Development of a Planer Microstrip Metametarial Resonator for Wideband Applications

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Abstract

This paper introduces a new, planar microstrip metamaterial resonator, using two circular split-ring resonators, and an array of conducting wires. The structure was simulated from 1MHz to 15GHz showing negative refractive index in several frequency ranges with wideband characteristics. The s-parameter matrix was analyzed to determine the effective permittivity and permeability. At frequencies where both the recovered real parts of ε and μ are simultaneously negative, the real part of the index of refraction is also found to be negative.

Keywords: Microstrip, Metamaterial, Split Ring Resonator, Wideband, Negative refractive index material.

1. Introduction

Metamaterials, first named and theoretically discussed by Veselago[1], are studied widely throughout the world. These are an artificially engineered material which shows electromagnetic properties that are not readily found in naturally occurring material, such as, negative refractive index and artificial magnetism (Smith et al.2002; Pendry 1996; Zilkowski et al. 2003; Si et al., 2008; Weng et al., 2007; Erentok et al., 2005).

Metamaterials are often characterized in terms of their effective material parameters, such as effective electric permittivity and effective magnetic permeability (Shalaev et al., 2005). One of these parameters may be negative, or both of them may be negative. The former is known as single negative material (SNG) (Hao et al., 2009; Cui et al., 2010), when only effective permittivity is negative it is called Epsilon negative material (ENG) (Ziolkowski 2006), whereas when only effective permeability is negative it is called as Mu-negative material (MNG) (F. Billoti 2008). The latter is referred to as left-handed metamaterials (LHM), double negative (DNG), or negative refractive index material (NRIM) (Sharma et al., 2011; Zharov et al., 2003; Weng et al., 2007; Shalaev et al., 2005; Hao et al., 2009).

Artificial plasmas show negative effective permittivity for all frequencies smaller than plasma frequency of the Plasmon medium (Si et al., 2008; Pendry et al., 1996; Pendry et al., 1998). Effective negative permeability can be obtained in the well known Split-ring-resonator structure, but only for a narrow magnetic resonant frequency band (Pendry et al. 1999).

In past few years, metamaterials has been a nascent topic of interest among the research fraternity. New innovative structures are being reported showing performance improvement in terms of size bandwidth, frequency bandwidth, ease of fabrication, tuning capability etc. (Cheng Zhu, 2010; Sabah, 2010).

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This paper presents design and simulation of a new planar microstrip metamaterial resonator, exhibiting negative index of refraction at multiple bands, with wide-band characteristics. It uses two circular split-ring resonators, placed adjacently on a substrate and an array of straight wire conductors on other side of the substrate. The geometry of the structure resembles the shape of mathematical symbol 'infinity' and thus will be referred to as Infinity Shaped Metamaterial (ISM). The structure has been simulated on HFSS and s-parameter values (S_{11} and S_{21}) thus obtained was used to calculate index of refraction.

One more method called NRW technique [4] is also used to calculate effective permittivity and effective permeability from s-parameters, using which refractive index can be calculated. So refractive index is calculated in two ways: directly with the help of s-parameters and indirectly with the help of ε and μ.

2. Design

The Fig.1 below shows a single Circular split-ring resonator, and Fig.2 (a) shows the Infinity Shaped Metamaterial (ISM).

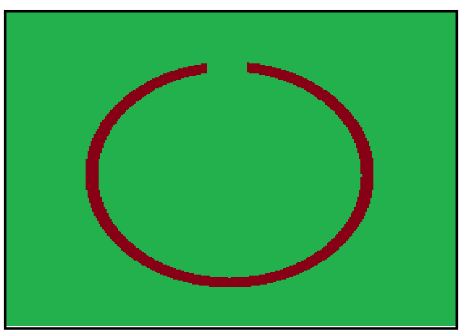

Fig.1 A Circular Split-Ring Resonator Structure (SRR)

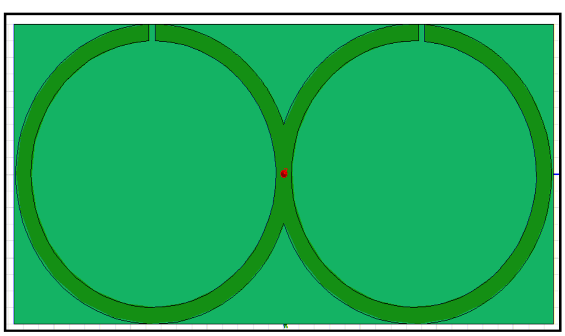

Fig.2 (a) Top view of Infinity Shaped Metamaterial (ISM)

It can be seen from these two figures that this metamaterial has the shape of mathematical symbol 'infinity', and can be formed by placing two circular SRRs adjacently. Fig.2 (b) shows the ground plane below the substrate, normally a continuous sheet of copper is used for implementing the ground plane but here an array of straight wire conductors is used.

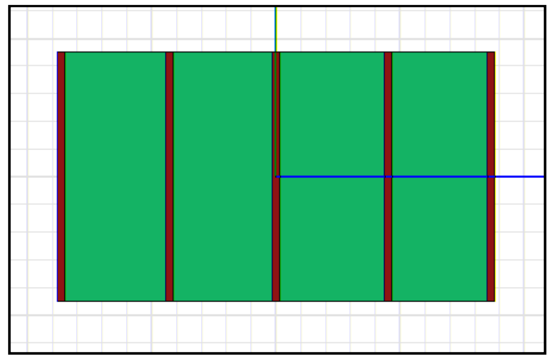

Fig.2 (b) Bottom view of ISM, showing Ground Plane arranged as an array of straight wire conductors.

The structure is fed RF signals ranging from 1MHz to 15 GHz, with the help of waveports. The boundary conditions and waveports are as shown below in fig.2(c) & 2(d).

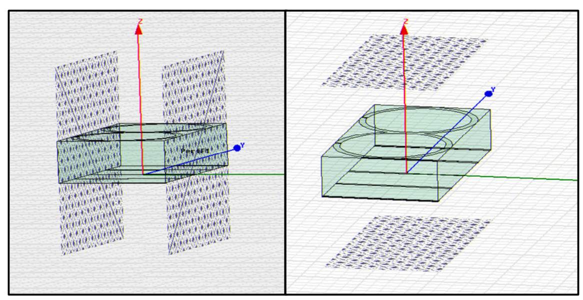

Fig.2 (c) Schematic diagram of ISM, showing the boundary conditions: PEC & PMC boundaries respectively.

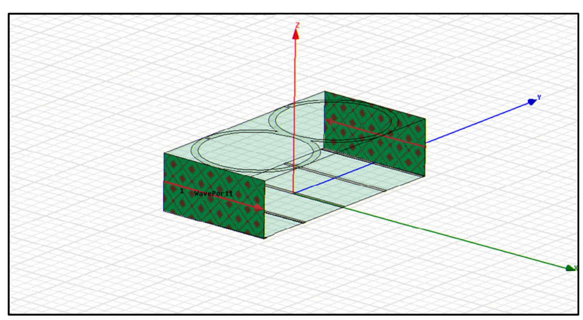

Fig.2 (d) Schematic diagram of ISM, showing the waveports.

The physical parameters of the structure are mentioned in Table 1 below.

Table 1

Parameters	Values
Substrate (Duroid(tm)) with Thickness	0.786 mm
Relative dielectric constant	2.2
Radius of outer circle of the ring	0.9 mm
Radius of inner circle of the ring	0.8 mm
Slot cut in the ring	0.03 mm

Thus, it can be deduced that ISM is a composite structure consisting of Split-rings and array of wires and both will be required to obtain negative effective permittivity and negative effective permeability in a single structure.

3. Results

The ISM structure was simulated on EM solver Ansoft HFSS. With s-parameter matrix obtained, value of refractive index n and wave impedance z is calculated using equation (1) & (2) [5].

$$n = \frac{1}{kd}\cos^{-1}\left\{\frac{1-S_{11}^2+S_{21}^2}{2S_{21}}\right\} \tag{1}$$

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

The values of effective permittivity ε and effective permeability μ can be calculated as $\varepsilon = n/z$ and $\mu = n*z$.
All of the above formulae were programmed in MATLAB 2009a to obtain the required plots. Refractive index versus frequency curve is shown in Figure 3.

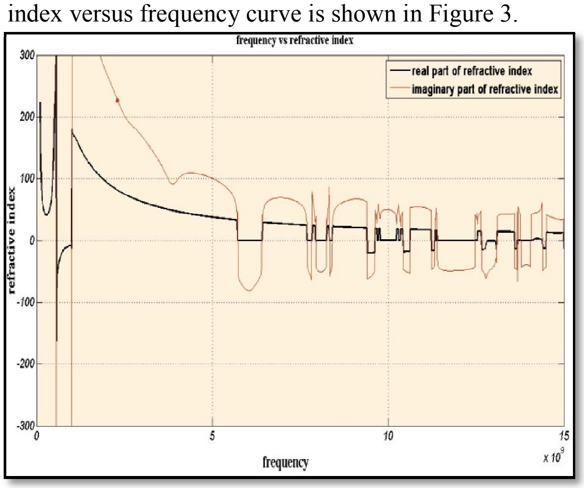

Fig.3 Frequency versus Refractive Index. Real part (mu) (Black), Imaginary part (mu) (Red).

It is apparent from Figure 3 that the ISM structure is exhibiting NRIM property (negative real part of refractive index) at several frequency bands such as: 570MHz to 1GHz, 5.72GHz to 6.42GHz, 7.7GHz to 7.82GHz, 7.95GHz to 8.24GHz, 8.34GHz to 8.4GHz, 9.4GHz to 9.62GHz, 10.43GHz to 10.62GHz, 11.25GHz to 11.32GHz, 11.39GHz to 12.48GHz, 12.67GHz to 13.1GHz, 13.79GHz to 14.06GHz, 14.4GHz to 14.5GHz respectively.

The dip in transmission coefficient S21(magnitude) at these frequencies accompanied with zero crossing in phase of S21[fig.4] gives indication of the presence of NRIM property at these frequencies (Sabah, 2010) which was further elaborated by calculating value of refractive index using equation(1).

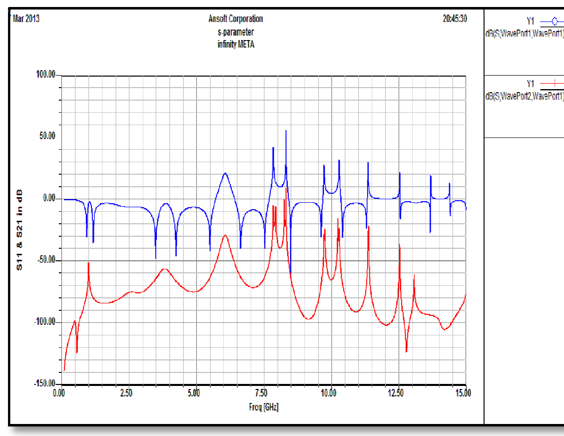

Fig.4(a) Magnitude of S11 (Blue), Magnitude of S21 (Red).

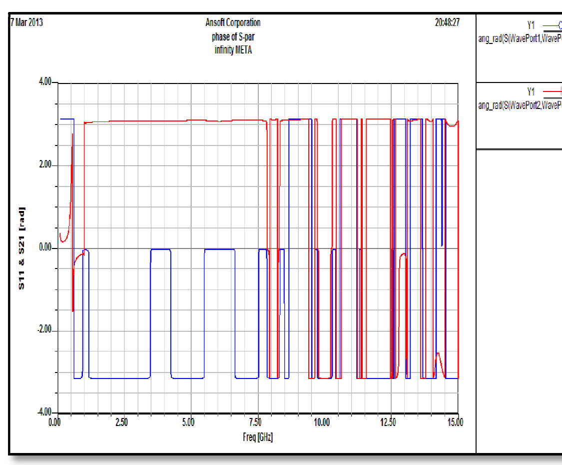

Fig.4 (b) Phase of S11 (Blue), Phase of S21 (Red) in Radians.

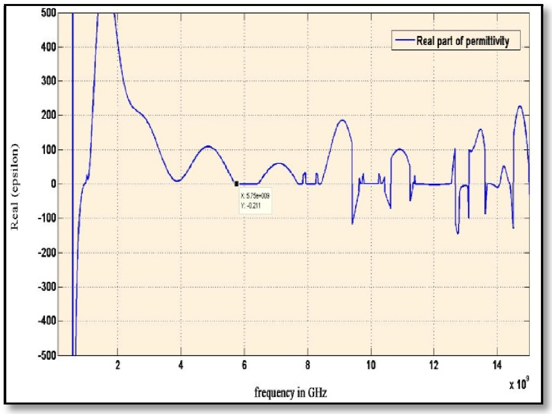

Fig.5 (a) Frequency versus Real (Effective Permittivity ε)

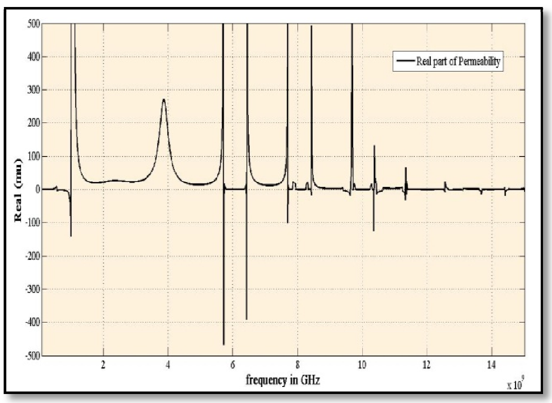

Fig.5 (b) Frequency versus Real (Effective Permeability μ)

The Real part of effective permittivity and effective permeability shown in fig.5 were obtained with the help of refractive index and wave impedance.

Another method called Nicholson-Ross-Weir (NRW) technique is also used in this paper. It is a conversion approach which can directly obtain values both of permittivity and permeability from any S-parameter, the values of ε and μ thus obtained may be used to calculate refractive index. It is a non-iterative method that can be applied easily. The procedure proposed by NRW method follows from the following equations:

$$S_{11} = \frac{\Gamma(1-\mathrm{T}^2)}{1-\Gamma^2\mathrm{T}^2} \tag{3}$$

$$S_{21} = \frac{\mathrm{T}(1-\Gamma^2)}{1-\Gamma^2\mathrm{T}^2} \tag{4}$$

The reflection coefficient Γ can be realized as:

$$\Gamma = \mathrm{X} \pm \sqrt{\mathrm{X}^2 - 1}\,, \tag{5}$$

where $|\Gamma| < 1$ is required for finding the correct root and in terms of s-parameter.

$$\mathrm{X} = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{6}$$

The transmission coefficient T can be written as:

$$\mathrm{T} = \frac{S_{11} + S_{21} - \Gamma}{1-(S_{11}+S_{21})\Gamma} \tag{7}$$

The permeability is given as:

$$\mu_r = \frac{1-\Gamma}{\Lambda(1-\Gamma)\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \tag{8}$$

where λ_0 is free space wavelength and λ_c is the cutoff wavelength and Λ is complex number of wavelength,

$$\frac{1}{\Lambda^2} = -\left(\frac{1}{2\pi L}\ln\left(\frac{1}{\mathrm{T}}\right)\right)^2 \tag{9}$$

where L is length of the material.

The permittivity can be defined as:

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left(\frac{1}{\lambda_c^2} - \left[\frac{1}{2\pi L}\ln\left(\frac{1}{\mathrm{T}}\right)\right]^2\right) \tag{10}$$

Equation (9) & (10) have an infinite number of roots as the imaginary part of ln(1/T) is $j(\Theta_T+2\pi n)$, where $n = 0, \pm 1, \pm 2, \pm 3, \ldots$, the integer multiple of (L/λ_g), λg is the wavelength in sample and θ_T is the phase of transmission coefficient in radians. The value of n can be determined by solving equations (11) and (12). The value of n must be rounded up to the nearest integer to get the actual root number.

$$\frac{1}{\Lambda^2} = \frac{\varepsilon_r * \mu_r}{\lambda_0^2} - \frac{1}{\lambda_c^2} \tag{11}$$

$$Re\left\{\frac{1}{\Lambda}\right\} = \frac{1}{\lambda_g} \tag{12}$$

where ε_r is the initial guess of material permittivity, μ_r is the initial guess of permeability. After calculating the value of ε and μ, the value of refractive index was calculated using;

$$n = \sqrt{\varepsilon * \mu} \tag{13}$$

All of the above formulae were programmed in MATLAB R2009a to obtain required plots.

The plot of frequency versus effective permittivity, effective permeability and refractive index is shown in figures.6 (a), (b) & (c) respectively.

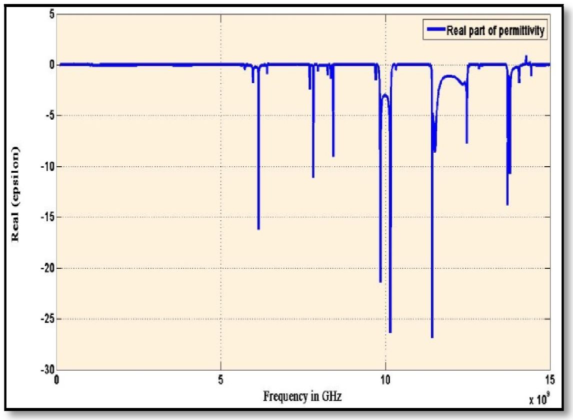

Fig.6 (a) Frequency versus Real (Effective Permittivity ε)

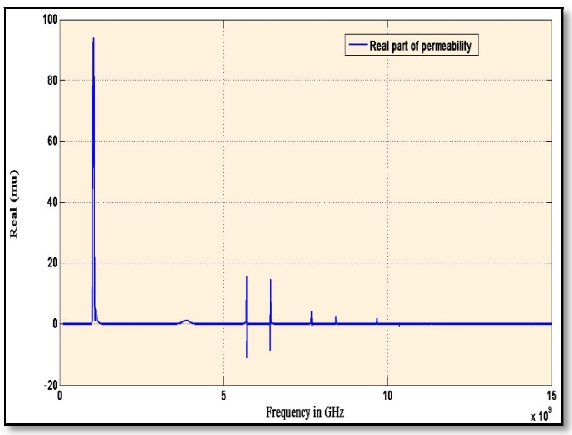

Fig.6 (b) Frequency versus Real (Effective Permeability μ)

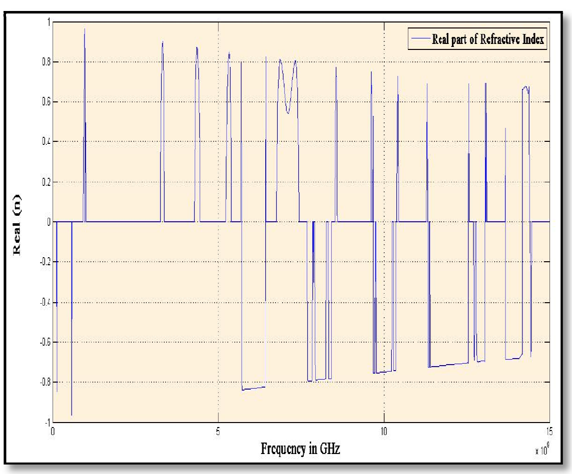

Fig.6 (c) Frequency versus Real (Refractive Index *n*)

The Plots in fig.3, 5 & 6, shows that the result obtained from both the methods are similar. Thus, negative refractive index was achieved at multiple bands, with wide band characteristics at few frequency bands, and confirmed by both of the methods.

Conclusion

A new planar multiband microstrip metamaterial resonator, using circular split rings in the shape of 'infinity' and array of straight wire conductors is demonstrated that exhibits property of negative index of refraction. The conventional SRR shows negative permeability at a narrow magnetic frequency resonant band but ISM shows negative permeability at wide bands. This type of ISM resonator can be easily incorporated with microstrip antennas to get highly directional beam patterns either by using it as a substrate or by using it as a metamaterial cover kept in front of the antenna. In future, work can be done in order to improve the bandwidth of the ISM resonator.

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