Metamaterial Loaded Compact Multiband Monopole Antenna for Wireless Applications

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***Abstract* –** This paper proposes the design of a compact monopole antenna loaded with metamaterial (MTM), for multiband operation for wireless local area network (WLAN) and Worldwide Interoperability for Microwave Access (WiMAX) applications. The monopole antenna is originally designed to operate in 2.8 GHz and 6 GHz The placement of MTM yields one additional band at 3.5 GHz corresponding to WiMAX with a shift in frequency of the original monopole to the WLAN frequencies of 2.4 GHz and 5.5 GHz with improved matching at the higher band. Dependencies of resonant frequencies on various parameters are formulated through regression analysis and a design equation for the proposed antenna is developed. The full-wave simulation and design equation of the three resonances show a negligible difference. A comparative study of the developed monopole with reported antennas shows that the developed structure is compact with an overall dimension of 19 x 31 mm^2. The measured results of the antenna show good impedance bandwidth of 6.25%, 24.57%, and 16.54% for the three bands centered at 2.4, 3.5, and 5.5 GHz The antenna compactness is obtained due to metamaterial loading. All the simulated radiation characteristics of the proposed antenna are validated experimentally. The proposed antenna obtains a compact electrical size of 0.248x0.152 λ_{0^2} at 2.4 GHz with multi-band operations at frequencies 2.4 GHz, 3.5 GHz, and 5.5 GHz corresponding to WLAN and WiMAX**.**

***Index Terms* –** Double negative material (DNG), metamaterial (MTM), monopole antenna, multiband antenna, WLAN, WiMAX.

I. INTRODUCTION

Multiband operation using a single antenna system is the basic need of modern wireless communication. Multiband antennas operating for wireless local area network (WLAN) and Worldwide Interoperability for Microwave Access (WiMAX) applications are one solution to the above problem. Several methods such as alteration of the ground plane, cutting slots on radiating patches, fractal antenna design, and use of metamaterial (MTM) structures have been suggested and explained for the design and development of multiband antennas [1–25] that could meet the requirements of modern wireless communication systems to a certain extent. System compactness and interference minimization can be achieved by using multiband antennas over ultra wideband antennas (UWB).

The era of multi-band operation developed through defected ground structure [1–2], providing multiple slots on radiator or ground [3–6], by the addition of metal strips [7–8], and also by adding strips and slots [9–12]. A rectangular patch antenna is made electrically small by engineering the patches of square and circular shape cuts [13]. By etching a rectangular slot in the ground plane and adding a fork-shaped strip in a modified rectangular ring, the antenna produced three resonant modes [14]. A recent development in the field is a triple-band modified Hilbert curve fractal antenna [15].

Metamaterials are artificial materials. The growing interest in the study of MTM applications in antenna development is due to the attractive properties such as negative permittivity and permeability possessed by the MTM. These properties of metamaterials help to improve the antenna performance such as miniaturization, gain, and bandwidth. Also, the use of metamaterials in multiband antenna design aids in increasing the number of operating frequencies. In antennas, metamaterials are used in different ways for obtaining multi-band operation. Single-cell MTM loading in monopole antenna results in dual-band operation for WLAN/WiMAX applications [16]. Complementary split ring resonators are loaded on a rectangular monopole antenna for producing multi-band operation [17]. Similarly, MTM cells and slots are loaded on the ground for

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obtaining multiband operation in a dual-band monopole antenna [18]. Another way of using MTM for multi-band operation is etching a meandering split-ring slot on printed antennas [19]. MTM-inspired antennas are yet another method of using MTM for multi-band operation. Triple-band MTM-inspired antenna has been designed and analyzed using FDTD [20]. Compact metamaterial multiband antennas for wireless applications have been reported in [21–22]. Two novel tri-band metamaterial antennas are proposed with TER and CTER [23]. Active devices are used on metamaterials for obtaining wide-band operation [24].

All the above-mentioned antennas exhibit good multi-band performance, but they are somewhat complicated in structure. The design of a simple compact multi-band antenna operating at 2.4 GHz, 3.5 GHz, and 5.5 GHz with good radiation characteristics is the objective of this paper. The designed antenna is experimentally validated. The proposed multiband antenna overcomes the drawbacks of existing antenna designs by the combination of a monopole antenna and a double negative (DNG) metamaterial structure. This simple and compact design will provide desirable radiation characteristics in the required band as mentioned earlier.

II. MULTIBAND ANTENNA DESIGN

The evolution of the proposed antenna on FR4 substrate with a relative permittivity(ε_r) of 4.4, loss tangent of 0.02, and thickness of 1.6 mm with an overall size of 31 x 19 x 1.6 mm^3 (0.407λ_g x 0.25λ_g x 0.021λ_g; λ_g is the wavelength in the substrate at 2.4 GHz) is detailed in the following procedural steps. It is derived from a simple monopole antenna operating in two bands, with the modified ground and a DNG structure as shown in Fig. 1.

1) A simple monopole with length L_3 as $\lambda_g/2$ of the frequency 2.8 GHz is placed on one side of the substrate. The monopole is loaded with an optimized stub of dimensions 2.5 mm x 4.25 mm to improve the impedance matching.
2) A DNG structure with inner radius R_1 = 6.5 mm and outer radius 6.85 mm with two stubs of length 6.3 mm is etched on the backside of the monopole. The dimensions can be optimized as explained in section 3 to excite MTM behavior.
3) The ground plane dimensions of the antenna are optimized for good matching on the chosen substrate and are shown in Table 1.

The monopole along with the defective ground is resonating at two frequencies 2.8 GHz and 6 GHz as shown in Fig. 2.

When an MTM cell is introduced into the monopole antenna, resonances are obtained at three frequencies 2.4 GHz, 3.5 GHz, and 5.5 GHz corresponding to WLAN and WiMAX applications. Since relative permittivity (ε_r) and relative permeability (μ_r) are two parameters that influence the wave propagation through a medium, alteration of these parameters changes the resonant frequencies of the antenna. On placing the MTM structure with DNG property on the monopole antenna, the substrate parameters and hence the resonant frequencies of the antenna change. The placement of MTM also produces one additional resonance and improves the S_{11} in the higher band. MTM size and position optimization are done in ANSYS® HFSS. The optimal position for an MTM unit cell is at the center of the overall geometry. When the radius of the MTM structure is

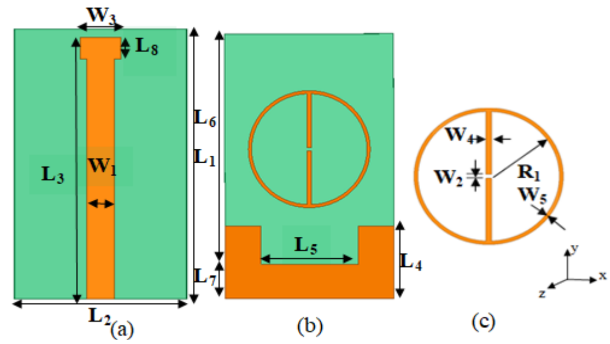
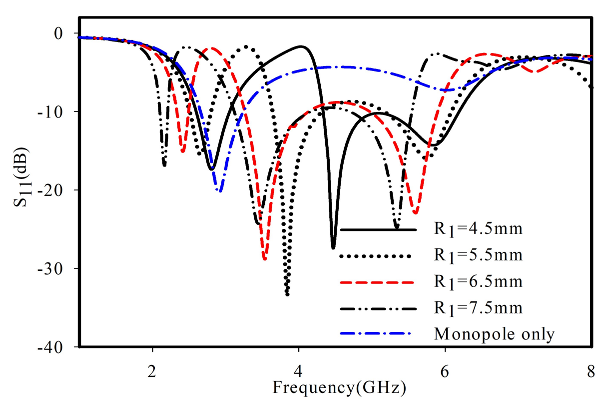


Fig. 1. The proposed Antenna (a) Front View, (b) Back View, and (c) MTM unit cell.

Table 1: Design parameters of the proposed antenna

Parameters	L_1	L_2	L_3	L_4	L_5
Size (mm)	31	19	30	8.5	11
Parameters	L_6	L_7	L_8	W_1	W_2
Size (mm)	27	4	2.5	3	0.4
Parameters	W_3	W_4	W_5	R_1	
Size (mm)	4.25	0.5	0.35	6.5	



(a)

Fig. 2. *Continued.*

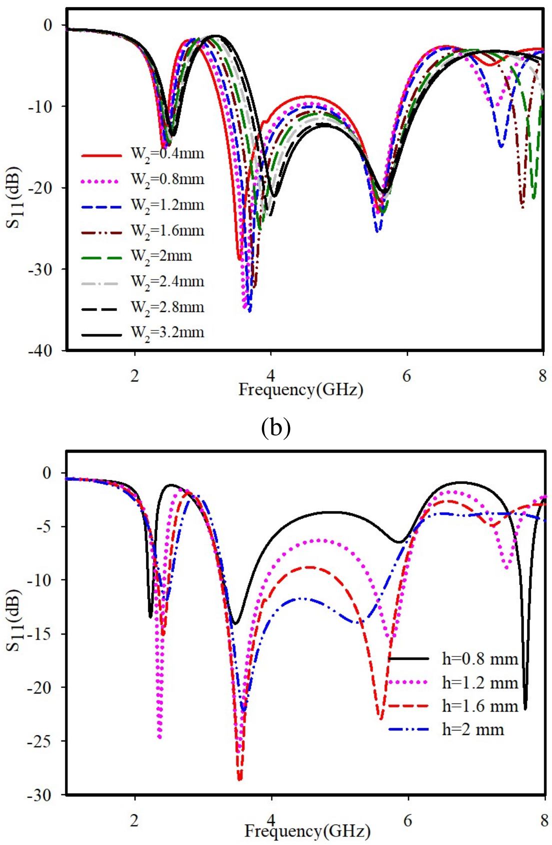


Fig. 2. Simulated S_{11} of the proposed antenna (a) variation of R1, (b) variation of W2, (c) variation of h.

altered, the antenna becomes tunable to different resonant frequencies.

The parametric analysis of the radius variation (R_1), gap (W2), and substrate thickness (h) are shown in Fig. 2. The antenna tuning over a wide range in three bands is possible through radius alterations as shown in Fig. 2 (a). Further fine-tuning of operating frequencies can be achieved by changing the gap between the stubs shown in Fig. 2 (b). Variation in substrate thickness (h) results in improved matching and bandwidth enhancement of three bands (Fig. 2 (c)).

III. MTM DESIGN

It is already stated in [26] that antenna miniaturization can be achieved by changing the relative permittivity and permeability. To lower the operating band of the chosen monopole, it is loaded with an MTM unit cell. The proposed MTM is a planar double negative material in which both permittivity and permeability are negative at 2.4 GHz and 5.5 GHz Fig. 4 shows the retrieved results of the refractive index (n) and impedance (z). The magnitude of n and z are retrieved from S_{11} and S_{21} characteristics of MTM, which are simulated using ANSYS® HFSS, and the parameters are retrieved using the s-parameter retrieval method [27–29].

To extract the S_{11} and S_{21} characteristics of MTM, a two-port waveguide configuration as shown in Fig. 3 can be used. For this boundary conditions are to be applied in such a way that the walls of the waveguide use a pair each, of both perfect magnetic conductor (PMC) and perfect electric conductor (PEC) along the planes x-y and x-z respectively. MTM structure is modeled as PEC on a dielectric slab located at the center of the waveguide.

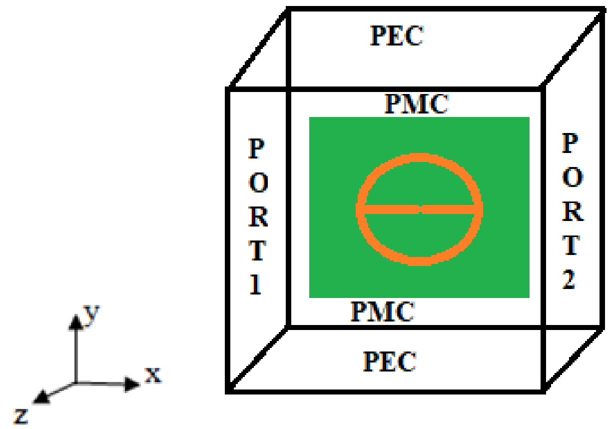


Fig. 3. MTM unit cell simulation model with boundary conditions and excitations.

Two waveguide ports are placed parallel to y-z planes. Then the input wave is launched from port1 and S_{11} and S_{21} are determined. Using these values, refractive index, impedance, permittivity, and permeability can be retrieved by S-parameter retrieval method using the following equations [29]. These equations are implemented in MATLAB™.

$$Z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}}, \tag{1}$$

$$e^{ink_0 d} = \frac{S_{21}}{1 - S_{11}\frac{Z-1}{Z+1}}, \tag{2}$$

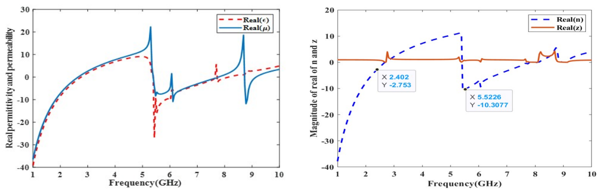
$$n = \frac{1}{k_0 d}\left\{\left[\left[ln\left(e^{ink_0 d}\right)\right]'' + 2m\pi\right] - i\left[ln\left(e^{ink_0 d}\right)\right]'\right\}. \tag{3}$$

Where k_0 is the wavenumber of the incident wave in free space, m is an integer which represents branch index of refractive index. Relative permittivity ε and relative permeability μ can be calculated using the relations (4) and (5).

$$\varepsilon = n/z, \tag{4}$$

$$\mu = nz. \tag{5}$$

Figure 4 shows the extracted values of relative permittivity ε, relative permeability μ, refractive index n,



(a) (b)

Fig. 4. (a) Retrieved results for relative permittivity ε, relative permeability μ. (b) Retrieved results for refractive index n and impedance z.

and impedance z. It can be observed in Fig. 4 (a) that, at 2.4 and 5.5 GHz, both permittivity and permeability show negative values. In Fig. 4 (b) the DNG property is exhibited at desired bands of 2.4 GHz and 5.5 GHz where n is negative. A passive material shows DNG behavior when its n shows negative values and z shows positive values. This proves the designed MTM can be used for miniaturisation of antennas in these two bands.

IV. REGRESSION ANALYSIS

The data derived from the full-wave simulation of the proposed structure was subjected to regression analysis. Dependencies of resonant frequencies on various parameters are formulated through the regression analysis and they are explained as follows. The regression equations are computed using the input values for L_3 and R_1 in a millimeter scale and the resulting resonance frequency values are in GHz.

A. First resonance

The first resonance of the proposed antenna is affected by monopole length, substrate permittivity, and size of the MTM structure. Therefore the first resonance (f_{r1}) can be calculated by:

$$f_{r1} = 5.03 - 0.02L_3 - 0.11\varepsilon_r - 0.22R_1. \quad (6)$$

The regression analysis gives the variable dependencies on the first resonance through equation (6) with 98% accuracy. The design method is validated through a comparative study done on the data from full-wave simulation and those calculated using a regression equation for various values of L_3, ε_r and R_1. The resonant frequencies calculated from the design equation agree well with the simulated results. L_3, ε_r and R_1 parameters show equal correlation with the first resonance, in the correlation analysis.

B. Second resonance

The L_3, ε_r, and R_1 parameters also affect the second resonance of the proposed antenna. The second resonance (f_{r2}) can be calculated by:

$$f_{r2} = 7.59 - 0.08L_3 - 0.17\varepsilon_r - 0.13R_1. \quad (7)$$

The regression analysis gives the variable dependencies on the second resonance through equation (7) with 87% accuracy. The comparative study between simulated results and the design equation for the second resonance shows good agreement.

C. Third resonance

The third resonance (f_{r3}) can be calculated by equation (8). Variable dependencies on third resonance through equation (8) are 98% accurate. The comparative study between simulated results and the design equation for the third resonance also shows good agreement.

$$f_{r3} = 11.48 - 0.1L_3 - 0.22\varepsilon_r - 0.29R_1. \quad (8)$$

V. RESULTS AND DISCUSSIONS

As per the values proposed in Table 1, a prototype has been fabricated and tested. The photograph of the fabricated antenna is shown in Fig. 5. A comparative study of the proposed antenna with the existing antennas shows that the proposed metamaterial-loaded compact multi-band monopole antenna is more compact than the other existing schemes used for miniaturization.

The simulated and measured S_{11} are plotted in Fig. 6. The (-10) dB impedance bandwidths at three operating bands 2.4 GHz, 3.5 GHz, and 5.5 GHz are 200

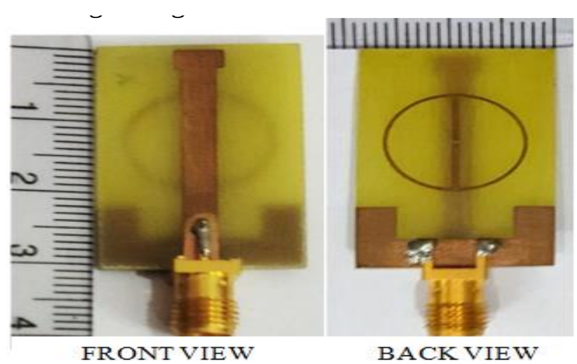


Fig. 5. Photograph of the fabricated antenna.

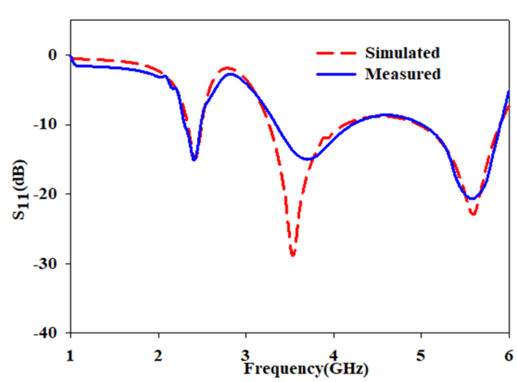


Fig. 6. Simulated and measured S_{11} of the proposed antenna.

MHz, 800 MHz, and 900 MHz respectively, which cover all the bands of WLAN and WiMAX simultaneously. The simulated and measured return loss are in good agreement.

To understand the influence of DNG structure on the monopole antenna, simulated current distribution at 2.4 GHz, 3.5 GHz, and 5.5 GHz frequencies are illustrated in Fig. 7. This illustrates that at 2.4 GHz and 5.5 GHz the monopole along with DNG jointly creates the resonance.

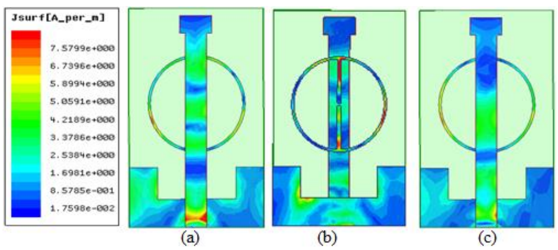


Fig. 7. Surface current distributions at (a) 2.4 GHz, (b) 3.5 GHz, and (c) 5.5 GHz.

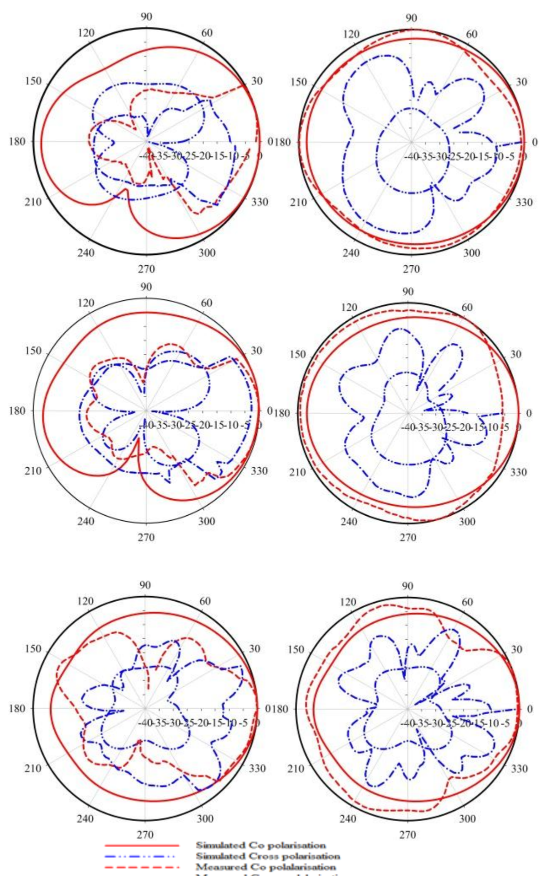


Fig. 8. Measured radiation patterns of the antenna at Y-Z and X-Z planes (a) 2.4 GHz, (b) 3.5 GHz, and (c) 5.5 GHz.

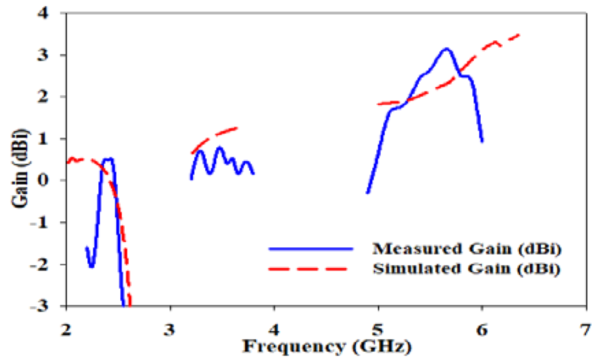


Fig. 9. Measured and simulated gain across operating bands for the proposed antenna.

At 3.5 GHz most of the current is in DNG alone, and it shows that the DNG structure generates the additional resonance.

Figure 8 shows the normalized radiation characteristics in the x-z plane and y-z plane at 2.4 GHz, 3.5 GHz, and 5.5 GHz of the proposed antenna. The proposed antenna is omnidirectional in the x-z plane and directional in the y-z plane in the desired bands; hence it can be used for portable wireless devices.

The measured and simulated gain in three wireless application bands is plotted in Fig. 9. This figure shows that all the bands have positive gain with a maximum of 3 dBi gain at 5.5 GHz A monopole antenna with a DNG structure gives improved gain characteristics than a simple monopole without DNG having comparable dimensions. This happens because the DNG eliminates substrate surface waves and the radiated energy is concentrated.

VI. CONCLUSION

An MTM-loaded compact multi-band monopole antenna for WLAN/WiMAX applications is proposed. The measured results of the antenna show good impedance bandwidth of 6.25%, 24.57%, and 16.54% for the three bands centered at 2.4, 3.5, and 5.5 GHz Measured and simulated radiation characteristics show good agreement. The proposed MTM structure is simple in design with double negative capability. The novelty of the proposed antenna is that a simple DNG structure is used and the monopole antenna loaded with the DNG results in miniaturization and an additional operating band. MTM loading enables the antenna to achieve a compact electrical size of $0.248 \times 0.152 \times 0.013\lambda_0^3$ at 2.4 GHz with improved radiation characteristics. Dependencies of resonant frequencies on various parameters are formulated. The full-wave simulation and design equation of the three resonances show a negligible difference. The proposed multiband antenna has the advantage of compact size, easiness of fabrication, and finds applications in wireless portable devices.

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