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A Novel Criss-Cross Shape Metamaterial

Kirti Inamdar, Y. P. Kosta, S. Patnaik.

Abstract— ***Metamaterials have been an attractive topic for research in the field of electromagnetic in recent years. This paper highlights the review work of some pioneers whose work has been very promising for scientific and engineering community. In the latter part, a new shape for metamaterial namely Criss-Cross shape has been discussed and its study has been presented in this paper. This shape has been inspired from the famous Jerusalem Cross and Cross with square loops structures. The unit cell response for this shape has been investigated for giving negative response of ε and μ.***

Keywords— ***Metamaterials, negative index, effective medium parameter, Jerusalem cross, DNG.***

I. INTRODUCTION

Metamaterials- this word has brought revolution in the electromagnetic domain in the last 12 years. However the theoretical foundations for this subject were laid far back in 1968 by Veselago in which his studies of uniform plane wave propagation in left handed media has been presented [1]. However at that time, the concepts were limited to papers. The vision of Veselago was brought in front of the world by Sir J. B. Pendry and D. R Smith in the form of 'medium' in microwave regime by arranging periodic arrays of split-ring-resonators and metallic wires in 1998-1999 [2]-[4]. The next pair of researchers which offered their contribution to this unique world of negativity was R. W. Ziolkowski and N. Engheta who answered many of the 'what-if' questions of the researchers. However, such MTMs are usually accompanied by two problems in measurement and application; one is the contact of the metal rods with the waveguide walls during refraction experiments, and the other is the bi-anisotropic properties of the SRRs [3], [4]. To solve the contact issue of the rods and the bi-anisotropy problem, an S-shaped resonator (SSR) was proposed [5]. The SSR MTM successfully produces simultaneous negative ε and μ within a relatively wide frequency range. Markeley and others proposed a planar negative refractive index (NRI) MTM in [6], which has conductive patterns orthogonal to the wave propagation direction, and its thickness is about 0.26 times that of the guided wavelength (λg). This MTM consists of narrow fishnet-grids and square patches that are connected with strips. The fabrication of this planar-type MTM is very simple; therefore, one can avoid an additional piling up process of individual cells using a hot-press technique to make "bulky" MTMs, which is needed for conventional non-planar MTMs. An MTM made up of metallic square loops and X-shaped cross poles showing DNG behaviour has also been validated leading to planar approach for fabrication [7]. Reviewing the literature well led to many innovative ideas for unconventional shapes of MM that can be derived from there.

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II. THEORITICAL APPROACH TO METAMATERIALS

In order to establish the material properties of metamaterial, the macroscopic level approach is used. The electromagnetic coupling as given by Maxwell's equation independent of media is given by

$$\nabla X E = -j\omega B - M \text{...........(i)}$$
$$\nabla X H = j\omega D + J \text{...............(ii)}$$
$$D = \varepsilon(\omega)E + \xi(\omega)H \text{.....(iii)}$$
$$B = \mu(\omega)H + \zeta(\omega)E \text{ ....(iv)}$$

The electromagnetic coupling terms in eqn. (iii) & (iv) are mathematically represented as

$$\xi(\omega) = \chi(\omega) - jk(\omega)\sqrt{\varepsilon_0\mu_0} \text{.......(v)}$$
$$\zeta(\omega) = \chi(\omega) - jk(\omega)\sqrt{\varepsilon_0\mu_0} \text{......(vi)}$$

Where χ (ω) i the Tellegen parameter and $k(\omega)$ is the chirality parameter.

Linear media that includes magneto-electric coupling referring to simultaneous production of $\vec{E}$ and $\vec{H}$ polarizations from excitation by $\vec{E}$ and $\vec{H}$ fields, formulations are used directly to describe the equivalent parameters of metamaterial. In case of negative isotropic medium where ε and μ both are negative, the plane EM wave will be of the form

$$\begin{bmatrix} E\ (r,t) \\ H\ (r,t) \end{bmatrix} = \begin{bmatrix} \vec{E} \\ \vec{H} \end{bmatrix} \cos(\vec{k}.\vec{r}.\omega t) \text{.........(vii)}$$

So the Maxwell's equation become

$$\vec{k} X \vec{E} = \varepsilon\mu\vec{H} \text{.......(viii)}$$
$$\vec{k} X \vec{H} = -\varepsilon\mu\vec{E} \text{......(ix)}$$
$$\vec{k}.\vec{E} = 0 \text{.................(x)}$$
$$\vec{k}.\vec{H} = 0 \text{................(xi)}$$

The power density is given by S = $\vec{E}\ X\ \vec{H}$. In case of NIMs, since both ε and μ both are negative,the Poynting's vector is in the opposite direction of $\vec{k}$ and so are the group and phase velocities with the three vectors $\vec{k}, \vec{E}$ *and* $\vec{H}$ form a Left Handed medium and the power propagates in a direction opposite to $\vec{k}$, thus the plave wave in NIM is a backward wave.

III. CRISS-CROSS SHAPE

For the creation of DNG medium, we want both ε and μto be negative simultaneously. Negative permittivity is often realised by a simple array of wires, capacitively –loaded strips etc. [8]. However negative permeability is more difficult to realise as the structure giving negative μ should behave like a 'magnetic plasma'.

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Such a thing does not exist in nature. SRRs were the first structure to exhibit negative μ and therefore they are popular till now [9]. SRRs are fully scalable with frequency which is very narrow band. They are also lossy in their resonance region. Several different methods of creating multiband structures have been proposed [10,11] that rely on SRRs or SRR like structures. But one main drawback of SRR based MM is that they are independent of structure rotation. Cross type structures have overcome this effect. Jerusalem Cross (JC) is used as Frequency Selective Surface (FSS) [12] i.e. high impedance for selected frequency. The bulk material approach for MM was done in [13]. Further replacement of SRRs by JCs has been studied by Alexander [14] thus proving that JCs can be used as DNG medium. His work has been referred for analysis of the new shape for MM by the author.

IV. JERUSALEM CROSS REVIEW

Alexander Remely Katko has presented the study of JC very well. He used the effective medium approach for analyzing the material. This part of paper presents the reproduced work of Alexander by the author just to create a test bench. The simulation set-up for a JC unit cell is shown in Fig. 4.1. The JC structure is made up of copper 20mils wide with a total unit cell size of 600x600x240 mils. The dielectric layer used is Dupont 951 ($\varepsilon_r = 7.8$) which is 40 mils thick. The unit cell was enclosed in a waveguide with proper boundary conditions. An EM wave was applied at both the ports of the waveguide. The model was simulated over a frequency sweep of 1 to 12 GHz. The S parameters were obtained using HFSS (version 13.0) and were exported to Matlab to find impedance Z, refractive index n, ε and μ. The method used for parameter extraction is described in [14].

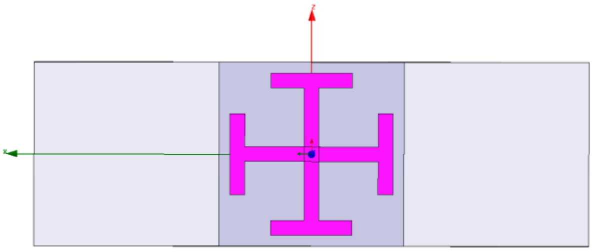

Fig. 4.1. Simulation setup for JC unit cell

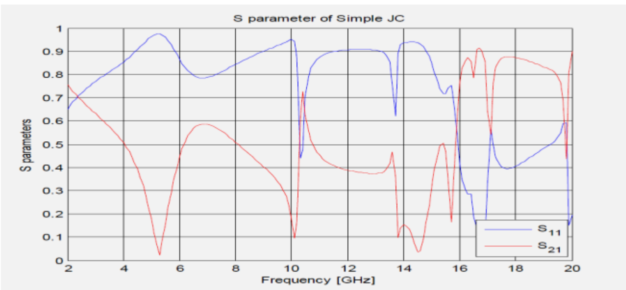

Fig. 4.2 S parameter of JC unit cell [13]

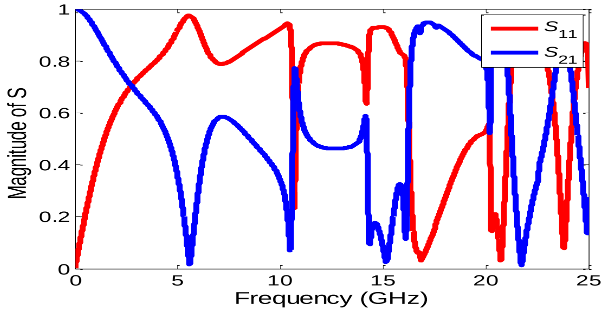

Fig. 4.3 Reproduced S parameter of the JC unit cell

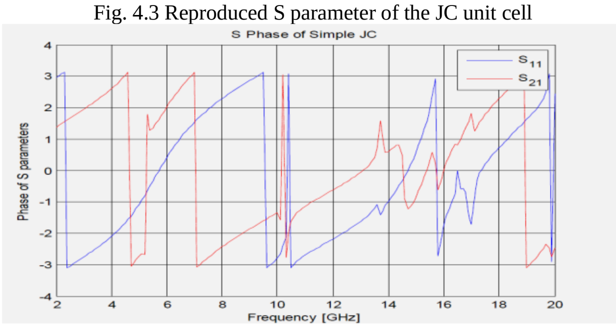

Fig. 4.4. Phase variation of JC unit cell [13]

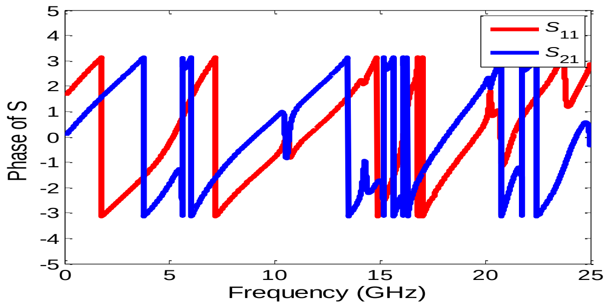

Fig. 4.5 Reproduced Phase variation of JC unit cell

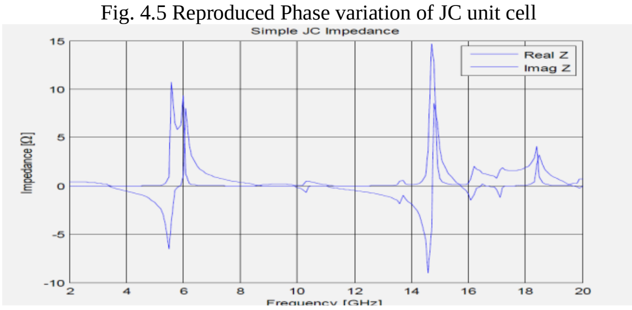

Fig. 4.6. Impedance variation of JC unit cell [13]

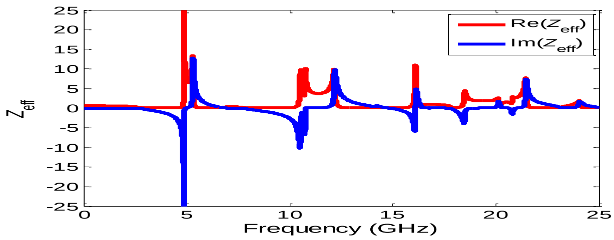

Fig. 4.7. Reproduced. Impedance variation of JC unit cell.

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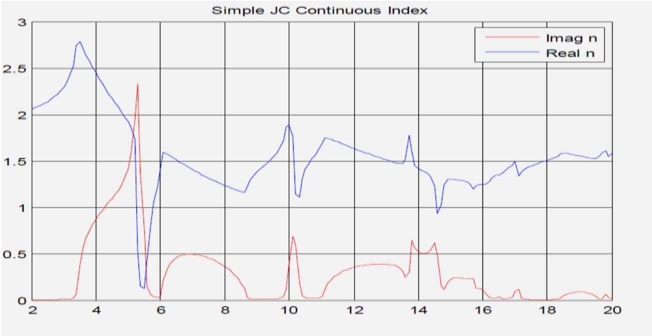

Fig. 4.8. Extracted Refractive index of JC unit cell [13].

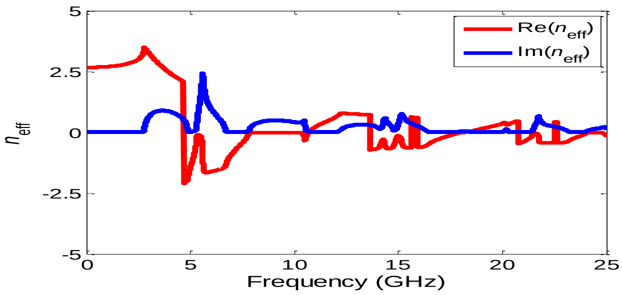

Fig. 4.9. Reproduced extraction of Refractive index of JC unit cell

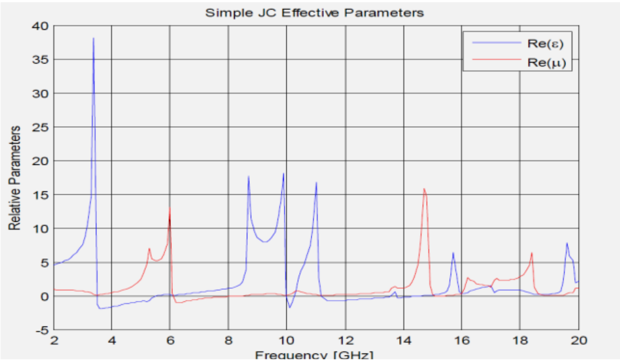

Fig. 4.10. Extracted μ and ε parameters of JC unit cell [13].

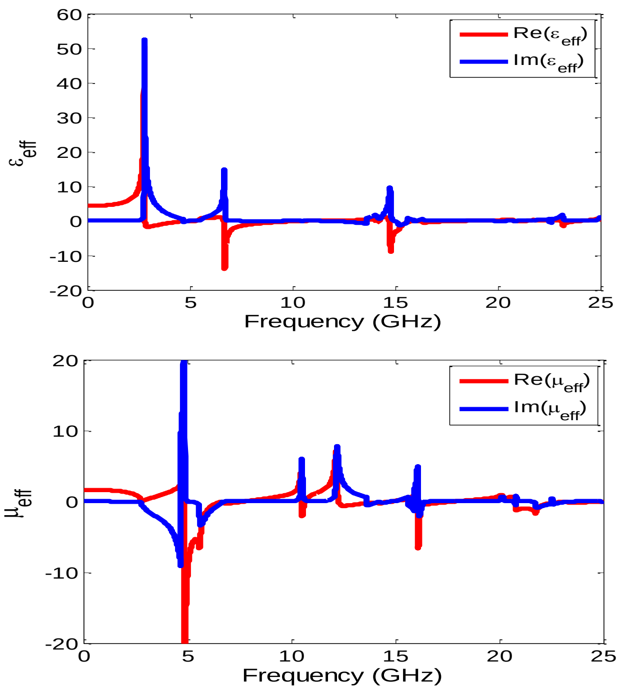

Fig. 4.11. Reproduced Extraction of μ and ε parameters of JC unit cell.

The results obtained by the author are matching well with that of [14]. So with this a perfect test bench giving validation of equations used is created. The next section introduces a new particle named Criss-Cross shape. The parameter extraction of it is done using the same test bench.

V. DESIGN OF CRISS-CROSS SHAPE UNIT CELL

In the Criss-Cross shape, there is a cross placed on upper face of substrate and the same cross is twisted by 45° and placed on the back side of the substrate as shown in Fig. 5.1 and Fig. 5.2. The substrate and other structural detail are kept the same i.e. as of JC in order to make the comparisons easily. Later the same structure was also made on FR4 (ε_r= 2.2 and RT Duroid (ε_r = 4.4) in order to analyse the negative behaviour of the structure well. All the results are mentioned combinations are presented in figures from Fig. 5.3(a)-(f), Fig.5.4 (a)-(f) and Fig. 5.5 (a)-(f) respectively.

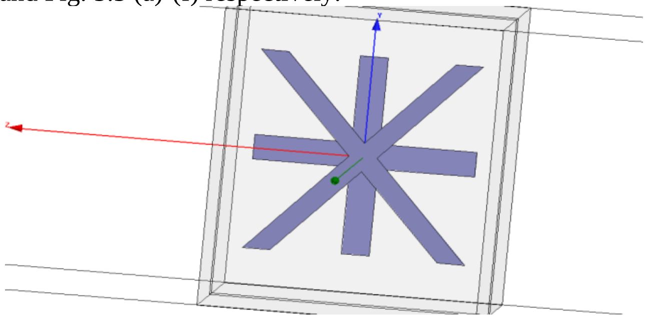

Fig.5.1. A Criss-Cross shape unit cell

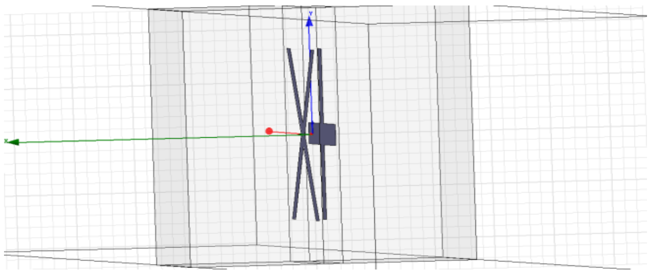

Fig.5.2. Alignment of a X and + on both sides of substrate

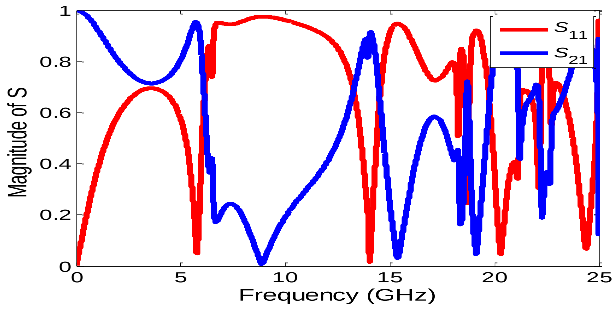

Fig. 5.3 (a)

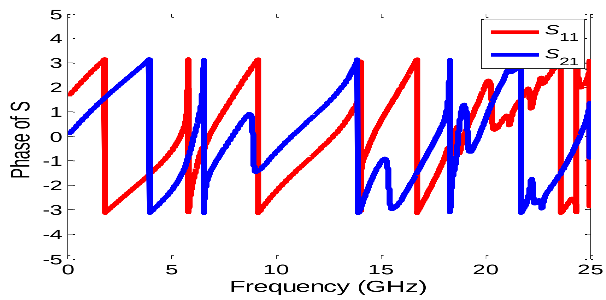

Fig. 5.3 (b)

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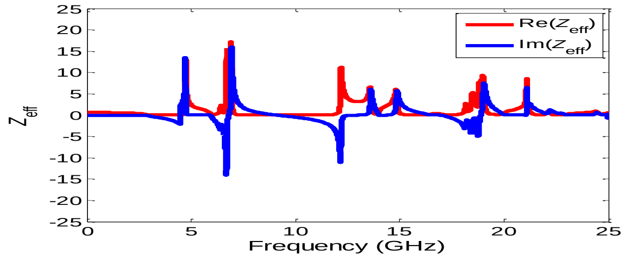

Fig. 5.3 (c)

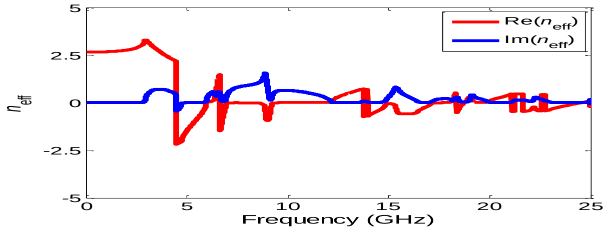

Fig. 5.3 (d)

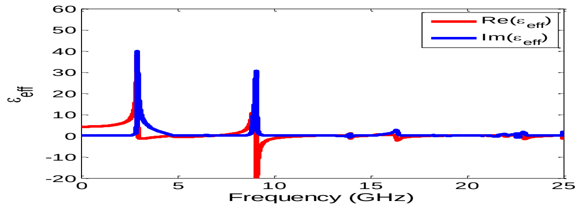

Fig. 5.3 (e)

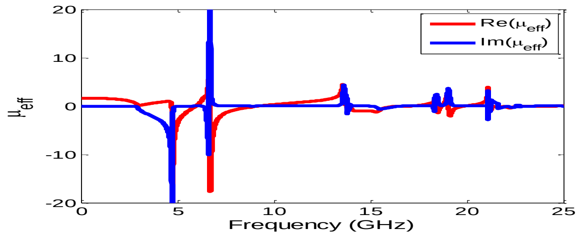

Fig. 5.3 (f)

Fig. 5.3.(a)-(f). The extracted parameters of Criss-Cross shape unit cell when made on the substrate of Dupont (ε_r = 7.8).

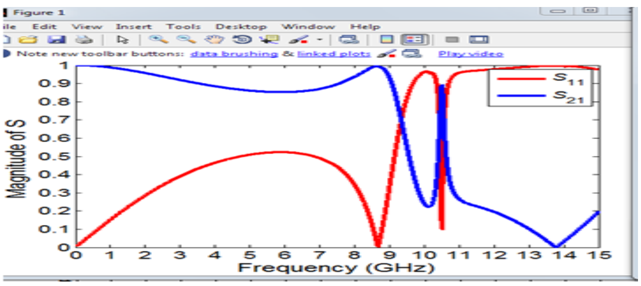

Fig. 5.4(a)

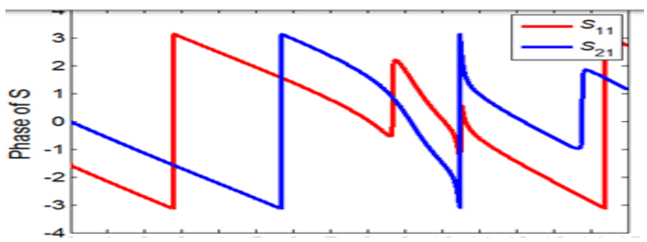

Fig. 5.4(b)

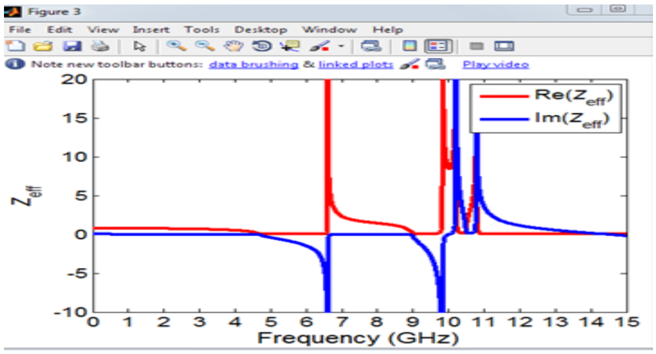

Fig. 5.4(c)

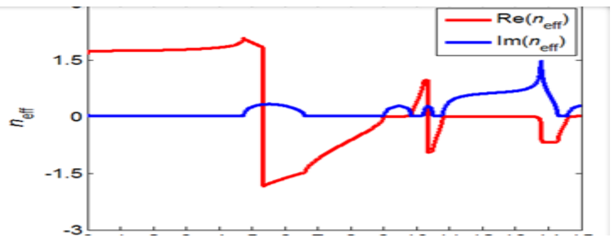

Fig. 5.4(d)

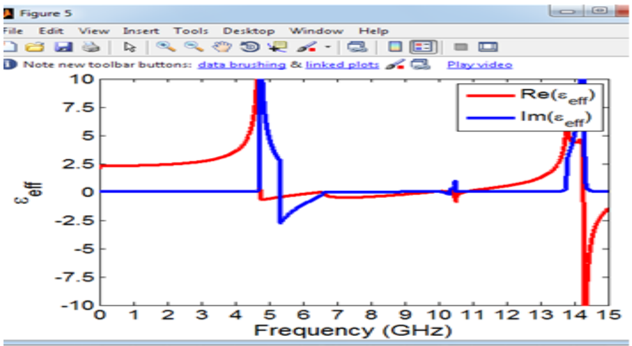

Fig. 5.4(e)

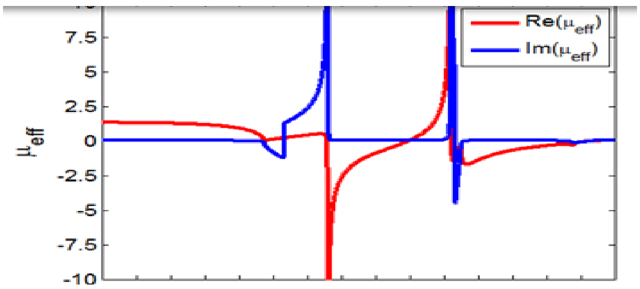

Fig. 5.4(f)

Fig. 5.4 (a)-(f). The extracted parameters of Criss-Cross shape unit cell when made on the substrate of RT Duroid (ε_r = 2.2).

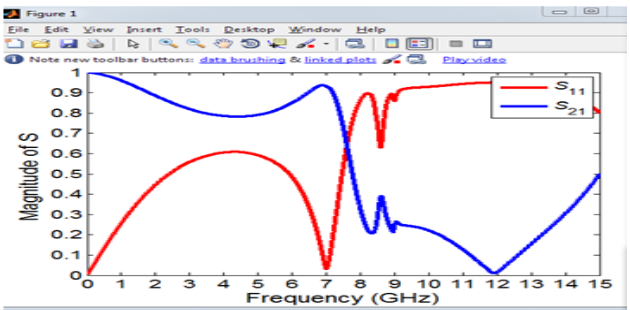

Fig. 5.5 (a)

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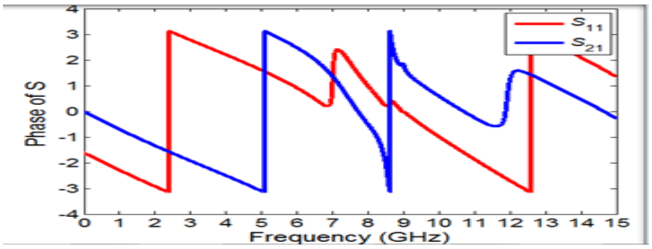

Fig. 5.5 (b)

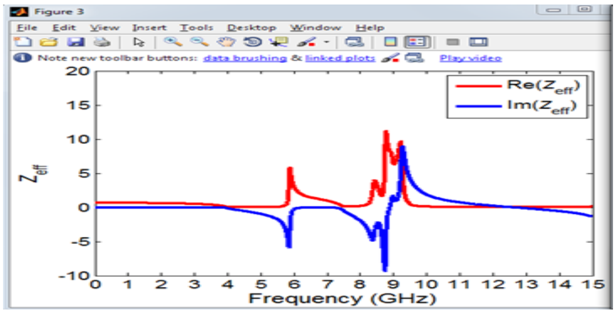

Fig. 5.5 (c)

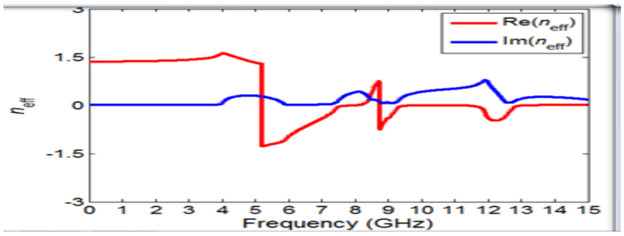

Fig. 5.5 (d)

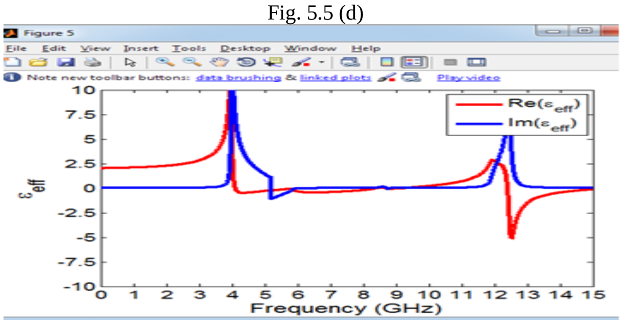

Fig. 5.5 (e)

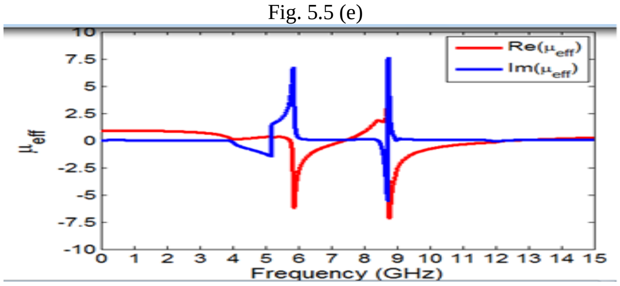

Fig. 5.5 (f)

Fig. 5.5 (a)-(f). The extracted parameters of Criss-Cross shape unit cell when made on the substrate of FR4 (ε_r = 4.4).

Table I. Comparison of exhibition of DNG bands of Criss Cross shape for three different substrate materials

	Criss Cross Unit cell			3x3 array of Criss Cross cell
	S11 (dB)	f_r (GHz)	DNG band. (GHz)	DNG band (GHz)
Dupont (ε_r = 7.8)	34	5.6	5 to 6	10
RT Duroid (ε_r = 2.2)	-51.8	8.7	6.5 to 9	4 to 7
FR4 (ε_r = 4.4)	-30	7	6 to 7	4.5 to 6

VI. CONCLUSION AND FUTURE WORK

After studying the extracted parameters for the implementation of Criss-Cross shape unit cell on three different substrates (Dupont, Duroid and FR4), one can say that this shape is exhibiting Double NeGative (DNG) behaviour. The results are summarised in Table I. If one compares the DNG band for all three cases, there is a minor shift in the bands. However, the return loss is minimum in the case of RT Duroid as it is least lossy among all. It is seen that the frequency band in which DNG effect is seen is matching with that of the resonance region. The effective ε and μ of this shape was also calculated for a 3x3 array of the unit cell. Due to array structure, multi resonance effect is seen. There is a shift in the DNG band in all the three cases. The novel Criss Cross shape can thus make its place in the family of metamaterials. Being a new member it has to sturggle to prove its identity but since it is derived from Jerusalem cross, there is definitely a bright future for it. This new shape can be used to improve preformance parameters of a microstrip patch antenna also.

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