Miniaturization of Rectangular Patch Antennas Partially Loaded With \(\mu\)-Negative Metamaterials


Abstract—A miniaturized rectangular patch antenna partially loaded by just three metamaterial unit cells, which operate as \(\mu\)-negative metamaterials (MNG), is proposed. The length \((L_P)\) and width \((W_P)\) of the proposed patch antenna are 20 mm and 15 mm, respectively. Achieved results of return loss and radiation pattern from the full-wave numerical simulation of the miniaturized antenna at the sub-wavelength resonance, which considered a finite ground plane, realistic feed and the influence of metamaterial loss, are compared to the parameters of the patch antenna at the conventional resonance frequency, which is about 6.35 GHz. The antenna shows a sub-wavelength resonance at 1.73 GHz. The total size of the radiator patch is considerably smaller than the wavelength of operation frequency, which brings about a 77% size reduction by a miniaturization factor on the order of 4.35.

Keywords—Miniaturized antennas, metamaterials, patch antennas, resonant spirals.

I. INTRODUCTION

Nowadays rectangular patch antennas have found extensive application in wireless communication systems. The demand in commercial and military wireless systems is due to their capabilities such as low weight, low profile, low cost, easily combined with design and technology, and relatively simple fabrication. Antenna miniaturization is extremely important for modern wireless communication systems, low power capability and compactness are two highly desirable features of any wireless systems.

Even though such antennas are very thin compared to the operating wavelength \((0.05-0.01\lambda)\), in their cross section, but, their transverse dimensions cannot be made arbitrarily small, its linear transverse dimension is of the order of half-wavelength. Many techniques are proposed over the years to compact the dimensions of microstrip antennas, such as using shorting posts [1], reactive loading of a patch antenna with suitably designed slots, shorting walls, and lumped elements.

These standard techniques however do not usually miniaturize the patch dimension significantly that needed for applications which was mentioned previously [2] and [3]. Another possibility to miniaturize the patch size is the employment of typically high permittivity dielectrics as substrate. Conventional microstrip patch antennas can be easily miniaturized by increasing the electric permittivity. However, their employment raises some problems, such as, difficulty in impedance matching or increasing of surface waves in the substrate that could decline the radiation efficiency and the radiation pattern. Bandwidth of the antenna maybe considerably becomes worse [4].

The standard techniques mentioned before, do not represent adequate tools to miniaturize patch antenna dimensions significantly. For this reason the use of metamaterials as antenna artificial substrates is studied as an alternative method to significantly miniaturize patch antennas. To date, many alternative techniques have been proposed, based on the use of artificially engineered materials. Metamaterials have been used for the patch antenna substrate to substantial achievements for the purposes of size reduction. Applications of double negative (DNG) and single negative (SNG) metamaterials have been widely studied by some research groups in miniaturization of sub-wavelength cavities [5], waveguides [6] and antennas [7]–[9]. In [10], magnetic metamaterials have been employed as substrate to raise both the effective permeability and permittivity. Although the patch size had reduced considerably, but their rectangular patch antenna shows low gain while being very heavy and complicated as far as fabrication is involved.

Another study have shown that conventional substrate materials partially loaded by SNG metamaterials can be employed for rectangular microstrip antennas to support a sub-wavelength resonance radiating mode, in which a filling ratio factor, rather than the total volume, determines their resonance frequency [11]. According to this idea, the performance of circular patch antennas with MNG metamaterial loading has been investigated in [12]. Miniaturization of rectangular and circular patch antennas with spiral resonators (SRs) loading are investigated experimentally in [10] and [13], respectively. The dimensions of the proposed antennas in [10] and [13] are reduced significantly at the cost of radiation gain.

In this paper, we explore possibility of miniaturization of
the conventional rectangular microstrip antennas by using a substrate consists of air as DPS material and three unit cells as MNG metamaterials. Using the proposed antenna design, lead to a miniaturized patch antenna with radiation patch dimension as small as $0.115\lambda \times 0.085\lambda$. However, the sub-wavelength mode of the rectangular patch antenna is narrow in bandwidth and is difficult to be matched.

II. METAMATERIAL UNIT CELL STRUCTURE

The metamaterial unit cell used to loading the patch antenna in this paper is based on the embedded circuit (EC) metamaterial described in [14]. This metamaterial unit cell of a typical periodic structure composed of an inductive spiral loop and a strip, which are etched on a host dielectric substrate, located at the middle of a TEM waveguide, which has proper magnetic and electric boundary conditions on walls, is shown in Fig. 1. A electric field parallel to the metallic strip and a magnetic field perpendicular to the plane of the spiral, induces a current in the loop, a phenomenon that effectively creates an inductance within the substrate and creates magnetic energy storage in the unit cell. This "induced" inductance along with the capacitance in the structure, forms a resonant structure.

The metamaterial unit cell substrate has a cell size of $d_x = 7 \text{ mm}$, $d_y = 0.7 \text{ mm}$ and $d_z = 7 \text{ mm}$. The spiral resonator and strip are from 0.05 mm thick (t) copper and printed on a 0.7 mm thick Rogers TMM 4 dielectric with $\varepsilon_r = 4.5$ with a line width ($l$) of 0.728 mm, strip width ($w$) of 1.456 mm and spacing ($s$) of 0.28 mm. The corresponding dimensions of the unit cell are shown in Fig. 2. The resonance frequency of this structure can be controlled by tuning the spiral, strip and substrate dimensions. By increasing the number of turns and line width or by decreasing the spacing between adjacent turns, metamaterial resonant frequency declines. Hence, by tuning of metamaterial, antennas with different miniaturization factors can be designed. The unit cell was modeled and simulated in the Ansoft HFSS so as to resonate approximately at 1.75 GHz.

The effective constitutive parameters of the unit cell ($\varepsilon_r$, $\mu_r$) have been calculated by S-parameters according to a retrieval method introduced in [15] extracted and real part of them are shown in Fig. 3. As can be seen in Fig. 3, this structure can exhibit negative permeability. For the unit cell shown in Fig. 3, this leads to a resonant frequency at 1.75 GHz, which is close to the TM$_{010}$ resonant frequency of the miniaturized patch antenna.

III. ANTENNA DESIGN PROCEDURE

In Fig. 4, the configuration of the rectangular patch antenna partially loaded with three metamaterial unit cells is depicted. The axes of the unit cells are parallel to the magnetic field vector under the patch to support the MNG behavior. It consists of a copper radiation patch with transverse dimensions $L_p \times W_p$ placed over a copper ground plane with transverse dimensions $(L_G \times W_G)$. For the antenna radiation patch geometry, $L_p = 20 \text{ mm}$, $W_p = 15 \text{ mm}$ for the ground plane, $L_G = 45 \text{ mm}$, $W_G = 40 \text{ mm}$ and the height of the substrate (h) is 7 mm. The antenna is fed by a 50Ω coaxial probe which is placed close to the patch edge. The underneath substrate is inhomogeneous, filled with two isotropic (air) and homogeneous materials (metamaterials).

The resonant frequency of the miniaturized patch antenna depicted in Fig. 4 depends on the metamaterial constitutive parameters [7]. This happens when the real part of effective permeability yields negative values. In the proposed miniaturized antenna, it is shown how partially loading a conventional rectangular patch antenna’s substrate with a MNG metamaterial, it is possible to excite a sub-wavelength resonant mode on the patch, even though its dimensions are considerably smaller than the operating wavelength. The physical phenomenon supporting this possibility for miniaturizing the size of patch antennas is represented by the excitation of a compact resonance at the interface between a conventional dielectric (air) and an MNG material [12].

![Fig. 1 The metamaterial unit cell structure. The spiral loop resonator responds magnetically and the strip responds electrically to electromagnetic fields](image1)

![Fig. 2 The unit cell dimensions and parameters: $d_x = 7 \text{ mm}$, $d_y = 0.7 \text{ mm}$, $d_z = 7 \text{ mm}$, $l = 0.728 \text{ mm}$, $s = 0.28 \text{ mm}$, $w = 1.456 \text{ mm}$, $\varepsilon_r = 4.5$, $t = 0.05 \text{ mm}$](image2)
IV. SIMULATION RESULTS AND COMPARISONS

Fig. 5 shows the simulation result of return loss for the proposed patch antenna using Ansoft HFSS. It resonates at frequency about 1.73 GHz. Metamaterial unit cells behave as regular dielectrics at frequencies far from their resonant frequencies, the patch higher resonance occurs at about 6.35 GHz which is equal to the conventional resonance of patch antenna with same dimensions. The miniaturized antenna’s frequency is close to the calculated resonant frequency of unit cell which was about 1.75 GHz. Consequently miniaturization percentage is about 77% for the proposed antenna by a miniaturization factor on the order of 4.35. The bandwidth decreases at sub-wavelength resonances, because of narrowband nature of these metamaterials. For the proposed antenna, the -10dB return loss bandwidth, which is standard define for antenna engineering applications, is about 0.7%.

The radiation pattern of the patch antenna at sub-wavelength resonance and conventional resonance frequencies of the antenna (1.73, and 6.35 GHz) are depicted in Fig. 6. The antenna gain at 1.73 and 6.35 GHz are -3.7 and 7.8 dB, respectively. The results show a significant decline in the radiation gain with a reduction in antenna size. Therefore, there is a tradeoff between size reduction and gain enhancement in the antenna design process. However, the antenna radiation gain can be improved by optimization of the unit cell parameters and their position under the radiation patch. In Table I, the performance of the patch antenna proposed in this paper is compared to that miniaturized patch antenna whose substrate is loaded by MNG metamaterial [10].

For a conventional microstrip antenna, patch size is about 0.5λ sub, where λ sub is the wavelength within the antenna substrate at the resonance frequency.

![Fig. 4 The patch antenna over air and metamaterial substrate (a) 3-D view (b) Side view (c) Front view](image)

![Fig. 5 Return loss of the simulated antenna](image)

V. CONCLUSION

A rectangular microstrip antenna was designed and simulated to investigate the application and drawbacks of metamaterial as a patch substrate for antenna miniaturization. Miniaturization factor on the order of 4.35 was achieved through this technique. It was shown that it is possible to reduce patch antenna size to 77% with use of a few unit cells and without using any dielectric in substrate. It is considered that a wide range of applications will be advantageous from metamaterials in the microwave regime.
Fig. 6 Radiation pattern for (a) The antenna at 1.73 GHz  
(b) The antenna at 6.35 GHz

REFERENCES


