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FEM and Transmission Line based Analysis of 'Closed Ring Pair' Metamaterial

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Abstract

This paper adumbrates a novel metamaterial named Closed Ring Pair (CRP). Ansoft HFSS has been used to design and analyze the MTM having Mylar (εr=2.89) as substrate material. Magnetic properties of CRP MTM have been used to mathematically demonstrate the negative permeability region. Nicolson Ross Weir (NRW) method has been used to retrieve the material parameters from transmission and reflection coefficient. Upon simulation the resonant frequency has been found to be 30.55 THz.

Keywords: *HFSS, metamaterial, antenna*

1. Introduction

'Metamaterials' (MTMs) are engineered to modify the bulk permeability and/or permittivity of the medium. It is realized by placing periodically, structures that alter the material parameters, with elements of size less than the wavelength of the incoming electromagnetic wave. It results in "meta" *i.e.,* "altered" behaviour or behaviour unattainable by natural materials. Slight changes to a repeated unit cell can be used to tune the effective bulk material properties of a MTM, replacing the need to discover suitable materials for an application with the ability to design a structure for the desired effect. Examples of MTMs are single negative materials (SNG) like ε negative (ENG) which have effective negative permittivity and μ negative (MNG) which have effective negative permeability, and double negative materials (DNG).

A fresh approach to microwave and optical devices presented itself with the interesting breakthrough in the area of MTMs at high frequencies. The need of hour is to optimize the antenna parameters (gain, bandwidth, directivity) without altering its dimensions i.e. external control over antenna parameters using MTM. The software tool HFSS is used because it is a high performance full wave electromagnetic (EM) field simulator for arbitrary 3D volumetric passive device modeling. It integrates simulation, visualization, solid modeling, and automation in an easy to learn environment where solutions to 3D EM problems are quickly and accurately obtained [1].

Section 2 abridges the design of Closed Ring Pair with resonant frequency 30.55 THz having Mylar (ε_r=2.89) as substrate material using FEM based software i.e. Ansoft HFSS. Section 3 gives the mathematical proof of the designed MTMs based on transmission line theory with comparison of the results obtained in Section 2. Section 4 concludes the paper.

2. Proposed Closed Ring Pair MTM

Closed Ring Pair (CRP) metamaterial has been proposed having magnetic resonance [2]. It behaves as MNG *i.e.,* Mu Negative Group. Such materials have negative permeability over some frequency region [3, 4]. The parameter retrieval *i.e.,* parameter extraction using S parameters [5] has been followed using NRW approach to observe the

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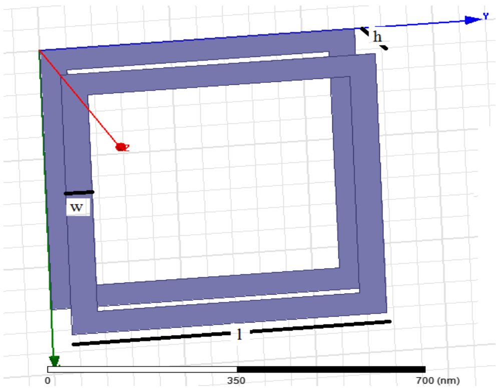
negative permeability region of SRR MTM. The constructional details along with the curve are as under.

2.1.Constructional Details

It is construction ally very simple, consists of a Closed Ring Pair with Mylar as substrate having ε_r=2.89.Mylar film has been used as spacer because of its transparency in both THz and visible regime. It is designed in such a way that the inclusions are much smaller than the operating wavelength. Such structures can be denoted by quasi-static equivalent LC circuit. Unit cell formed in HFSS is shown in Figure 1(a) with constructional details in Figure 1(b) where thickness 't' of the conducting metallic inclusions is 2nm, height 'h' of the substrate is 220nm, bulk conductivity is 38000000Siemens/m , 'd' is the distance between two rings, 'w' is the width of the ring, 'l' is the side length.



(a)

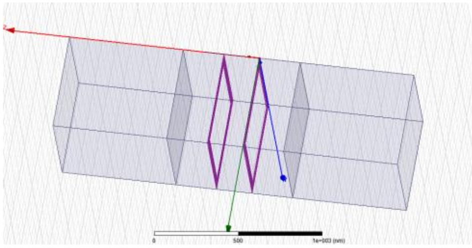
Parameter	Value (in nm)
w	50
l	600
h	220
d	40

(b)

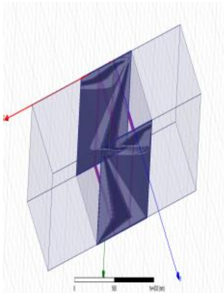
Figure 1. CRP MTM a) Unit Cell Designed in HFSS b) Constructional Details

2.2.FEM based Simulation Results

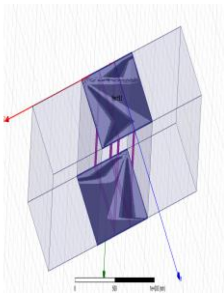
Ansoft HFSS has been used to simulate the unit cell designed in Figure 2(a) having metamaterial in the dielectric substrate bounded by box on either side having air as material and radiation boundary. The boundaries and lumped ports (1 and 2) have been assigned as per Figure 2(b), (c), and (d). Nicolson Ross Weir (NRW) method has been used to calculate the material properties from transmission and reflection coefficients.



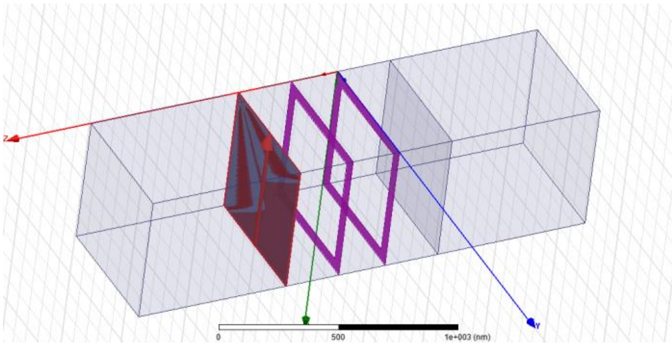
(a)



(b) H Field



(c) E Field



(d) Lumped Port

Figure 2. a) Unit Cell for Simulation b) H Field c) E Field Specifying Boundary Condition d) Lumped Port

It can be observed as in Figure 3 that magnetic resonance is seen at 30.5466THz.

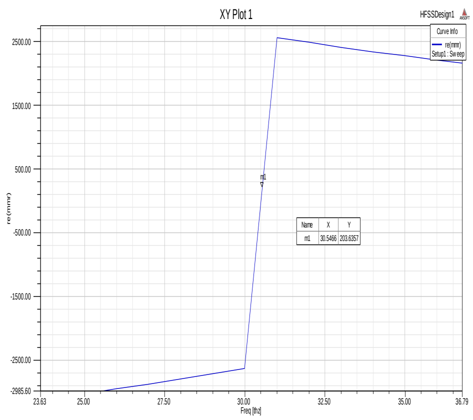
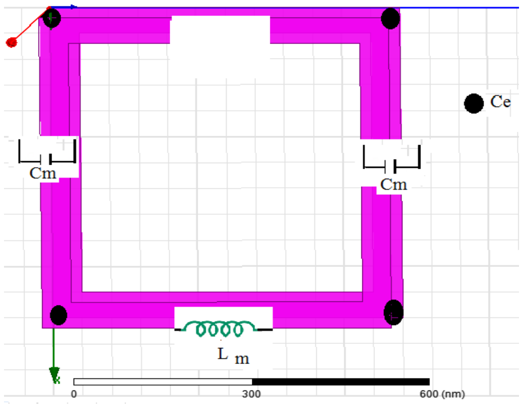


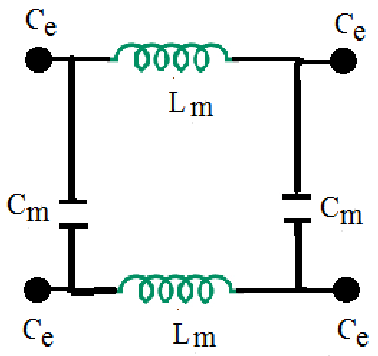
Figure 3. Resonance in Permeability at 30.5466THz

3. Transmission Line Theory Based Calculations

CRP MTM has magnetic properties because of internal inductances and capacitances. It can be simplified in terms of combinations of C and L. Using transmission line theory (quasi-static regime); we can draw its equivalent circuit as in Figure 4 (a), (b).



(a)



(b)

Figure 4. (a), (b) Equivalent LC Circuit of CRP

The Lm is the inductance per unit length of the loop and Cm is the capacitance of the gap. Also, Ce, refers to near field coupling coefficient between the adjacent rings on the same surface as shown in Figure 4 (b).

The expressions for L and C are given by equation 1 and 2 as below:

$$L_m = \frac{\mu}{2}\frac{hl}{w} \tag{1}$$

Where μ=μo is the vacuum permeability and parameter values can be referred to Figure 1(b).

Therefore, Lm is 1.66 X 10^{-12}H.

$$C_m = \varepsilon \frac{w c_1 l}{h} \tag{2}$$

Where ε=2.89εo, c1 and c2 are numerical factors ranging between 0 and 1 and is assumed to be 0.6.Therefore, Cm is 2.094X10^{-18}F.

Expression for calculating Ce is given by equation 3

$$C_e = c_2 l(\varepsilon_0 + \varepsilon)\frac{K\left(\sqrt{1-k^2}\right)}{2K(k)} \tag{3}$$

Where k is given by expression 4.

$$k = \frac{d}{d + 2w} \tag{4}$$

Upon substituting values from Figure 1(b), we get k=0.29.

K is the first completed elliptical integration and can be obtained using expression 5.

$$K(k) = \frac{\pi}{2} + \frac{\pi}{8}\left(\frac{k^2}{1-k^2}\right) - \frac{\pi}{16}\left(\frac{k^4}{1-k^2}\right) \tag{5}$$

Therefore,

K (k) = 1.608

K' (k) =4.059=K $(1-k^2)^{1/2}$

Thus, Ce=1.565X10^{-17}F

Neglecting high frequency losses, magnetic resonance frequency is given by equation 6.

$$\omega_m = \sqrt{\frac{1}{L_m.(C_m + C_e)}} \tag{6}$$

Thus, magnetic resonance frequency is found out to be 29THz.However, using simulational study of CRP in Ansoft HFSS, magnetic resonance frequency has been found out to be 30.5466THz. Thus, net error between simulational and analytical study of CRP is 5%.

4. Conclusion

In this paper, Closed Ring Pair metamaterial has been designed having resonant frequency around 30.55THz. Nearly 5% deviation has been obtained between the results from Finite Element Method (FEM) based Ansoft HFSS and transmission line theory based quasi-static regime. Thus the results obtained using circuit analyses are well in coherence with the FEM based Ansoft HFSS software. The exigency of metamaterials as substrate or superstrates in antenna can be seen with various improvements in optimization of its parameters, like gain, bandwidth, side lobes, directivity, and size in near future.

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