Parameter Extraction for Negative Index Metamaterials

Nilam T. Kadam
Student
D. J. Sanghvi College of Engineering
Department of Electronics and Telecommunications

Kiran S. Janwalkar
Student
D. J. Sanghvi College of Engineering
Department of Electronics and Telecommunications

Anuja A. Odhekar
Assistant Professor
D. J. Sanghvi College of Engineering
Department of Electronics and Telecommunications

ABSTRACT
The Metamaterials are artificial composite structures that exhibit a homogeneous effective permittivity ε and permeability μ, which become negative over an operating frequency range. At this frequency, direction of propagation is reversed. In this paper we demonstrate a polarization independent negative index metamaterial(NIM) at microwave frequencies. A negative-index is verified by using the retrieval procedure. This paper demonstrates the method of parameter extraction of negative index metamaterial with the help of matlab code. Backward wave propagation is observed in the numerical simulations at frequencies. The metamaterial used here is thin wire, Split ring resonator(SRR) and combination of SRR and two open complementary SRR(OCSRR). These structures are simulated and parameter extraction proves that the effective permittivity and permeability becomes negative over an operating frequency range.

Keywords
Parameter extraction, thin wire, SRR, OCSRR

1. INTRODUCTION
To obtain the most efficient and compact satellite system, physical separation between transmitting and receiving antennas has been reduced to very few wavelengths. Also This leads to increased mutual coupling between them. Reduction in isolation between two antennas degraded the system performance. This reduces sensitivity and resolution of the system. Also in case of antenna array, close placement of antenna elements improves mutual coupling which reduces its performance [1, 2]. Researchers had tried various methods to enhance isolation between two closely spaced antennas. These methods were placement of baffle between two antennas. Nowadays researchers came up with artificial material which is Metamaterial (MTM). Here comes the need of metamaterial. The MTMs are artificial composite structures that exhibit a homogeneous effective permittivity ε and permeability μ, which become negative over an operating frequency range [3]. At this frequency, direction of propagation is reversed. The nature of unit cell decides the nature of consecutive parameters which are permittivity (ε) and permeability μ. ε and μ are related to refractive index η by η=√εμ When permittivity and permeability both had negative values, refractive index also results in negative value and material is known as MTM .MTM are nothing but unit cell of specific shape and material which are periodically arranged at intervals shorter than the specified wavelength. Since MTMs are generally not available in nature and one has to imposed them, they can be classified as

i) Single negative MTM (SNG)

ii) Double negative MTM (DNG)

iii) Electromagnetic Band-gap MTM (EBG)

Thin Wire (TW), split ring resonator (SRR), omega, mushroom, Fishnet and many more. These structures can be constructed using either metal or any dielectric material. Every homogenous structure results into either negative ε or negative μ or both. The response of a material to an incident electromagnetic wave is determined by the materialparameters, dielectric permittivity (ε), and magnetic permeability (μ). Although, in ordinary materials both ε and μ are positive, it is possible to tailor these electromagnetic parameters in metamaterials, which are artificially engineered composite structures [4]. Metamaterials play a key role in accessing the negative and positive values of permittivity and permeability in a controlled manner. In recent years, there has been a growing amount of interest in metamaterials research because metamaterials offer exciting phenomena such as negative refraction, sub-wavelength imaging, and cloaking. The negative refractive index in metamaterials is a consequence of the effective parameters of permeability and permittivity that are simultaneously negative. A negative-index is verified by using the retrieval procedure. Here the metamaterial is used in the form of thin wire, SRR and OCSRR. Thin wire gives negative ε at specific frequency, SRR exhibits negative μ and OCSRR exhibits negative ε at specific frequency. Thin wire and SRR are designed on low loss RT-Duroid substrate and SRR and OCSRR is designed on low loss FR-4 substrate. Finally, we simulated the electric field distribution and studied the wave propagation inside the metamaterial. Backward wave propagation is verified at the negative-index region.

2. PROPOSED METAMATERIAL STRUCTURES WHOSE PARAMETERS ARE EXTRACTED

2.1 Realization of thin wire structure
The metamaterial unit cell used to extract the parameters is described below. The metamaterial unit cell of a typical periodic structure composed of a capacitive thin wire, which is inserted through the dielectric substrate of height ‘h’. The thin wire structure is shown in figure 1.Thin wire results into negative ε and positive μ in desired frequency range which is decided by dimensions of thin wire which are described in figure 1. This metamaterial exhibits a plasmonic type permittivity frequency[5]. This frequency is given as,

$$\omega pe = \sqrt{2\pi C^2/p^2}\ln(\frac{p}{a})$$

Where, a= radius of thin wire,

p= distance between two thin wire elements

C= speed of light.

From this formula, radius(a) of thin wire is calculated which is obtained as 0.3mm by considering p as 0.6mm and ωpe as

2.4GHz. Thin wire unit cell of dimension a=0.3mm at 2.4GHz is simulated using Ansoft HFSS-11 software. As shown in fig.1 thin wire unit cell is excited by applying electric field E parallel to the axis of thin wire and magnetic field H is applied perpendicular to the axis of thin wire which induces the current along the wire and generates equivalent electric dipole moments. When the unit cell of thin wire is simulated using HFSS software, S-parameters are checked in dB as well as isolation characteristics S_{21} and S_{12} angle is verified in angular radians. If the structure is acting as metamaterial, then the angle in radians is shifted from positive to negative or vice versa. This indicates that the direction of propagation is reversed. From the resultant S-parameters, unit cell's refractive index(η) and wave impedance (z) can be calculated as below. From the η and Z the electromagnetic parameters permittivity (ε) and permeability (μ) had been retrieved as[6]

$$\varepsilon = \frac{n}{z} \quad , \quad \mu = nz \text{..............................}(1)$$

$$n = \frac{1}{kd} cos^{-1}[\frac{1}{2S_{21}}(1 - S_{11}^2 + S_{21}^2)] \text{.....}(2) ,$$

$$z = \frac{\sqrt{(1+S_{11})^2 - S_{21}^2}}{\sqrt{(1-S_{11})^2 - S_{21}^2}} \text{........}(3)$$

2.2 Realization of SRR structure

SRR results into negative μ and positive ∈ in desired frequency range which is decided by dimensions of SRR structure which are described in figure 2. Spiral loop SRR structure is designed on RT-Duroid substrate whose dielectric constant is 2.2. The dimensions of SRR is 4mm X 4mm X 1.568mm. The width between two loops is 0.4mm. resonating and plasma frequency is same that is 2.4 GHz. The structure is excited by H-Field parallel to the structure and E-field perpendicular to structure.

2.3 Realization of SRR and OCSRR

This structure is the combination of SRR and open complementary SRR (OCSRR). SRR is at the front side of FR-4 substrate and OCSRR is at the bottom plane. The geometry of the proposed metamaterial unit cell is shown in fig.3. Two symmetrical OCSRRs and a SRR structure were placed on both sides of FR-4 dielectric substrate (relative permittivity=4.4, thickness=1.6mm). The OCSRR has been derived from two former planar resonant structures: the open split ring resonator (OCSRR) and the complimentary split ring resonator (CSRR). As compared to SRR and CSRR, the electrical size of OCSRR is smaller and it can be modeled as an open parallel resonant circuit. The OCSRR is modified CSRR structure exhibiting negative permittivity and the SRR structure exhibits negative permeability. The structure is simulated at the frequency of 2.5GHz. The frequency characteristics of unit cell structure were simulated by using a periodic boundary condition (PBC) method as shown in fig. 4. The dimension of unit cell was 7.4mm X 7mm X 1.6mm. The proposed unit cell was placed inside a waveguide with PBC walls and a vertically polarized TEM wave impinged upon this structure from the port 1. The perfect electric conductor (PEC) boundary condition was applied to the top and bottom walls of the bounding box whereas perfect magnetic conductor (PMC) boundary condition was applied to the side walls of the waveguide[7].

3. PROPOSED TECQNIQUE TO EXTRACT THE PARAMETERS OF METAMATERIALS

The technique used to extract the parameters is given in this section. We here used the matlab code for parameter extraction. Before that we have to export the s-parameter file from HFSS software to matlab file. Algorithm for parameter extraction is shown as follows:

1. Design the metamaterial unit cell, excite it by E electric field and H field and simulate it using HFSS software.

2. Then from the solution setup option, open the matrix data file. Import this file into matlab by saving it by extension .matlab.

3. Automatically the file which you have saved by .matlab extension will open in matlab editor window.

4. Write the code for getting μ and ∈ values at specific frequency.

5. Run the program and you will get the graphs of μ and ε vs. frequency and also the values of μ and ε at all frequencies.

Same algorithm is used for parameter extraction of SRR unit cell and OCSRR and SRR. Now, the algorithm for matlab code is written below.

1. Import S-parameters from HFSS file to matlab file.

2. Define c and d. 'c' is the velocity of light and 'd' is the radius of thin wire or in case of SRR it is the spacing between two loops.

3. S_{11} and S_{21} are taken from the table for corresponding value of frequency.

4. Now, calculate 'k' by using formula k=2πf(j)/c

5. $\boldsymbol{n = \frac{1}{kd} cos^{-1}}[\frac{1}{2S_{21}}(\boldsymbol{1 - S_{11}^2 + S_{21}^2})]$

6. calculate $\boldsymbol{z = \frac{\sqrt{(1+S_{11})^2 - S_{21}^2}}{\sqrt{(1-S_{11})^2 - S_{21}^2}}}$

7. ep(j) = n(j)/z(j)

8. mu(j) = n(j)*z(j)

Using this matlab code table and graphs have been plotted to show the negative indices of metamaterial structures. Figure 5 shows the graph of ε vs frequency plotted for thin wire structure. Figure 6 shows the graph plotted for SRR structure. Table 1,2 and 3 shows the negative values of ε and μ at respective frequencies of thin wire, SRR and combination of SRR and OCSRR simultaneously.

4. CONCLUSION

The manuscript discusses parameter retrieval for various MTM structures. The results showed that the discussed parameters retrieval process is applicable for material exhibiting negative epsilon as well negative permeability. Also this applicable for single negative and double negative MTM structure. It is widely used to calculate the effective parameters of the metamaterial under investigation. From this parameter extraction operating range of frequencies over which material exhibits negative refractive index can be calculated. This parameter extraction procedure is dimension specific and not material specific. Even the procedure is applicable to the complementary structures. This is the effective and simple way to retrieve the parameters.

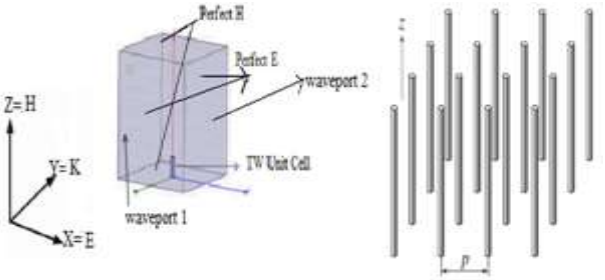
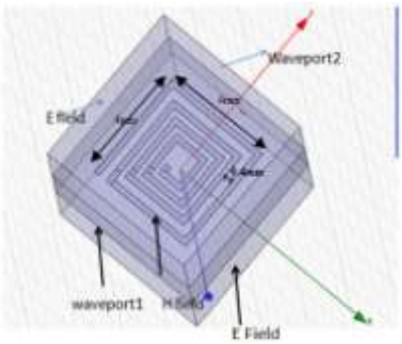


Fig 1: Thin wire structure



The SRR Unit cell of dimension L=W=4mm at frequency 2.4 GHz had been simulated using HFSS-11. Width between each loop is 0.4 mm.

Fig 2: SRR structure

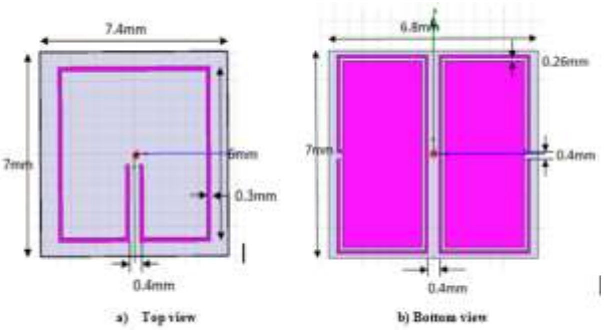


Fig 3: SRR and OCSRR

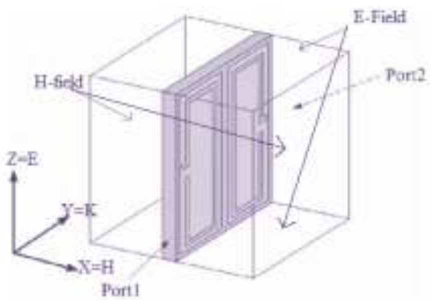


Fig 4: Simulation setup for SRR and OCSRR

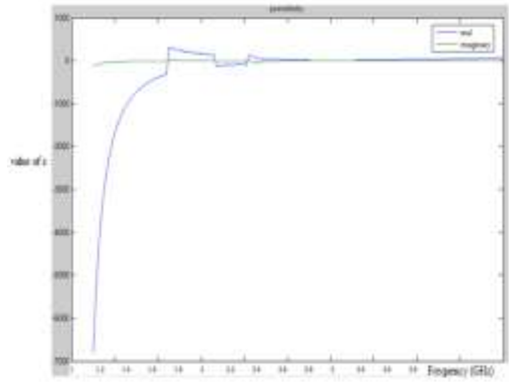


Fig 5: Graph showing -ε v/s frequency using matlab code

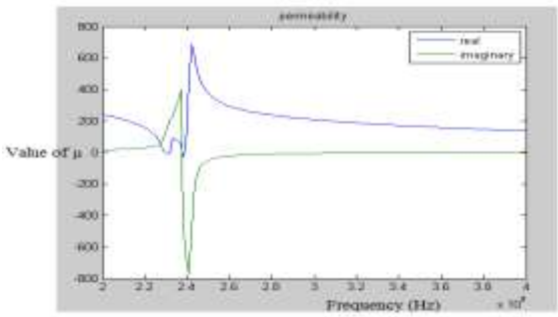


Fig 6: Graph -μ VS frequency using matlab code

Table 1. Negative values of ε at specific frequencies of thin wire from matlab program

Frequency (GHz)	Permittivity value
2.394	2.5618+5.1234i
2.395	2.8952+4.2371i
2.396	3.6962+7.5599i
2.397	4.9325+8.3256i
2.398	-4.010+77.2168i
2.399	-3.9325+6.6776i
2.4	-3.2144+6.1844i
2.401	-2.38+47.8267i
2.402	-2.5400+5.7460i
2.403	1.6981+7.2346i
2.404	1.3085+5.0050i
2.405	0.2131+4.4077i

Table 2. Negative value of ε and μ at specific frequency of SRR structure

Frequency(GHz)	Permittivity	Permeability
2.37	-2.9698+4.7203i	9.0757+90.7646i
2.39	5.3156+3.9830i	-6.8727-1.0857i
2.40	-0.0025+0.5941i	-7.0222-56.5794i
2.41	-0.1097+0.6888i	-13.9419-80.3121i

Table 3. Negative values of μ at specific frequencies of SRR and OCSRR structure from matlab program

Frequency (GHz)	Value of μ
2.365	29.1238-91.4682i
2.37	9.4519 -86.5389i
2.375	-4.0109 -77.2168i
2.38	-12.3420 -67.0498i
2.385	-17.0741 -57.5115i
2.39	-19.4092 -49.1137i
2.395	-20.1986 -41.9504i
2.4	-20.0223 -35.9380i
2.405	-19.2650 -30.9287i
2.41	-18.1773 -26.7638i
2.415	-16.9192 -23.2967i
2.42	-15.5913 -20.4013i
2.425	-14.2557 -17.9728i
2.43	-12.9496 -15.9255i
2.435	-11.6941 -14.1903i
2.44	-10.5003 -12.7115i
2.445	-9.3729 -11.4444i
2.45	-8.3129 -10.3529i
2.455	-7.3186 - 9.4077i
2.46	-6.3871 - 8.5852i
2.465	-5.5150 - 7.8661i
2.47	-4.6981 - 7.2346i
2.475	-3.9325 - 6.6776i
2.48	-3.2144 - 6.1844i
2.485	-2.5400 - 5.7460i
2.49	-1.9058 - 5.3550i
2.495	-1.3085 - 5.0050i
2.5	-0.7452 - 4.6907i
2.505	-0.2131 - 4.4077i
2.51	0.2903 - 4.1522i
2.515	0.7673 - 3.9208i

5. REFERENCES

[1] Anuja A Odhekar , G Arunkumar, D DPoddar, "Isolation Enhancement for closely coupled microstrip antenna", ICMARS, 2012.

[2] Frontiers of Microwave and optoelectronics ,Proceedings of International Conference on Microwave and Optoelectronics,2007,'Antenna Isoaltion Considerations for CW Radar'.

[3] V. G. Veselago, Soviet Physics Uspekhi, Volume 10, Number 4 January-February 1968."The Electrodynamics Of Substances With Simultaneously Negative values Of E And μ" P. N. Lebedev Physics Institute, Academy Of Sciences, U.S.S.R. Usp. Fiz. Nauk 92, 517-526 (July, 1964).

[4] Koray Aydin, Zhaofeng Li, LeventSahin, and EkmelOzbay, "Negative phase advance in polarizationindependent, multi-layer negative-indexmetamaterials", Optical society of America, 2008.

[5] Qun Wu, Fan-yi, Ming-Feng Wu, "Research on negative permittivity effect of the Thin Wires array in left-handed material by transmission line theory", progress in Electromagnetics Research Symposium 2005, August22-26.

[6] D. R. Smith, D.C.Vier, ThKoschny, C.M.Soukoulis, Phys. Rev E 71, 036617,2005.

[7] H.S.Lee, H.M.Lee, "Isolation Improvement between Loop Antennas with OCSRR and SRRs", 978-1-4244-9561-0/11, IEEE 2011.