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High Gain Metamaterial Antenna Using Linear Displacement of SRR Elements

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***Abstract* -** Herein, a novel and successful incorporation of split ring resonators (SRR) as metamaterial on microstrip patch antenna is presented. The antenna is designed by placing 3 x 3 shifted rectangular split-ring resonator (SRR) array on a conventional rectangular patch antenna. Furthermore, a comparative study of this novel prototype with the conventional SRR introduced patch antenna shows the influence of the change in position of the square SRR elements on the different parameters especially on the gain of the patch antenna. The gain achieved in case of linearly displaced SRR elements on the patch antenna is increased by almost 70% of the gain of the patch antenna with normal 3 x 3 SRR array incorporation. The rectangular patch antenna design has been made feasible due to the quasistatic resonance property of the split-ring resonators. The measured results are reported at their resonant frequency 2.45 GHz which validates the observation of gain enhancement in this article.

Keywords- DNG, ENG, LHM, MNG, metamaterial, microstrip line, split ring resonator

I. Introduction

In recent years, microstrip antennas are extensively used as printed antenna because of its interesting characteristics such as light weight, low cost and easy compatibility with MMIC components [1]. Most of the work on metamaterials has been concentrated in split ring resonators (SRRs) to provide magnetic response. SRR behaves as an LC resonant tank that can be excited by an external time-varying magnetic field applied parallel to the particle axis, thus producing a quasi-static resonant effect. Therefore, the SRR has sub-wavelength dimensions at its quasi-static resonance, allowing very compact device designs [2]. The theoretical analysis presented in the work [3] describes that the gain of a microstrip antenna can be enhanced by incorporating metamaterial lens (MM) in the coplanar waveguide (CPW) fed UWB patch antenna. A compact UWB antenna using planar patterned metamaterial structures is introduced in [4]. Here the metamaterial unit cell is made up of two capacitive loaded strips (CLSs), a split ring and a gapless ring. The initial unit cell is based on an SRR made of two oppositely located loops: a smaller loop within a bigger one. The SRR is a magnetically resonant structure that responds to a perpendicular magnetic field which can be used to create negative permeability. Splits (gaps) added to the ring introduce capacitance, which allows for the control of the resonant characteristic of the structure. The modification is the closing of the loop on the inner ring, which reduces the series capacitance of the SRR. In this context, a rectangular patch antenna surrounded by a ring and diagonal slot operating at

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2.43GHz is described in [5]. However, the research work shown in [6] describes the pin-loaded technique to design a kind of circularly polarized high gain patch antenna having high gain of 7dB considering its large dimension and it is depended on the shorting position and pin radius.

The authors in [7] proposed a triple band microstrip patch antenna by etching metamaterial unit cells in the ground plane. The objective is to generate multi-resonance response by using two different types of metamaterial unit cells. The proposed design of a compact low cost wideband microstrip patch antenna [8] describes the modification of 50-Ω microstrip feed line with tapering and creating a defect in regular metamaterial lattice by removing a unit cell near the feed position of radiating patch. A circularly periodic EBG substrate is introduced in [9] to increase the gain of a circular microstrip antenna. The effect of magneto-dielectric materials is discussed in [10] where materials with permeability higher than one are used to increase the in-phase reflection bandwidth of the mushroom-type EBGs, and the designed EBG structure is used to implement a low-profile wideband antenna. The characteristics of input resistance as a function of feed position are described in [11] that differ when using a probe or a microstrip line feed. The RF energy can be harvested by using the stub integrated microstrip antenna (SIM) with resonant frequency 2.56GHz and acceptable gain of 4.7dB is presented in [12]. In the work proposed in [13], the coupling effects of a pair of diagonal slots are observed to achieve higher gain of 4.29dB and wide axial ratio bandwidth.

In this paper, a novel prototype of extremely high gain metamaterial patch antenna is proposed in which 3 x 3 SRR array elements are placed above the patch. The antenna gain is further increased by shifting the inner rings from the core of outer rings of the SRR in a linear fashion. The proposed antenna resonates at 2.45 GHz. This proposed work is organized as follows: Sec.2.describes the fundamentals of metamaterial. Under this section, the unit cell structure of a square split ring resonator is depicted along with the equivalent circuit model. Sec.3. shows the array formation of 9 elements (3x3) SRRs with all the parametric values. In the sec. 4, the relevant parameters of antenna such as return loss, input impedance, input resistance, reactance and radiation pattern are presented and compared with other designed prototypes.

The concluding part of this section contains a table containing the comparison of antenna gain of this work with previous research works. Then the conclusive report is produced in sec. 5. The proposed prototype design is unique and can be easily fabricated and also can be recognized as one of the most innovative method of antenna gain enhancement in modern research.

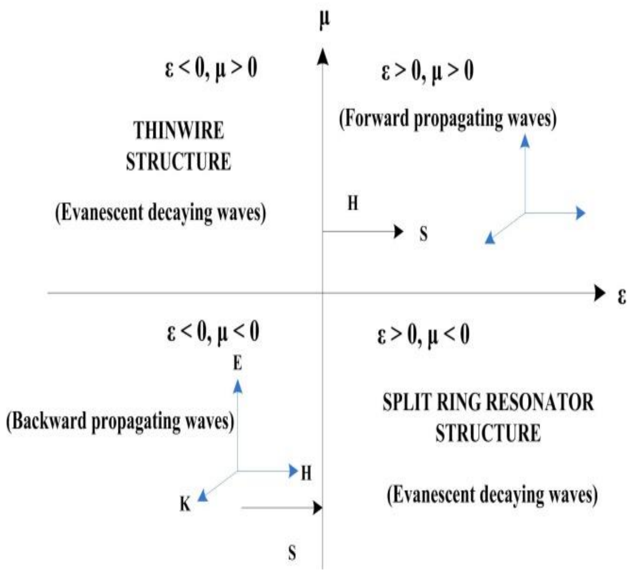

Fig.1. Different types of wave propagation

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II. Theory Of Metamaterial

The metamaterial classification was first proposed by Veselago by considering the permittivity ε, and the permeability μ of a homogeneous material. The relationship between the refractive index and the constituent parameters ε and μ is given by the formula (1):

$$n = \pm (\varepsilon_r \mu_r)^{1/2} \qquad (1)$$

where ε_r and μ_r are the relative permittivity and permeability of the material, related to the free space permittivity and permeability. From Eq. (1), sign ± of n can get 1 in the four cases, which depends on the pairs of sign of ε_r and μ_r. The electromagnetic metamaterials are classified based on each case of the pair sign ε and μ, they are shown in Figure 1.

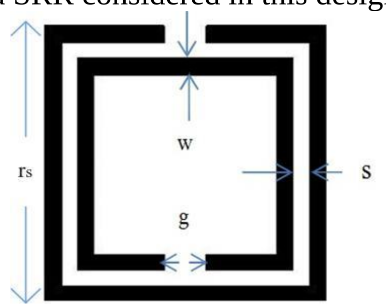
In the quadrant I, both parameters ε and μ are positive, and are called Double Positive (DPS) or right-handed medium (RHM). These materials can be found in nature, such as dielectric materials, in which the electromagnetic waves can propagate. In the quadrant II, the parameters are ε < 0—negative, and μ > 0— positive and such material is called as epsilon negative (ENG) medium. In the quadrant III , parameters ε < 0—negative, and μ < 0—negative, this region is called double-negative (DNG) or left-handed medium (LHM), and such material could not be find in nature. The quadrant IV ε > 0—positive, and μ < 0—negative, and such material is called μ—negative (MNG), represented by ferrite materials. Most waves can propagate in two mediums namely: at region I and III. Non-propagating evanescent waves are found in regions II and IV. Currently, two basic types of structures are being used for designing the most metamaterials : a dense array of thin wires (the electrical dipoles) and an array of split-ring resonators (SRRs) (the magnetic loops).

A. *Square Split Ring Resonator (S-SRR)*

The mu-negative (MNG) material, the most popular structure has been using is split ring resonators (SRRs). A unit cell of the SRR is composed of two concentric metallic rings and separated by a gap "s" is depicted in figure 2(a). Each ring has a narrow slot, and they are spaced 180^0 apart on each side. The gap between inner and outer ring acts as a capacitor, while the rings themselves act as an inductors. Therefore, the combination of the two rings acts as an LC resonance circuit. The effective permeability of MNG metamaterials is given by the formula (2):

$$\mu_{eff} = \mu'_{eff} - j\,\mu'_{eff} = \frac{1 - f^2_{mp} - f^2_o}{f^2 - f^2_0 - j\gamma f} \qquad (2)$$

Where, f is the frequency of the signal, f_{mp} denotes the frequency at which (in the lossless case) μ_{eff} = 0 ("magnetic plasma frequency"), f_0 is the frequency at which μ_{eff} diverges (the resonant frequency of the SRR), and γ represents the losses. The frequencies f_{mp} and f_0 depend on the lattice constant (p), and the geometry parameters of the SRR such as inner and outer radii of the rings, the width of the gap between the rings, and the slit width. The basic cell structure of a square split ring resonator is shown in Figure 2. The unit cell dimension of a SRR considered in this design is shown in the given Table 1.



(a)

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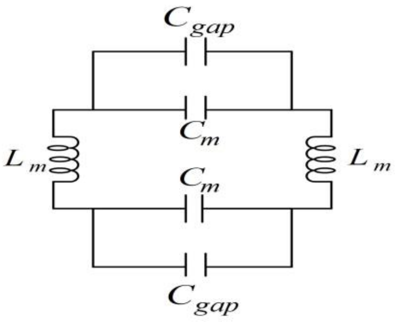

(b)

Fig.2. (a) Unit cell S-SRR (b) Equivalent circuit

TABLE.I. UNIT CELL DIMENSION

Parameter	***Notation***	***Value (mm)***
Outer ring length	r_s	*12*
Width	*s*	*0.2*
Gap	*g*	*1*
Thickness	*w*	*1.5*

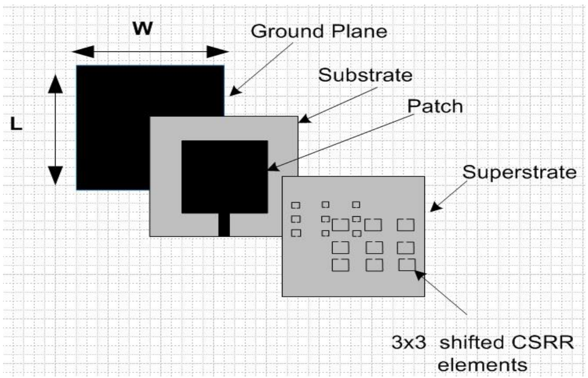

Fig.3. Schematic diagram of the proposed antenna prototype

III. Antenna Design Using Csrr Array

In our proposed antenna, we at first consider a square antenna with FR-4 substrate; the dimension of which is W=L=45 mm and thickness h = 1.6 mm. The rectangular patch placed over the substrate. The width and length of the substrate is 33 mm and 28.5 mm respectively. The loss tangent is 0.009. Microstrip line is used as feed line. The feed length and width are measured 8 mm and 3.08 mm respectively. In order to achieve better high gain, 9 element 3x3 split ring resonator arrays (SRR) have been incorporated and placed over the patch. Figure 3 shows the schematic lay out of the proposed antenna with linearly displaced ring elements on the patch.

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The antenna gain is extensively increased from 3.6dB to 6.09dB when the individual inner ring elements of the SRR array are being shifted symmetrically from the center of the outer ring elements. The linear displacement of elements causes the current distribution much more aligned towards the edge and increases the resonance effect resulting in enhancement of total gain of antenna

IV. Measurement Set Up And Results

The patch antenna parameters like return loss, input impedance, reactance, gain and radiation pattern have been simulated in CST Microwave studio 2016. The simulated results are then validated with the antenna prototype. The corresponding experimental setup is shown in Figure 4.

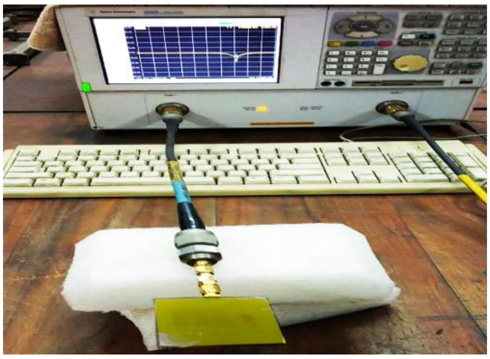

Fig.4. Experimental setup for antenna measurement

A. Comparison between simulated and measured results of Return Loss (S_{11})

B. Radiation Pattern Analysis

The radiation pattern of the proposed antenna is shown in Figure 6 on XZ and YZ plane for constant pi = 0 and 90 respectively.

C. Gain Enhancement due to Linear Displacement of Ring Element

The comparative gain analysis of simple patch, conventional SRR incorporated patch and SRR array with displaced ring elements is depicted in Figure 7. It shows an extensive impact on the antenna gain due to the ring element displacement phenomenon. The gain increases almost 70% as compared to that of conventional SRR array loaded antenna.

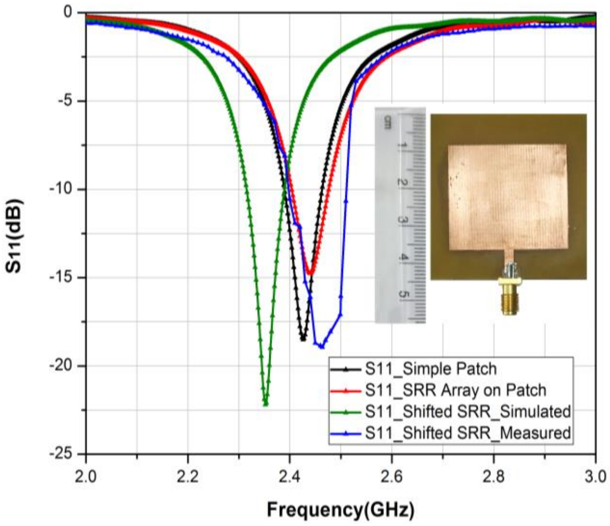

Fig.5. Return loss comparison

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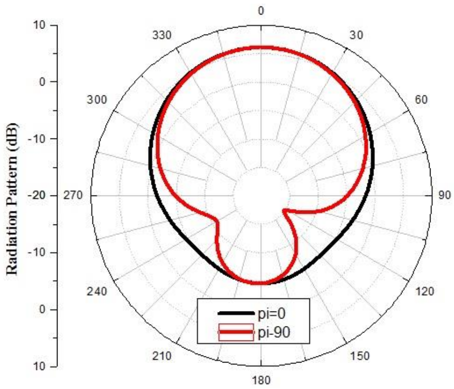

Fig.6. Radiation Pattern

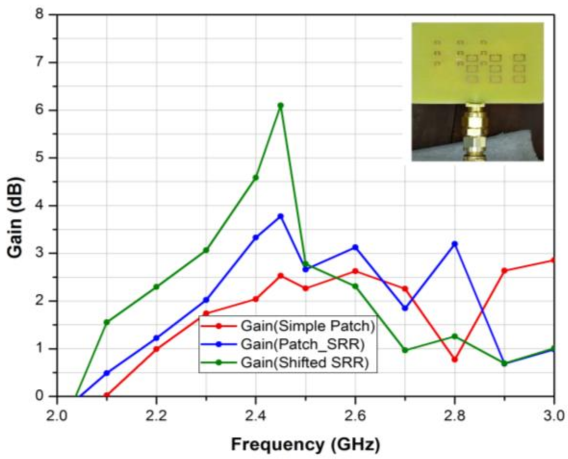

Fig.7. Comparative gain analysis

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TABLE.II. GAIN COMPARISON WITH EXISTING ANTENNA PROTOTYPES

Reference	Antenna Type	Dimension (mm^3)	Frequency (GHz)	Gain (dBi)
[5]	Planar with slot and ring	(0.317x0.317x 0.001) λ_0^3	2.43	2.0
[6]	Planar with shorting pin	(0.416x0.416x 0.02) λ_0^3	2.45	7
[12]	Planar with stub	(0.346x0.328x 0.013) λ_0^3	2.56	4.7
[13]	Planar with pair of diagonal slots	(0.29 x 0.29 x 0.013) λ_0^3	2.496	4.29
Proposed Prototype	**Planar with shifted SRR elements**	**(0.33 x 0.285x0.016) λ_0^3**	**2.45**	**6.09**

This work presents a unique solution for the conventional SRR loaded antenna which has some limitations in terms of gain. This can be overcome simply just displacing the square ring elements linearly over the patch. The reason behind the increment in antenna gain because of the shifting of ring element lies in the concept of current vector analysis. The SRR array itself behaves as secondary radiating element that adds the gain with the gain of primary radiating element patch thus enhancing the gain. Now since we change the position of inner elements of the array towards the edge, the current vectors become more aligned and cover the path in comparatively delayed time period and create much more resonance. Hence the gain increases up to 6.09 dB which is considered to be much better with the dimension taken for this design. From the comparative study as discussed in Table 2, it is observed that the antenna dimension becomes much more compact and exerts comparatively better gain than other designs operated in the similar frequency range.

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