this paper we have presented a new double negative metamaterial structure on Rogers RT 6010 that resonates at frequency in 5.09 GHz which is in the C-band of microwave spectra. We have then changed the substrate by popular FR-4 substrate and we have found the resonance at point of 6.65 GHz which is also in the C-band. However, it does not show double negative characteristics at 6.65GHz. C-band of microwave spectra specially used for long distance communication like, satellite communications. We have used two popular substrates to demonstrate its metamaterial characteristics and we have done comparative analyses between them. So, this structure can be used besides other metamaterials especially in the C-band metamaterial applications.

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