Cylindrical Rods Artificial Dielectric Material Inspired Sub-wavelength and Directive Microstrip Antenna

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Abstract: - In this paper two novel techniques are proposed, one for designing sub-wavelength antenna and the other for designing of directive patch antenna by utilizing cylindrical rods artificial dielectric. Rectangular patch antenna is taken as a reference antenna due to its low profile, simple structure, and easy fabrication. Cylindrical rods behave as artificial dielectric material at plasma frequency and are designed according to the resonant frequency range of reference patch antenna. Embedding of rods in the dielectric substrate of the patch makes it compact, improving its return loss and enhancing impedance bandwidth. A technique to increase the gain and directivity of patch antenna by utilizing cylindrical rods embedded superstrate is also proposed in this paper. Mathematical analysis of results is also provided in this research work. The proposed directive antenna has a gain of 7.01 dB and it resonates at 3.88 GHz with -32.81 dB of reflection coefficient. The presented antenna has applications in field of wireless communication.

Key-Words: - epsilon negative (ENG), compact, artificial dielectric, multiband, double positive (DPS), sub-wavelength.

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1 Introduction

In the electronics and the wireless industry, demand for lightweight, directive, low cost, and powerful antennas has increased over the last few decades. The microstrip patch antenna provides the solution because of its qualities of lightweight, low profile, low cost, simple and easy manufacturing process. Even though these antennas are small about their operational wavelength, radiator dimensions cannot be arbitrarily small because they need to be half wavelength long for resonance, [1]. Antenna designers have reported several techniques in literature to achieve miniaturization such as shorting walls [2], shorting pins [3], and high dielectric constant material, [4], [5].

Nowadays, there has been rising interest in the design of antennas using metamaterial, [6], [7], [8], [9] and artificial material for miniaturisation and performance improvement. Artificial dielectric is also the type of metamaterial. “An artificial material, [10] is a special class of metamaterial obtained by arranging a large number of conducting obstacles in a regular three-dimensional pattern”.
Rods have a negative dielectric constant; hence it is an artificial dielectric and also called SNG metamaterial. In miniaturization of waveguides antennas [11] and sub-wavelength cavities [12], the applications of SNG metamaterials are comprehensively studied, [13], [14] in which resonant frequency is calculated by filling ratio factor rather than by total volume. For materials with opposite signed permeability or permittivity, a compact plasmonic resonance can occur, resulting in arbitrary squeezing of antenna dimension, [15]. For the Global Navigation Satellite System antenna operation, bandwidth improvement and weight reduction using cylinder pin structure was done in [16]. A broad band antenna design using SRR metamaterial is presented in [17], [18]. Metamaterial absorbing techniques are presented in [19] and in [20] use of metamaterial antenna as a sensor is presented.

The above-mentioned researches, however, delivered the solution for the reduction of antenna size, but they have not given an in-depth analysis of the cylindrical rods artificial dielectric material and how their parameters affect the patch antenna's resonant frequency and its performance parameter. This paper presents the complete analysis of cylindrical rod medium and its use in patch antenna to design a compact, subwavelength, efficient and high gain antenna. This paper proposes a novel antenna using cylindrical rods that resonates at 3.88 GHz with -32.81 dB of reflection coefficient and gain of 7.01 dB. The antenna proposed in this work can be used for wireless communication applications.

This research work is structured into subsequent parts. Designing of cylindrical rods medium according to patch antenna is shown in section 2. The design, analysis, and results of cylindrical rods implanted subwavelength patch antenna are shown in section 3. Mathematical and parametric analysis is also provided in this section. Section 4 provides the design, analysis and results of highly directive antenna using cylindrical rods. In section 5, the paper is concluded.

2 Design of Cylindrical Rods as Artificial Dielectric Medium

Cylindrical rods medium acts as artificial dielectric and isotropic plasma, when rods are placed in a cubical lattice structure. For this, diameter of rods and lattice constant of the cubical structure should be small as compared to the operating wavelength. Anisotropic plasma property is shown by rods when they are positioned in any of one or two direction. It is defined using a permittivity tensor as presented by equation (1).

$$\varepsilon = \varepsilon_o \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix} \quad (1)$$

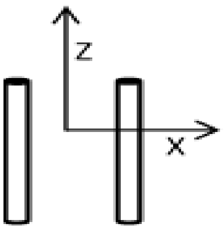

Fig 1: Positioning of cylindrical rods along Z axis

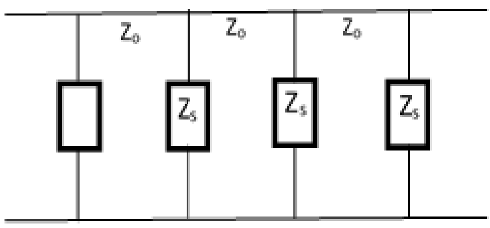

Fig. 2: Equivalent structure (transmission line) of rods

When alignment of cylindrical rods is done in z axis and electrical field is also parallel to rods axis i.e. z axis, as shown in Figure 1, then the circuit depicted in Figure 2 for a transmission line equivalent can present this topology.

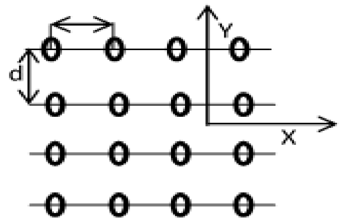

Fig 3: Equivalent view in x-y plane

Figure 3 represents the cylindrical rods view in x-y plane. Dielectric constant $\varepsilon_z$can be calculated using transmission line as given by equation (2).

$$\varepsilon_z = 1 - \frac{{\lambda_o}^2}{2\pi d^2 \ln\left(\frac{d}{r}\right)} = 1 - \frac{{\lambda_o}^2}{{\lambda_p}^2} \quad (2)$$

$${\lambda_p}^2 = 2\pi d^2 \ln\left(\frac{d}{r}\right) \quad (3)$$

$${\omega_p}^2 = \frac{2\pi c^2}{d^2 \ln\left(\frac{d}{r}\right)}(1) \quad (4)$$

Here, Zo= characteristic impedance of transmission line and Zs = jωL, where L = inductance of rods, λ_0 = free space wavelength, ω_p = plasma frequency of the cylindrical rod medium, $\lambda_{p=}$ cut-off wavelength in plasma, r = radius of rods, d = distance between the rods.

For isotropic medium dielectric constant can be calculated as:

$$\varepsilon = \varepsilon_o\left(1 - \frac{{\lambda_o}^2}{{\lambda_p}^2}\right) = \varepsilon_o\left(1 - \frac{{\omega_p}^2}{{\omega_o}^2}\right) \quad (5)$$

Equations (4) & (5) can be applied to calculate the dielectric constant of cylindrical rods medium. For designing artificial medium in wireless frequency range of 5.2 GHz, matlab program on basis of equations (4-5) is written and graphs are plotted for various values of radius and distance between the rods.

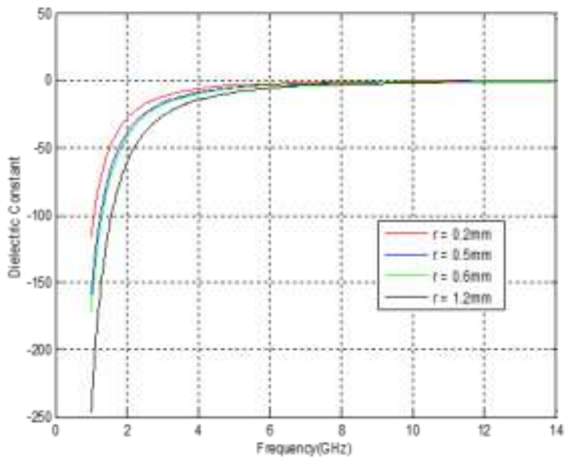

Fig. 4: Relative dielectric constant ε_r of cylindrical rods medium with variable r and d=6mm

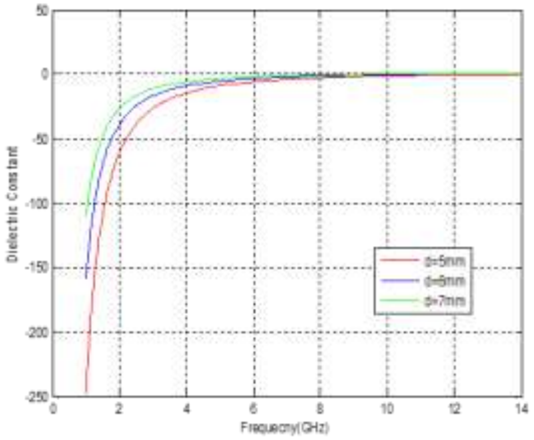

Fig. 5: Relative dielectric constant ε_r of cylindrical rods medium with variable d and r=0.5mm

The dielectric constant of cylindrical rods is shown in Figure 4 and Figure 5 for various values of rod spacing and radius. These graphs show that the dielectric constant r for cylindrical rods in the frequency region below 10 GHz is negative. Hence n this range, cylindrical rods medium behaves like artificial dielectric material.

3 Design and Results of Subwavelength and Compact Patch Antenna using Cylindrical Rods Medium

For designing a subwavelength antenna, microstrip patch antenna designed on Fr4 substrate with loss tangent, δ =.0025 and dielectric constant, ε_r = 4.4 is taken as reference antenna. Using transmission line equations (6-8), antenna is designed at 5.2 GHz. Then it is modelled and optimized in HFSS software as shown in Figure 6.

$$W = \frac{c}{2\, f_o \sqrt{\frac{(\varepsilon_r + 1)}{2}}} \tag{6}$$

$$\varepsilon_{reff} = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2}\left(1 + \frac{12h}{W}\right)^{-1/2} \tag{7}$$

$$l = \frac{c}{2\, f_o \sqrt{\varepsilon_{reff}}} \tag{8}$$

Here, W= width of patch, l =length of patch, εr = substrate material relative permittivity, ε_{reff} = substrate material effective dielectric constant.

The optimized reference patch antenna width is 13 mm and 17.56 mm. The antenna shown in Figure 7 has a return loss of -11.83 dB and resonates at 5.2 GHz. Antenna's bandwidth of impedance is 70 MHz.

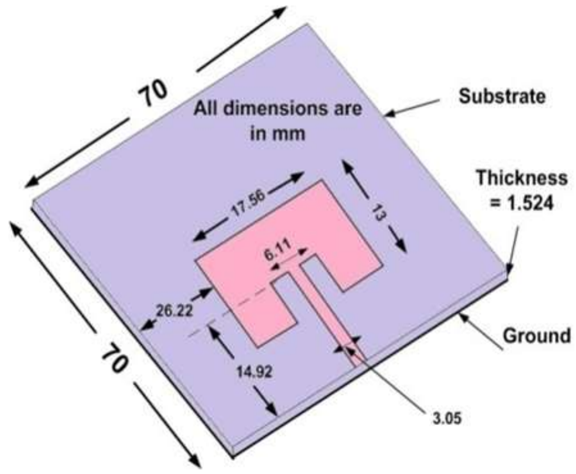

Fig. 6: Reference rectangular patch antenna

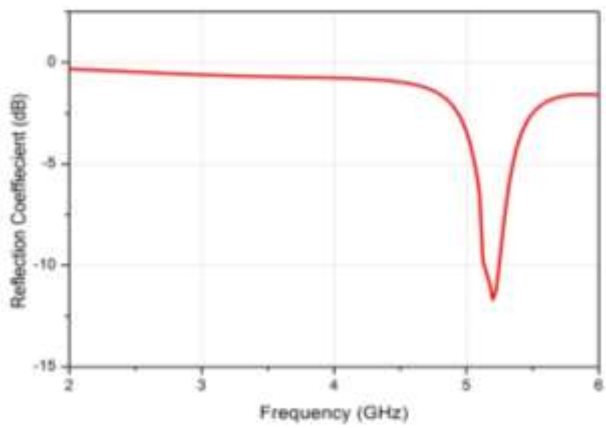

Fig. 7: Reference rectangular patch antenna's reflection coefficient

To design a subwavelength and compact antenna, cylindrical rods designed in section 2 are embedded in reference rectangular shaped microstrip patch antenna. The rods embedded patch antenna is presented in Figure 8. Electric field in patch and rods are in z direction. Embedding of rods in substrate of patch antenna changes its dielectric constant. As patch antenna's resonant frequency depends on dielectric constant of substrate, so it shifts to the lower side in the cylindrical rods embedded patch and makes the antenna compact. The addition of cylindrical rods of radius =0.5 mm, height =1.5 mm, and distance d= 6mm, shifts the resonant frequency to 3.88 GHz from 5.2 GHz as presented in Figure 9. This can be observed from this graph that antenna resonates with a reflection coefficient of -32.81 dB at 3.88 GHz and impedance bandwidth of 120 MHz. Figure 10 displays the antenna's radiation pattern in H and E plane. The antenna has 3dB bandwidth of 93.02^{0} at $\varphi=0^{0}$ and 102.98^{0} at $\varphi=90^{0}$.

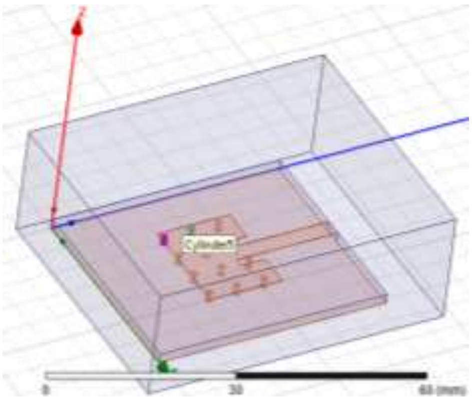

Fig. 8: Patch antenna with integrated cylindrical rods

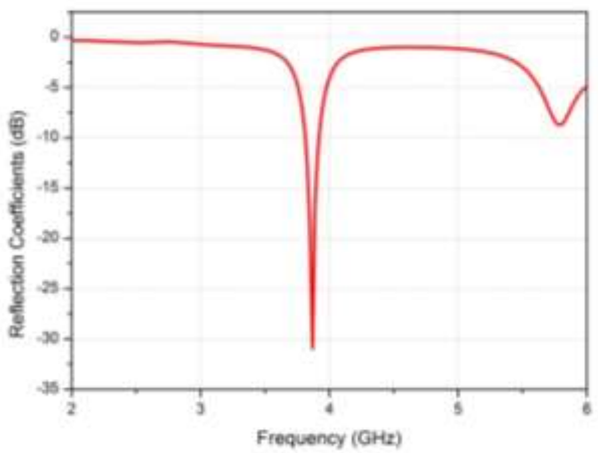

Fig. 9: Reflection coefficient of proposed antenna

A complete parametric analysis of the effect of rod parameters on resonant frequency is also done and provided in the following section.

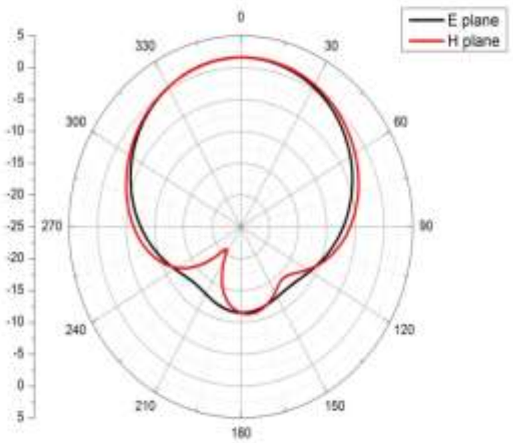

Fig. 10: Proposed patch antenna's radiation pattern

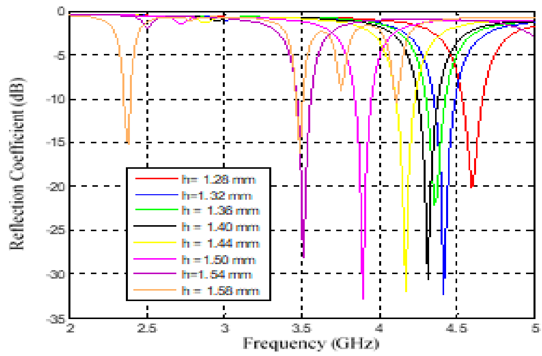

Fig. 11: Subwavelength antenna's reflection coefficient with h vary (d=6 mm, r=.5 mm)

3.1 Parametric Study

Patch antenna performance parameters and resonance frequency are evaluated as a function of the rods' radius (r), spacing (d), and height (h).

Effect of cylindrical rods height on performance parameters of antenna: - As rod height is increased, as seen in Figure 11, the antenna's resonant frequency shifts to the lower side. By raising the rods' height, the antenna gets more and more compact. However, conduction loss rises and antenna efficiency drops as the number of rods increases.

Effect of cylindrical rods radius on performance parameters of antenna: - Figure 12 depicts the effect of a larger rod radius on the antenna's resonance frequency. With increased rod radius, the antenna's resonant frequency shifts to the lower side. However, as the radius of the rods is extended, there is a decline in the efficiency and gain of the antenna due to higher copper losses.

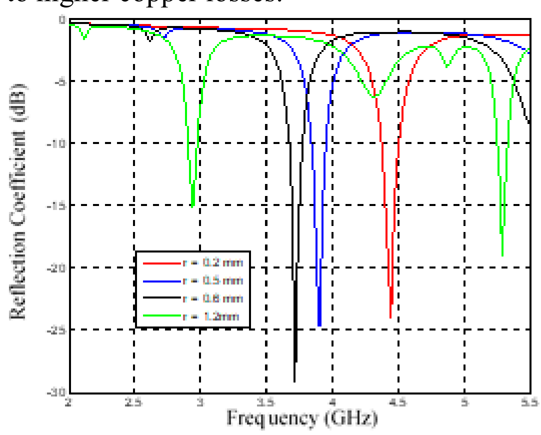

Fig. 12: Subwavelength antenna's reflection coefficient with r vary (h= 1.5 mm,d=6 mm,)

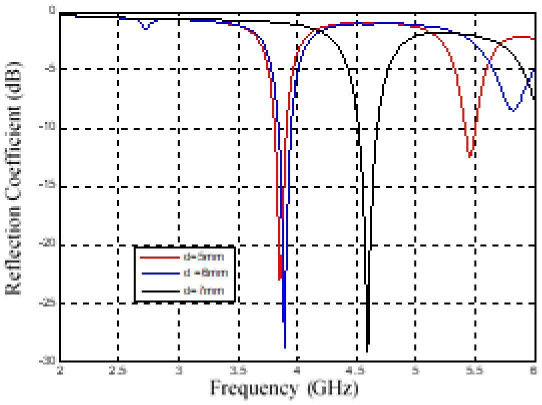

Fig. 13: Subwavelength antenna's reflection Coefficient with variable d and fixed r =0.5mm and h=1.5 mm

Effect of spacing (d) on performance parameters of antenna: - Figure 13 shows the change in resonant frequency with a change in distance d between the cylindrical rods. Resonant frequency shifts to the lower side, as the distance d is increased and the antenna come to be more compact. It also affects the efficiency and gain of the antenna, so an optimized value of d should be chosen to design a high gain and compact antenna. Table 1 (Appendix) displays the performance parameter of subwavelength antenna as the r, d, h of artificial cylindrical rods medium is changed. From Table 1 (Appendix) it can be observed that by applying cylindrical rods medium antenna becomes compact, its bandwidth increases, return loss improves and gain decreases in comparison to reference antenna. The best optimized results are achieved when distance between rods d=6mm, radius r=0.5mm, and h=1.5 mm. Subwavelength antenna resonates at 3.88GHz with return loss -32.81 dB at these optimized values. The optimized antenna has impedance bandwidth of 120MHz.

3.2 Mathematical Analysis

The resonant frequency of a patch antenna with inhomogeneous substrates filled with two homogeneous and isotropic materials can be calculated using a standard cavity model [8–9]. The rectangular cavity of a patch antenna becomes filled with TM_{0mo} modes when rods are placed in the substrate. These modes can be derived using boundary conditions and dispersive equations (9–10).

$$\sqrt{\frac{\mathcal{E}1}{\mu 1}}\tan(k_1\eta W) = -\sqrt{\left|\frac{\mathcal{E}2}{\mu 2}\right|}\tan(k_2(1-\eta)W) \quad (9)$$

$$k_1 = \omega\sqrt{\mathcal{E}1\mu 1}$$

$$k_2 = \omega\sqrt{|\mathcal{E}2||\mu 2|}$$

Here, $\mathcal{E}_1$ = permittivity of double positive substrate, μ_1 =permeability of double positive substrate, $\mathcal{E}2$= permittivity of cylindrical rods medium, μ_2= permeability of cylindrical rods medium, η = filling ratio of double positive substrate. Equation 9 can be simplified and shown as follows if the values of ω and η are chosen in the aforementioned equations in such a way that small argument approximation can be utilized for tangent components.

$$\frac{\eta}{(1-\eta)} \cong -\frac{\mathcal{E}2}{\mathcal{E}1} \quad (10)$$

The relation given in equation 10 implies that at definite frequency size of patch antenna is not constrained by the resonant frequency. Instead if that if permittivity sign of the two materials used in the patch substrate is opposite and equation 10 is satisfied, a subwavelength and compact antenna can be designed. This concept is used in this paper for designing the proposed compact and subwavelength antenna. In this designed antenna, η =0.7 (filling ratio of double positive material i.e. FR4), and the mathematically calculated value for the resonant frequency of patch using equation 10 comes out to be 3.82 GHz which is in agreement with the simulated value of 3.88 GHz.

The rods embedded patch antenna provides a compactness of 47.2. % and demonstrate improvement in reflection coefficient to -32.81 dB from 11.68 dB. Impedance bandwidth improvement to 120 MHz from 70 MHz is also shown by the proposed antenna.

4 Design, Analysis, and Results of Directive Antenna with Artificial Dielectric Superstrate

The directivity and gain of an antenna can be enriched using artificial material. Cylindrical rods implanted in a superstrate can be used to build an antenna with good gain and directionality. By using the superstrate of cylindrical rods directionality, gain and radiation efficiency of the antenna will increase and there will be a decrease in 3 dB beam width. The explanation for enhanced performance can be done using the equation (11) :

$$\mathcal{E}_{eff} = \left(1 - \frac{\omega_p{}^2}{\omega_o{}^2}\right) \quad (11)$$

Effective permittivity is negative when the operating frequency is below the plasma frequency. ε_{eff} will be zero at plasma frequency and the refraction index ($n = \sqrt{\mu_r \epsilon_r}$) will also be zero. The cylindrical rods' medium effective permittivity is positive, close to zero and less than one, just above the plasma frequency. The value of refractive index for this is also close to zero and less than one. Hence incident rays coming out from artificial medium superstrate to free space will be normal to the superstrate surface. As a result, the antenna directivity will rise as the operating frequency approaches the plasma frequency.

Design of cylindrical rods superstrate is done such that its plasma frequency is equivalent to the resonant frequency (3.88 GHz) and it will increase directivity of the above-designed antenna. The estimated value of d= 14.43 mm and r= 0.15 mm is calculated from the equation (4)-(5) for resonant frequency of 3.88 GHz.

Two cylindrical rods embedded superstrate are applied over the antenna designed in section 3 as presented in Figure 14. The frequency at which the antenna resonates remains unchanged after applying the superstrate as shown in Figure 15. Antenna gain increases from 1.5 dB to 7.01 dB as shown in Figure 16. At 3.88 GHz, the proposed antenna's radiation pattern is depicted in Figure 17. The proposed antenna has 3 dB beamwidth of 77.01^0 and 79.67^0 at $\varphi=0^0$ and $\varphi=90^0$ respectively.

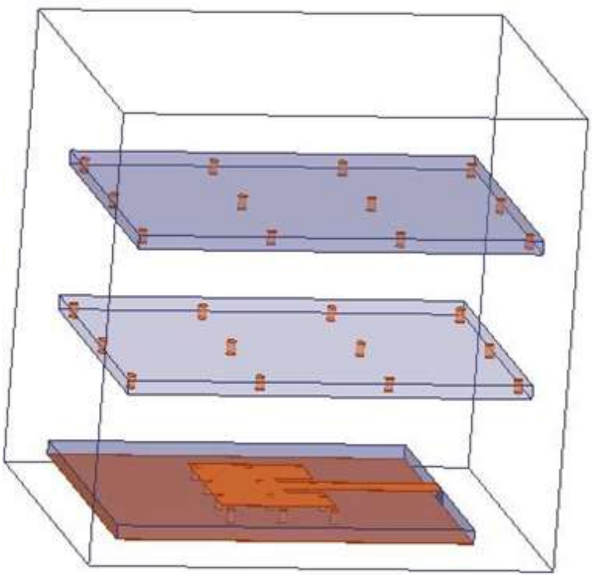

Fig. 14: Proposed subwavelength patch antenna with superstrate

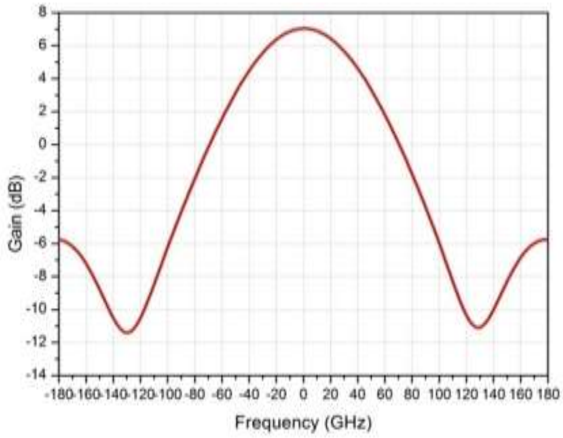

Fig. 15: Proposed patch antenna's Reflection coefficient

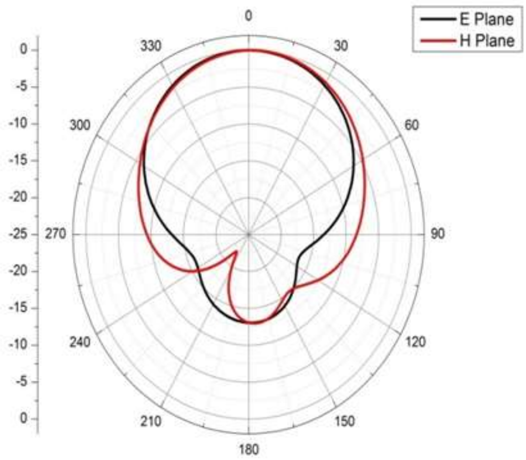

Fig. 16: Proposed patch antenna's Gain at a frequency of 3.88 GHz

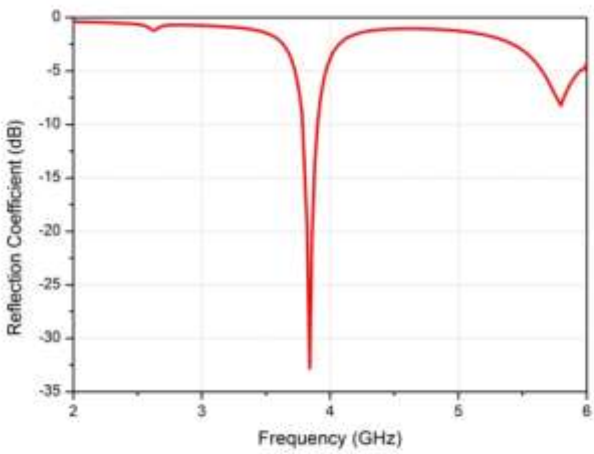

Fig. 17: Radiation pattern of proposed patch antenna at a frequency of 3.88 GHz

5 Conclusion

This paper presents a detailed analysis of cylindrical rods as artificial dielectric and their influence on the performance parameters of patch antennae. Study and analysis of results show that epsilon negative, cylindrical rod medium can be used for the patch antenna in different ways for different purposes. Rods can be inserted in the substrate of a patch antenna to create a subwavelength and small antenna. Cylindrical rods inserted in a superstrate can be used to increase the patch antenna's gain and directivity. Using these approaches, a sub-wavelength patch antenna resonating at 3.88 GHz with -32.81 dB of return loss and having an impedance bandwidth of 120 MHz is presented. The presented proposed antenna has gain of 7.01 dB and has good directivity. Mathematical analysis of results is also provided and agrees with simulated results. The antenna proposed in this research work can be used for wireless communication. Future studies can be carried out using other epsilon negative metamaterial for enhancing the antenna performance and its compactness.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The author Preet Kaur has contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.

APPENDIX

Table 1. Analysis of Performance Parameters of Proposed Antenna Structure

Radiusof rods (mm)	Height of rods in mm	Distance d between rods in mm	Resonant freq. in GHz	Gain in dBi	Reflection coefficient in dB	Impedance Bandwidth in MHz	Efficiency (%)	Compactness %
.5	1.28	6	4.59	3.42	-20.073	150	51.90	22.6
.5	1.32	6	4.4	3.02	-31.85	120	50.38	29.04
.5	1.36	6	4.34	2.86	-21.95	130	50.35	31.05
.5	1.40	6	4.31	1.96	-30.63	140	50.2	32.03
.5	1.44	6	4.17	1.81	-31.76	120	48.67	36.47
.5	**1.50**	**6**	**3.88**	**1.5**	**-32.81**	**120**	**44.78**	**47.2**
.5	1.54	6	3.5	1.16	-27.85	100	40.23	55.56
.5	1.58	6	2.37	0.43	-14.77	60	29.96	79.83
Radius of rods (mm)	Height of rods in mm	Distance d between rods in mm	Resonant freq. in GHz	Gain in dBi	Reflection coefficient in dB	Impedance Bandwidth in MHz	Efficiency (%)	Compactness %
0.2	1.5	6	4.56	2.29	-17.93	130	53.7	23.7
0.5	1.5	6	3.88	1.5	-32.83	120	44.78	47.2
0.6	1.5	6	3.38	1.25	-18.19	90	30.18	58.71
1.2	1.5	6	2.95	0.05	-13.73	70	5	68.59
Radius of rods (mm)	Height of rods in mm	Distance d between rods in mm	Resonant freq. in GHz	Gain in dBi	Reflection coefficient in dB	Impedance Bandwidth in MHz	Efficiency (%)	Compactness %
0.5	1.5	7	4.58	0.5	-28.86	160	18	22.9
0.5	1.5	6	3.88	1.5	-32.83	120	44.78	47.2
0.5	1.5	5	3.84	1.4	-22.88	110	42.18	46.32