

Double-E-Triple-H-Shaped NRI-Metamaterial for Dual-Band Microwave Sensing Applications

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Abstract: This paper presents a new Double-E-Triple-H-Shaped NRI (negative refractive index) metamaterial (MM) for dual-band microwave sensing applications. Here, a horizontal H-shaped metal structure is enclosed by two face-to-face E-shaped metal structures. This double-E-H-shaped design is also encased by two vertical H-shaped structures along with some copper links. Thus, the Double-E-Triple-H-Shaped configuration is developed. Two popular substrate materials of Rogers RO 3010 and FR-4 were adopted for analyzing the characteristics of the unit cell. The proposed structure exhibits transmission resonance inside the S-band with NRI and ENG (Epsilon Negative) metamaterial properties, and inside the C-band with ENG and MNG (Mu Negative) metamaterial properties. A good effective medium ratio (EMR) of 8.06 indicates the compactness and effectiveness of the proposed design. Further analysis has been done by changing the thickness of the substrate material as well and a significant change in the effective medium ratio is found. The validity of the proposed structure is confirmed by an equivalent circuit model. The simulated result agrees well with the calculated result. For exploring microwave sensing applications of the proposed unit cell, permittivity and pressure sensitivity performance were investigated in different simulation arrangements. The compact size, effective parameters, high sensitivity and a good EMR represent the proposed metamaterial as a promising solution for S-band and C-band microwave sensing applications.

Keywords: Metamaterial; NRI; MNG; ENG; dual-band; sensing; S-band; C-band



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1 Introduction

At the starting of the 21st century, the well-established field and classical academic subject with a 150-year history named electromagnetism was shaken to its foundation and rebuilt in years to come. This manifestation is called Metamaterials. We can define metamaterials as an engineered material developed artificially that does not exist in nature and can demonstrate superb electromagnetic properties [1,2]. Their appropriate orientation, volume, shape, and geometry grant them to manipulate electromagnetic waves that are not possible in conventional materials. It can manipulate the electromagnetic wave in a remarkable way such as negative refraction [3,4], reverse Doppler effect, diffraction-limit breaking imaging [5–8], reverse Vavilov-Cerenkov effect [9] etc. For different frequency ranges, (i.e., GHz, THz and optical) metamaterials have been examined and exhibit advanced applications such as invisibility cloaking [10], sensing [11], satellite communication [12,13], solar energy harvesting [14], microwave-imaging [15,16], optical switching [17], super-lenses [7], data storage [18], slow light [19], antenna systems [20,21] and so on. Metamaterials can be classified by two material parameters named electric permittivity and magnetic permeability. The NRI property is formed by permittivity and permeability. It does not exist in any conventional materials and has attracted the researchers' massive attention because of its potential application. There are different types of metamaterial constructions that have been proposed according to the purposes like U-shape, V-shape, S-shape, Triangular, etc. and very few of them are relevant for C-band microwave spectra [22–25]. A WU-shaped metamaterial proposed by Sinha et al. [26] for dual-band microwave application. For the sensitivity study, they adopted three separate substrate materials named FR-4, Rogers RT6006, and Rogers RT6010. The metamaterial unit cell displays a negative refractive index (NRI) within the C-band and X-band for each of these substrate materials. Another group of researchers [27] has designed a novel single negative metamaterial (MTM) with crossed lines based on concentric rings. They designed their unit cell using an HFSS-based 3D full-wave simulator and further tested it with the 'Advanced Design System (ADS)' formulation using the transmission line matrix (TLM). Islam et al. [28] designed an SNG metamaterial using FR-4 substrate material where they acquired one resonance for their design with a 1.9 Effective Medium Ratio. They obtained resonance frequency at 5.133 GHz and present the metamaterials for the C-Band application used for remote communication such as satellite communication. A new tunable microstrip leaky-wave antennas (LWA) investigated by Sarkar et al. [29] operates in the microstrip's second higher-order mode from 50–65 GHz. They designed the antenna for V-band, which is a potential candidate for multiple millimeter-wave applications, such as automotive radar systems, wireless applications. A new metamaterial leaky-wave array antenna for millimeter-wave beam-forming applications has been studied by Mohammad et al. [30] that operates from the frequency range of 55 to 65 GHz. Here, E-shaped transverse slot metamaterial unit cells are used to enhance the performance of the array antenna. H-shaped resonator on FR-4 substrate material [31] was introduced by another group of researchers for dual-band application with negative refractive index (NRI) properties. Double U-H shaped design proposed in [32] with DNG Properties. The EMR value was 0.8 for their proposed metamaterial. A new ultra-broadband perfect absorber with a simple nanostructure that concentrated a significant volume of sunlight energy with near-perfect absorption covering a wavelength range from 400 to 1500 nm [33]. The wavelength range of absorption is up to 1.1 μm , which is far higher than most other electromagnetic wave absorbers active in the solar spectrum. A polarization-independent, broadband metamaterial absorber has been developed in [34] for future applications such as sensing, optical networking, and thermal imaging.

In developing new generation sensing technology, metamaterials have been showing novel opportunities in recent years. Goran et al. [35] offered metamaterial-based sensor for measuring soil moisture. This sensor operates on the resonant frequency shifting principle. The output of that

proposed sensors ranges from 2 to 20 percent for soil moisture, corresponding to the real-life values. This proposed sensor's main downside is that it has a relatively small loss of insertion at the resonant frequency, particularly in high soil humidity. Mehmet Bakır et al. [36] designed a metamaterial sensor for detecting the quality of water. The sensor was developed by collecting water samples and electrical properties were measured in the microwave range. The frequency change between the water samples was observed at about 130 MHz. However, like any flourishing technology, metamaterials-based study faces many challenges. Usually, a good metamaterial must assure a good EMR to ensure proper metamaterial operation in bulk context. So, a metamaterial design with good EMR in a different band is needed. Besides, the performance of sensors based on metamaterials is limited by fluctuation phenomena. Due to small feature sizes on substrates and difficulty obtaining high sensitivity, metamaterials-based sensors still need improvements in their accuracy and sensing ability. So, metamaterials with good EMR and shifting ability are required for multi-band sensing applications.

A new metamaterial has been proposed in this article that exhibits transmission resonance within S-band with NRI and ENG properties for X-axis wave propagation. It also shows ENG metamaterial properties within the C band for X-axis wave propagation. For the Z-axis wave propagation, it exhibits ENG properties within S-band and MNG (Mu-negative) metamaterial properties within the C band in further analysis. The effective medium ratio (EMR) of 8.06 has been achieved for the proposed structure which is good for metamaterials design. An equivalent circuit model has been extracted and calculated to prove the validity of the proposed unit cell structure. Various analysis has been done using two different substrate material, Rogers RO 3010 and FR-4 to investigate the potentials and economical use of the proposed metamaterial. The finite-integration technique (FIT)-based simulation tool (CST microwave studio simulation software) has been used to acquire the results and for analyzing different parameters of the unit cell. Finally, the sensitivity of the unit cell in microwave sensing applications considering permittivity and pressure sensitivity has been analyzed with different simulation arrangements.

2 Design and Simulation Setup

2.1 Design of the Unit Cell

The proposed unit cell structure is a mutually connected double-H shape metal having an interconnected double-E shape in the middle of the structure with a centered horizontal H shape. The designed structure and design parameters are shown in Fig. 1 and Tab. 1.

The copper resonators are composed on a dielectric substrate material. The substrate material's length and width are kept $A = 15$ mm and the width of all copper strips is kept at 0.5 mm. Initially, the structure has been designed on an FR-4 substrate (dielectric constant is 4.3 and loss tangent is 0.025) material of thickness 1.6 mm, then the FR-4 has been replaced by the Rogers RO 3010 substrate (dielectric constant is 10.2 and loss tangent is 0.002) material and analyzed for better results. For FR-4, the effective medium ratio (EMR) is obtained at 5.53, whereas for the Rogers RO 3010 material, it is 8.06. The EMR for the proposed unit cell has been calculated by using the equation: $EMR = \lambda/L$, where λ represents the wavelength and L represents the length of the proposed unit cell. For perfect metamaterial operation, the EMR should be kept more than 4 [37] to ensure proper metamaterial operation in bulk context Figs. 2a–2e demonstrates the stepwise design procedure of the unit cell structure and Fig. 2f shows the back view of the design structure. First, in step-1 mutually connected double H shape 10 mm apart from each other has been applied shows in Fig. 2a. Then an interconnected double E shape has been applied in the middle of the structure in step 2. The inner

shape is 1 mm apart from the outer shape on every side shown in Fig. 2b. In step 3, the split gaps of 0.25 mm have been created on the double E shape shown in Fig. 2c. In Fig. 2d, the split gaps of 0.5 mm have been created on the double H shape. The design procedure has been reached to the final proposed design by adding copper strips of length 1 mm with the two-outer side of the outer H-shaped ring along with the X-axis.

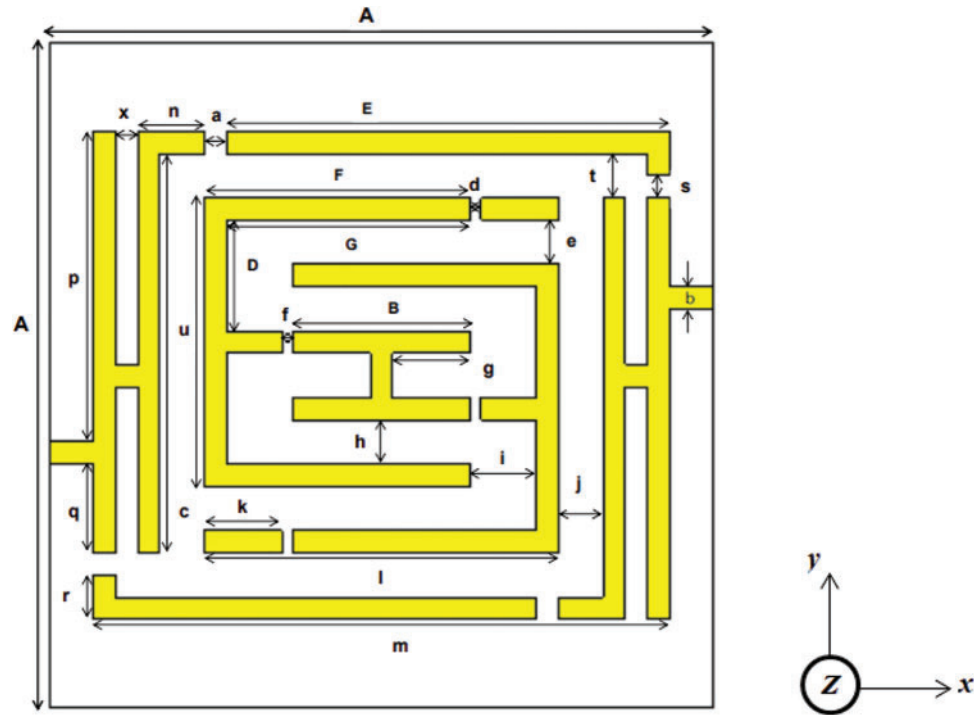


Figure 1: The proposed unit cell structure

Table 1: Specifications of proposed unit cell structure

Parameters	a	b	c	d	e	f	g	h	i	j	k	l	m	n
Value (mm)	0.5	0.5	9.0	0.25	1	0.25	1.75	1	1.5	1	1.75	8	13	1.5
Parameters	x	p	q	r	s	t	u	A	D	E	F	G	B	
Value (mm)	0.5	7	2	1	0.5	1	6.5	15	2.5	10.0	6.0	5.5	4.0	

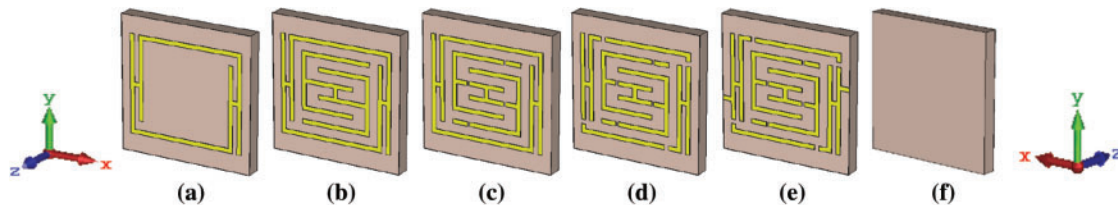


Figure 2: Stepwise design procedure of unit cell in 3D view, (a) step-1 (b) step-2 (c) step-3 (d) step-4 (e) final design of the proposed structure (f) back view of the unit cell

2.2 Equivalent Circuit Model

An equivalent circuit model is formulated to verify the design structure and estimate the operating frequency of the proposed metamaterial unit cell as shown in Fig. 3a. Such metamaterial structure includes passive LC circuits with a resonant frequency:

$$F = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where L and C stand at generally structural inductance and capacitance. The current induced in the metal strip creates inductance and the split gap between two metal strips causes capacitance in the metamaterial design [38]. In the structure, copper strips of the unit cell are thus considered as inductance (L) and split gaps on the metal strips are considered as capacitance (C). Following a Quasi-Static theory, the total capacitance between the gaps is frequently stated as:

$$C = \epsilon_o \epsilon_r \frac{A}{D_a} \quad (2)$$

where ϵ_o = Free space permittivity

ϵ_r = Relative Permittivity

D_a = Gap length

A = Cross-sectional area of the gap

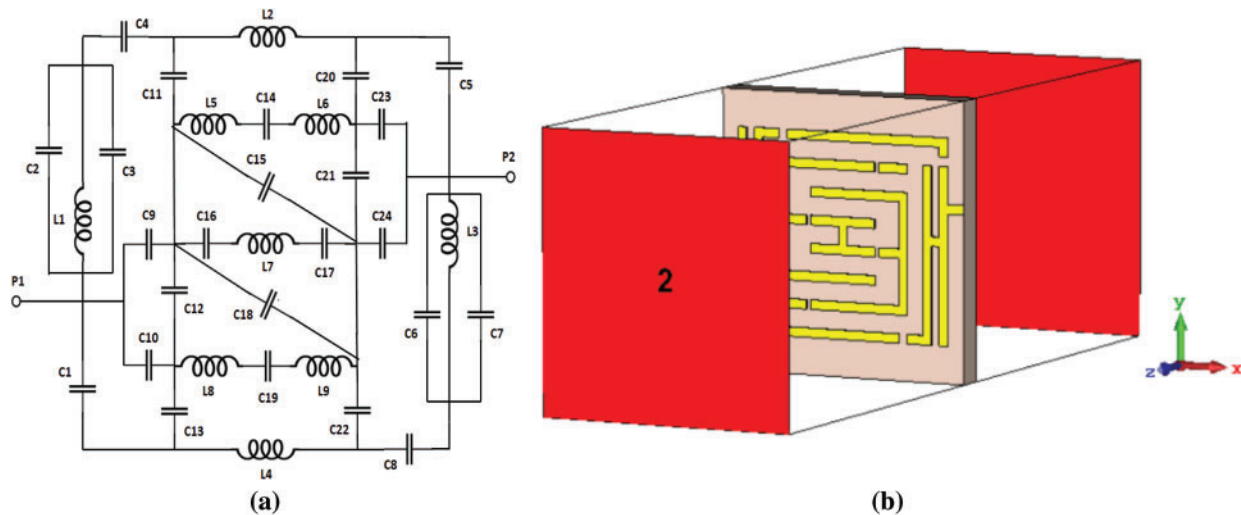


Figure 3: (a) Equivalent circuit model of the proposed unit cell and (b) Simulation geometry of the proposed structure in Z-axis field excitation

So, for the proposed Double-E-Triple-H-Shaped resonator, the resonant frequency is:

$$F = \frac{1}{2\pi\sqrt{LC_p}} \quad (3)$$

where the inductance for the proposed structure can be calculated as:

$$L = \mu_o T \left[\frac{(x + n + a + E)}{2b} + \frac{(s + t)}{m^2 + (p + q + b + r)^2} \right] \quad (4)$$

And the equivalent capacitance can be demonstrated as:

$$C_p = (c + t)\epsilon_o \left[\frac{(u + e + b) - 3h}{\pi} \times \ln \frac{(B + 2i)}{A - (l + 2j) - 4(d + f)} \right] \quad (5)$$

where, $\mu_o = 4\pi \times 10^{-7} \text{ H/m}$ and $\epsilon_o = 8.85 \times 10^{-12} \text{ F/m}$

T=thickness of substrate material = 1.6 mm. A summary of the above equations is available in [3,39]. By using Eqs. (4) and (5), the calculated value of inductance would be, $L = 3.591 \times 10^{-8} \text{ H}$ and the value of capacitance is $C = 1.192 \times 10^{-23} \text{ F}$. Therefore, according to Eq. (3), the calculated resonance frequency is found at 2.43 GHz for Rogers RO 3010 substrate material along the X-axis whereas the simulated one is found at 2.48 GHz which is almost the same.

2.3 Simulation Setup and Methodology

The commercially available CST Microwave Studio simulation software works on the principle of finite integration technique (FIT) is utilized to investigate the performance and calculate the proposed unit cell's S-parameters. Simulation and analysis approaches are adopted from reference [40]. The simulation geometry for the unit cell structure in Z-axis wave propagation is depicted in Fig. 3b. To ensure the proper simulation setup with perfect boundary conditions, the structure was excited by transverse electromagnetic (TEM) wave taking perfect electric-magnetic (PEM) boundary conditions perpendicular to the excitation field. The perfect electric conductor (PEC) and perfect magnetic conductor (PMC) boundary were taken through X-axis and Y-axis respectively for Z-axis field excitation, and for X-axis field excitation, PEC and PMC boundary were taken through Y-axis and Z-axis respectively. The frequency range was chosen 1-6 GHz to acquire the best result from the designed structure and the frequency domain analysis was considered. Among the several existing methods, the Nicolson-Ross-Weir methodology referenced in [41,42] was adopted to extract the effective medium parameters of the designed structure from the S-parameter simulation results. The simplified formulas for effective parameters extraction are,

$$V_1 = S_{21} + S_{11} \quad (6)$$

$$V_2 = S_{21} - S_{11} \quad (7)$$

$$\epsilon_r \approx \frac{2}{jk_0 d} \frac{1 - v_1}{1 + v_1} \quad (8)$$

$$\mu_r \approx \frac{2}{jk_0 d} \frac{1 - v_2}{1 + v_2} \quad (9)$$

$$\eta = \sqrt{\epsilon_r \mu_r} \quad (10)$$

where, ϵ_r = Effective permittivity.

μ_r = Effective permeability.

d = Substrate thickness.

k_0 = Wave number.

η = Refractive index.

3 Results Analysis and Discussion

3.1 Stepwise Evaluation of the Proposed Structure

The designed structure has been evaluated step by step up to the final design of the unit cell. Tab. 2 demonstrates the effective parameters for the different design steps of the proposed structure. To make the proper evaluation of the structure the Rogers RO 3010 substrate has been considered.

Table 2: Effective parameters comparison of the design steps

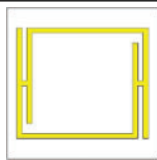
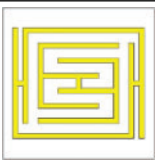
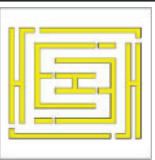
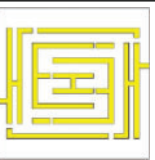
Design steps	Step-1	Step-2	Step-3	Step-4	Final design
					
Minimum resonance (GHz)	3.855	3.245	3.435	2.885	2.48
EMR	5.18	6.16	5.82	6.93	8.06
MM type	ENG	ENG	ENG	MNG	NRI

Fig. 4 demonstrates the unit cell structure's performance compared to the previous design steps made on the transmission resonance curve S_{21} and reflection coefficient curve S_{11} . The transmission resonance curve shows more sharpness with minimum resonance, high magnitude, and maximum EMR compare to the step-1 to step-4. In the table, we can see that the minimum resonance for the design step-1 is 3.855 GHz with a maximum EMR 5.18, and the type of the metamaterial is epsilon negative (ENG). The design has been modified to get a better result and gradually the better performances have been acquired. The final proposed design shows the best performance with negative refractive index (NRI) metamaterial properties at the minimum resonance of 2.48 GHz and the maximum EMR 8.06 is achieved at this frequency. It also shows the ENG metamaterial properties at the resonance frequency of 3.805 GHz. The magnitude of the resonance curve S_{21} for the proposed design is -53.94 dB at 2.48 GHz and -50.03 dB at 3.805 GHz, which is far greater than that are for design step-1 to 4.

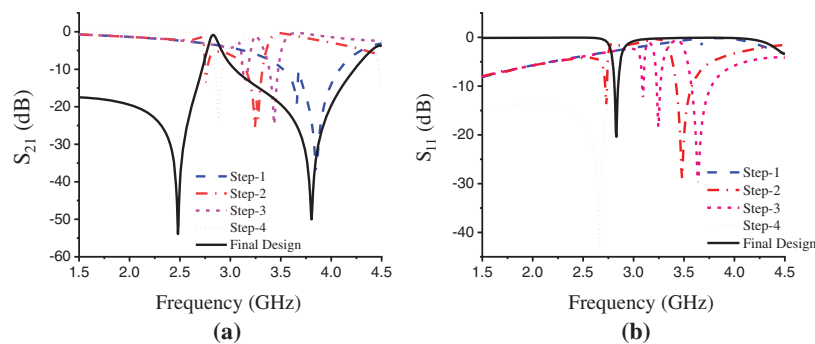


Figure 4: (a) The transmission coefficient (S_{21}) and (b) reflection coefficient (S_{11}) view for the design steps

3.2 Simulated Results Using FR-4 and RO 3010 Substrate

The simulated results for the proposed structure for two different substrates considering a thickness of 1.6 mm are discussed here based on Z-axis and X-axis field excitation.

3.2.1 Z-Axis Wave Propagation

In the Z-axis wave propagation, the structure exhibits Epsilon-Negative (ENG) metamaterial properties within S-band and Mu-Negative (MNG) metamaterial properties within C-band with EMR 6.45 for RO 3010 substrate and EMR 4.33 for FR-4 substrate.

Fig. 5 shows the simulation results for FR-4 substrate in the Z-axis field excitation. The transmission coefficient (S_{21}) in Fig. 5a shows the transmission resonance at the frequency of 4.615 GHz with a magnitude of -24.15 dB. The EMR has been found 4.33 for FR-4 substrate in the Z-axis wave propagation. The frequency vs. permittivity curve in Fig. 5b depicts a positive real value of 18.12 for permittivity at the resonance frequency of 4.615 GHz. The effective permeability curve in Fig. 5c and refractive index curve in Fig. 5d demonstrate negativity and positivity for permeability and refractive index with the real values of -24.78 and 28.94 at this frequency. Thus, in Z-axis field excitation the designed structure shows MNG metamaterial properties within the C-band of microwave spectra.

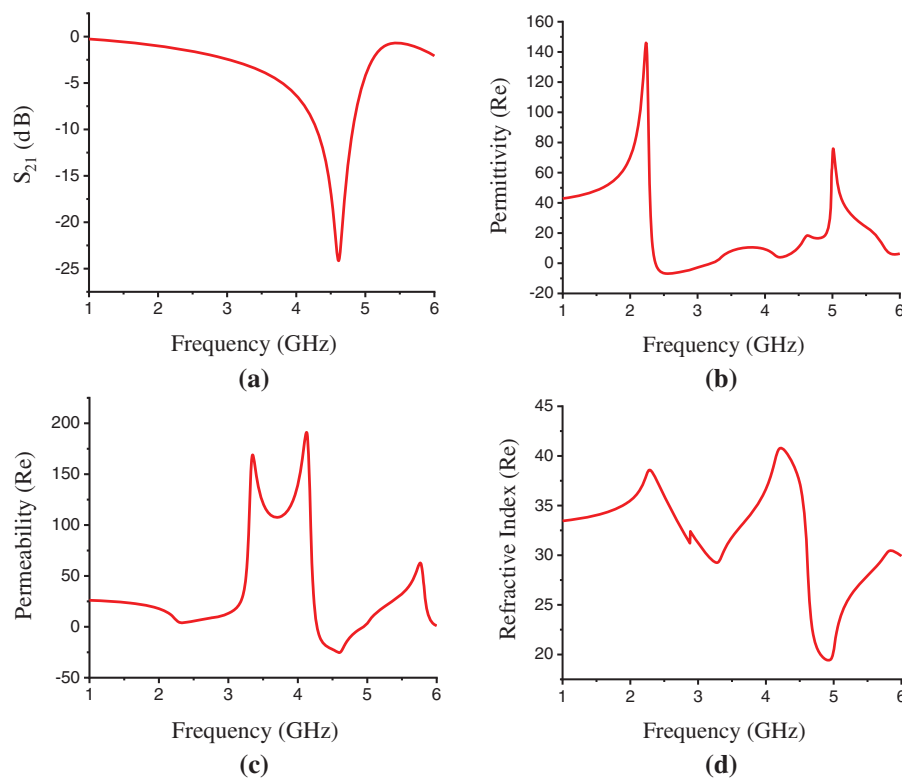


Figure 5: FR-4 Substrate results. (a) Transmission Resonance (S_{21}), (b) Permittivity(ϵ) (Real) curve, (c) Permeability(μ) (Real) curve, (d) Refractive index (η) (Real) curve in Z-axis propagation

Fig. 6 shows the simulation results for RO 3010 substrate in the Z-axis field excitation. The transmission coefficient (S_{21}) in Fig. 6a shows the transmission resonance at the frequency of 3.1, 4.305 and 5.055 GHz with the magnitude of -40.97 , -25.19 , and -21.43 dB. The EMR has been found 6.45 for RO 3010 substrate in the Z-axis wave propagation. The frequency vs. permittivity curve in Fig. 6b depicts a negative real value of -2.275 for permittivity at the resonance frequency of 3.1 GHz. The effective permeability curve in Fig. 6c and refractive index curve in Fig. 6d demonstrate positivity for permeability and refractive index with the real values of 464.22 and 16.967 at this frequency. Thus, the structure shows ENG metamaterial properties at the resonance frequency of 3.1 GHz for the Z-axis wave Propagation. At the resonance frequency of 4.305 GHz that is within the C-band, the frequency vs. permeability curve shown in Fig. 6c exhibits the negative real value of -36.61 for permeability. And, the positive real values of effective permittivity and refractive index at this frequency have shown in Figs. 6b and 6d are, 14.03 and 32.99 respectively. At the resonance of 5.055 GHz the permittivity, permeability, and refractive index values are found 24.27, -12.21 , and 28.05.

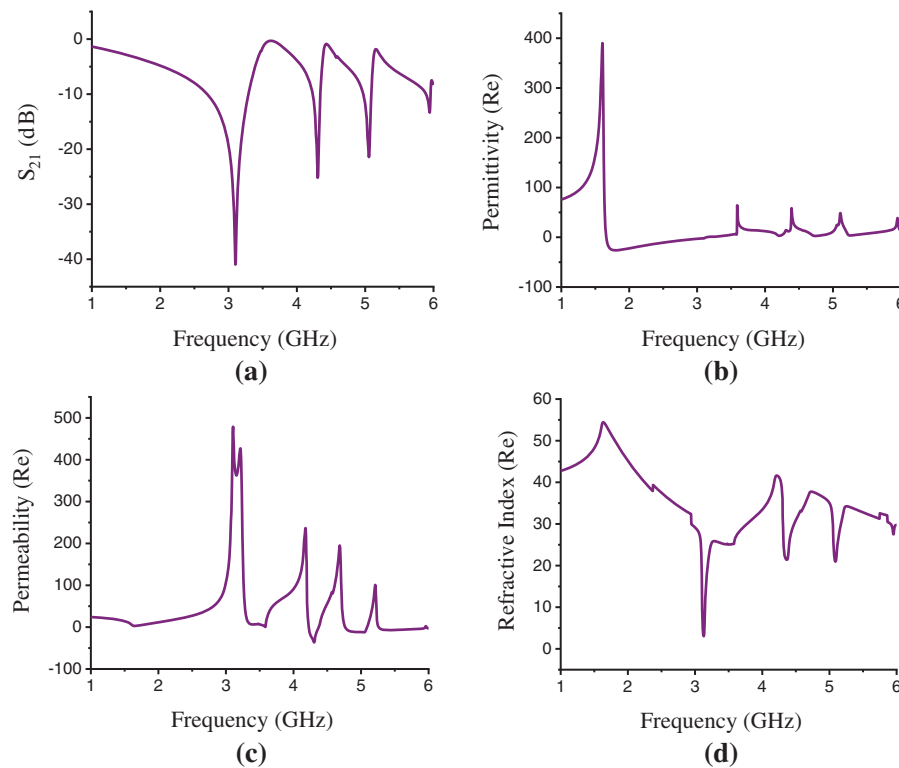


Figure 6: Rogers RO 3010 Substrate results. (a) Transmission resonance (S_{21}), (b) Permittivity(ϵ) (Real) curve, (c) Permeability(μ) (Real) curve, (d) Refractive index (η) (Real) curve in Z-axis propagation

As the proposed structure exhibits the MNG metamaterial properties at the resonance of 4.305 and 5.055 GHz, the material thus is characterized as Mue-Negative (MNG) or Single-Negative (SNG) metamaterial within the C-band of microwave spectra. The overall comparisons of substrate materials based on different effective parameters for Z-axis field excitation are shown in Tab. 3.

Table 3: Comparisons of substrate materials in the Z-axis wave propagation based on effective parameters

Substrate	Minimum resonance(GHz)	Permittivity (ϵ)	Permeability (μ)	Refractive index (η)	EMR	MM type
Rogers RO 3010	3.1	-2.275	464.22	16.967	6.45	ENG
FR-4	4.615	18.12	-24.78	28.94	4.33	MNG

3.2.2 X-Axis Wave Propagation

The proposed structure shows the Negative Refractive Index (NRI) and Epsilon-Negative (ENG) metamaterial properties within S-band and Epsilon-Negative (ENG) metamaterial properties within C-band in the X-axis wave propagation. The maximum EMR 8.06 is achieved in this wave propagation for Rogers RO 3010 substrate and EMR 5.53 is found for FR-4 substrate. The simulation results for FR-4 substrate in the X-axis field excitation are presented in Fig. 7. The transmission coefficient (S_{21}) in Fig. 7a shows the transmission resonance at the frequency of 3.615 and 5.595 GHz with the magnitude of -41.75 and -35.599 dB. The EMR has been found 5.53 for FR-4 substrate in the X-axis wave propagation. The frequency vs. permittivity curve in Fig. 7b depicts a positive real value of 169.79 for permittivity at the resonance frequency of 3.615 GHz. The effective permeability curve in Fig. 7c and refractive index curve in Fig. 7d demonstrate negativity for permeability and refractive index with the real values of -8.01 and -11.44 at this frequency. Thus, the structure shows NRI metamaterial properties at the resonance frequency of 3.615 GHz for the X-axis wave propagation. At the resonance frequency of 5.595 GHz that is within the C-band, the frequency vs. permittivity curve shown in Fig. 7b exhibits the negative real value of -79.43 for permittivity. And, the positive real values of effective permeability and refractive index at this frequency have shown in Figs. 7c and 7d are, 5.44 and 8.00 respectively.

The simulation results for Rogers RO 3010 in the X-axis field excitation are shown in Fig. 8. The transmission coefficient (S_{21}) in Fig. 8a shows the transmission resonance at the frequency of 2.48 and 3.805 GHz with the magnitude of -53.94 and -50.03 dB. The maximum EMR 8.06 is found here for RO 3010 in the X-axis wave propagation. Fig. 8b shows that the effective permittivity curve at the resonance frequency of 2.48 GHz does not show negativity and the real value for effective permittivity is 323.162. The effective permeability curve in Fig. 8c and the refractive index curve in Fig. 8d demonstrate negativity at this frequency. The real values for permeability and refractive index at the resonance frequency of 2.48 GHz are -15.549 and -14.40. Now, it can be concluded that, at a resonance frequency of 2.48 GHz, the structure shows NRI metamaterial properties and the material thus can be identified as Negative Refractive Index (NRI) metamaterial. At the resonance frequency of 3.805 GHz, only the effective permittivity curve in Fig. 8b depicts that the permittivity is negative with the real value of -185.926. The other two-parameter curves, frequency vs. permeability in Fig. 8c and frequency vs. refractive index in Fig. 8d exhibit positive real values of 9.986 and 11.55 for permeability and refractive index at this frequency. So, at a resonance frequency of 3.805 GHz, the structure is characterized as a Single Negative (SNG) or ENG metamaterial. Tab. 4 presents the overall comparisons of substrate materials based on different effective parameters for X-axis field excitation.

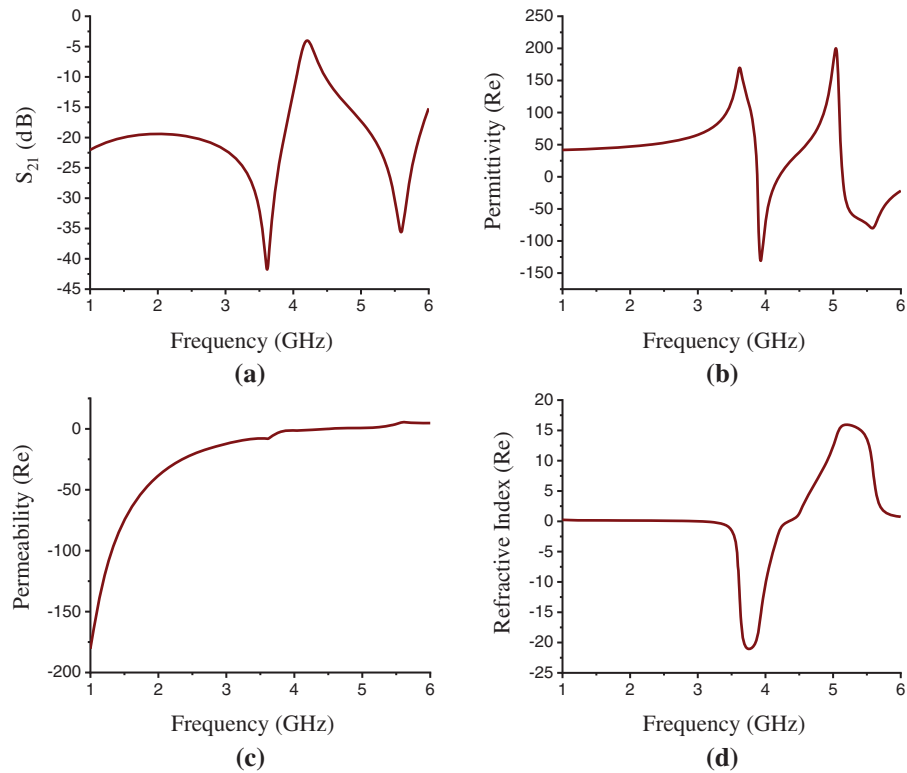


Figure 7: FR-4 Substrate results. (a) Transmission resonance (S_{21}), (b) Permittivity(ϵ) (Real) curve, (c) Permeability(μ) (Real) curve, (d) Refractive index (η) (Real) curve in X-axis propagation

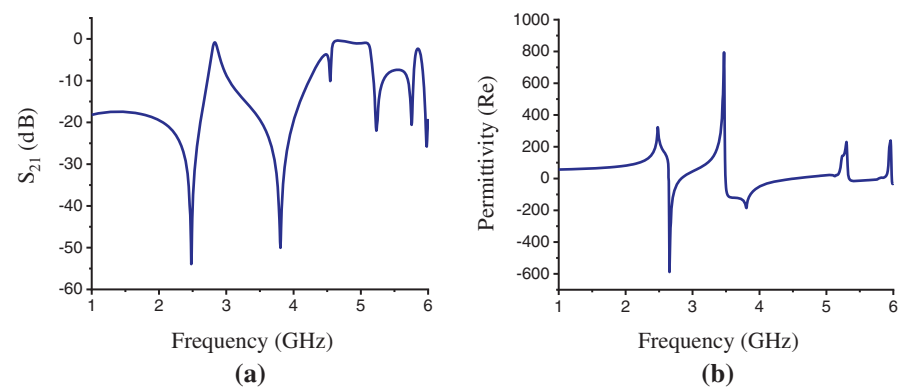


Figure 8: Continued

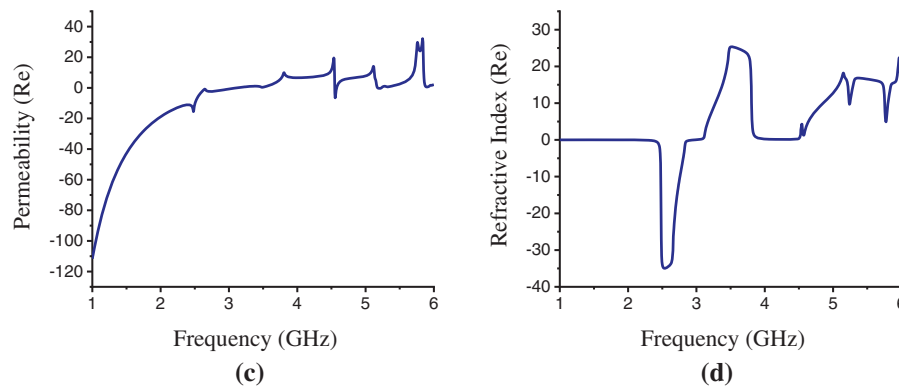


Figure 8: Rogers RO 3010 Substrate results. (a) Transmission resonance (S_{21}), (b) Permittivity(ϵ) (Real) curve, (c) Permeability(μ) (Real) curve, (d) Refractive index (η) (Real) curve in X-axis propagation

Table 4: Comparisons of substrate materials in the X-axis wave propagation based on effective parameters

Substrate	Minimum resonance(GHz)	Permittivity (ϵ)	Permeability (μ)	Refractive index (η)	EMR	MM type
Rogers RO 3010	2.48	323.162	-15.549	-14.40	8.06	NRI
FR-4	3.615	169.79	-8.01	-11.44	5.53	NRI

3.3 Effect of Rogers RO 3010 Dielectric Substrate Thickness

The proposed design structure has been analyzed for a different commercially available substrate thickness of Rogers RO 3010 substrate material. The effect of substrate thickness change on transmission resonance and different effective parameters of the structure has been considered. The available thickness of 0.25, 0.64, 1.28, and 1.6 mm has been taken for this performance analysis. Fig. 9a depicts the substrate thickness changing effect on transmission resonance and Tab. 5 shows the comparison of the effective parameters of different available Rogers RO 3010 substrate material thickness for the Z-axis wave propagation. In this propagation, the metamaterial properties change with the substrate thickness change, that is, for 0.25 and 0.64 mm thickness the design shows MNG metamaterial properties. But, for 1.28 and 1.6 mm thickness the structure shows ENG properties in minimum resonance.

There is a significant effect has been seen on transmission resonance, that is the effective medium ratio (EMR) increases for an increase in substrate thickness. The maximum EMR achieved for Z-axis wave propagation is 6.45 for the thickness of 1.6 mm. In the figure thus the transmission resonance is shifting downward with the increase in substrate thickness.

Fig. 9b depicts the thickness changing effect on transmission resonance for the X-axis wave propagation. Tab. 6 demonstrates the comparison of the effective parameters for different substrate thickness considering X-axis wave propagation. In this propagation, the metamaterial properties are not changing for different substrate thickness and being unchanged with NRI properties. But the transmission resonance shifts downward with the increase in substrate thickness shown in Fig. 9b.

The effective medium ratio (EMR) increases for an increase in substrate thickness, and a maximum EMR 8.06 is achieved for a substrate thickness of 1.6 mm in the X-axis wave propagation.

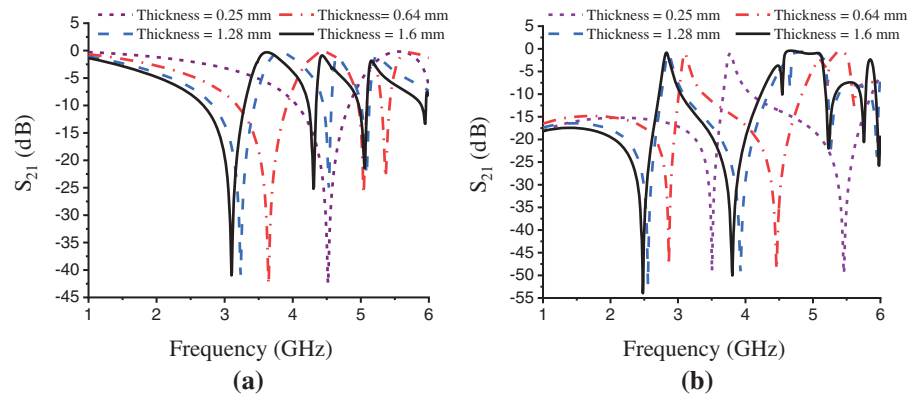


Figure 9: Effect on transmission resonance (S_{21}) for different available Rogers RO 3010 substrate material thickness. (a) Z-axis wave propagation and (b) X-axis wave propagation

Table 5: Effective parameters comparisons of different available substrate thickness for the Z-axis wave propagation

Substrate	Thickness (mm)	Minimum resonance (GHz)	Permittivity (ϵ)	Permeability (μ)	Refractive index (η)	EMR	MM type
Rogers RO 3010	0.25	4.52	105.49	-377.1	167.71	4.42	MNG
	0.64	3.645	9.62	-662.56	88.961	5.48	MNG
	1.28	3.235	-0.76	1071.4	17.65	6.18	ENG
	1.6	3.1	-2.275	464.22	16.967	6.45	ENG

Table 6: Effective parameters comparisons of different available substrate thickness for the X-axis wave propagation

Substrate	Thickness (mm)	Minimum resonance (GHz)	Permittivity (ϵ)	Permeability (μ)	Refractive index (η)	EMR	MM type
Rogers RO 3010	0.25	3.505	1326.75	-48.92	-75.07	5.70	NRI
	0.64	2.865	637.28	-26.22	-35.634	6.98	NRI
	1.28	2.555	388.16	-17.42	-21.22	7.82	NRI
	1.6	2.48	323.162	-15.549	-14.40	8.06	NRI

3.4 Permittivity Sensor on Simulation Environment

The proposed unit cell is optimized for the permittivity sensing applications of solid or liquid materials in the simulation environment. A simulation arrangement for permittivity measurement

where a SUT (Sample Under Test) is placed on the unit cell's resonator plane is depicted in Fig. 10a. The idea of permittivity measurement of solid or liquid material by placing SUT on metamaterial sensor in a simulation environment is found from the previous work referenced in [43]. Here, we have taken the SUT material of thickness 1 mm, length and width are the same as the dielectric substrate of the sensor unit cell. To evaluate the unit cell's permittivity sensitivity through simulation, we have added a parametric sweep for permittivity of the SUT from 2 to 10 with a step size of 2.

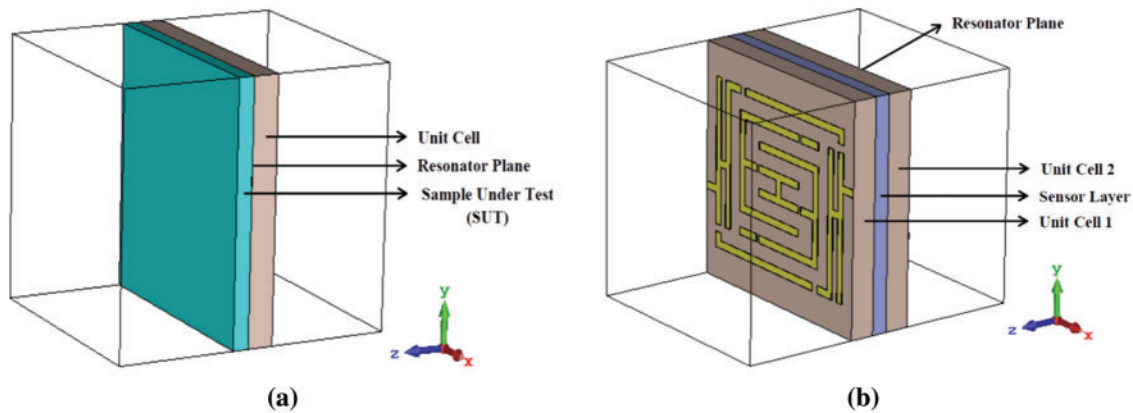


Figure 10: Simulation setup for (a) permittivity sensor and (b) pressure sensor using proposed metamaterial unit cell

The simulated result is made on transmission resonance S_{21} at Figs. 11a and 11b illustrates the resonance frequency shifting for the sensor unit cell with the permittivity changing of the SUT material for the Z-axis and X-axis field excitation respectively. The resonance shifting in the figure shows an inversely proportional relation to the permittivity changing of the SUT material; with the increase of permittivity the resonance frequency decreases. The sensor unit cell shows a good permittivity sensing ability with high sensitivity in the simulation environment. The average resonance shift on S_{21} for X-axis and Z-axis wave propagation is found to be 0.113 GHz/Step and 0.138 GHz/Step respectively, which are a notable number of shifts compared to the other existed permittivity sensors. Thus, the unit cell can be used in S and C-band permittivity sensing applications for solid or liquid materials.

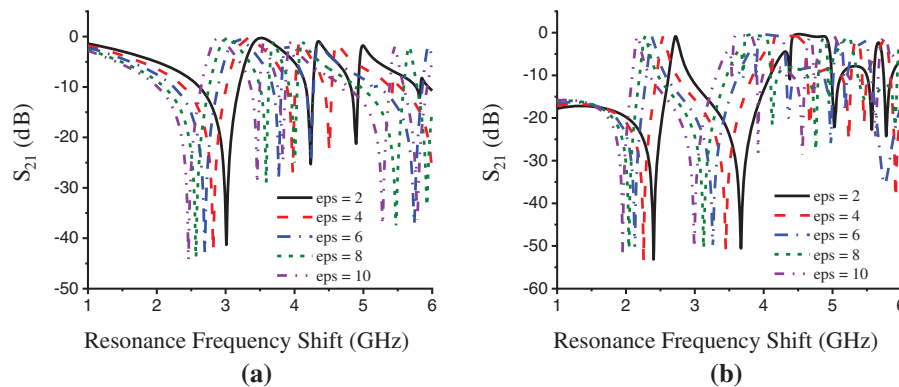


Figure 11: Permittivity sensitivity (resonance frequency shift concerning SUT permittivity) of the unit cell in simulation. (a) Z-axis excitation and (b) X-axis excitation

3.5 Pressure Sensor on Simulation Environment

The proposed structure is also optimized for the pressure sensing applications within S-band along with permittivity sensing applications in the simulation environment. A simulation arrangement for pressure sensing application is depicted in Fig. 10b, where two-unit cells are sandwiched with a sensor layer in middle. The sensor layer used here in the middle is the air cushion. The idea of a pressure sensor with sandwiched unit cells having a sensor layer in the middle and using air cushion as sensor layer are found from the previous works referenced in [44,45].

To evaluate the pressure sensitivity of the unit cell through simulation, we have considered the sensor layer thickness gradually increasing from 0.0 to 0.8 mm with taking 0.2 mm/observation. To perform the increase of sensor layer thickness we have made a parametric sweep on sensor layer thickness by taking a step width of 0.2 mm. Figs. 12a and 12b depict the simulated result for the sensor's pressure sensitivity within C and S-band respectively, that are made on S_{21} . An increase in sensor layer means increasing the distance between two-unit cells works as two plates of a capacitor. As capacitance is inversely proportional to the distance, with the increase in distance the capacitance decreases that makes resonant frequency shift upward (according to the Eq. (1)/ $\sqrt{LC}$).

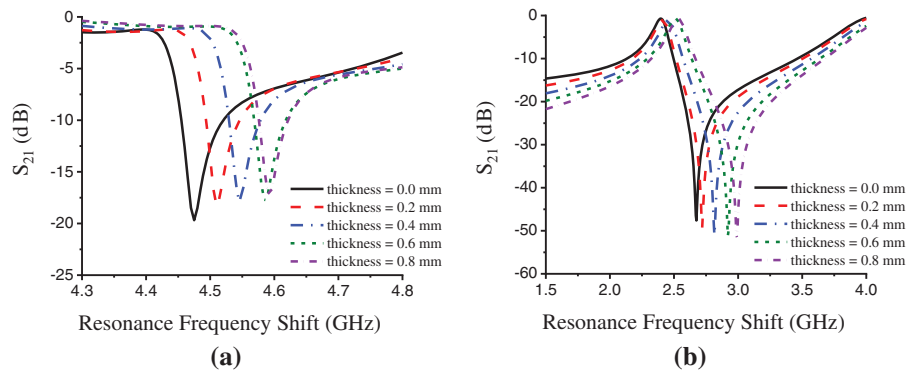


Figure 12: Pressure sensitivity (resonance frequency shift concerning sensor layer thickness) of the unit cell in simulation. (a) within C-band and (b) within S-band

Thus, the figures depict a proportional relation of resonance frequency shifting to the change in sensor layer thickness that is with the increase of layer thickness the resonance frequency also increases. The average resonance shift on S_{21} is found 0.0788 GHz/observation shown in Fig. 12a and 0.0288 GHz/observation shown in Fig. 12b. As the unit cell shows a good pressure sensing ability with high sensitivity, the unit cell thus can be used in S and C-band pressure sensing applications. Tab. 7 demonstrates a comparison of the proposed metamaterial unit cell structure with some existed metamaterial unit cells in different sensing applications.

Table 7: Comparison of the proposed metamaterial unit cell in different sensing applications

Ref.	Size (mm ²)	Substrate material	Operating frequency (GHz)	Application	Max. E.M.R.	Remarks
[46]	22.86 × 10.16	FR-4	X-band	Chemical sensor	1.31	MM based sensor
[47]	30 × 24	FR-4	3-6	Temperature sensor	4.55	MM absorber-based sensor
[48]	36 × 36	FR-4	2-6	Multifunctional sensor	1.52	MM absorber-based sensor
[49]	35 × 28	FR-4	3-5	Micro-fluid sensor	2.19	MM based sensor
[43]	30 × 30	FR-4	5-9	Permittivity sensor	1.22	MM based sensor
[50]	24 × 24	FR-4	3-5	Refractive index sensor	3.03	MM absorber-based sensor
[36]	22.86 × 10.16	Isola IS680	X-band	Water Pollution sensor	1.31	MM based sensor
[44]	22.86 × 10.16	RT 5870	X-band	Multifunctional sensor	1.41	MM absorber-based sensor
[45]	35 × 35	Arlon DiClad 527	5-8	Multifunctional sensor	1.33	MM absorber-based sensor
[51]	20 × 20	FR-4	X and Ku-band	Pressure sensor	1.09	MM absorber-based sensor
This Work	15 × 15	Rogers RO 3010	1-6	Multifunctional sensor	8.06	MM based sensor (Compact size and better EMR)

4 Conclusions

In this article, a new metamaterial unit cell structure is investigated for sensing applications. To identify the criteria for the proposed unit cell, a parametric analysis was performed for FR-4 and Rogers RT-3010 substrate material. The proposed design shows the NRI and ENG metamaterial properties within S-band and ENG properties within C-band for the X-axis wave propagation. The maximum EMR 8.06 is achieved in this wave propagation for Rogers RO 3010 substrate material and EMR 5.53 is found for the FR-4 substrate material. In the Z-axis wave propagation, the structure exhibits ENG metamaterial properties within S-band and MNG metamaterial properties within C-band with EMR 6.45 for RO 3010 substrate material and EMR 4.33 for FR-4 substrate material. Further analysis has been done by changing the thickness of the substrate of Rogers RO 3010, and only at 1.6 mm thickness, it displays EMR 8.06 with NRI properties. The numerical result was verified mathematically for the metamaterial operations for Rogers RO 3010 substrate material in the X-axis propagation. At last, we have simulated the structure (using Rogers RO 3010 substrate of thickness 1.6 mm) for permittivity sensing applications of solid or liquid material and pressure sensing applications. The average resonance shift on S_{21} is found 0.0788 and 0.0288 GHz per observation for the pressure sensor, and the average resonance shift on S_{21} is seen at 0.113 and 0.138 GHz per step permittivity change for the permittivity sensor through numerical study. Thus, the new metamaterial has the potential for communication and satellite applications within S-band and C-band considering the permittivity and pressure sensing applications.

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