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Characterization of metamaterial based patch antenna for worldwide interoperability for microwave access application

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ABSTRACT

Electromagnetic metamaterial is an artificial material that is made up of different types of structural designs on dielectric substrates. In this paper a broad and elite investigation is being carried out by designing and simulating a metamaterial cell comprising a square split ring resonator with a copper wire strip etched on the ground plane to discover its some unusual parameters such as double negativity of cell which are naturally not found in other materials of nature. A course of action of these unit cells in a grouping shapes metamaterial. These metamaterial cells show exceptionally great applications in the design of microstrip patch antennas by improving their characteristics such as bandwidth, return loss, and gain. The proposed microstrip line feed patch antenna is designed at a 3.5 GHz resonance frequency useful for various worldwide interoperability for microwave access (WiMAX) applications. The ground plane of a substrate of a patch antenna is loaded with a square split-ring resonator, the proposed antenna is fabricated to obtain experimental parameters. A conventional and proposed patch antenna is simulated, fabricated tested analysed, and reported for performance comparison of its parameters.

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1. INTRODUCTION

A metamaterial is an artificial material that is made up of an array of metallic resonant cells. The lattice constant of metamaterial should be very much smaller as compared to the wavelength. The artificial materials which are having negative electric permittivity and magnetic permeability are called double negative metamaterials. When both are close to zero but less than zero are referred to as zero-index metamaterials [1], [2]. Mu negative metamaterials are cells of material with only negative permeability. A metamaterial cell made up of a square split ring resonator (SSRR) with a copper wire strip etched on the ground plane of the substrate was designed and simulated at 3.5 GHz to determine some of its parameters such as cell double negativity. A cell containing SSRR is also designed and simulated in order to determine the mu negativity of a cell at the same resonance frequency. The proposed double negative and mu negative metamaterial cells are designed and tested using MATLAB and CST microwave software. A conventional antenna and a proposed novel microstrip feed rectangular patch antenna (RMPA) with the resonance frequency of 3.5 GHz and a ground plane of the substrate is loaded with square split-ring resonators are simulated using FEKO software, analysed, and comparison of parameters such as return loss, bandwidth, gain and voltage standing wave ratio (VSWR) has been presented in this paper. This microstrip patch antenna is built on a FR-4 substrate with a permittivity of 4.4 and a thickness of 1.6 mm. FR-4 material is cheaper and easily available. Surface wave propagation is reduced by metamaterial-loaded substrate, thereby increasing the performance of the antenna. Many researchers have studied SRRs [3]-[7]. This metamaterial-based patch antenna with improved parameters can be used for worldwide interoperability for Microwave access (WiMAX) application. WiMAX is a wireless broadband communications technology based on IEEE 802.16 standard that provides high-speed data over a wide area. WiMAX it is a technology for point-to-multipoint wireless networking [8], [9]. It works in three layers, physical layer, medium access control (MAC) layer, and convergence layer. The bandwidth required for a band with a center frequency 3.5 GHz is about 200 MHz. And the bandwidth of the proposed patch antenna is 274.2 MHz.

2. METAMATERIAL

2.1. Double negative metamaterials

They are also called Left-Handed metamaterials. They are artificially manufactured materials that depicts negative permittivity negative permeability and negative refractive index. These characteristics do not exist in natural materials. Because of the negative refractive index, the group velocity and phase velocities of electromagnetic waves are in opposite directions, resulting in opposite energy flow. Negative refraction can be achieved when both μ_r and ε_r are negative [10]-[15]. The metamaterial can be understood from Maxwell's equations. The Maxwell's equations are used to derive the wave equation. If ϵ_r and μ_r are considered real numbers, then we don't find any change in the wave equation when signs of Єr and μ r are simultaneously changed. Due to the aforementioned facts, these materials are known as left-handed metamaterials. The Drude–Lorentz model describes the material properties of classical electromagnetic. The effective permeability as shown in (1).

$$\mu_{eff} = 1 - \frac{f_{mp}^2 - f_0^2}{f^2 - f_0^2 - j\gamma f} \quad (1)$$

In (1), fmp denotes plasma frequency, f_0 the resonance frequency, and f the signal frequency and the damping factor, which is related to material losses. This equation can depict material properties ranging from the optical to the microwave range [16]-[18]. Figure 1 shows the SSRR Structure with a metalic surface is designed using MATLAB code, The SSRRs and conductor strip on a ground plane create negative μ and negative ε respectively near resonance frequency. The magnetic field vector of the incident plane wave, which is perpendicular to the SSRR, induces currents, which result in an effective magnetic moment and negative permeability. the metamaterial that only allows backward waves to propagate in the direction perpendicular to the SSRR. To confirm a cell's double negativity, the properties of a metamaterial cell can be retrieved using MATLAB. The inherent feature of CST is used to invoke the CST platform through the MATLAB script file [19].

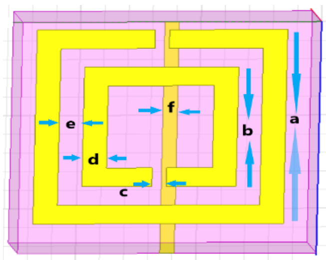


Figure 1. Square split-ring resonator (SSRR)

2.1.1. Design of SSRR cell

The SSRR and strip are designed on FR-4 substrate with permittivity equal to 4.4 and thickness of 1.6 mm. The dimensions of 6.8 x 6.8 mm SSRR are, a= 5.8 mm, b=4 mm, c=0.34 mm, d=0.4 mm, and e=0.5 mm. Strip width f = 0.44 mm and strip length= 6.8 mm.

2.1.2. Parameters of SSRR cell

S_{11} and S_{21} of SSRR cells are shown in Figure 2. It resonates at a 3.5 GHz frequency which is indicated by the lowest magnitude of reflection coefficient S_{11}. The magnitude of S_{11} and S_{21} at 3.5 GHz resonance frequency is 0.2 and 0.79 respectively. This implies that at resonance frequency the return loss is low. Both of the cell's S parameters are required to calculate epsilon and mu. Frequency v/s mu and epsilon are plotted using MATLAB software. Figure 3 shows the epsilon and mu of SSRR in real form. The negative epsilon and mu appear between the frequency 3.3GHz to 3.7GHz. The metamaterial-based antenna may be designed to operate in the given frequency range. From (1), in the lossless condition when $f_{mp}^2 - f_0^2 = f^2 - f_0^2$ that is f=f_{mp} (magnetic plasma frequency) μ_{eff} =0. The curve diverges at the resonance frequency of the cell. γ represents the losses. At 3.5 GHz permeability is -7.1, and permittivity is -8.6.

Figure 4 shows the imaginary and real impedance and refractive index of SSRR. It is observed that the refractive index is negative near resonance frequency. Imaginary impedance is equal to almost zero and real impedance is equal to 50 ohms at the resonance frequency. The outer dimensions of our proposed cells are 6.8 x 6.8 mm, if we design a cell with smaller dimensions then it will show the negative value of permittivity and permeability at a higher frequency some authors have designed such cells. 2.2 x 2.2 mm cell shows negative values of all the parameters at around 10 GHz [20].

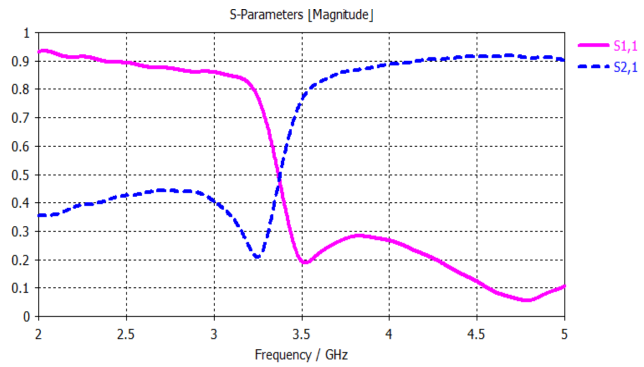
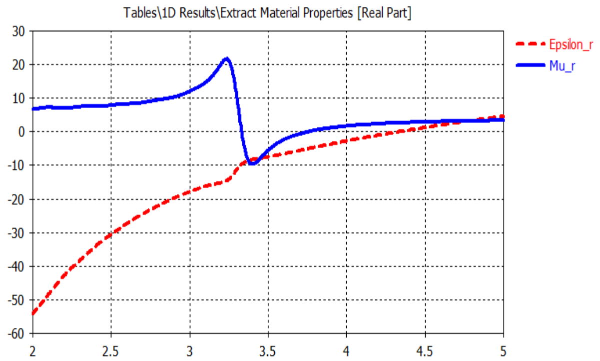


Figure 2. S_{21} and S_{11} of SSRR cell



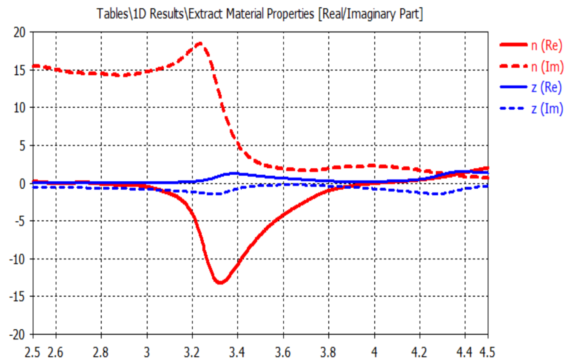


Figure 3. Permittivity and permeability of SSRR

Figure 4. Refractive index and impedance of SSRR

2.2. Single or mu negative metamaterial cell

Cells that show either permeability negative or permittivity negative are referred to as single negative metamaterial cells. If permeability is negative then it is called a mu negative metamaterial cell. The SSRR was designed on an FR-4 substrate having permittivity equal to 4.4 and thickness of 1.6 mm. The dimensions of 6.8 x 6.8 mm SSRR are, a =5.8 mm, b=4 mm, c=0.4 mm, d=0.4 mm, and e=0.5 mm. Figure 5 displays Mu values for the SSRR in both real and imaginary forms. Between frequencies of 3.35 GHz and 3.8 GHz, the negative mu is present. As a result, the antenna needs to be built to work with the available frequencies. Because 3.5 GHz is one of the frequency bands used for WiMAX applications in India [21]–[23], we took that into consideration in this paper. The effective parameters of certain complex structured metamaterials are difficult to calculate. In this case, parameters can be determined through numerical simulation. The cell's transmission and reflection coefficients can be calculated using algorithms finite difference time domain (FDTD) and the finite element method (FEM). This method can also be used to obtain other S parameters [20].

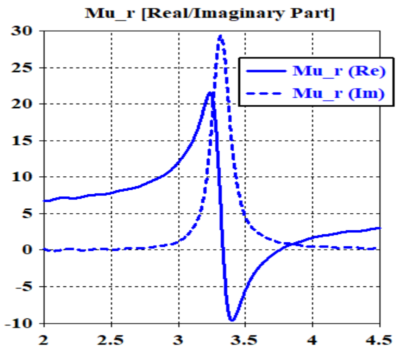


Figure 5. Mu of SSRR at frequency 3.5 GHz

3. DESIGNING RECTANGULAR MICROSTRIP PATCH ANTENNA USING METAMATERIAL

Antennas are made using single negative (SNG) or double negative (DNG) metamaterial cells. This is employed to improve the system's performance. These cells could significantly boost an antenna's gain and output power. These antennas can also enhance performance in terms of efficiency and bandwidth. It is possible to employ different metamaterial-based antennas for wireless communication and mobile phones.

3.1. RMPA design on the substrate without metamaterial

RMPA has been designed to operate at a 3.5 GHz resonance frequency. Width W of the rectangular patch, length L of the rectangular patch, effective permittivity, fringing length, and delta L are calculated using various design equations of RMPA [24], [25]. Length of substrate = L + 6h, width of substrate = W + 6h, h is the height of the substrate, W and L are width and length respectively of the rectangular patch, the Figure 6 depicts the design of conventional RMPA. Table 1 presents the dimensions of a microstrip feed RMPA without metamaterial cells. Resonance freq. of the antenna is 3.5 GHz and uses FR-4 substrate with εr =4.4 and height of substrate(h) =1.6 mm.

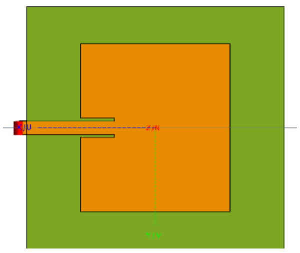


Figure 6. RMPA without metamaterial substrate

Table 1. Dimensions of RMPA

	Calculated dimensions (mm)	Optimized dimensions (mm)
Width of patch	26.08	24
Length of patch	19.98	18.8
Substrate width	35.68	35
Substrate length	29.66	29
Feed length	9.3	9.3
Feed width	1.8	1.8

The important graph of reflection coefficient v/s frequency of RMPA is depicted in Figure 7. It resonates at 3.5 GHz. The bandwidth (BW) of RMPA is 122.9 MHz and the return loss=-35.8 dB. The return loss of antenna depends on its impedance matching. Return loss is comparitively very low for the perfectly matched antenna.

The far-field plot of conventional RMPA is depicted in Figure 8. The gain of the conventional antenna is 2.72 dBi at phi=0 and phi=90 degrees. The gain of the microstrip antenna is comparatively lower than the coaxial feed antenna.

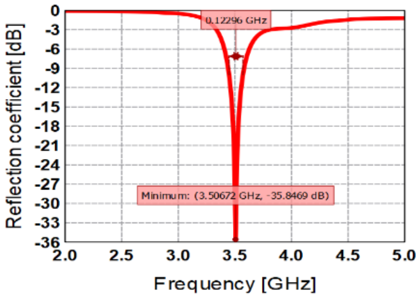


Figure 7. Reflection coeff. v/s freq. of conventional RMPA

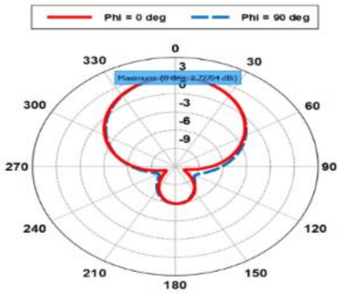


Figure 8. Gain of patch antenna

3.2. RMPA design on metamaterial substrate

The resonance frequency for the RMPA is 3.5 GHz tested using software FEKO and used for WiMAX applications. Table 2 displays the antenna's dimensions. The ground plane of the RMPA has cells of mu negative metamaterial placed on it. The FR-4 substrate with ε_r=4.4 and loss tangent=0.01 is used for fabricating the antenna.

Table 2. Dimensions of metamaterial loaded RMPA

	Optimized dimensions (mm)
Width of patch	23.5
Length of patch	17.6
Substrate width	35
Substrate length	30
Feed length	10.4
Feed width	2.0

Figure 9 shows cells of SSRR on the substrate ground of RMPA obtained from FEKO. In general plasma frequency, f_{mp}, and resonance frequency f_0 depends both on the lattice constant and the geometric parameters of the SSRR like outer and inner lengths of split rings, the width of the gap between the rings, and the slit width. All these dimensions of SSRR have been set in such a way that it resonates at 3.5 GHz. The metamaterial cell has been optimized using MATLAB. We have placed seven metamaterial cells on the antenna ground plane as shown in Figure 9. The novel idea is to place seven cells of metamaterial on the substrate ground in an English letter U shape pattern to obtain very good impedance matching, improved bandwidth and gain compare to conventional patch antenna. Edge port feeding has been used in this antenna.

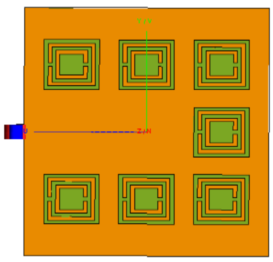


Figure 9. SSRR cells on the ground plane of RMPA

Figure 10 presents a graph of the frequency v/s reflection coefficient of RMPA with a metamaterial. The RMPA resonates at 3.5GHz. The BW of RMPA is 274 GHz. The reflection coefficient of antenna is -30 dB. Decrease in return loss, increases the radiating power. Excitation of surface wave becomes easy when a material with higher dielectric constants and thicker material is used. Metamaterial cells reduce surface wave propagation thereby reducing the surface wave quality factor and increasing the bandwidth of the RMPA. The bandwidth is inversely proportional to the total quality factor of the antenna. Ultimately reduces the reflected power and hence increases transmitted power.

Impedance matching of RMPA with SSRR at 3.5 GHz is shown in the smith chart (Figure 11). The impedance at 3.5 GHz is 50 ohms and the reactive part is almost zero. Figure 12 presents the simulated 2D cut view and 3D far-field E-plane radiation patterns of this antenna. From these results, we infer that a microstrip patch antenna mainly radiates in the vertical direction. This is in agreement with the theoretical radiation pattern for these structures. It is also observed that the radiation pattern possesses a high directivity and symmetry, Figure 12(a) presents 2D cut view of the E-field at phi=0 and phi=90 degrees (dotted curve). Figure 12(b) shows the 3D view of the far-field of SSRR loaded patch antenna at 3.5 GHz. Maximum antenna gains of 5 dBi has been observed with the main lobe in the direction of theta=0 degrees and phi=0 degrees. Figure 12(c) depicts total directivity. The gain of the antenna at 3.3 GHz and 3.7 GHz is 4 dBi. Gain remains almost constant over total bandwidth. The directivity of the antenna is 6 dBi.

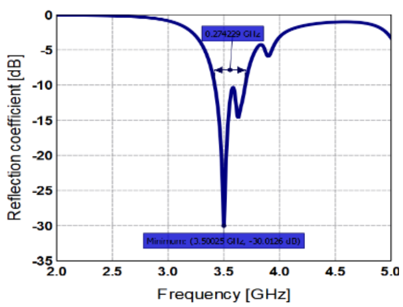


Figure 10. Reflection coeff. v/s freq. of RMPA with metamaterial

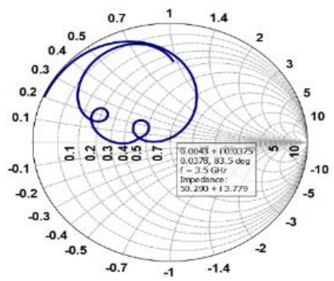
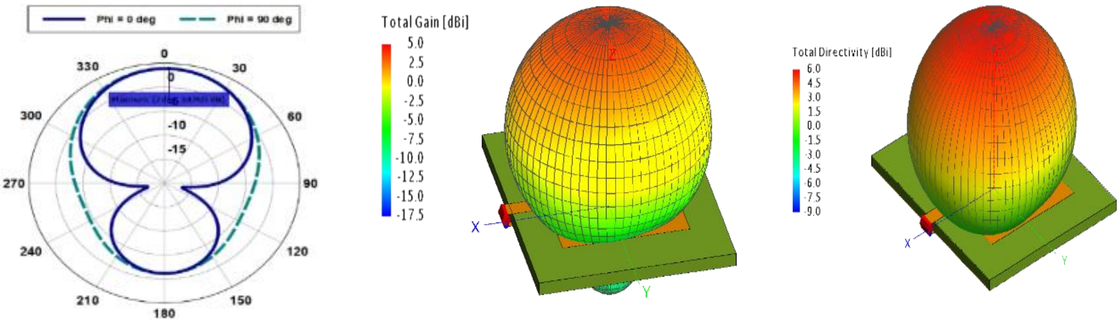


Figure 11. Impedance matching of RMPA



(a) (b) (c)

Figure 12. Far-field E-plane radiation patterns for a metamaterial loaded RMPA (a) 2D cut view of E-field at phi=0 and phi=90 degrees (dotted curve), (b) 3D far-field distribution at 3.5 GHz, and (c) total directivity at 3.5 GHz

VSWR is the ratio between the maximum voltage and minimum voltage in the transmission line. It shows the system matching. For a zero reflection coefficient the value of VSWR is 1 and it is the lowest value possible. It is the best value for any antenna. The smaller the value of VSWR better the impedance matching of the antenna with the source and hence more power is delivered. Performance comparison with previous work is shown in Table 3.

Table 3. Performance comparison with previous work [26]-[28]

Reference no	Resonance frequency (GHz)	Size (λ_g)	Max Gain (dBi)	Bandwidth (MHz)
[26]	3.5	0.70 x 0.47	2.2	140
[27]	3.5	0.68 x 0.25	4.38	170
[28]	3.5	0.88 x 0.75	2.0	110
This work	3.5	0.50 x 0.39	5	274

3.3. Experimental parameters of metamaterial-based RMPA from vector network analyser

A practical graph of frequency v/s reflection coefficient of RMPA with metamaterial obtained from vector network analyser (VNA) is depicted in Figure 13. The fabricated antenna resonates at 3.5 GHz which is the same as the simulated frequency. The bandwidth is 210 MHz and the return loss is -40 dB.

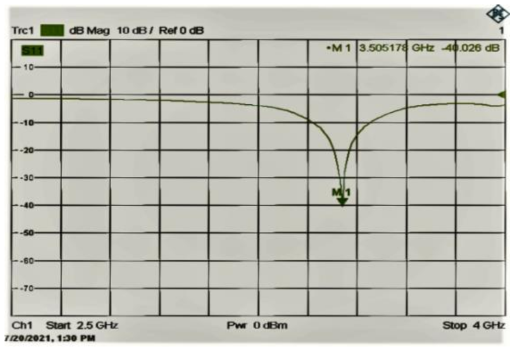


Figure 13. Frequency v/s reflection coefficient of RMPA with metamaterial obtained from VNA

Figure 14 presents the reflection coefficient v/s frequency of metamaterial loaded RMPA generated using a .csv file obtained from VNA. This graph is plotted by converting real and imaginary values of S11 into magnitude in dB. The resonance frequency obtained using this procedure is 3.5 GHz. The impedance at 3.5 GHz is 49.6 ohms, which has been obtained from the smith chart. Which is almost equal to the design impedance of 50 ohms.

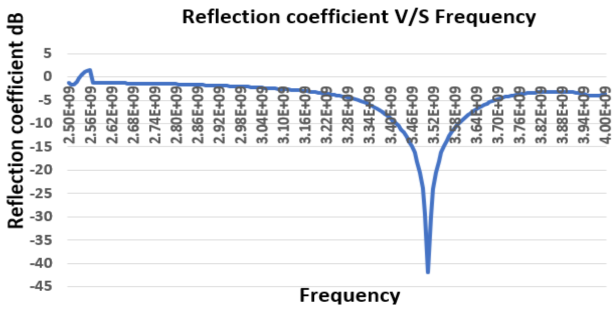


Figure 14. Reflection coeff.v/s freq.of RMPA with metamaterial generated using csv file obtained from VNA

The top view and bottom view (metamaterial loaded) of RMPA is presented in Figure 15. Double-sided copper clad with a 1.6 mm thick FR4 substrate is used for fabrication. Fabrication is done using the .gbr file.

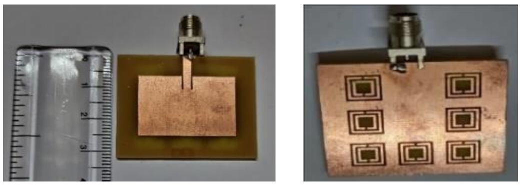


Figure 15. Fabricated top view and metamaterial loaded bottom view of RMPA

4. SIMULATION RESULTS

The metamaterial cell is made up of copper strip and SSRR on the substrate's ground plane. It has been discovered that the cell consisting of SSRR and copper strip on a ground plane is a double negative cell with negative permittivity, negative permeability, and negative refractive index. Metamaterial cells incorporating SSRR are built and simulated using MATLAB and CST software. while the other cell with only SSRR is single negative cell that shows negative permeability. Table 4 compares the properties of the RMPA with metamaterial and without metamaterial. Metamaterial-based RMPA is fabricated using double-sided copper clad with a 1.6 mm thick FR4 dielectric substrate. It is observed that the practical value of resonance frequency is equal to design frequency.

Table 4. Different parameters of RMPA

Parameters of RMPA	RMPA without metamaterial	Metamaterial based RMPA	Experimental parameters of RMPA
Reflection coefficient	-35.84 dB	-30 dB	-40 dB
Bandwidth at (-10 db)	122.9 MHz	274.2 MHz	210.2 MHz
Gain	2.74 dBi	5 dBi	
VSWR	1.1	1.04	

FEKO is used to simulate RMPA with metamaterial cells and also without metamaterial cells. It has been discovered that the bandwidth of metamaterial loaded antenna increases significantly compared to RMPA without cell. RMPA without cells has a return loss of -35.84 dB and a bandwidth of 122.9 MHz. Return loss and the bandwidth for RMPA with metamaterial are -30 dB and 274.2 MHz, respectively. The gain of RMPA is 2.74 dBi without cells and 5 dBi with cells. As a result, the bandwidth is enhanced by 151.3 MHz. Furthermore, the gain is increased by 2.23 dBi. Based on simulation results, the RMPA bandwidth and gain have been improved. The conventional and metamaterial-loaded antennas have voltage standing wave ratios (VSWRs) of 1.1 and 1.04 respectively. The lower the value, the better the impedance matching. The lowest value that is a perfectly matched antenna is having VSWR equal to one.

5. CONCLUSION

This paper presents a metamaterial cell comprising SSRR and copper strip on a ground plane of the substrate. And metamaterial cell comprising of only SSRR, by observing simulated results, it has been found that the permeability, permittivity, and refractive index are negative in the former case and permeability is negative in the latter case, which implies that the former one is a double negative cell and the latter one is mu negative cell or also called as single negative cell. From the simulated results of RMPA, it has been found that the RMPA resonates at 3.5 GHz and the parameters of antenna have improved considerably by loading the proposed mu negative metamaterial structure at the ground plane of the antenna. That reduces surface wave propagation. The simulated results show a considerable increase in BW, low return loss, increase in gain, and decrease in VSWR. Also, the fabricated antenna resonates at 3.5 GHz, which is the same as its design frequency. It has been shown that the proposed patch antenna has higher gain and bandwidth and the antenna has miniaturized in size compared to previous work. The center frequency of one of the WiMAX bands in India is 3.5 GHz and with improved antenna parameters, The proposed antenna can be used for WiMAX application. For an ideal antenna, VSWR is equal to one. The required impedance matching of 50 ohms at 3.5GHz is presented in the smith chart. The maximum power is transmitted when the antenna impedance is perfectly matched.

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