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Gain Enhancement of Planar Dipole Antenna Using Grounded Metamaterial

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Abstract—In this paper, a simple approach for enhancing the gain of a planar dipole antenna using the concept of grounded metamaterial (MTM) has been proposed. In this regard, a magnetic metamaterial with Mu-very large (MVL) property has been placed over the ground plane of the antenna to increase the gain of the electric dipole source. A fully planar structure has been configured due to the placement of the metamaterial just over the ground plane. A significant amount of gain improvement of about 3.7 dB for the dipole has been attained using the metamaterial. In addition, increase of fractional bandwidth by 2.2% has been obtained due to the loading of the metamaterial. A comparative study with respect to recently reported literature for the gain enhancement of planar dipole has also been discussed. The proposed antenna is a worthy candidate for wireless communication owing to the high gain, low profile, and wide bandwidth characteristics.

1. INTRODUCTION

For the last few decades, planar antennas have been widely used in the field of wireless communication due to small size, ease of fabrication, low cost, and their potential for high efficiency operation. Usually, small antennas suffer from low gain and efficiency. For improving performances of a small antenna, earlier trends were to use high dielectric superstrate, partially reflective surfaces (PRS), photonic band gap (PBG) resonator, magnetodielectic material, etc.

Nowadays, many researchers are interested in various applications of artificial material, i.e., metamaterial due to its unusual behavior like left-handed characteristics such as negative values of permittivity (ε) and permeability (μ). In the literature, metamaterials are used for controlling various antenna performances like miniaturization [1, 2], wideband characteristics [3], ultra wideband with dual notches [4], compactness, and wide bandwidth [5, 6]. Metamaterial has also been used for gain enhancement of a small antenna which was first theoretically reported by Ziolkowski and Kipple [7]. After that, different properties of metamaterial like low refractive index [8], zero refractive index [9], and high refractive index [10] have been used by the researchers to enhance the antenna gain. Apart from metamaterial, gain or directivity of the antenna has also been increased using different superstrates like electromagnetic band gap (EBG), frequency selective surfaces (FSS), etc. [11–14]. In [13], a detailed comparison among three different superstrates of FSS, dielectric slab, and double-negative metamaterial slab has been rigorously studied. In spite of the considerable amount of gain enhancement, the overall configurations of superstrates based structures are very bulky. Therefore, these types of configurations are not suitable for different planar antenna applications.

To overcome this problem, now the researchers tend towards the grounded metamaterial concept so that the overall antenna becomes more planar and compact. This concept was first theoretically developed by Lovat et al. for electric as well as magnetic dipole source in [15, 16] where the

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gain/directivity enhancement was achieved through mu-near-zero (MNZ) material and/or an epsilon-very-large (EVL) material for a magnetic dipole source and epsilon-near-zero (ENZ) and/or a mu-very-large (MVL) material for an electric dipole source, respectively. Recently, according to the concept, the directivity of a magnetic dipole, i.e., slot antenna has been successfully enhanced using an EVL based metamaterial structure in [17, 18]. It is known that EVL characteristic could be achieved from the electric resonance of an electric inductive capacitive (ELC) resonator type metamaterial structure [19].

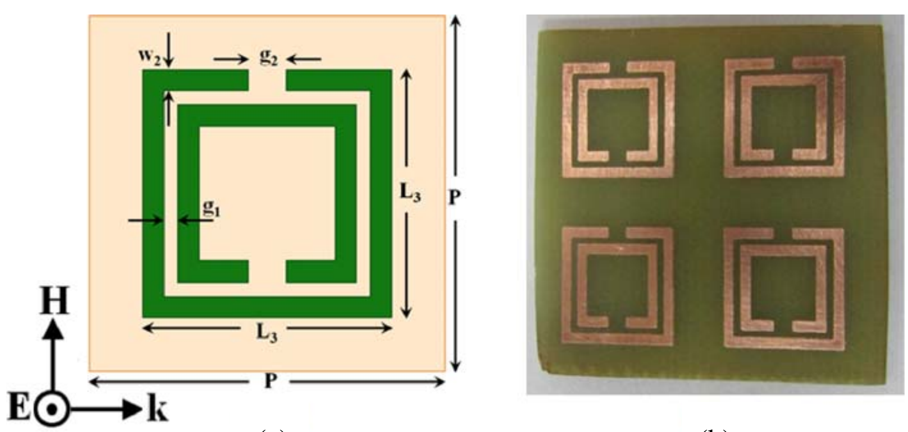
In this paper, a grounded metamaterial slab with MVL property is effectively used to enhance the gain of a planar dipole source. For designing the metamaterial slab, a split ring resonator (SRR) has been chosen as unit cell because, in general, SRR offers magnetic resonance features with MVL property. The metamaterial slab has been designed by 2×2 arrays of the unit cell. The MTM slab has been placed here just over the ground plane of the dipole. Therefore, a fully planar configuration has been developed. Gain enhancement of 3.7 dB has been achieved for the proposed antenna. In addition to gain enhancement, the proposed design exhibits better fractional bandwidth than the unloaded antenna. The effects of metamaterial slab on antenna gain, efficiency, and bandwidth over the whole working band are investigated.

2. ANALYSIS OF THE DIPOLE ANTENNA LOADED WITH METAMATERIAL

An array of 2×2 unit cells is printed on a dielectric substrate FR4 Epoxy having dielectric constant 4.4 and thickness 0.8 mm to realize the metamaterial slab. The unit cell structure is a simple split ring resonator with the outer loop size of 10.5 mm × 10.5 mm. The split gap (g_2) and the gap between two slots (g_1) are 1.6 mm and 1.2 mm, respectively. Width of each loop is 1.8 mm. The optimized dimensions of the SRR unit cell for achieving MVL property are provided in Table 1. Figure 1 depicts the schematic topology of the unit cell and the fabricated prototype of the 2×2 arrays of the unit cell.

Table 1. Dimensions of the unit cell of the metamaterial.

P (mm)	L_3 (mm)	w_2 (mm)	g_1 (mm)	g_2 (mm)
15	10.5	1.8	1.2	1.6



(a) (b)

Figure 1. Split ring resonator structure. (a) Schematic topology of the unit cell. (b) Fabricated prototype of 2×2 arrays of the unit cell.

The metamaterial slab has been effectively designed to enhance the gain of the planar dipole. In this regard, the following equation for enhancement of the broadside power density of electric dipole is obtained from [16]:

$$P_J(0) = \frac{k_0^2 \eta_0}{8\pi^2} \eta_r^2 \tag{1}$$

where,

$$\eta_r = \sqrt{\mu_r/\varepsilon_r} \tag{2}$$

$P_J(0)$ is the broadside angular power density; η_r is the intrinsic impedance; μ_r and ε_r are permeability and permittivity of the metamaterial. It has been clearly stated that the gain/directivity of an electric dipole source is enhanced using the grounded metamaterial with the ENZ and/or MVL property. From Equation (2) it can be observed that the value of the normalized intrinsic impedance (η_r) can be increased either by increasing the value of μ_r or decreasing the value of ε_r. Moreover, from Equation (1), it is clear that the value of broadside power density will be increased with the value of η_r. Hence overall directivity will be increased either using an MVL or an ENZ material. Here the MTM slab with MVL property acts as an artificial dielectric to increase the space field, and thus the effective radiated power density has been enhanced.

The details described in [20] have been followed for extracting effective medium parameters of the unit cell. The extracted effective permeability of the metamaterial has been presented in Figure 2. It has been observed from the figure that the magnitude of the real part of the permeability is more than 10 which is the condition for showing MVL property described in [16] in the range of frequency from 4.57 GHz to 4.83 GHz.

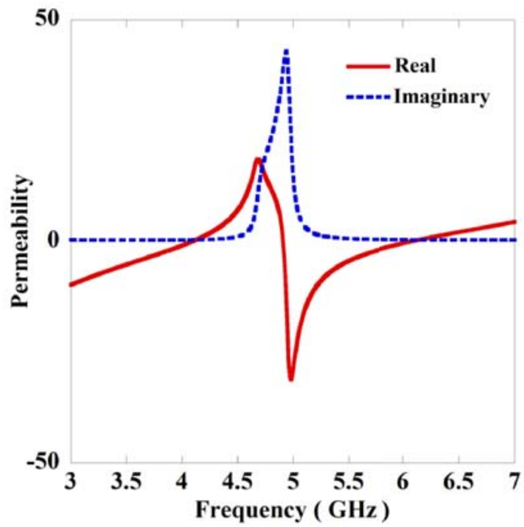


Figure 2. Retrieved effective permeability of the unit cell of SRR.

Both the front and back views of the schematic topology and fabricated prototype of the loaded antenna are shown in Figure 3. The dimensions of the planar dipole are optimized to operate at near 4.75 GHz. The optimized dimensions for the unloaded dipole antenna are provided in Table 2. The MTM slab is placed just over the antenna as shown in Figure 3. The overall proposed structure is simulated using high frequency structure simulator (HFSS 19.0).

Table 2. Dimensions of the proposed antenna.

L (mm)	**L_1 (mm)**	**L_2 (mm)**	**L_4 (mm)**	**w_1 (mm)**	**w_g (mm)**
70	36	12	11	2	25

3. RESULTS AND ANALYSIS

The return loss characteristics of the planar dipole antenna with and without loading the metamaterial are shown in Figure 4. A single resonance with good impedance matching at the frequency 4.75 GHz

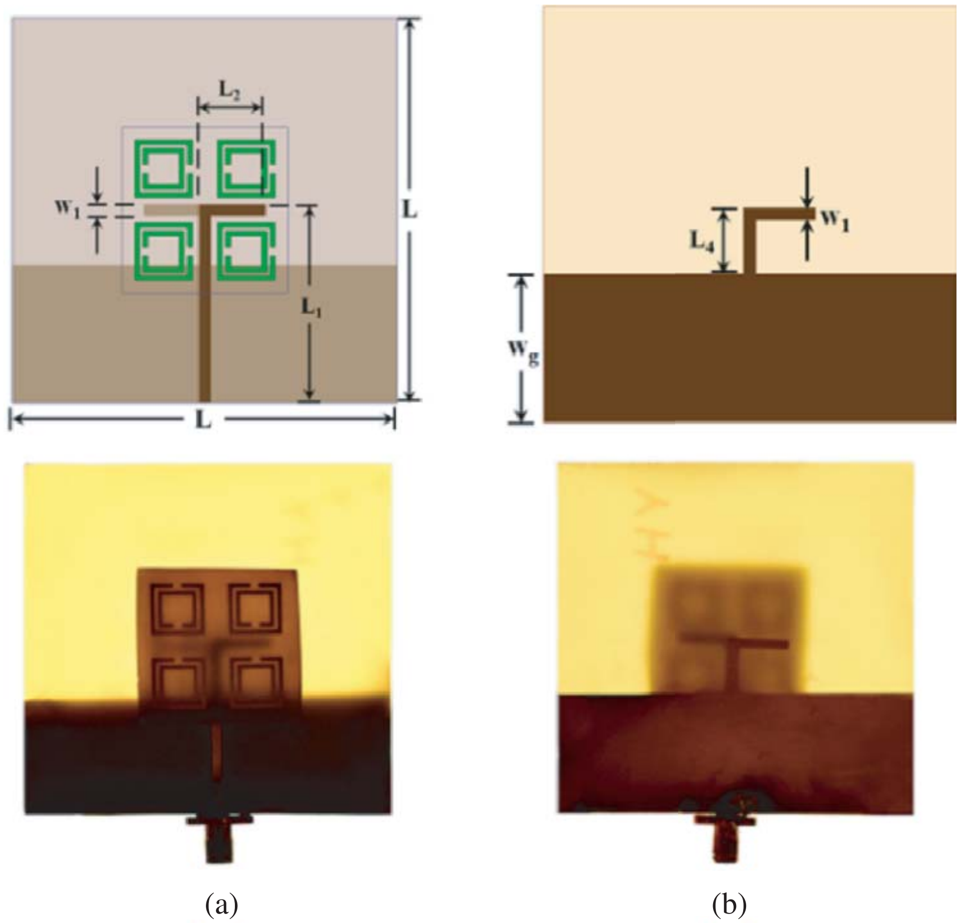


Figure 3. Schematic topology and fabricated prototype of the loaded antenna. (a) Front view. (b) Back view.

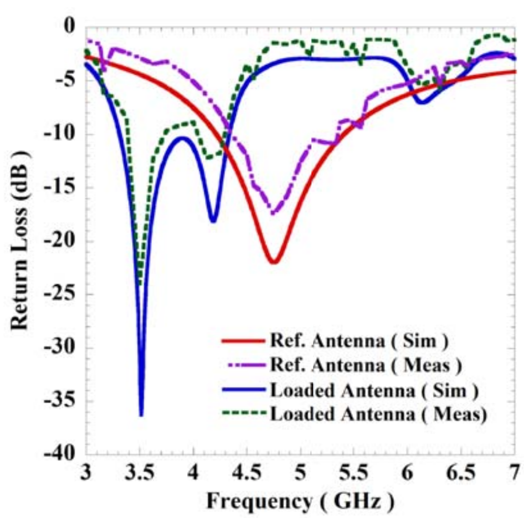


Figure 4. Simulated and measured return loss characteristics for the metamaterial loaded and the reference dipole planar antenna.

is observed for the unloaded antenna. However, at 3.52 and 4.2 GHz two resonance frequencies are observed for the loaded antenna. Hence more than 2% improved fractional bandwidth is observed for loaded antenna with respect to reference antenna.

The gain performance and efficiency over the operating band are also investigated. In Figure 5, the gain is plotted with respect to the overall working frequency band for the antenna with and without metamaterial. A significant amount of gain enhancement is observed with respect to the reference antenna over the band. Efficiency of the loaded antenna is also enhanced throughout the operating frequency band with respect to the reference antenna.

The radiation patterns are measured at the frequency where maximum gain is found from Figure 5. The E and H plane radiation patterns for both loaded and unloaded antennas are shown in Figure 6.

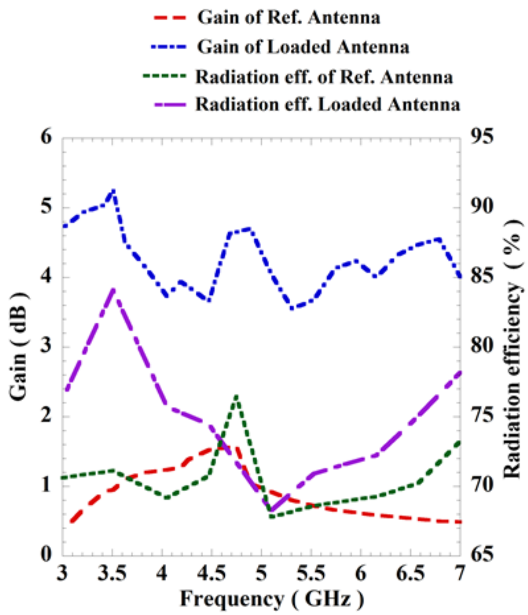


Figure 5. Measured gain and efficiency vs. frequency plot of MTM loaded dipole w.r.t reference dipole.

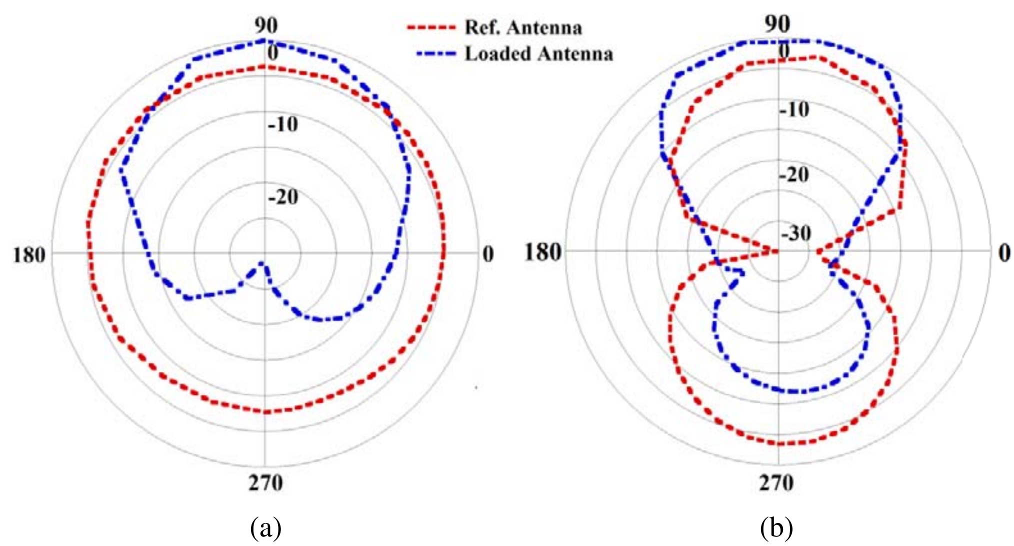


Figure 6. Normalized measured **r**adiation pattern of MTM loaded dipole w.r.t reference dipole (a) E-plane and (b) H-plane.

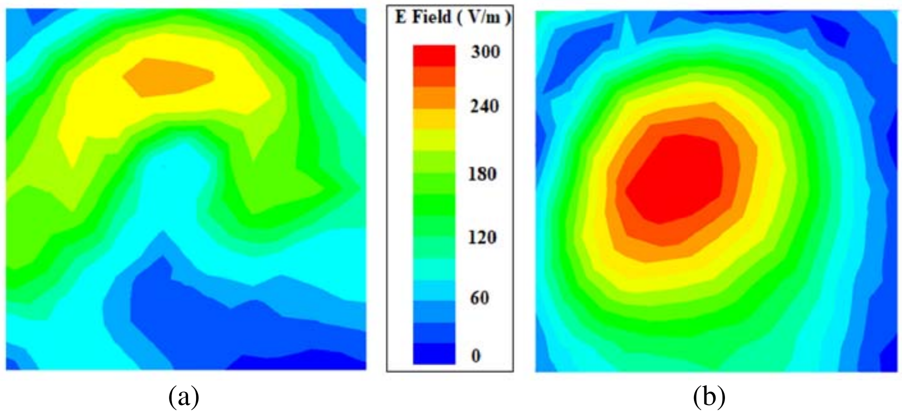


Figure 7. Simulated electric field distribution at the respective resonance frequency. (a) Reference antenna. (b) Metamaterial loaded antenna.

Comparing the radiation patterns with and without metamaterial, the gain enhancement is observed for the loaded antenna. It is also observed from the H plane radiation pattern that the dipole antenna is more directive when the metamaterial slab is placed just over the dipole.

To understand the effect of the metamaterial over the reference dipole, the electric field distributions at the respective resonance frequency of the reference and loaded antennas are shown in Figure 7. It is observed that the fields are concentrated due to the presence of the metamaterial.

Comparison of the performances of different gain enhancement techniques for planar dipole antenna is studied in Table 3. It is observed that the gain improvement of the proposed antenna is more than [22, 23]. The proposed antenna configuration is laterally smaller than that in [21, 22], whereas it is vertically smaller than that in [21, 23].

Table 3. A comparative study of different gain enhancement techniques for planar dipole antenna.

Parameters	Ref. [21]	Ref. [22]	Ref. [23]	Proposed work
Centre frequency (GHz)	28	2.2	11	3.52
Lateral antenna size	$1.68\lambda_0 \times 1.12\lambda_0$	$1.1\lambda_0 \times 0.632\lambda_0$	$0.56\lambda_0 \times 0.42\lambda_0$	$0.82\lambda_0 \times 0.82\lambda_0$
Vertical antenna size	$0.024\lambda_0$	$0.012\lambda_0$	$0.388\lambda_0$	$0.019\lambda_0$
Improvement of Gain (dB)	5	2	1.06	3.69
Technique used	High refractive index property of metamaterial loading	Parasitic effect for multiple Directors loading	ENZ property of metamaterial loading	MVL property of metamaterial loading

4. CONCLUSION

In this paper, MVL property based magnetic material is used to enhance the gain of a planar dipole antenna. Due to common use of the ground plane by metamaterial and antenna, the fully planar design has been configured. About 3.7 dB gain enhancement at the resonance is observed by using this concept. The overall configuration of the proposed design is very compact and planar than the earlier reported superstrates based structures. A significant amount of gain enhancement is also observed over the whole operating frequency band. Moreover, the proposed structure offers reasonable radiation efficiency throughout the operating region. Due to high gain and compact nature of the structure, the proposed design can be applied to various application of wireless communication in near future.

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