Experimental Studies on the Effect of Substrate Dielectric Constant on the Resonant Frequency of Split-Ring Resonator Metamaterial Structure

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Abstract: ***The results of an experimental study for tuning the resonant frequency of a split ring resonator (SRR) metamaterial structure at microwave frequencies, by changing the material and thickness of substrate are presented. The SRR structure is fabricated by photochemical etching on a copper foil glued on a thin low loss polymer film of negligible thickness. The transmission properties are studied using a unit cell of SRR between two monopole antennas. The materials used for the fabrication of substrate are the Poly Methyl Methacrylate (PMMA) and Wax. The experimental results predicts the possibility of tuning the resonant frequency of the SRR unit to any desired value by changing the material or thickness of the substrate and are in good agreement with theoretical expectations. This possibility may be used for the fabrication of wide band frequency selective and cloaking materials. This method may be extended to the design and fabrication of tunable negative index materials.***

Keywords: metamaterial, split-ring resonator (SRR), frequency tuning, negative permeability.

1. Introduction

Metamaterials are artificial materials that exhibit unusual electromagnetic properties that are not observed with natural materials. The extraordinary properties of these materials such as negative refraction, reversed Doppler effect etc. are due to its negative values of permittivity μ, permittivity ε and index of refraction n. In these negative materials, the electric field **E,** magnetic field **H,** and wave vector **k,** form a left-handed triplet and the Poynting vector **E**×**H** is anti-parallel to the wave vector. So these materials are also called left handed media (LHM), double negative media (DNG) and backward wave media. Focusing beyond the diffraction limit, amplification of evanescent waves, frequency selective surfaces, miniaturization of antennas, cloaking, sensing etc. are some of the promising applications of these materials.

The metamaterial concept was theoretically introduced by Victor Veselago in 1968 [1]. For several years nobody can materialize it due to the non availability of negative permeability structures. In 1999 Pendry *et.al* fabricated negative permeability structures using an array of split ring resonators (SRR) at microwave frequencies [2]. The first left handed metamaterial was materialized by Smith and colleagues in 2000 by periodically arranging negative permeability and permittivity unit structures [3], [4].

Split ring resonators are the most fundamental unit cell used for almost all microwave metamaterial applications. It has two interleaved metallic rings with two opposite gaps. Each unit cell acts as an LC oscillator in an external magnetic field causing sharp absorption of power corresponding to the resonance frequency. The resonant properties of SRR structures have been studied by different researchers [5], [6], [7]. Almost all experimental studies related to the resonant frequency are performed using structures fabricated on some rigid substrate like FR4 circuit board. To analyze the effect of ε on resonance frequency experimentally, SRR structures with certain specific geometric parameters are to be fabricated using boards of different substrate materials. An attempt in this direction using two substrate samples of the same material but of two different thicknesses is presented by Zhongyan *et. al* along with some numerical results [8]. Detailed numerical analysis of this problem is available in [9], [10] and [11] also. Recently the authors have reported a flexible SRR structure at microwave frequencies fabricated on a thin polymer film of negligible dielectric constant using photochemical etching [12]. We have used this structure for the experimental study of the effect of substrate dielectric constant on the resonant frequency of SRR. Two key factors that influence the resonant frequency of SRR are the permittivity and thickness of the substrate. In this paper we present the effect of both these parameters on the resonant frequency of SRR.

2. Resonance frequency of SRR

The schematic representation of the SRR unit is pictured in Fig. 1. The geometrical parameters that affect the resonant frequency are inner radius r, metal width w, slit width d and gap distance s.

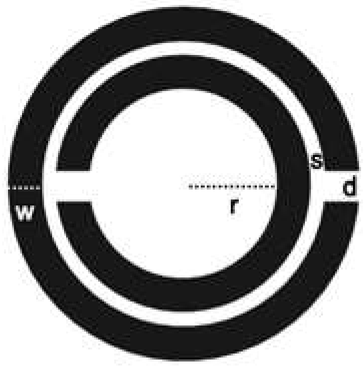

Figure 1: The schematic representation of the SRR unit cell.

SRR unit cell structures arranged in two or three dimensional pattern can be considered as a homogeneous medium if the

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interacting radiation is of wavelength much greater than the array spacing (lattice constant) a. The effective permeability of this artificially engineered medium can be written as

$$\mu_{eff} = 1 - \frac{\pi r^2 / a^2}{1 + \frac{i2\rho l}{\omega r \mu_0} - \frac{3l}{\mu_0 r^3 \pi^2 \omega^2 C_1}}$$

where ρ is the resistance per unit length and l is the vertical lattice parameter. The resonance frequency of the SRR unit cell depends on its intrinsic values of inductance and capacitance. The dielectric constant and thickness of the substrate material changes the capacitance of the material considerably. The capacitance of a SRR unit with a substrate of dielectric constant ε_r is given by

$$C_1 = \frac{\epsilon_0 \epsilon_r}{\pi} \ln \frac{2w}{s}$$

The resonance frequency of SRR with the dielectric becomes

$$\omega_{0m} = \sqrt{\frac{3lc_0^2}{\pi \epsilon_r r^3 \ln \frac{2w}{s}}}$$

3. Fabrication of the Structure

The SRR units are fabricated using a copper foil of thickness 20 µm. Two methods were tried for the fabrication. One method is using photolithographic etching and the other is by direct printing technique. In the first method the copper sheet after fixing on a thin polymer film is coated with liquid photo-resist and exposed to ultraviolet radiation with proper mask and subjected to chemical etching using dilute ferric chloride solution. The second method also uses chemical etching, but instead of photo masking direct printing of the SRR pattern on the copper sheet is made using a printer. For this study, the SRR structure fabricated on a thin polymer film of thickness 18 µm using photochemical etching method is used. Fig. 2 shows the photograph of the fabricated structure. The structural parameters are inner radius r = 3 mm, metal width w =1.25 mm, slit width d = 0.3 mm and gap between rings s = 0.5 mm.

The SRR is glued on substrates of PMMA and Wax having different thickness and are used to study the effect of relative permittivity on resonance frequency. PMMA is a vinyl polymer made by free radical polymerization from the monomer methyl methacrylate. Fig. 3 shows the photograph of PMMA and wax samples prepared for the study. PMMA substrates used are of thicknesses 0.15 mm, 0.24 and 0.29 mm. The thicknesses of wax samples used are 0.68 mm, 0.91 mm and 1.07 mm.

Figure 2: Photograph of the SRR structure fabricated on a low loss flexible polymer film. The dimensions are d = 0.3 mm, w = 1.25 mm, r = 3 mm, s = 0.5 mm and a = 9 mm. Thickness of metallization (copper) 20 µm.

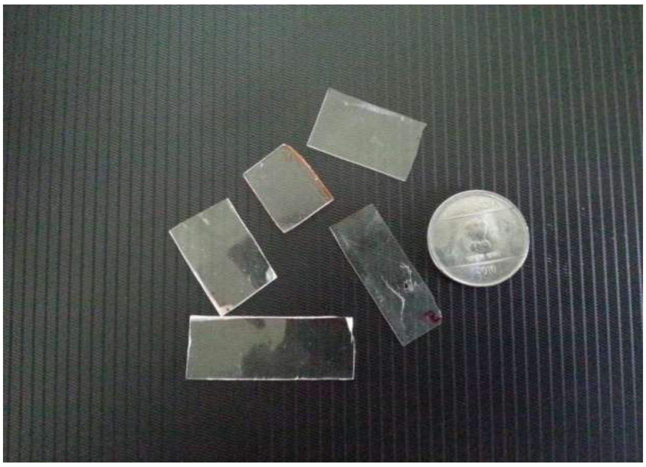

Figure 3: Photographs of the samples of PMMA and Wax prepared for using as substrates for the SRR

4. Measurements and Results

The transmission properties are studied by placing the SRR unit cell between two monopole antennas. It is schematically represented in Fig. 4. Measurements are performed using a Network Analyzer system. The effect of substrate dielectric constant on the resonant properties of SRR is studied using different PMMA and Wax sheets. The dielectric constants of samples used are measured using the waveguide method proposed by Dube *et. al* [13]. The measured values of ε_r are around 2.6 for PMMA and 2.2 for wax. When the substrate thickness increases, the capacitance between rings increases and correspondingly, resonant frequency shifts to the lower frequency region because of its inverse dependence. Fig. 5 and Fig. 6 depict the resonant frequency variation of SRR with PMMA and Wax substrates for different thicknesses. The resonant frequency obtained for PMMA substrate for thickness 0.15 mm is 6.37 GHz. It shifts to 6.32 GHz and 6.23 GHz for substrates of thickness 0.24 mm and 0.29 mm respectively. For the wax samples the resonance frequencies are at 6.41 GHz for t = 0.68 mm, 6.39 GHz for t = 0.91 GHz and 6.35 GHz for t = 1.07 mm. The study clearly shows that an increase in dielectric constant or thickness of the substrate decreases the resonance frequency considerably. These

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results are in good agreement with the theoretical predictions and previous numerical studies.

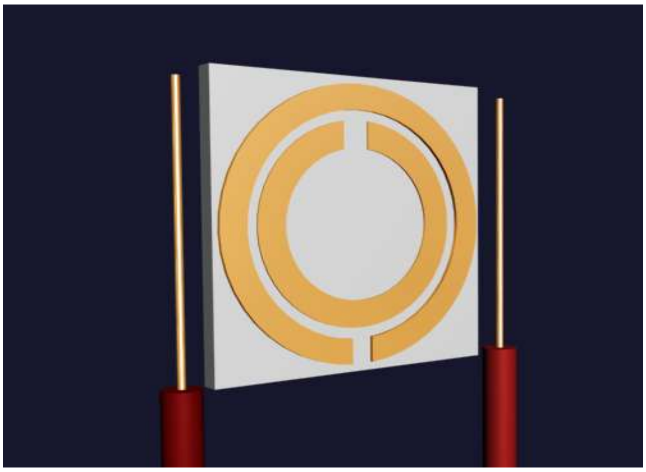

Figure 4: Schematic diagram of the experimental arrangement used for the study of transmission spectra, with the SRR unit cell between two monopole antennas.

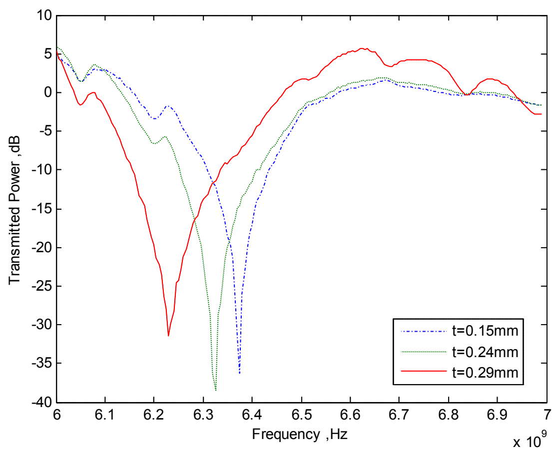

Figure 5: Measured transmission spectra of a SRR unit cell, for different values of substrate (PMMA) thickness *t*. The dimensions are $d = 0.3$ mm, $s = 0.5$ mm, $w = 1.25$ mm, $r = 3$ mm and metallization thickness 20 µm.

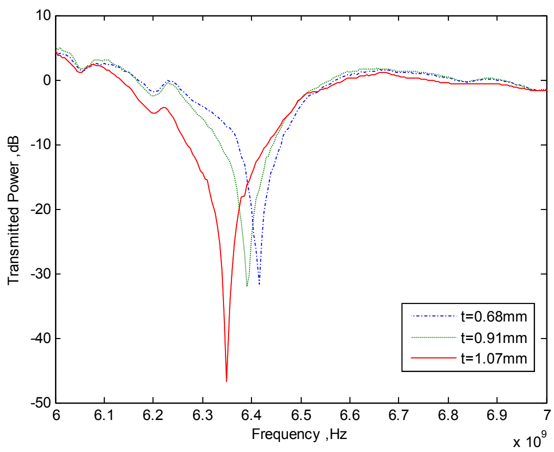

Figure 6: Measured transmission spectra of a SRR unit cell, for different values of substrate (Wax) thickness *t*. The dimensions are $d = 0.3$ mm, $s = 0.5$ mm, $w = 1.25$ mm, $r = 3$ mm and metallization thickness 20 µm.

5. Conclusions

The resonance tuning properties of SRR by changing the permittivity or thicknesses of the substrate are presented. The result of this experimental study clearly shows the possibility of tuning the resonant frequency of the structure to any desired value by changing dielectric constant or thickness of the substrate. This method of fabrication can easily be extended to the design and fabrication of flexible and tunable negative index materials. This structure may be used for realizing cloaking media and for frequency selective applications.

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