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Design and Fabrication of a Miniaturized Microstrip Antenna Loaded by DNG Metamaterial

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Abstract**—**In this paper the design, fabrication, and testing of a miniaturized rectangular microstrip patch antenna loaded with DNG metamaterials is reported. The metamaterial is composed of two nested spiral strips and a single straight strip which are etched on two sides of a 5.7 mm×5.7 mm Rogers RT/duroid 5880 with 0.5 mm thickness and dielectric constant of 2.2. Two units of this structure as a double negative (DNG) medium in combination with air as a double positive (DPS) medium are used as substrate of the microstrip patch antenna. By placing these metamaterial structures under the patch, a sub-wavelength resonance occurs which leads to a smaller size patch antenna compared to the conventional antenna at that frequency. The total size of the proposed antenna is reduced 54.6%. The dimensions of the proposed patch antenna are significantly smaller than the wavelength of the operation frequency with respect to the conventional patch antenna. Simulation result and test result for the proposed patch antenna are given and compared.

Keywords**—**Antennas, Metamaterials, Microstrip Antennas, Miniaturization.

I. INTRODUCTION

MICROSTRIP antennas are one type antenna which are low profile, low weight, low cost, easy to fabricate and installation and integrable with other microwave devices [1]. Due to these advantages, microstrip antennas are used in mobile radio and wireless communication systems, radars, spacecraft, satellite, missile applications, etc. Recently the demand for compact radiators and small size antennas is continuously getting increased. Therefore, antenna miniaturization plays an important role in wireless communication systems.

Although microstrip antennas are of small thickness, their transverse dimension is in the order of half wavelength. Therefore, they are not small enough in their transverse dimension. By now, several different techniques have been proposed in order to reduce the size of the patch antenna e.g. making slots in the patch [2] or using shorting posts [3]. These methods are not able to miniaturize antennas to an acceptable extent for the mentioned applications.

Another technique that is used to reduce the size of the patch antenna is to place the patch on a high permittivity dielectric substrate [4]. Although this method well miniaturizes the antenna, it brings about some side effects. Using a substrate with a high dielectric constant increases the flow of surface waves, which results in the gain reduction and deterioration of the radiation efficiency. Also, the characteristic impedance in a high permittivity medium is rather low, so it causes difficulties in impedance matching. In order not to deal with these problems, nowadays, metamaterial structures are used for miniaturization of the antenna.

Metamaterials are artificial periodic structures that their electromagnetic properties do not exist in nature. The primary electromagnetic properties of metamaterials are determined from the unit cell which is much smaller than wavelength. The constitutive parameters of metamaterials such as permittivity (ε) and permeability (μ) are used to explain their electromagnetic properties.

Metamaterial with simultaneously negative permittivity and permeability which is called DNG[1] metamaterial was considered theoretically by Victor Veselago for the first time in 1968 [5]. In 1999, Pendry introduced SNG[2] structures which contained TW[3] and SRR[4] [6], [7]. The first DNG metamaterial was fabricated experimentally by Smith and his colleague in UCSD [8]. By now many other structures are designed and fabricated based on TWs and SRRs.

Employing metamaterials in microstrip antenna result in the improvement of the antenna parameters like bandwidth, gain, efficiency, etc. Additionally, it is possible to miniaturize the antenna as much as desired with these structures, without dealing with surface waves problems. To date, many different miniaturization techniques have been proposed, based on the use of metamaterials. Applications of DNG and SNG metamaterials have been widely studied by some research groups in miniaturization of sub-wavelength cavities [9], waveguides [10], and antennas [11]-[13]. In 2007, a new CSRR[5] structure was designed to miniaturize the microstrip patch antenna and results were compared with a high dielectric substrate [14]. In 2013, a novel DNG metamaterial structure was designed and used in patch antenna substrate which led to 50% size reduction [15]. Also, many other researches have been done on miniaturization of microstrip patch antenna [16]-[18].

In this paper, the possibility of miniaturization of rectangular microstrip patch antenna by placing a novel DNG metamaterial structure as the substrate is investigated. At first, the resonance structure of proposed metamaterial unit cell is analyzed. Then, the rectangular microstrip patch antenna which its substrate is composed of air as a DPS medium and two unit cells of proposed DNG metamaterial is analyzed and

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[1] Double-Negative
[2] Single-Negative
[3] Thin Wire
[4] Split Ring Resonator
[5] Complementary Split Ring Resonator

its return loss and radiation pattern are compared with the conventional patch antenna with the same dimension. The proposed antenna structure is fabricated and test results are compared with simulation results. By using proposed metamaterial structure in antenna substrate, a sub-wavelength resonance occurs. For this resonance frequency the dimensions of the proposed antenna would be smaller than the conventional patch antenna, so a miniaturization happens.

II. PATCH ANTENNA THEORY

Fig. 1 shows the configuration of a rectangular microstrip patch antenna which consists of a metallic patch placed on a substrate and a ground plane. Due to the fringing effect, parts of some electric field lines radiated from the patch exist in air. So an effective dielectric constant (ε_{reff}) is introduced which is defined by [1]:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{1}$$

where, h is the height of substrate, W is the width of the patch, and ε_r is the relative dielectric constant of the substrate.

The practical width of the patch is calculated using (2) [1]:

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2}$$

By considering fringing effect, the length of the patch is extended on each end by a distance ΔL. This parameter is determined by (3) [1]:

$$\frac{\Delta L}{h} = 0.412\frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \tag{3}$$

The effective length and actual length of the patch are calculated using (4) & (5) [1]:

$$L_{eff} = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\varepsilon_0\mu_0}} \tag{4}$$

$$L = L_{eff} - 2\Delta L \tag{5}$$

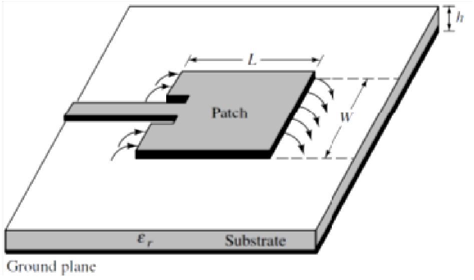


Fig. 1 Configuration of a rectangular microstrip patch antenna and the fringing effect

III. METAMATERIAL AND ANTENNA DESIGN

A. Metamaterial Unit cell Structure

The configuration of the metamaterial unit cell structure is shown in Fig. 2. As it is seen from the figure, this unit cell is composed of two nested spiral strips and a single straight strip which are etched on the two sides of a dielectric substrate. The substrate is Rogers RT/duroid 5880 with dielectric constant of 2.2. The dimensions of the substrate, $L_s \times W_s$, are 5.7 mm×5.7 mm and the thickness, t, is 0.5 mm. The straight and spiral strips are made of copper with 0.02mm thickness. Each spiral strip has three turns. The width of the straight strip, w, and the width of the spiral strip, l, are 0.3 mm. the distance between the spiral strips, s, is set to 0.1 mm.

To analyze the metamaterial unit cell structure, it is embedded in the middle of a TEM waveguide, which has proper magnetic and electric boundary conditions on walls. By applying boundary conditions, a current will be induced in the spiral structure, which produces an inductor and stores energy in the unit cell. This inductor in combination with the capacitors which are produced within the spiral strips, constitute a resonance structure. The resonant frequency of this structure depends on the number of spiral turns, the width of the spiral strips and the distance between strips. By changing the metamaterial structural parameters, different resonant frequencies and antenna miniaturization rate can be achieved.

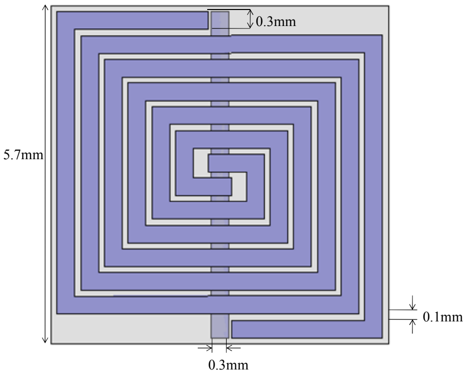


Fig. 2 Metamaterial unit cell structure and its dimensions
$L_s = W_s$ =5.7 mm, $w = l$ =0.3 mm, s =0.1 mm

The simulation results for return loss and relative constitutive parameters of the unit cell, including permittivity and permeability, are shown in Figs. 3 and 4 respectively. All the simulations were done using Ansoft HFSS software. The constitutive parameters are calculated from S-parameters by using retrieval method introduced in [19]. As it is seen in Fig. 4, both of the permittivity and permeability are negative in a specific frequency band (2.5-2.6 GHz). So this structure shows double negative property and it is considered as a DNG medium.

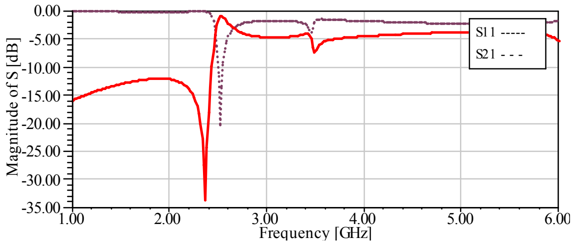
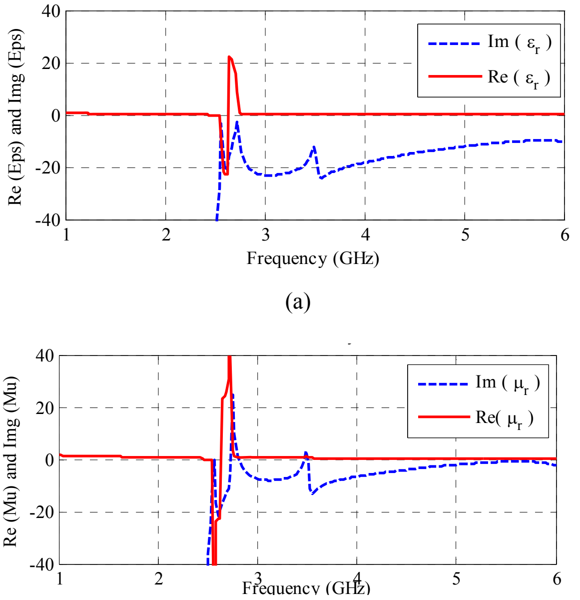


Fig. 3 Magnitude of S-parameters



(a)

(b)

Fig. 4 Metamaterial constitutive parameters (a) permittivity (b) permeability

B. Antenna Design

The configuration of the microstrip patch antenna which is loaded with two proposed metamaterial structures is shown in Fig. 5.

By knowing the resonant frequency of the antenna, f_r, relative dielectric constant, ε_r, and the height of the substrate, h, the patch dimensions can be calculated using (1) to (5). This antenna is designed for the operation frequency of 5.5 GHz, so the dimensions of the patch, $L_p \times W_p$, are 20 mm×22 mm. The ground dimensions are calculated from (6) and (7):

$$L_g = 6h + L_p \tag{6}$$

$$W_g = 6h + W_p \tag{7}$$

The height of the substrate is considered 5.7 mm in order to place the unit cells under the patch. By using (6) and (7), the ground length, L_g, and width, W_g, are determined 54.2 mm and 56.4 mm respectively.

The location of the two unit cells under the patch is shown in Fig. 6. The antenna is fed by a 50 Ω coaxial probe. The location of the coaxial probe is set in order to have the best impedance matching and minimum return loss. As it is shown in Fig. 6, the probe is located close to the patch edge and is in the distance of 0.7 mm from it.

The substrate is inhomogeneous which is composed of two materials; air as an isotropic material, and the metamaterials as homogeneous materials. The resonant frequency of the conventional patch antenna differs from the resonant frequency of loaded patch antenna with metamaterial unit cells and depends on the constitutive parameters of the metamaterial [11]. The antenna resonates at the frequency where the constitutive parameters of the metamaterial, permittivity and permeability, are negative simultaneously.

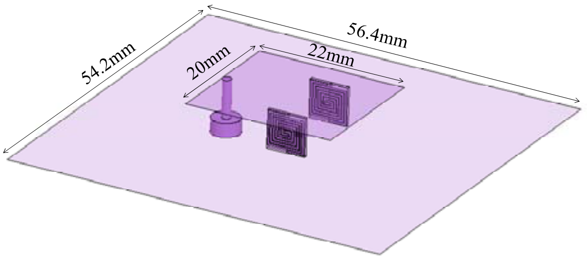


Fig. 5 The patch antenna structure in the presence of metamaterials W_g =56.4 mm, L_g =54.2 mm, W_p =22 mm, L_p =20 mm

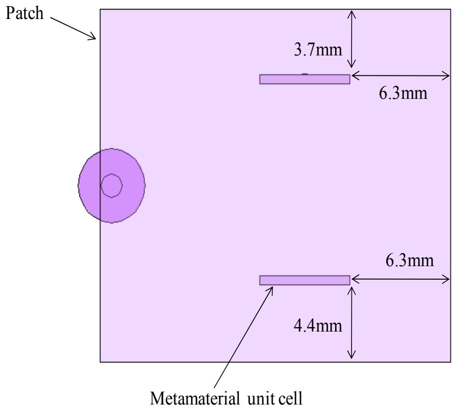


Fig. 6 The top view of the proposed antenna

IV. SIMULATION RESULTS AND COMPARISON

Simulation result for return loss of the proposed antenna is shown in Fig. 7. As it can be seen, this structure has two different resonant frequencies. The first is related to the presence of metamaterial and occurs where the permittivity and permeability are negative, and the second is for the conventional patch antenna. By incorporating metamaterial, the resonant frequency of the antenna decreases from 5.5 GHz to 2.52 GHz. By reducing the resonant frequency of the antenna, miniaturization happens, because the dimensions of the proposed patch antenna which resonates at 2.52 GHz is smaller than the conventional patch antenna which operates at the same frequency - the lower the frequency, the bigger the size of the antenna. This phenomenon is described by the excitation of a compact resonance at the interface between air as a conventional dielectric and a DNG material. The dimensions of the proposed patch antenna are as small as

0.183λ×0.166λ which is equivalent to 54.6% size reduction. This significant miniaturization is achieved using only two unit cells, which is remarkable compared to similar works.

Since these metamaterial structures are naturally narrowband, the bandwidth of the proposed antenna is smaller than the conventional antenna. The -10dB return loss bandwidth of the proposed antenna, which is standard definition for antenna engineering applications, is 1%, while the bandwidth of the conventional antenna is 9.6%.

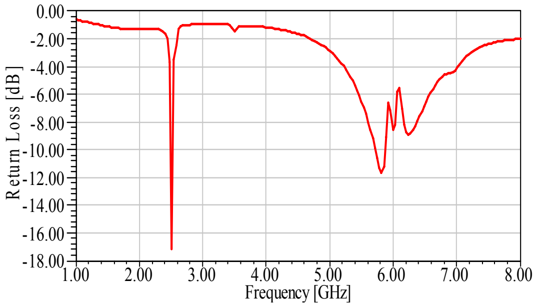
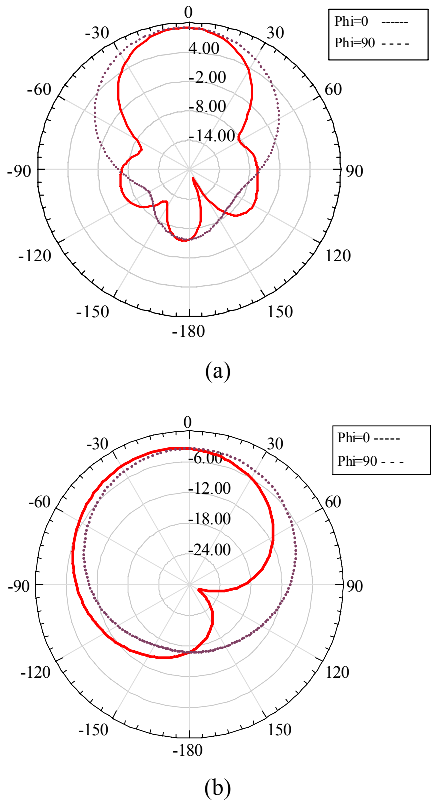


Fig. 7 Return Loss of the proposed patch antenna

The radiation pattern for the conventional antenna at 5.5 GHz and proposed patch antenna at 2.52 GHz are shown in Figs. 8 (a) and (b) respectively. Using these structures leads to change in the direction of radiation. As it is seen in Fig. 8 (b) radiation pattern has been wider due to lossy structure of metamaterials.



(a)

(b)

Fig. 8 The radiation pattern (a) conventional antenna at 5.5 GHz (b) proposed antenna at 2.52 GHz

The comparison between the resonant frequency and dimensions of the conventional antenna and proposed antenna is indicated in Table I.

TABLE I
COMPARISON OF TWO ANTENNAS

Options	Resonant Frequency (GHz)	Patch dimensions
Conventional antenna	5.5	0.404 λ×0.367 λ
Proposed antenna	2.52	0.183 λ×0.166 λ

V. FABRICATION OF THE ANTENNA AND TEST RESULTS

After achieving proper simulation results, the proposed antenna is fabricated and tested in lab. The picture of the fabricated antenna is shown in Fig. 9.

Measured result of the return loss of the fabricated antenna is shown in Fig. 10. Comparing Figs. 10 and 7, it is obvious that the simulation result is in good agreement with experimental results. The fabricated antenna resonates at two frequencies; the first is the frequency where the metamaterial constitutive parameters are negative and the second is the frequency of the conventional antenna.

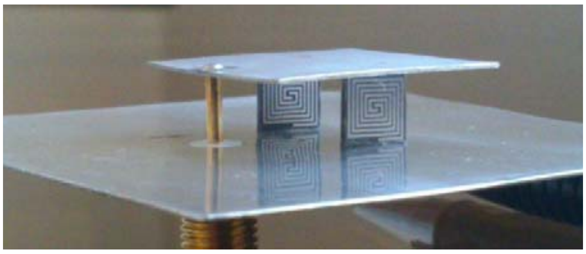


Fig. 9 Fabricated antenna

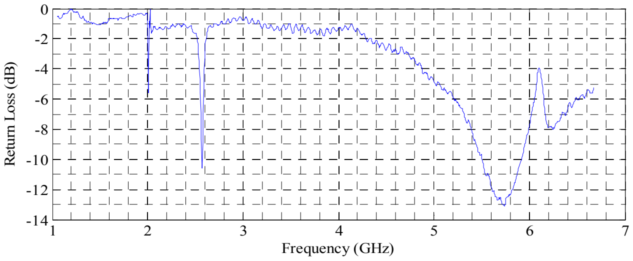


Fig. 10 Measured return loss of the fabricated antenna

VI. CONCLUSION

A miniaturized rectangular microstrip patch antenna loaded with two DNG metamaterial unit cells was designed and fabricated. The overall size of the proposed antenna is reduced by about 54.6%. The antenna in the presence of the metamaterials resonates at the frequency which is lower than the resonance frequency of the conventional antenna. This lower frequency is where the metamaterial constitutive parameters, permittivity and permeability, are negative. This phenomenon is due to the excitation of a compact resonance at the interface of metamaterial unit cell and air. The location of the operating frequency is tuned effectively by resonance structure of the metamaterial; therefore a sub-wavelength resonance was produced with the help of metamaterials.

However, as a result of this miniaturization, the sub-wavelength mode of the rectangular patch antenna is narrow in bandwidth.

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