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Investigations on Characteristics of Metamaterial Based Patch Antenna for RF Energy Harvesting at GSM 900

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Abstract In this work, a 5 x 5 metamaterial array split ring resonator is introduced onto a C -shaped rectangular patch antenna with a defective ground plane. The patch antenna was designed to operate at the downlink radio frequency band of GSM 900 with a pair of bevel shaped structure and a horizontal slot on top which was closely put at the center of the patch. The objective of this paper is to investigate the effect of metamaterial and the orientation of DSRRs with strip lines behind on the characteristics of patch antenna keeping in view of maintaining the bandwidth, return loss and ameliorating in gain. The results indicates that the amelioration in impedance bandwidth was 23.33% (77 MHz), gain of 44.4% (0.993 dB) and increase in return loss of 19% (6.71 dB) when compared to the conventional patch antenna.

Keywords Metamaterial, C-shaped patch, Defective ground plane, Downlink, GSM 900, Impedance bandwidth, Gain

1. Introduction

Microstrip patch antennas are being widely used in wireless communication systems due to their simplicity, but have drawbacks of low gain and narrow bandwidth. Several techniques have been proposed: Increasing the height of substrate and decreasing its permittivity [1], different types of feeding [2], introducing patch antenna with a diamond slot [3], ring [4], ice cone [5], E shaped [6], stepped [7] slots and bevel shape [8]. Another advanced approach is to introduce metamaterial superstrate onto the antenna structure. Feature of metamaterial has also been used in military applications, super lens, sensor, and biomedical applications. The property of negative permittivity and permeability in metamaterials can improve the radiation efficiency of the antenna and provide improvements on gain and radiation characteristic when it acts as a superstrate on an antenna. The basic proposed metamaterial structures found in literature are symmetrical-ring, circular, omega and S [9]. Also in recent years other structures such as fishnet, EBG structure [10] planar patterned array [11] and frequency selective surface [12] were introduced in various applications.

These show that the metamaterial can be used as a superstrate, substrate or directly printed onto the patch antenna to achieve gain and bandwidth enhancement whilst miniaturizing the size of the antenna In this article the antenna designed has novelty in determining a specific orientation (180 degree) of DSRRs along with strip lines to obtain better performance in the desired frequency band prior to introduce onto the patch antenna. In addition the double negative properties of the superstrate are verified from the S-parameters. The special features are in superstrate orientation, the verification of double negative properties from S-parameter and the frequency of operation (downlink radio frequency range of GSM 900) which all differs from the previous work.

Sections 2 describe the antenna design. Section 3 describes the methodology used. Section 4 describes the analysis on properties of superstrate. Section 5 describes the results obtained and section 6 is the conclusion.

2. Antenna Design

The configuration of the proposed antenna structure is shown in Figure 1(a) and 1(b). The design structure consists of three layers which are: a C-shaped patch with a defective ground plane, an air gap and a superstrate layer. In the simulation study, the antenna was designed on a FR4 substrate with a 1.6 mm thickness. The copper used is a lossy metal with an electric conductivity of 5.8×10^7 S/m and the permittivity of the epoxy glass substrate is 4.7 with a loss tangent of 0.025. The patch antenna consists of two bevels and a horizontal slot, which is denoted by B1, B2 and S1, which are printed at the top of the substrate and the defective ground plane on the other side. The horizontal slot is used to control the resonant frequency and help to reduce the size of the patch antenna. A partial ground plane with a notch on it at the bottom side of the substrate is used to enhance the

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impedance bandwidth. The width (W), length (L) and the effective dielectric constant ε_reff of the patch antenna are determined using the equations (1), (2) and (3), which was obtained from [13].

$$W = \frac{1}{2f_r\sqrt{\mu_o\varepsilon_o}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{v_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

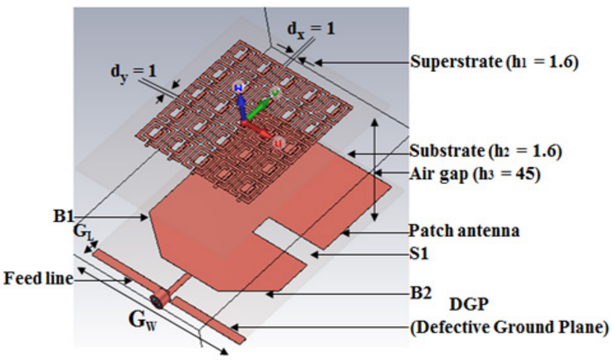
$$L = \frac{\lambda}{2} - \Delta L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\mu_o\varepsilon_o}} - 2\Delta L \quad (2)$$

Normalized extension of ΔL is given by

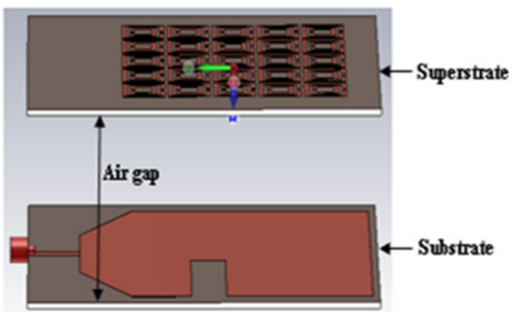
$$\Delta L = 0.412 \times h \times \frac{(\varepsilon_{reff}+0.3)(\frac{w}{h}+0.264)}{(\varepsilon_{reff}-0.258)\left(\frac{w}{h}+0.8\right)} \quad (3)$$

For $W/h > 1$, Effective dielectric constant is given by

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{w}\right]^{-\frac{1}{2}} \quad (4)$$



(a)

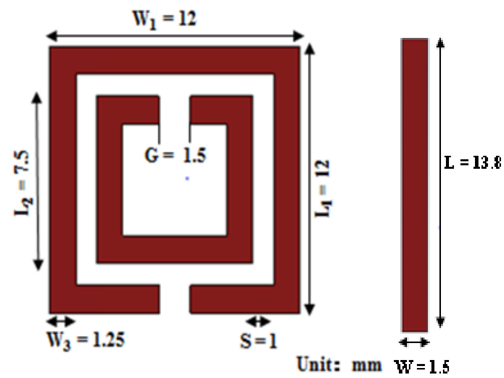


(b)

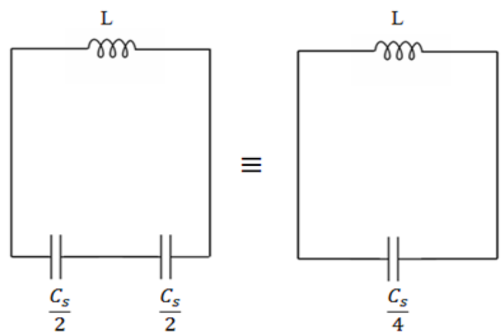
Figure 1. Proposed antenna: (a) Configuration (b) Side view

In order to obtain the desired performance, the dimensions of patch, shape of bevels; size and position of slot for the proposed antenna was optimized and the optimized dimensions are shown in the Table 1.

The superstrate layer is constructed on a FR4 substrate which possessed the same characteristic of the substrate used for the patch antenna. This is placed above the patch antenna with an air gap of 45 mm to achieve gain enhancement. The superstrate array consists of a 5 × 5 unit cells of dual split ring resonator (DSRR) on the substrate and 5 metallic strip lines on the other side of the substrate. A unit cell structure and its equivalent circuit showed in Figure 2(a) and 2(b). The length of each DSRR is 12 mm and the spacing between each DSRR is 1 mm. The dimensions and structure of the superstrate is optimized to obtain better impedance match and performance at the downlink radio frequency range of GSM 900 band. Dual negative (μr and εr) properties of the superstrate over a given frequency range can be obtained in a periodic array of DSRRs and in the nanowires respectively for certain frequency range which is smaller than ω_p (plasma frequency). The DSRR can be represented as a RLC circuit with a resonant frequency of $\omega_0 = \sqrt{1/LC}$ where the metallic structure and the air gap in the ring represents the inductance L and the capacitance C respectively. The output of the proposed antenna is connected to a 50 Ω SMA connector through micro strip feed line.



(a)



(b)

Figure 2. DSSR (a) Geometry along with strip line (b) Equivalent circuit [14]

Table 1. Dimensions of patch antenna structure

Basic Config.	Patch antenna						Feed Line		Ground Plane	
Variable	W	L	B1, B2		S1					
			W	L	W	L	W	L	W	L
Dimension (mm)	74	84	21	15	31	10	2.93	15	84	4

3. Methodology

The proposed antenna with and without the superstrate structure was designed, simulated and optimized using the time domain solver of the Computer Simulation Technology (CST) microwave studio, version 14. First the patch antenna was designed and simulated at the downlink radio frequency range of GSM 900 band. After that the superstrate layer was designed, simulated for double negative properties and optimized for the desired frequency band. Next the superstrate is introduced onto the patch antenna with an air gap between them. In order to achieve the objectives of the proposed antenna the structure of the antenna, superstrate layer and the air gap between them were optimized by using parametric optimization in CST at the desired frequency band.

4. Analysis on Properties of Superstrate

The structure of the superstrate array 5 × 5 DSRRs along with the strip lines was simulated for various orientations at 0, 90, 180 and 270 degree in order to get better transmission (S_{21}) and reflection (S_{11}) coefficients. The S-parameter results obtained are used to verify the dual negative characteristics (μr and εr) of the superstrate in the desired frequency band.

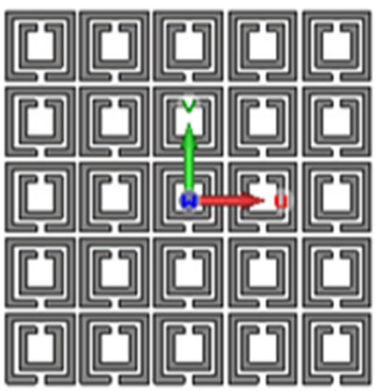


Figure 3. Schematic of 5 × 5 DSRR superstrate layer oriented at 180 degree

The results of the analysis indicated that better performance was obtained when the superstrate orientation was at 180 degree and its schematic is shown in Figure 3. In this design Nicolson-Ross-Weir (NRW) method [15] was used to verify the double negative properties of superstrate and the values of the permeability and relative permittivity are computed using equations (5) and (6).

$$\mu r = \frac{2*c(1-v_2)}{\omega*h*i*(1+v_2)} \quad (5)$$

$$\varepsilon r = \mu r + \frac{2*S_{11}*c*i}{\omega*h} \quad (6)$$

where,

$v_2 = S_{21}\text{-}S_{11}$,
ω = Frequency in Radians,
h = Thickness of the substrate,
c = Speed of light,
v_2= Voltage Minima,
μr = Relative permeability,
εr = Relative permittivity.

Scattering parameter is the key to extract the permeability and permittivity of the superstrate layer and the complex values of transmission and reflection coefficients (S_{21} and S_{11}) are obtained from simulation is shown in Figure 4.

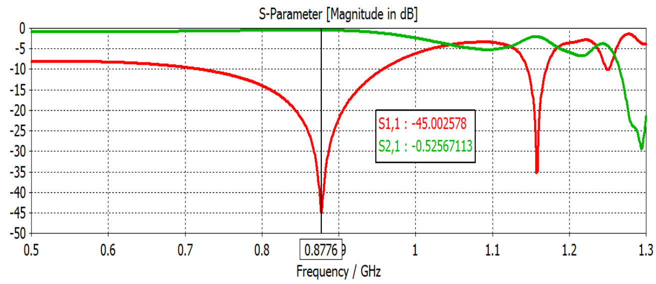


Figure 4. Transmission and reflection coefficients for 5 × 5 DSRR superstrate oriented at 180 degree

The results obtained for negative permeability and permittivity of superstrate at 180 degree orientation in the de-sired frequency band is shown in Figure 5 (a) and (b). The maximum double negative value of -9.1 is observed from the graphs.

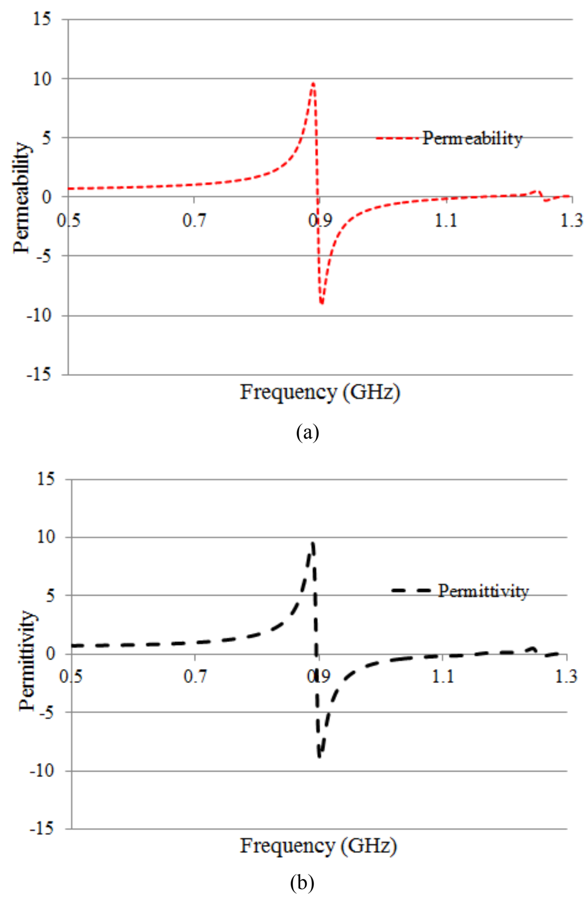


Figure 5. 5 × 5 DSRR superstrate layer for orientation at 180 degree, (a) Permeability (b) Permittivity

5. Results and Discussions

The results of the return loss for different heights (gh) of the air gap are shown in Figure 6 and its performance was shown in Table 2. Comparison of the results shown that the resonant frequency at an air gap of 45 mm is close to the centre radio frequency (947.5 MHz) of the desired frequency band.

Table 2. Performance of proposed antenna for variation in air thickness

Air gap (gh) (mm)	Resonant Frequency (MHz)	Return Loss (dB)	Impedance Bandwidth (MHz)	Gain (dB)
42	948	-29.11	415	3.18
43	947	-28.83	413	3.19
44	947	-28.7	409	3.21
45	947	-28.6	407	3.23
46	946	-28.4	403	3.25
47	946	-28.2	400	3.26
48	946	-27.99	394	3.28

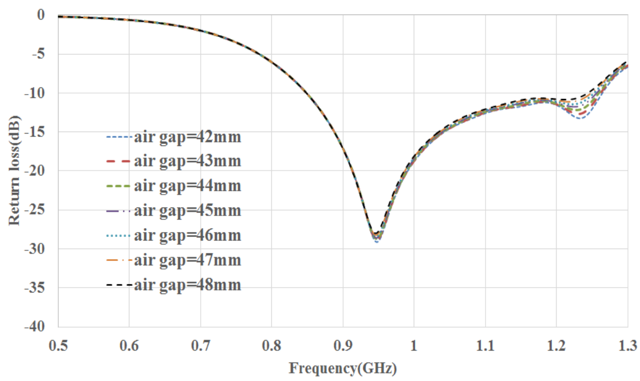


Figure 6. Comparison of return loss of proposed patch antenna with different air gaps between patch and superstrate

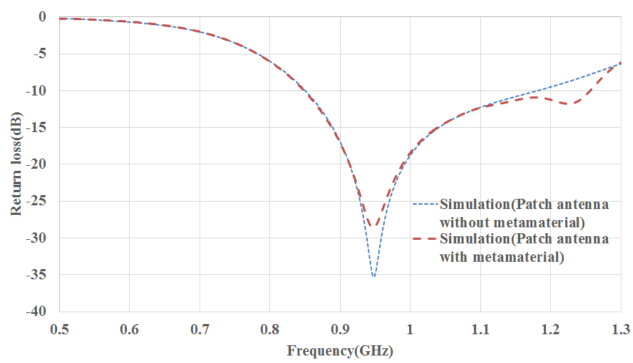


Figure 7. Comparison of return loss for the proposed antenna with and without metamaterial

The performance on the lower side of 45 mm showed a slight decrease in return loss, gain and enhancement in bandwidth. At the higher side of 45 mm there is a slight decrease in bandwidth, increase in gain and return loss. Based on analysis the performance is better at 45mm air gap, hence it is chosen for the proposed structure. Authors in [16], [17] and [18] show that the thickness of air gap between the metamaterial and antenna need to choose at λ/2 or λ/4 in order to achieve the impedance matching. In this article, due to optimization of the structure for the thickness of air gap at λ/8 providing impedance match with in the desired frequency band. The gain of the antenna is enhanced 24.4%, even though the return loss slightly increased. The gain of antenna increases as the thickness of air gap increases [19] and agree with the result shown in Table 2.The results of return loss for the proposed antenna with and without material are shown in Figure 7. The analysis shows that there is 23.33% (77 MHz) increase in bandwidth (330 MHz to 407 MHz) at the resonant frequency and has a good impedance matching at the air gap of λ/8 even though the return loss is slightly increased by 19 % (-35.3 dB to -28.59 dB) over the conventional patch antenna.

The performance of return loss for various orientations of superstrate is shown in Figure 8, comparison indicates the orientation at 180 degree a return loss of -28.59 dB is obtained at the resonant frequency, in other orientations even though the return loss is slightly better but the resonant frequency is shifted away from the desired frequency.

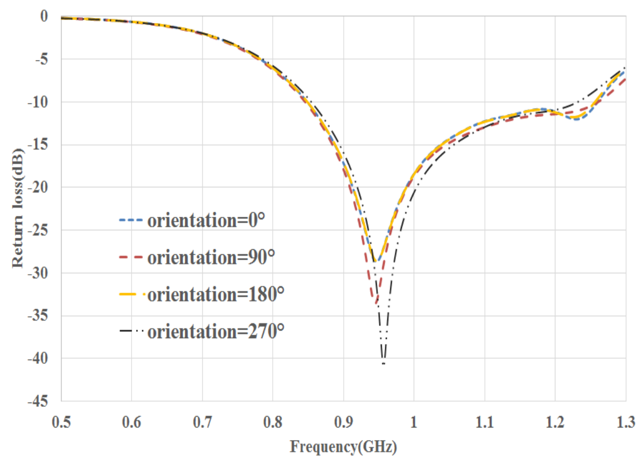
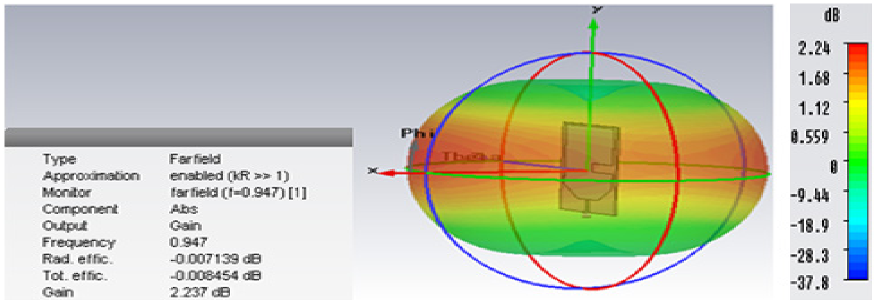
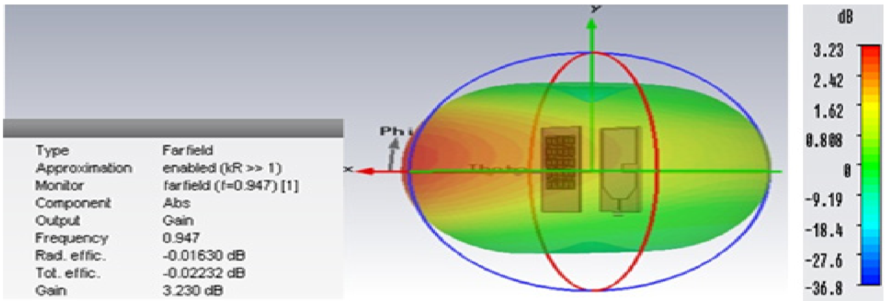


Figure 8. Comparison of return loss of the proposed superstrate at different orientations

The 3D gain radiation pattern of the antenna with and without the superstrate are shown in Figure 9 (a) and (b).The result indicates that the gain is enhanced from 2.237 dB to 3.230 dB with superstrate which represents 0.993dB (44.4%) increase in gain. The E plane gain radiation patterns of proposed antenna with and without superstrate are shown in Figure 10 (a) and (b). The gain is increased by 44.2% (2.24 dB to 3.23 dB) and main lobe direction is changed from back to front side of antenna. The H plane gain radiation patterns of proposed antenna with and without superstrate are shown in Figure 11(a) and (b). The gain is increased by 45.4% (2.18 dB to 3.17 dB) and main lobe direction is changed from back to front side of antenna.

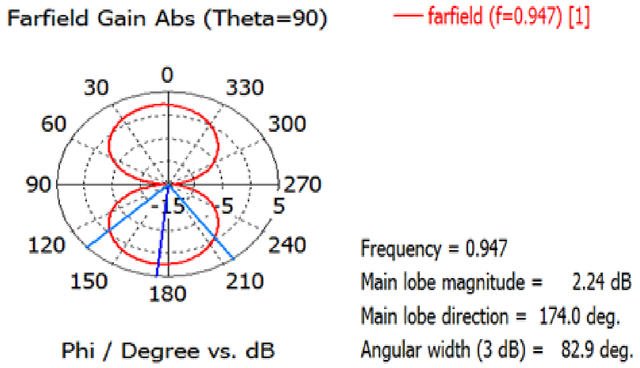


(a)

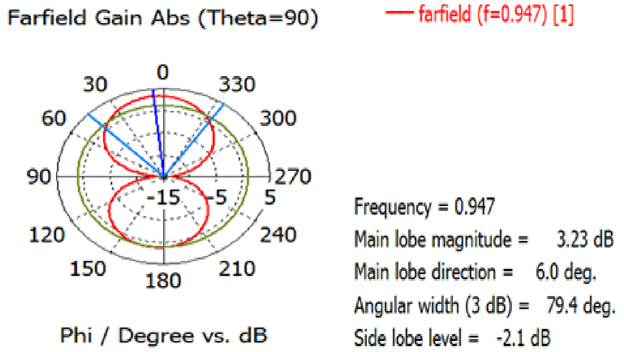


(b)

Figure 9. 3D Gain radiation pattern of the proposed antenna without superstrate (b) with superstrate



(a)

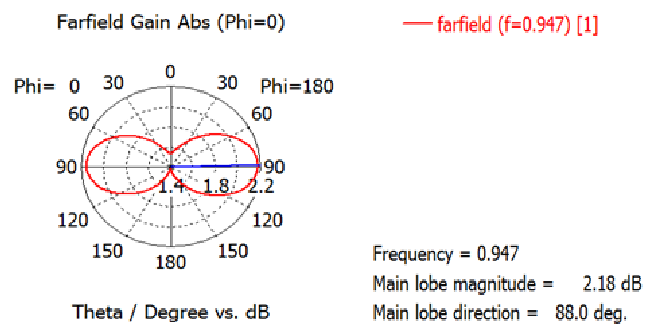


(b)

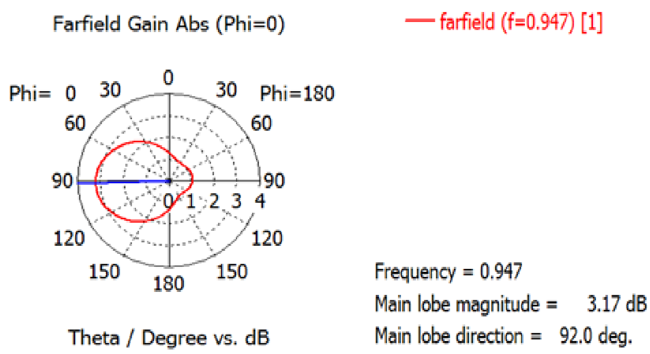
Figure 10. E plane gain radiation patterns of the proposed antenna (a) without superstrate (b) with superstrate

Table 3. Summary on performance

Simulation Results	At -10 dB f_l and f_h frequency (MHz)	Impedance Bandwidth (MHz)	Return Loss (dB)	Gain (dB)
(without metamaterial)	851 to 1181	330 (34.3%@947)	-35.3 (948 MHz)	2.237
(with metamaterial)	849 to 1256	407 (40.22%@947)	-28.59 (947 MHz)	3.230



(a)



(b)

Figure 11. H plane gain radiation patterns of the proposed antenna (a) with superstrate (b) with superstrate

The performance summary of the designed antenna is shown in Table 3 and is described in conclusion.

6. Conclusions

Investigations on effect of a 5 x 5 DSRR superstrate introduced onto C -shaped patch antenna are discussed. The result showed that the impedance bandwidth and gain are enhanced to 23.33%, and 44.4% respectively; and a slight increase in return loss over the conventional patch antenna. Observation made showing that the proposed antenna is more directional, which is an important feature for RF energy harvesting antenna. The RF energy harvested using this antenna can be converted into DC voltage and power the low power devices such as mobile phones, sensors, webcams, etc. within the range of GSM-900 band. This will inherently prolong the life of the battery life of the mobile devices. As for the future enhancement on the performance of proposed antenna, the gain and the impedance matching can be further improved by using different structure of metamaterials.

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