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Comparative Analysis of Different Single Cell Metamaterial

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ABSTRACT

Artificially constructed metamaterial have become of considerable interest due to their negative properties. Under normal circumstance the electromagnetic energy inside metamaterial flows in the reverse direction. In this research, we compare seven different metamaterial structures against their negative frequency, simulation time, memory requirement and mesh cell. We also present a comparative analysis on tunability of single cell metamaterial structure to a different frequency band of interest. To come up with proper analysis we have restricted cell size of 2.5mm x 2.5mm and simulated structure from 0 Hz to 20 GHz. SRR structure has a negative frequency response in a lower band while Jerusalem cross takes less simulation time. S structure has lowest memory and mesh cell requirement, but it is hard to tune. However, CLS loaded split ring resonator has advantages over all the parameters of comparison and is found best.

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INTRODUCTION

V.G. Vesslago in the negative direction and hence also called as Left handed Material. J. B. Pendry in 1968 introduced the concept of metamaterial and described their distinct negative properties (Vesslago, V., 1968). Under normal condition the electromagnetic energy in metamaterial flows fabricated first metamaterial by arranging metal rod into an array (Pendry, J.B., 2000). This array when exposed to electromagnetic energy was capable of focusing energy into a narrow beam. J. B. Pendry also showed that negative permittivity and permeability can be obtained using Split Ring Resonator (Pendry, J.B., *et al*., 1999).

Due to their unique negative property Metamaterial find many applications in optimizing electromagnetic waves. One of the first application as proposed by Pendry was to create an electromagnetic lens of sub wavelength resolution. Ran (Ran, L-X., *et al*., 2005; Wu, B-I., *et al*., 2005) carried out several experiments on metamaterial such as Power transmission experiment, Prism refraction, Beam Shifting experiment, and focusing experiment. These experiments form the basis of all the application areas of metamaterial (Islam, M., *et al*., 2011; Faruque, M., *et al*., 2011; Ziolkowski, R.W., 2006; Buell, K., *et al*., 2006). Specific experiments have been conducted to enhance gain of antenna by using metamaterial in different forms and places surrounding the antenna.

We present comparison of 7 types of metamaterial structures. The comparison is done against their negative frequency range by keeping substrate size and its properties constant. Simulation of each model is performed using CST and corresponding 2 port S-Parameter is extracted. NRW method is used to extract constitutive parameter from simulated S-Parameter. Nicholson-Ross-Weir (NRW) (Nicolson, A., G. Ross, 1970) method provides a direct calculation of both permittivity and permeability from the s-parameter. However, the method diverges for low loss material at frequencies corresponding to integer multiples of one-half wavelength in the sample which is due to the phase ambiguity, Hence it is restricted to an optimum sample thickness of $\lambda g/4$ and used preferably for short samples. The comparison is also extended to analyze tunability, size as compared to resonance frequency, memory consumption while simulating and meshing, simulation time and number of mesh cell required. This comparison is helpful in determining the type of metamaterial cell for desired application.

Metamaterial Design and Simulation:

This paper shows a comparison between following four metamaterial structures.

A. Split ring resonator structure

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B. Omega Structure
C. S Structure
D. Symmetrical Ring Structure
E. Jerusalem Cross
F. Offset Fed Split Ring [DSRR]
G. CLS loaded SRR

To come up with fair comparison, several constrain on simulation and modeling single cell structure is enforced. The modeling constraints such as substrate size should not exceed 2.5mm x 2.5mm, substrate is 0.25mm thick regular FR4. The copper pattern used on top and bottom layer of PCB has 0.017mm thickness. Regular FR4 has permittivity (ε) of 4.35 and loss tangent (tan δ) of 0.025 at 20 MHz. All the single cell metamaterial structures are made to fit in the above set physical parameter. Simulation constrains such as the space surrounding metamaterial is constant and is vacuum, the boundary condition is kept same.

Split Ring Resonator Structure:

Split Ring resonator has two rings on top layer and one strip at the back acting as a rod. The outer ring has opening on top side while the opening of inner ring is rotated by 180°. The outer ring has length is 2.2 mm and the inner ring length is 1.5 mm. The trace width of both rings is 0.2 mm. Inner ring and outer ring are separated by 0.15mm. The gap between inner ring and outer ring is 0.3 mm. The trace on bottom layer of PCB is of 2.5 mm length and the width of trace is 0.2 mm.

The inductance is provided by the ring pattern formed on top layer while the capacitance is provided by the separation between inner ring and outer ring. Additionally the strip on the bottom side of the PCB provides some more inductance and capacitance.

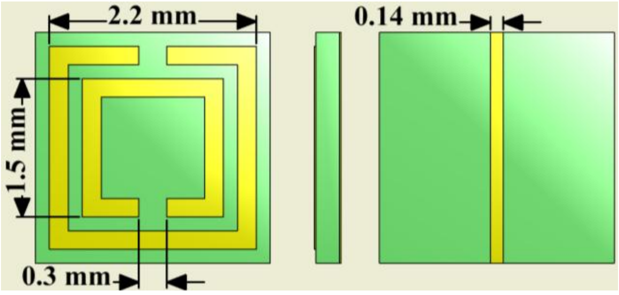

Fig. 1: Single cell split ring resonator structure

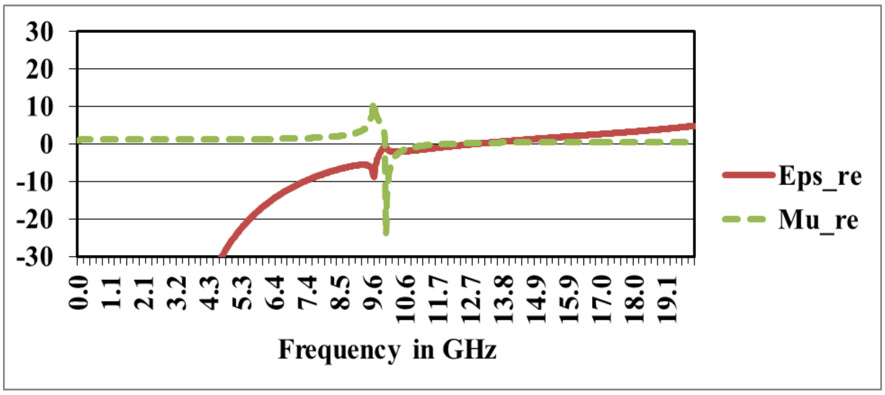

Fig. 2: Extracted negative permittivity and permeability

Omega Structure:

Omega structure (Huangfu, J., *et al.*, 2004) consists of an omega shape structure on top and bottom surface of the PCB. The ring traces width is 0.2 mm with inner ring radius of 0.9 mm. The trace at the lower section of omega is also 0.2 mm wide. The gap at the lower center of the structure is 0.4 mm wide. The ring of Omega structure provides inductance. Since the ring is printed on both the side of PCB they couple to provide capacitance. Additional capacitance is provided by the 0.4mm split in the ring.

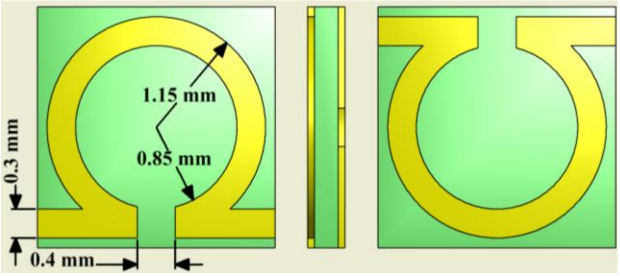

Fig. 5: Single cell omega structure

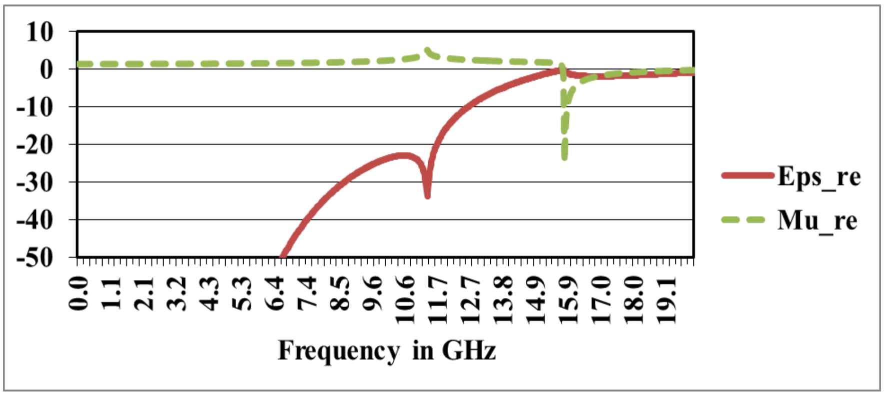

Fig. 5: Simulated results of Omega structure

S Structure:

Figure 5 shows the simulated single cell S-Structure (Chen, H., *et al.*, 2004). The trace width used to create S-Structure is 0.2 mm. S-Structure is placed in substrate of 3 mm x 2.5 mm. The width of the substrate used here is 0.25 mm. It is very difficult to fit S-Structure in 2.5 mm x 2.5 mm substrate and get a negative response below 20 GHz.

The inductance is provided by the trace forming S pattern while capacitance is provided by coupling between S pattern on top and bottom layer. In this case, the mutual coupling is limited due to limited overlap of pattern between top and bottom layer, hence the negative permeability response is weak. The inductance providing negative permittivity response is weaker as compared to Omega pattern.

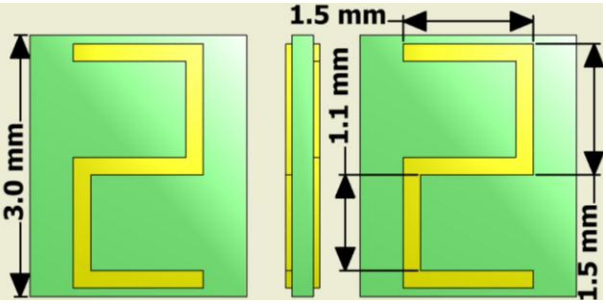

Fig. 5: Single cell S Structure

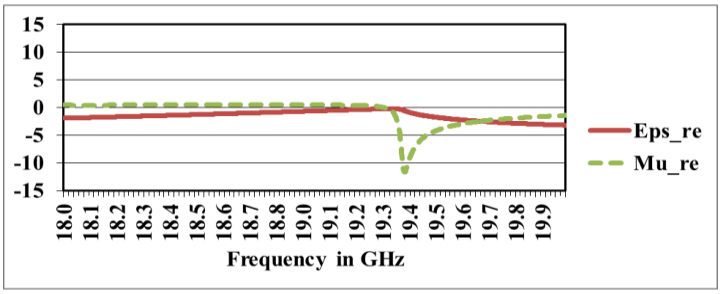

Fig. 6: Simulated results of S Structure

Symmetrical Ring Structure:

Another type of metamaterial structure which exhibits negative permittivity and permeability is symmetrical ring structure as shown in figure 7. This structure is made to fit in the physical constrain set earlier (O'brien, S., J. Pendry, 2002).

Trace width 0.2 mm is used to construct a symmetrical ring. Two symmetrical ring of 1.1 mm in length are placed facing each other at a gap of 0.1 mm. The rod on the bottom layer of the PCB is 0.4 mm and 2.5 mm in length.

The major part of the inductance of symmetrical ring structure is due to two ring structure on top while the capacitance is due to the coupling between one side of both the rings on top layer. The split on both the ring provides additional capacitance. Additionally the strip on the back has the same effect as to strip in SRR structure.

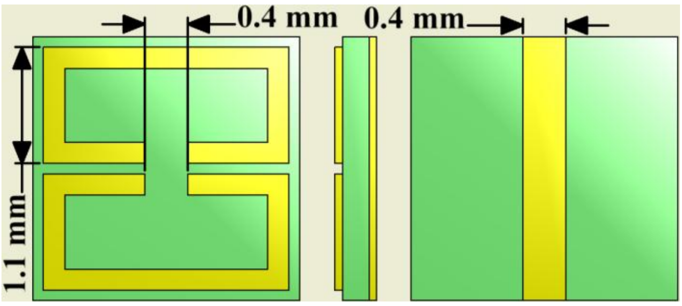

Fig. 7: Symmetrical ring structure.

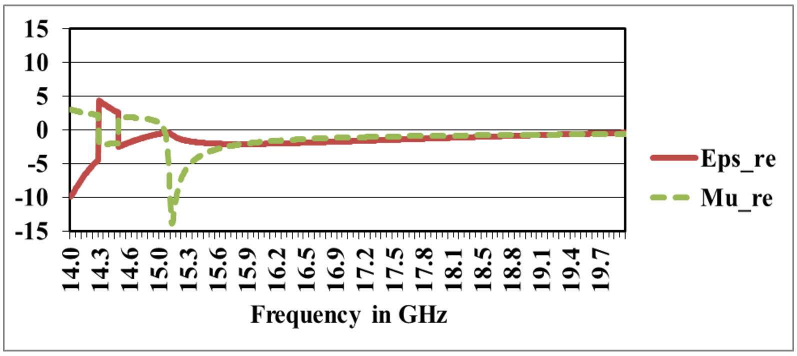

Fig. 8: Simulated results of Symmetrical ring structure

Jerusalem Cross:

Jerusalem cross metamaterial is very similar to Jerusalem cross and hence the name (Dongying, L., *et al.*, 2012). The design used for our simulation is a single layer design with 0.1 mm wide trace constructing cross. Each arm of the cross is 1.9 mm long as shown in figure 9. The simulated permittivity and permeability is as shown in Figure 10. Jerusalem cross is a complex structure in analyzing capacitance and inductance. The 0.1 mm traces forming part of the Jerusalem cross structure provides inductance while the capacitance is provided by the coupling formed on four corners of the Jerusalem cross. If the width and height of the trace are increasing the capacitance will also increase. Since Jerusalem cross has pattern on top layer it has limited capacitance and inductance. If the Jerusalem cross is used in array the capacitance will increase exponentially due to coupling with outer arm of the cross.

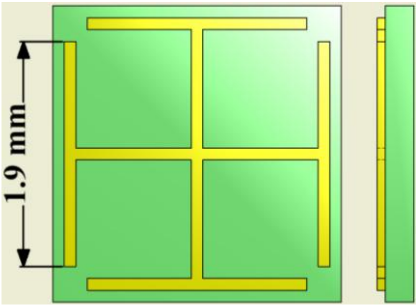

Fig. 9: Jerusalem cross structure

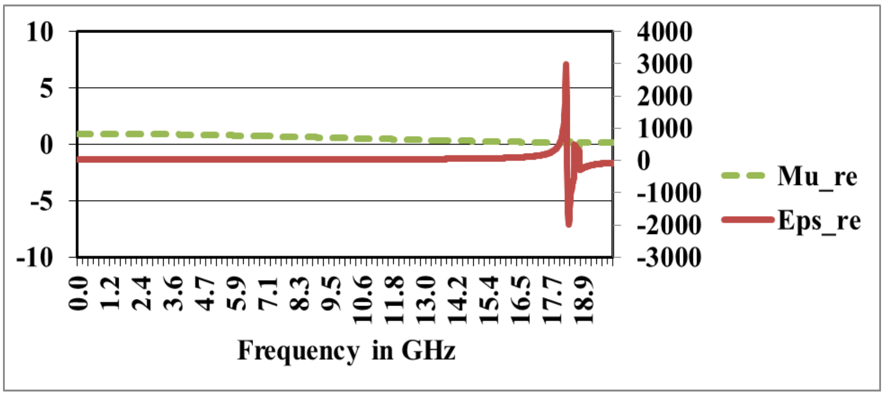

Fig. 10: Simulated results of Jerusalem cross

Offset Fed Diamond Shape Split Ring Resonator [DSRR]:

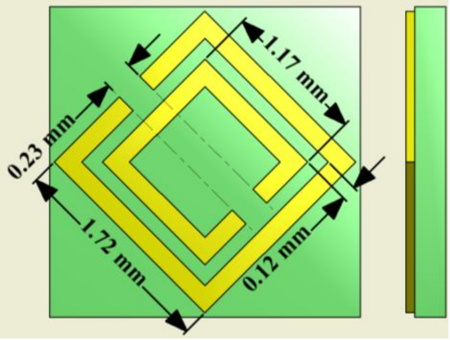

Fig. 11: DSRR Metamaterial

DSRR is similar to split ring resonator but rotated by 45˚ angle anti clockwise (Joshi, J., *et al*., 2009). Due to limitation applied on substrate size the dimensions of the rings are changed. The trace is 0.16mm wide. The outer ring is 1.72 mm long while the inner ring is 1.17 mm long. The gap between inner and outer ring is 0.2 mm as shown in Figure 11. Simulated permittivity and permeability is shown in Figure 12.

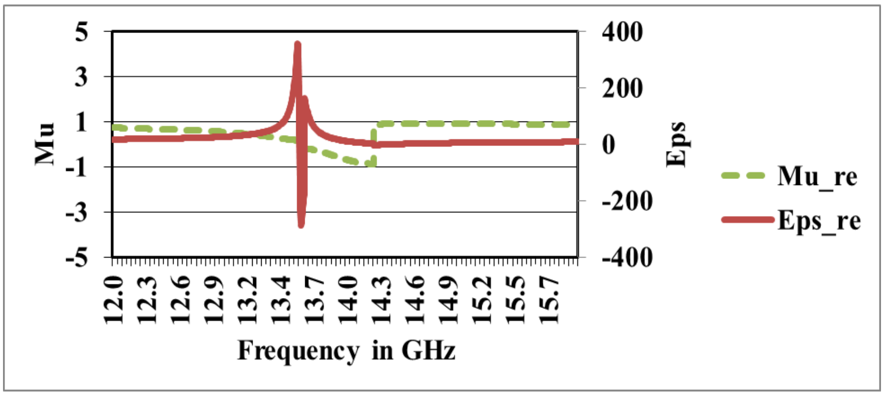

Fig. 12: Simulated results of DSRR Metamaterial

Capacitive Loaded Strip with Split Ring Resonator:

As the name suggests capacitive loaded strip SRR has two additional strips on sides of SRR (Majid, H.A., *et al*., 2009). The capacitive strip is I in shape with 1.32mm in length and 1.15mm wide. The gap between two capacitive strips is 0.05mm as shown in figure 13. The simulated permittivity and permeability is shown in figure 14. CLS loaded SRR has the advantage of SRR and I pattern. Additional I pattern increased the amount of capacitance exponentially. The coupling of I pattern to I pattern and both I pattern to outer ring brings the resonance frequency down. The SRR structure is 3.5 times smaller but the negative response and resonance are close to SRR.

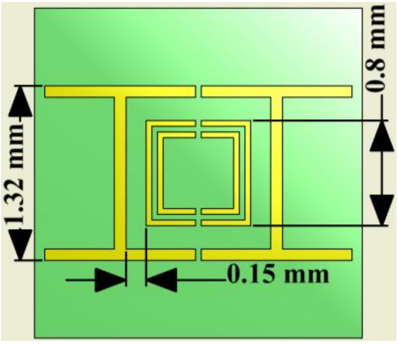

Fig. 13: Capacitive loaded strip with SRR

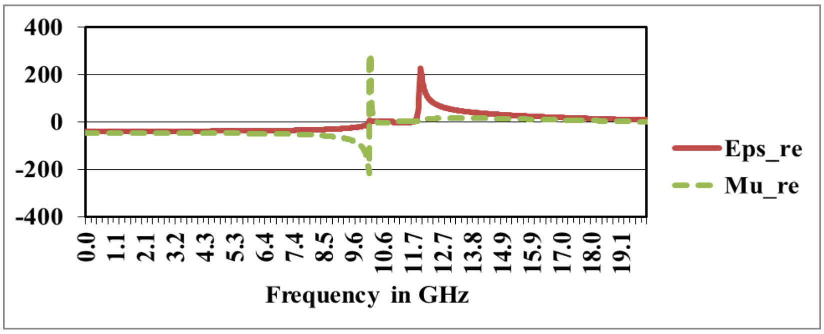

Fig. 14: Simulated results of Capacitive loaded strip with SRR

Comparison and Observation:

To have fair comparison all the structure is constrained to be designed for 2.5mm x 2.5mm x 0.25mm FR4 substrate. The only exception here is S-Structure which was about 2.5mm x 3.0mm x 0.25mm. We are comparing the simulation result against their resonance frequency, negative permittivity and permeability frequency and ease of tuning structure to operate at the desired frequency band. We are also listing the amount of memory consumed while simulating along with number of mesh cell generated and simulation time. While simulating care is taken to maintain structure orientation and the space surrounding structure constant.

The two most important parameters for antenna design are simulation time and size. In terms of simulation time CLS loaded SRR and Jerusalem cross takes the least amount of time. The amount of memory consumed by these structures is also low. However, Jerusalem cross has negative permittivity and permeability at higher frequencies that CLS. In terms of negative parameters SRR and CLS loaded SRR provides negative permittivity and permeability at the lowest frequency, so has a huge size advantage. Omega structure, S Structure and Symmetrical structure are complex to tune and shows negative parameter at higher frequency.

Table 1: Comparison of simulated parameters

	Resonance Freuqency (GHz)	Negative Permittivity (GHz)	Negative Permeability (GHz)	Tunability
Split Ring Resonator	10.4	≤ 10	≥ 10	Easy
Omega Structure	16.8	Entire Band	≥ 15.7	Hard
S Structure	19	≥ 15.7	15.7	Hard
Symmetrical Ring Structure	15.5 & 19.1	≥ 14.3	≥ 14.3	Hard
CLS Loaded SRR Structure	Low Loss, Entire bandwidth	≤ 10.2	≤ 10.2	Easy
DSRR	14.4	13.6~13.7	13.6~14.2	Hard
Jerusalem Cross	no clear resonance	≥18.3 GHz	18.3~18.4	Moderate

Simulation time of DSRR is highest. Symmetrical ring has 2 resonance frequency once at 15.5 GHz and second at 19.1 GHz but it is hard to tune and simulate. CLS loaded SRR and Jerusalem cross has very wide resonance frequency and hence no clear peak is observed. CLS-SRR has low loss over the entire frequency band.

Table 2: Comparision of Simulation time & memory requirement

	Simulation Time (Sec)	RAM Memory (MB)	Mesh Cell
Split Ring Resonator	121	78	195,250
Omega Structure	367	71	213,120
S Structure	111	50	107,712
Symmetrical Ring Structure	92	57	150,672
CLS Loaded SRR Structure	88	54	149,124
DSRR	680	88	248,400
Jerusalem Cross	72	59	110,400

Conclusions:

CLS loaded SRR offers the best solution for small size and lowest simulation time. The next alternative is the Split Ring Resonator which is easily tunable, but takes 33 seconds more to simulate. DSRR on the other side takes 680 second to simulate and has higher memory requirement. The negative response of DSRR is also on the higher side.

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