Design and analysis of modified-split-H-shaped DNG metamaterial for microwave application

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Abstract

This paper presents a modified-split H-shaped structure of a double negative metamaterial unit cell designed for a Rogers RO 3010 substrate material. The proposed structure reveals transmission resonance inside the C-band of microwave spectra and indicates a double negative (DNG) property at that resonant frequency for z-axis wave propagation. The finite integration technique based simulation tool was used to acquire unit cell parameters. Equivalent circuit model has been provided for the metamaterial. The simulated result agrees well with the calculated one. In addition, an analysis has been done with the same design by replacing the substrate material with popular FR-4 and then it behaves as a zero index metamaterial (ZIM) at the same frequency band. Further analysis has been performed for the x-axis propagation through the structure. NRI (Negative Refractive Index) and MNG (Mue-Negative) properties are found for Rogers RO 3010 and FR-4 substrate material in a row.

1. Introduction

Metamaterials are artificially developed materials which can exhibit some extra ordinary electromagnetic property and no longer naturally found. It might also show off negative value of permittivity and permeability simultaneously at a particular frequency range. The metamaterials with either of the permittivity or permeability negative is referred to as single negative metamaterial. The metamaterials with simultaneous negative permeability (\(\mu\)) and permittivity (\(\varepsilon\)) are referred to as double negative (DNG) or negative refractive index (NRI) metamaterials. In 1968, Victor Vesselago explained and theoretically showed, in comparison to ordinary materials observed in nature [1], that materials have negative permeability (\(\mu < 0\)) and permittivity (\(\varepsilon < 0\)), have certain unique properties, but this subject was not very fascinating to researchers until 1999, given the absence of such natural materials. Although there are some materials that exhibit the property of effective negative permittivity but materials with tremendous negative permeability was once still a difficult issue. In 2000 Smith et al effectively affirmed another developed material of such double negative property where, Snell’s law, Cherenkov radiation, Doppler Effect are altered [2]. Because of these selective electromagnetic properties of these materials, it may be utilized in numerous fundamental purposes like designing antenna, electromagnetic cloaking, SAR (Specific Absorption Rate) reduction and plenty of others [3–6]. Nowadays, in the communication sector researchers have seen a promising technique in the fields of highly profitable multi-band antenna designing, multi-band metamaterial or a metamaterial with negative refractive index or near-zero refractive index. Although only a small number of studies concentrated on such designs are often found in literature [7–9]. In literature, different shapes of metamaterial structures have been proposed according to the applications like U-shape, V-shape, Triangular shaped etc [10–12]. However, very few of these designs are found displaying negative refractive index property for two-component (in x-and z-axis) operation.

A modified split H-shaped unit structure consisting of two joined split-square resonators is expressed in this paper. The parameters of transmission and the frequency of resonance were obtained by CST (Computer Simulation Technology) Microwave Studio Software. The metamaterial shows Zero Index and DNG property in...
the z-axis and MNG and NRI characteristics in the x-axis at the C-band area of microwave spectrum for FR-4 and Rogers RO 3010 substrate material respectively.

2. Design of a unit cell

The proposed structure and design parameters are presented in figure 1 and table 1. The design’s structure founded on two copper resonators split square. The thickness of all the elements was kept 0.035 mm. The gap between the 2 resonators is 2 mm. The substrate material is FR-4 and the length and width was kept $A = 10$ mm. The substrate’s thickness was kept 1.6 mm. The ‘CST Microwave Studio’ simulation software was utilized for the design and respective analysis of the structure.

The design specifications of that structure are provided in table 1. The effective medium ratio (EMR) for proposed structure with FR-4 substrate is 4.8 wherever with Rogers RO 3010 is 6.7. To confirm proper metamaterial operation the EMR has to be kept over 4.
Afterwards for further investigation, the popular FR-4 substrate material has been replaced by the Rogers RO 3010 substrate of the proposed design structure. The substrate’s dielectric constant is 4.3, loss-tangent is 0.002. The same numerical methodology was followed to see the impact of the change.

3. Equivalent circuit model

This kind of metamaterial structure involves passive LC circuits with a frequency of resonance:

\[ f = \frac{1}{2\pi\sqrt{LC}} \]  

(1)
Where $L$ and $C$ severally are the general structural inductance and capacitance. Total capacitance between the gaps are frequently in accordance with a Quasi-Static theory:

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

(2)

Where, $\varepsilon_0$ = Free space permittivity
$\varepsilon_r$ = Relative Permittivity
$A$ = Cross-sectional area of the gap
$d$ = Gap length

The equivalent circuit is given in figure 2.

Where, $L$ = Inductance
$C$ = Capacitance
$C_p$ = Capacitance of LC resonance

Figure 5. For FR-4 substrate material in the z-axis: (a) Effective permeability (Real) (b) Effective permittivity (Real).

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For that proposed modified- H-shaped resonator, the resonance frequency is:

$$f = \frac{1}{2\pi\sqrt{LC_p}}$$  \hspace{1cm} (3)

Where an inductance can be estimated for the proposed inductance as:

$$L = \mu_0 I \left( \frac{2g + f}{2n} + \frac{(2c + m)}{(2g + f)^2 + a^2} \right)$$  \hspace{1cm} (4)

And it is possible to approach the equivalent capacitance:

$$C = \varepsilon_0 \left( \frac{2(h - b) - i - j}{\pi} \ln \frac{2g}{A - a} \right)$$  \hspace{1cm} (5)

Where, $\mu_0 = 4\pi \times 10^{-7}$ H m$^{-1}$

$\varepsilon_0 = 8.85 \times 10^{-12}$ F m$^{-1}$

A further information can be found in [13–15] on the above equations. From equations (4) and (5), the value of inductance is $1.0837 \times 10^{-14}$ H and the value of capacitance is $1.18 \times 10^{-7}$ F. Therefore, the resonance frequency will be 4.55 GHz for Rogers RO 3010 for $z$-axis.

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Table 1. Design Specifications of Structure.

| Parameters | Value (mm) |
|------------|------------|
| a          | 8          |
| b          | 0.3        |
| c          | 0.3        |
| d          | 6          |
| e          | 3.5        |
| f          | 2          |
| g          | 3          |
| h          | 3.5        |
| i          | 0.4        |
| j          | 2.5        |
| k          | 1          |
| l          | 1          |
| m          | 1          |
| n          | 1          |

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Figure 6. Refractive Index (Real) For FR-4 substrate material in the z-axis.
The inductance for Rogers RO 3010 for x-axis can be found as:

\[
L = \mu_0 \left( \frac{2k}{3g - 2l} + \frac{\sqrt{(2g + f)^2 + a^2}}{(2\epsilon + m)} \right)
\]  

(6)

And the capacitance can be found:

\[
C = \varepsilon_0 \left( \frac{m}{20(h + b)} \ln \frac{2g}{A - a} \right)
\]  

(7)

Using equations (6) and (7), inductance is found $1.4795 \times 10^{-8}$ H and capacitance is found $1.27988 \times 10^{-13}$ F respectively. Thus, the frequency will be 3.66 GHz for Rogers RO 3010 for x-axis.

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**Figure 7.** For Rogers RO 3010 substrate material for z-axis: (a) comparison of $S_{21}$ with CST and HFSS software (b) Permittivity (Real) graph.
4. Methodology

The software CST had been utilized to count complex dissipating parameters. These parameters were used for retrieving successfully permitted cell structure permeability and permittivity. The simulation geometry is revealed in figure 3.

There are several strategies exists for effective parameters extraction of metamaterials like TR methodology, Lossy-Drude methodology, Nicolson-Ross-Weir methodology etc. The effective medium parameters were obtained from the simulation result of $S_{21}$ and $S_{11}$ referenced in [16].

The simplified formula have been given below,

$$V_1 = S_{21} + S_{11}$$  \hspace{1cm} (8)
$$V_2 = S_{21} - S_{11}$$  \hspace{1cm} (9)
$$\mu_r \approx \frac{2}{jk_0d} \frac{1 - V_2}{1 + V_2}$$  \hspace{1cm} (10)
$$\varepsilon_r \approx \frac{2}{jk_0d} \frac{1 - V_1}{1 + V_1}$$  \hspace{1cm} (11)
$$\eta = \sqrt{\mu_r \varepsilon_r}$$  \hspace{1cm} (12)

where the $\varepsilon_r$ is that the effective permittivity, $\mu_r$ is that the effective permeability, ‘d’ is that the thickness of the substrate, $k_0$ is that the wave number and $\eta$ is the index of refraction.

5. Results and discussion

The simulation result for this proposed structure of the transmission resonance ($S_{21}$) for FR-4 substrate material with $z$-axis is presented in figure 4. The simulated transmission coefficient spectra ($S_{21}$) show the transmission resonance at 6.296 GHz using the CST tool.

For comparison and justification of the simulation results obtained from CST (Computer Simulation Technology), HFSS (High Frequency Structural Simulator) was adopted as well and showed in figure 4. These two software works on different methods from each other. CST works based on Finite Integral Technique (FIT) method and HFSS operates based on Finite Element Method (FEM).

According to figure 4, it is clear that for FR-4 substrate material with $z$-axis propagation (with the structure), the points of resonance frequency (of $S_{21}$) have matched well for two different software’s.

The figure 5(a) reveals that permeability for the FR-4 does not show negativity at resonant frequency and the real value of it is $\mu = 0.47$ there. In figure 5(b), the frequency versus permittivity curve for FR-4 depicts that permittivity is near zero and it’s real value is $\varepsilon = 0.05$. So, now it is clear that the design based on FR-4 substrate
Table 2. Effective parameters comparisons of two substrate materials for the z-axis wave propagation.

| Substrate material | Dielectric Constant | Minimum Frequency (GHz) | Permeability (μ) | Permittivity (ε) | Refractive Index (η) | Max. EMR | Metamaterial Type |
|--------------------|---------------------|-------------------------|------------------|------------------|----------------------|----------|------------------|
| Rogers RO 3010     | 10.2                | 4.456                   | −8.01            | −0.85            | −2.61                | 6.7      | DNG              |
| FR-4               | 4.3                 | 6.296                   | 0.47             | 0.05             | 0.15                 | 4.8      | ZIM              |
material does not show double negative characteristics and therefore the real refractive index value of figure 6 shows the positive 0.15 value that means $\eta = 0.15$. The material can thus be identified as Zero Index Metamaterial (ZIM) for FR-4 substrate material.

After using the Rogers RO 3010 substrate material (having dielectric constant 10.2) for the same design structure it is seen in figure 7(a) that S-parameter has changed a bit using CST. Previously, the sharp transmission resonance ($S_{21}$) was found at 6.296 GHz with magnitude $-61.78$ dB for the design on FR-4 substrate material (having dielectric constant 4.3). On the other hand, the transmission resonance for the substrate material Rogers RO 3010 has been found at the frequency of 4.456 GHz with the magnitude of

![Figure 9. For Rogers RO 3010 substrate material (a) Permeability (Real) (b) Refractive Index (Real).](image-url)
-67.11 dB. Actually, this difference in the transmission coefficients of figures 4(a) and 7(a) has occurred due to the difference in dielectric constants.

For verification of transmission coefficient investigation was also done with HFSS tool for Rogers RO 3010 substrate material in z-axis propagation. Transmission co-efficient (S21) for Rogers RO 3010 with z-axis propagation using CST and HFSS software is showed in figure 7(a) as well. According to figure 7(a), it is clear that

Figure 10. For FR-4 substrate material in the x-axis: (a) Transmittance (S21) (b) Permittivity curve.
for Rogers RO 3010 substrate material with z-axis propagation (with the structure), the points of resonance frequency (of $S_{21}$) have matched well for two different software’s.

In figure 7(b), the frequency versus permittivity curve for Rogers RO 3010 depicts that permittivity is negative and it’s real value is $\varepsilon = -0.85$ which was 0.05 for FR-4 based design. Figure 8 indicates the current distribution at frequency 4.5 GHz. This frequency of transmission resonance for Rogers RO 3010 at 4.456 GHz agrees well with the calculated one according to the equation (3).

However the figure 9(a) reveals that permeability for the Rogers RO 3010 substrate material for the same design shows negativity and the real value is $\mu = -8.01$ which was previously 0.47 for FR-4 substrate material. So, now it is clear that the design based on Rogers RO 3010 substrate material shows double negative characteristics. The structure can be expressed as a double negative (DNG) metamaterial. In figure 9(b), the refractive index is negative at frequency 4.456 GHz and $\eta = -2.61$. The overall comparative results for z-axis are presented in table 2.
For further analysis, the wave had been propagated through $x$-axis of the unit cell structure for the $x$-axis. So, the waveguide ports had been set at the two sides of the structure along the $x$-axis the same simulation setup had been considered. The transmission co-efficient ($S_{21}$) shows the two resonance at 5.384 GHz and 5.784 GHz for FR-4 substrate material in figure 10(a). The permittivity curve shows positive peak at the frequencies of 5.384 GHz and 5.784 GHz with value, $\varepsilon \approx 11.79$ and 34.51 respectively in figure 10(b).

In figure 11(a), permeability curve at 5.384 GHz and 5.784 GHz displays negative magnitude with the value of $\mu = -105.56$ and $-36.12$. As a result, the material is characterized as SNG (single negative) or Mu-negative. From the refractive index curve, it is seen that the refractive index at 5.384 GHz and 5.784 GHz is found positive with real value of $\eta = 43.65$ and 27.697 respectively in figure 11(b).
From transmission co-efficient ($S_{21}$) curve, three resonances at 3.648 GHz, 3.84 GHz and 8.232 GHz are achieved in figure 12(a). 3.648 GHz as the frequency of transmission resonance ($S_{21}$) for Rogers RO 3010 with x-axis propagation at 3.66 GHz agrees well with the calculated one according to the equation (3). In figure 12(b), the values of permeability, $\mu = 276.29, -316.89, -24.89$ at 3.648 GHz, 3.84 GHz and 8.232 GHz correspondingly.

Permittivity curve at the 3.648 GHz, 3.84 GHz and 8.232 GHz shows negative, positive and positive magnitudes with the values of $\varepsilon = -9.03, 5.90, 35.36$ respectively in figure 13(a). And negative refractive index (NRI) properties shows at 3.648 GHz and 3.84 GHz are obtained negative with real values of $\eta = -14.21$ and $-10.01$ in figure 13(b). Consequently, the metamaterial displays NRI (negative refractive index) property. Another positive value of $\eta = 4.76$ at 8.232 GHz is acquired in figure 13(b). The overall comparative results for x-axis are presented in table 3.

Figure 13. For Rogers RO 3010 substrate material in the x-axis: (a) Permittivity curve (b) Refractive Index.
| Substrate material | Permittivity (ε) | Permeability (μ) | Minimum Frequency (GHz) | Maximum EMR Metamaterial Type |
|--------------------|-----------------|-----------------|-------------------------|-----------------------------|
| Rogers RO 3010     | 3.648           | 3.84            | 276.29                  | NRI                         |
| FR-4               | 4.3             | 5.384           | 11.79                   | MNG                         |
| NRI                | 5.6             | 43.65           | 8.2                     |                             |
6. Conclusion

A new modified split H-shaped double negative metamaterial structure is showed in this paper. Initially for FR-4 substrate material, the resonance at 6.296 GHz that is within the C band and it shows zero index characteristics at that frequency and it may be characterized as a zero index metamaterial. But changing the substrate material by Rogers RO 3010, the transmission resonance is found at 4.456 GHz that is additionally within the C band and it shows double negative characteristics at 4.456 GHz. However, the structure displays NRI and MNG properties for Rogers RO 3010 and FR-4 substrate materials due to x-axis propagation separately. Generally, C-band can be used for satellite communication. Two popular substrate materials have been used to demonstrate the metamaterial characteristics. The comparative analyses have been done between them. DNG materials can be used for bandwidth and gain expansion in antenna application. ZIM materials can be utilized to create the far-field design narrower of an antenna. In addition this structure can be used significantly within the C band application of metamaterial. Moreover, improved EMR is achieved for x-axis wave propagation than z-axis propagation for the structure. Two way simulated verification had been done for metamaterial operations for FR-4 and Rogers RO 3010 substrate material with z-axis propagation.

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