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Analysis and Design of High Gain NRI Superstrate Based Antenna for RF Energy Harvesting System

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Abstract

A high gain patch antenna inspired by 4 layers of negative refractive index (NRI) metamaterial (MTM) superstrate is proposed to operate at downlink radio frequency (RF) band (935MHz to 960MHz) of GSM 900). The MTM unit cell consists of a nested split ring resonator (SRR) on one side and strip line laminated on other side of FR4 substrate. The effective permeability and permittivityof the unit cell are designed synchronously to approach zero, which leads the NRI superstrate to have impedance match with zero negative refractive index.The NRI superstrate is studied using Fabry-Perot (F-P) resonant cavity. The gain of the antennas is improved by 82.29% at the air gap of 55 mm in the desired frequency band. The gain is effectively enhanced based on the negative refractive index MTM. The measured radiation pattern and s parameter results showed that it has good agreement with the simulation results.

Keywords: *Negative refractive index, Metamaterial, Nested split ring, Patch antenna, Gain*

1. Introduction

The environmental energy harvesting has recently emerged as a viable option to supplement battery supplies. Energy harvesting by RF is themost attractive approachto power low power wireless devices especially for the embedded wireless device applications.

The microstrip patch antennas are widely used due to its inherent characteristics and several of its advantages for wireless communications, but have drawbacks of low gain and narrow bandwidth which limits their application. To vercome these limitations numerous techniques such as low permittivity and thick substrate [1], stacking of microstrip element [2], truncating and slotting the microstrip patch [3] were proposed to improve its performance.

Antenna is the major vital component in RF energy harvesting system. In order to have a more efficient antenna, the unusual properties (negative refractive index) of MTM is integrated with the patch antenna for the application of RF energy harvesting system.This can be used as a lens to focus the Electromagnetic (EM) wave radiated from the free space toward the normal direction of the antenna. It is a medium consists of permeability and permittivity simultaneously negative at certain frequency range.

In [4] explored the properties of isotropic media where both the permittivity and the permeability are simultaneously negative (negative refractive index). The propagation vector k, electric field E and magnetic fieldHof these materials form a left handed set of vectors which are opposite to the commonly known right handed materials. Therefore, these materials also are known as the left-handed materials (LHM). shapes of MTM structures were proposed using ZIM such as Omega and S as antenna aubstrate to enhance gain [7], fishnet-numerical simulations of Terahertz double-negative MTM with The first LHM prototype using split ring resonator (SRR) and thin wire (TW) was made successfully [5]. A metamaterial (MTM) for directive emission [6] pointed that the gain of the antenna can be enhanced through the use of zero index metamaterial (ZIM). In the recent yearsvarious isotropic [8], Labyrinth-bandwidth enhancement of RMPA using ENG MTMs [9], Square rectangular SRR [10], Triangular- tunable MTM design [11] all of them exhibit the properties of ZIM. High directivity aperture patch using MTM [12]. A near-zero refractive index meta-surface structure forimprovement of antenna performance [13]. Split ring and CSRR use MTM [14]-[15]. So far authors not come across the analysis/investigations on the affect of MTMs on the antenna design at low frequency applications. Our Objective is

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to enhance the gain of the antenna integrating with MTMs for the application of energy harvesting system. The draw back observed in the investigations is the higher air gap.

In this article, a defected ground plane patch antenna with 4 layers of NRI superstrate is realized and investigated. Appropriate design has been done to make the NRI unit cell to have negative refractive index and the impedance match with the air, efficiently to enhance the gain. The proposed NRI based superstrate antenna has been demonstrated by simulation and experiments

2. Antenna Design and Configuration

The configuration of the NRI superstrate based patch antenna with its design parametersare shown in Figure 1. A patchsize of $102\,mm \times 84\,mm$ is printed on FR4 substrate having thickness 1.6 mm, permittivity 4.7, and loss tangent 0.014. It consists of one ring slot S1 at the center and bevels at the edges of the patchto enhance the impedance bandwidth. The antenna is direct fed through a 15mm length of transmission line and excited by a 50Ω microstrip feed line ofwidth 2.93 mm through an SMA connector situated on edge of dielectric. Defected ground structure (DGS) which is printed at bottom of the FR4 substrate also contributes to increasethe impedance bandwidth. The optimized design dimensions of the antenna are shownin Table 1. The width *(W)*, length (*L)*, length extension (ΔL) and effective dielectric constant ε_{reff} of the patch antenna are calculated using the equations (1), (2), (3) and (4) obtained from [16].

$$W = \frac{1}{2 f_r \sqrt{\mu_o \varepsilon_o}} \sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{V_o}{2 f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

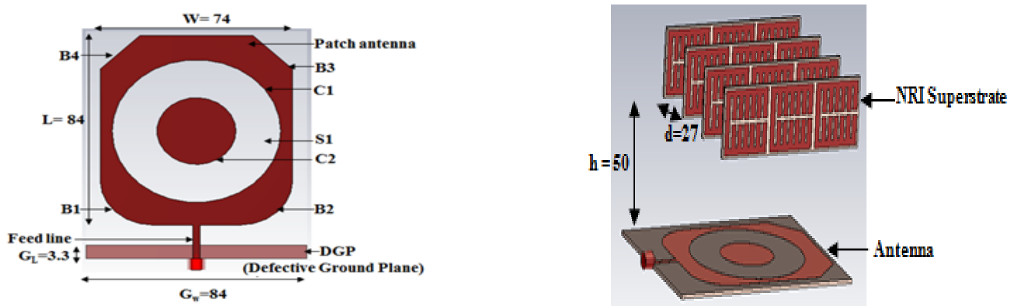
$$L = \frac{\lambda}{2} - \Delta L = \frac{1}{2 f_r \sqrt{\varepsilon_{reff}} \sqrt{\mu_o \varepsilon_o}} - 2\Delta L \tag{2}$$

Extensionlength ΔL is given by

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

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

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



(a) (b)

Figure 1. Configuration of antenna (a) patch antenna (b) patch antenna with NRI superstrate

Table 1. Dimensions of the patch antenna

Basic Configuration			Patch antenna				Feed Line		Ground Plane	
Variable			B1, B2		C1	C2				
	W	L	W	L	Radius	Radius	W	L	G_W	G_L
Dimensions (mm)	74	83	21	15	32	15	2.93	15	84	5.5

3. Designand Simulation of the NRI Unit Cell

The configuration of the proposed unit cell is illustrated in Figure 2. It consists of nested split ring resonator (SRR) and strip line. Nested SRRs produces the negative magnetic response so it exhibits negative permeability μ and array of strip lines will provide negative permittivity ε below the plasma frequency. Thus, the combination of these two structures will yield a negative refractive index so it is called as NRI material. In Figure 2(a), W_1, L_1, d, s and g represents the width, length, thickness, distance between the nested combs and gap in the nested SRR. The width W_{sl} and length $L_{sl.}$ of the strip line are shown in Figure 2(b).

The simulated retrieval parameters of the unit cellare s-parameters: permeability, permittivity, impedance and refractive index are shown in Figure 3. All the simulations are done using the Computer Simulation Technology Microwave Studio (CST-MWS) software. The results of the s-parameter in Figure 3(a) illustrates the magnitude of S_{21} is grater than S_{11} in the desired frequency band. This indicates that the EM waves can easily pass through the NRI superstrate within this frequency band.

Effective constitute parameters μ_{eff} and $\varepsilon_{eff}$of the unit cell are extracted from the corresponding transmission and reflection coefficients using a standard retrieval algorithm [17] are in Figure 3(b) and (c). Thr results indicates that the effective permeability μ_{eff} and permittivity ε_{eff} approachesto zero which make the corresponding effective refractive index is negative.in the frequency band 935 MHz to 960 MHz. In addition, the effective permeability and permittivity has the same value at the center frequency 947MHz of desired band which leads the NRI unit cell to have both negative refractive index and perfect impedance match with air.

The effective refractive index n is further calculated based on the effective constitute parameters and it is depicted in Figure 3(e), illustrates that it is negative in the desired frequency band. Gain of the antenna can be enhanced by using negative refractive index MTM [7]. It is also noted from the results that theimaginary part of the refractive index is relatively small at the desired frequency bandwhich means the low loss and result in high gain enhancement.

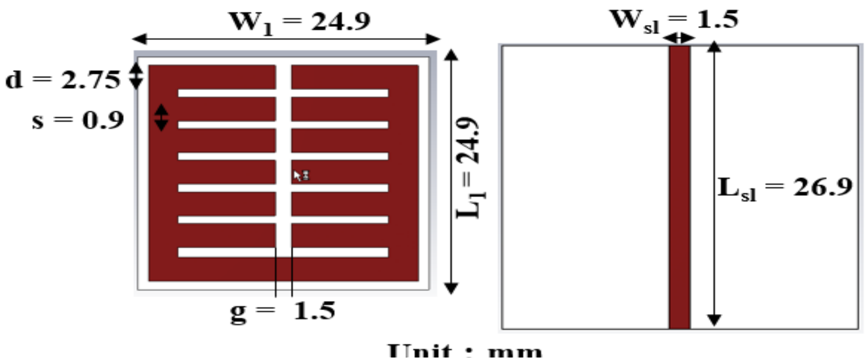


Figure 2. Confuguration of unit cell (a) SRR (b) Strip line

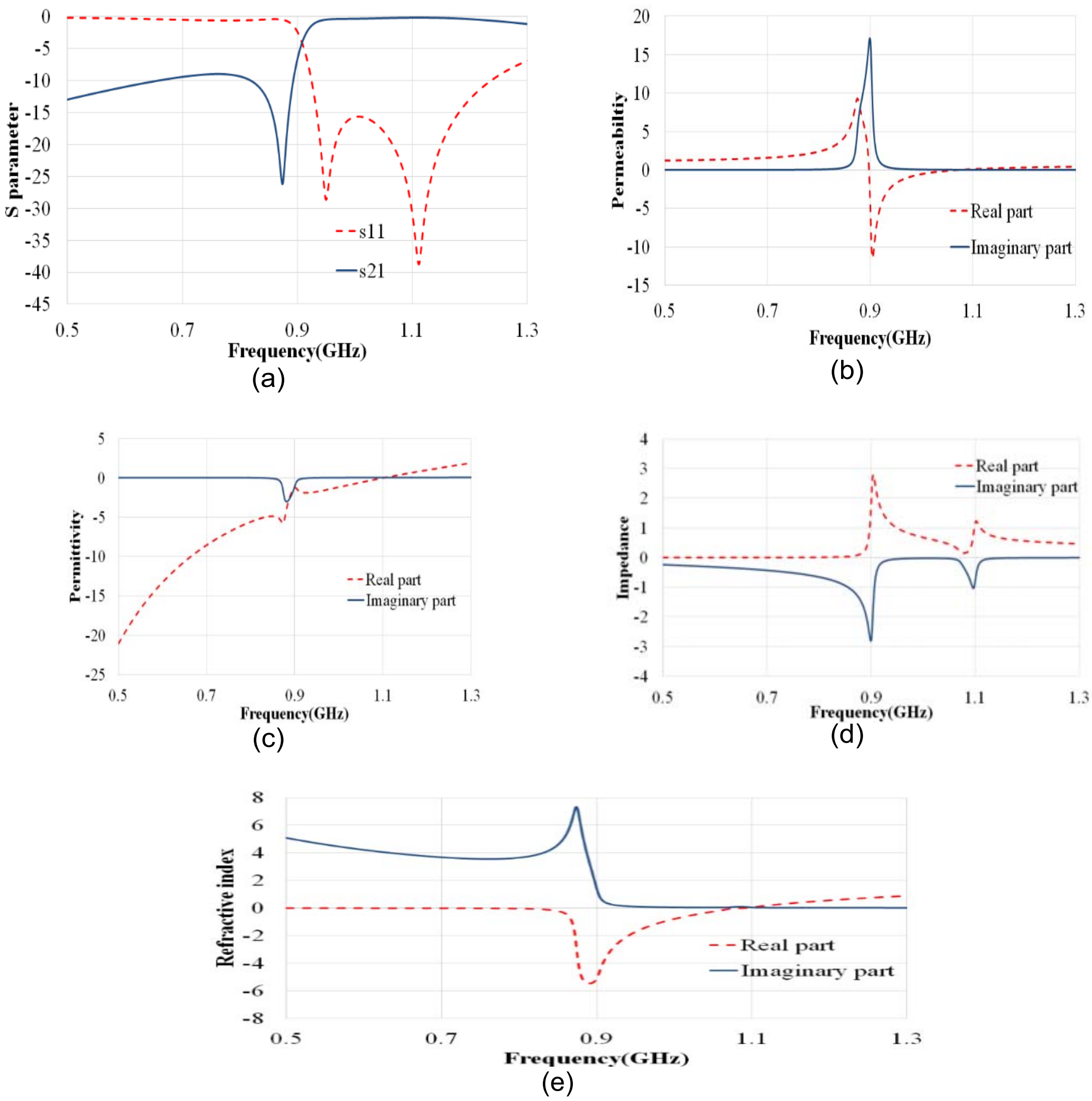


Figure 3. Simulated results of unit cell (a) s parameter (b) permeability (c) permittivity (d) Impedance (e) refractive index

4. Analysis on the Air Gap of the Proposed Antenna

Figure 1 shows the geometry of the proposed patch antenna. The air gap h is between two structures, with reflection coefficient phases φ_{GND} and φ_{NRI} respectively. From the point of the ray, an electromagnetic (EM) wave is excited by the Fabry-Perot cavity. In order to superimpose in phase, the phase shift of the EM waves is the multiple of 2π, it can be written as

$$\frac{-4\pi h}{\lambda_o} + \varphi_{NRI} + \varphi_{GND} = N \times 2\pi, N = 0,1,2.... \text{[18]} \quad (5)$$

From (5), the thickness of air gap of the NRI superstrate based patch antenna is determined by

$$h = (\varphi_{NRI} + \varphi_{GND})\frac{\lambda_o}{4\pi} + \frac{\lambda_o}{2}N, N = 0,1,2.... \quad (6)$$

Generally, the antenna profile has always close to $\lambda/2$ because the $\varphi_{GND} = \varphi_{NRI} = \pi$. In this paper, φ_{GND} is the reflection phase of the antenna ground plane, which is smaller than 180 degree for a defected ground plane, h is the height of the air gap and λ_o is the free-space wavelength. It can be observed from Figure 4 the reflection phase $\varphi_{NRI}$of the NRI unit cell is close to 27degree and the reflection phase φ_{GND} of the antenna is approximately equal to -121 degree at 947 MHz. Furthermore, the cavity height h obtained by equation (6) is equal to 41.32 mm. This is a close with the simulated result of 55 mm.The optimized gain of the antenna can be achieved by using the resonant height of the F-P cavity.

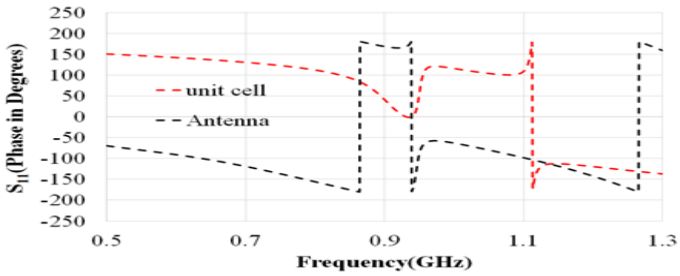


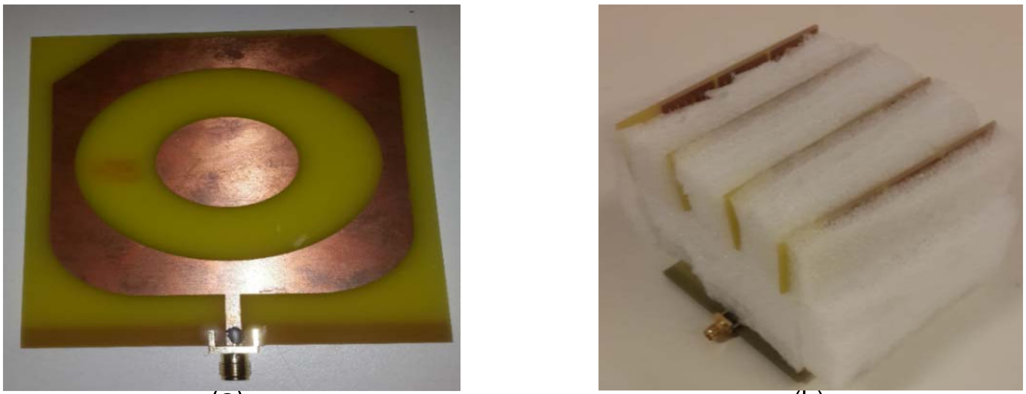
Figure 4. Results on phases of reflection coefficients for the unit cell

5. Metodology

First, patch antenna is designed and simulated to obtain the desired performance at down link RFband of GSM 900 using CST-MWS. To validate the performance of the antenna three frequencies (935 MHz, 947 MHz and 959 MHz) are considered in the desired frequency band of GSM 900 for both in simulation and measurement. Next, the nested (SRR) unit cell is designed and simulated by using frequency domain solver in CST environment. All the parameters of the nested SRR are optimized to achieve a low loss NRI NSRR unit cell. After that, the NRI superstrate is introduced on to the patch antenna and the air gap between the antenna and NRI superstrate is optimized based on F-P theory. Finally the proposed antenna is fabricated and measured the return loss S11 and radiation pattern to validate the performace of simulation results.

6. Results and Discussion

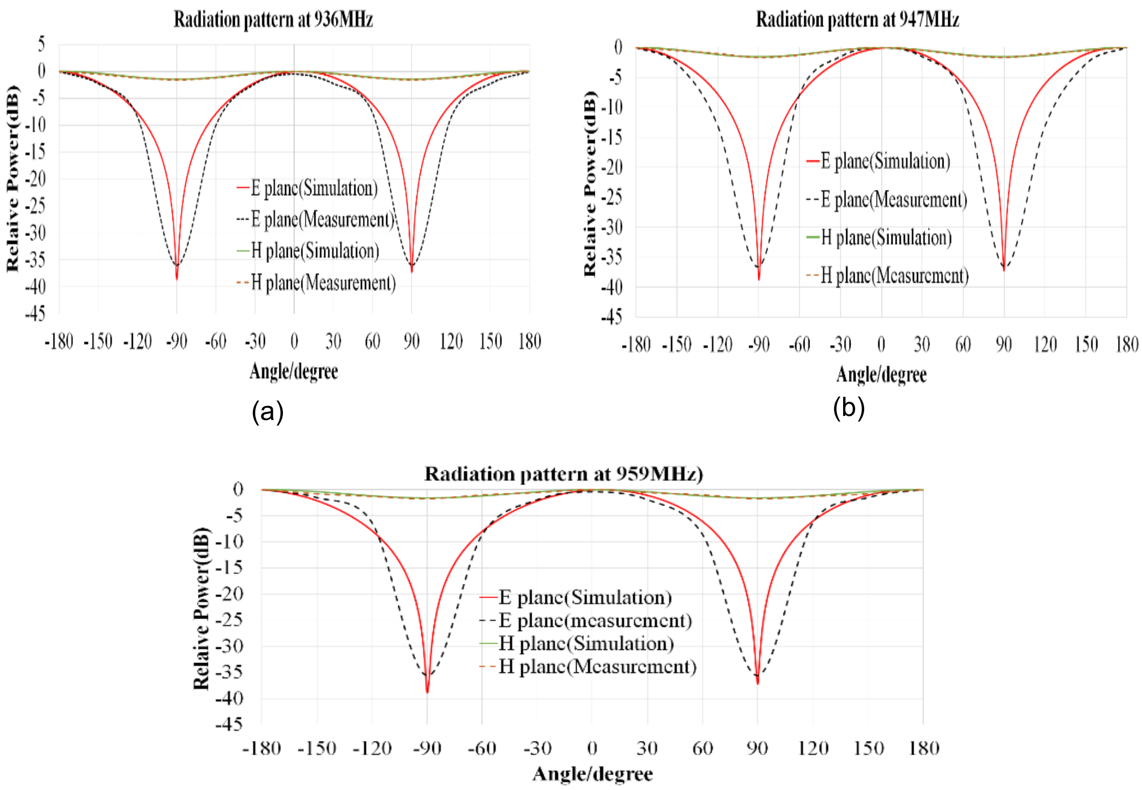
The photograph of the proposed fabricated antenna is shown in Figure 5. Measurements are done using a vector network analyser, Anapico Apsin 3000 signal generator and Gwinstek Gsp-830 spectrum analyzer.at the open space. The radiation patterns of the patch antenna with and without the NRI superstrateby simulation and measurement are shown in Figures 7 and 8. The results comparison is given at 935MHz, 947 MHz and 959 MHz. It is noted that placing the NRI superstrate onto the patch antenna reduces the half power beam width in E plane from 82.3° to 76.6°. Also comparedthe H plane pattern with and without NRI superstrate, it can be seen that, in contrast to the E plane pattern, the half power beam width in H plane is also narrowed down to 102.2°. Moreover, the measured results of E and H plane radiation pattern showed a great consistence with the simulation results.



(a) (b)

Figure 5. Photograph of the proposed fabricated (a) patch antenna (b) patch antenna with 4 layers of NRI superstrate

The simulation results of patch antenna witout with NRI superstatein polar form is shown in Figures 9 and 10.The gain of the patch antenna is increased from 2.71 dB to 4.94 dB at 947MHz. Due to the high transmission properties of NRI superstrate.



(a) (b)

(c)

Figure 7. Radiation pattern of patchantenna at (a) 936 MHz (b) 947 MHz (c) 959 MHz

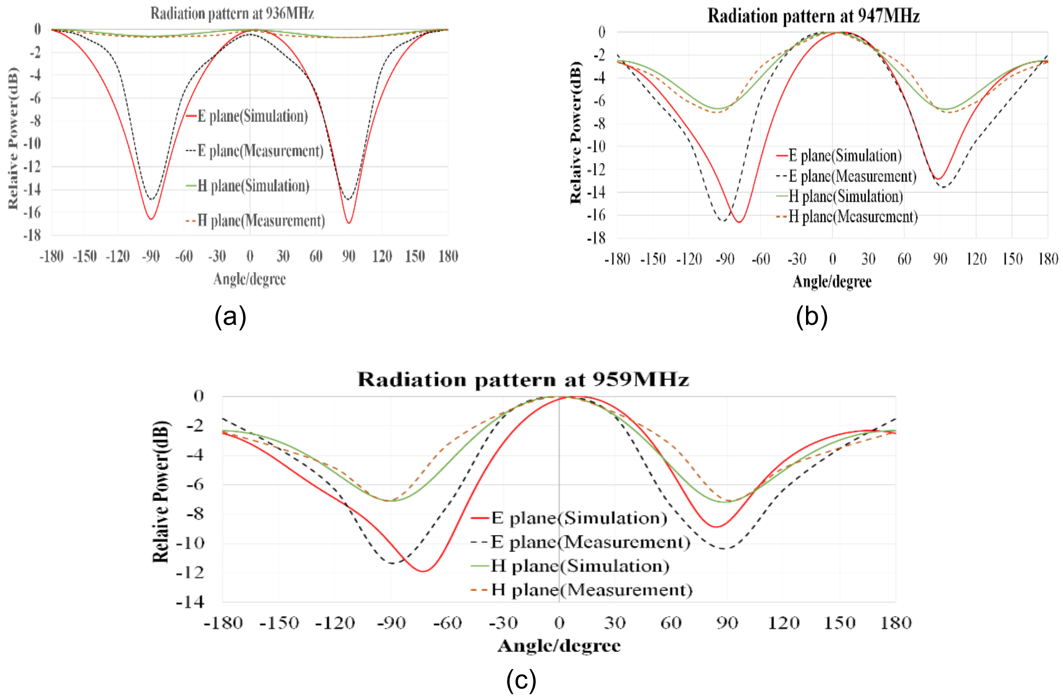


Figure 8. Radiation pattern of proposed antenna at (a) 936 MHz (b) 947 MHz (c) 959 MHz

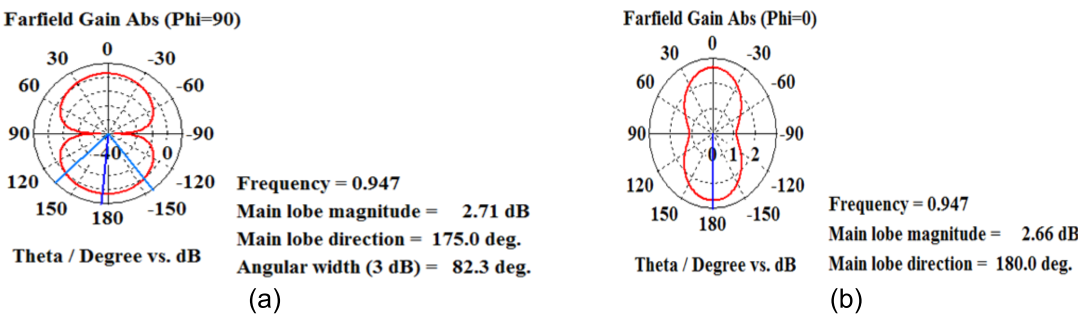


Figure 9. Without MTM gain radiation pattern of patch antenna (a) E plane (b) H Plane

Based on F-Ptheory the air gap is not vital parameter to affect the gain of the antenna. The results on gain at different heights of air gap are depicted in Figure 11. The gain enhancement is slightly influenced by the air gap and highest gain was obtained at the air gap of 55 mm.

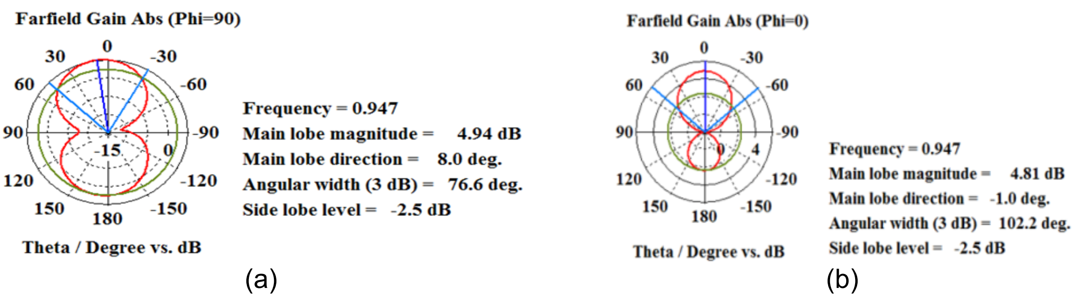


Figure 10. With MTM gain radiation pattern of patch antenna (a) E plane (b) H Plane.

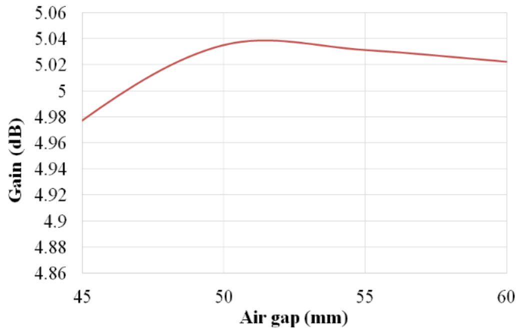


Figure 11. Comparison on the gain of theproposed antenna verses air gap

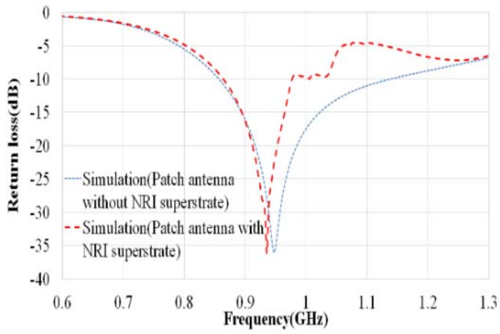


Figure 12. Comparison on simulation return lossof patch antenna

Comparison on simulated return loss for the patch antenna without and with NRI superstrate is shown in Figure 12. The result indicates that the return loss and the impedance bandwidth are reduced by 1.89% and 60%. Comparison on simulated and measured return loss of the patch antenna without and with NRI superstrate is shown in Figures 13. It is observed that the return loss and impedance bandwidth are reduced to 28.08% and 25%. Moreover, Figure 14 illustrated the simulated and measured return loss of the proposed antenna. The results showed that the return loss and impedance bandwidth are reduced to 1.24% and 36.36%. The slight decrease in impedance bandwidth is due to the high quality factor characteristic of NRI superstrate. Even then it is 2.5 times higher than desired bandwidth. However it seems to be good agreement between the measured and simulated results.

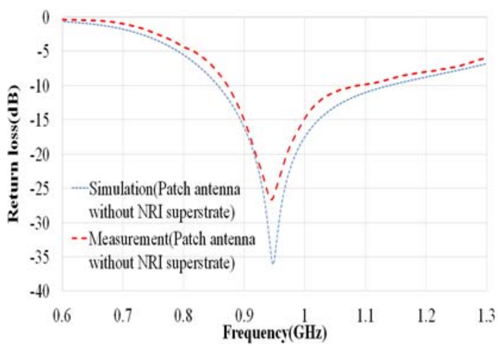


Figure 13. Comparison of sim.and test return results of the proposed antenna without NRI superstrate

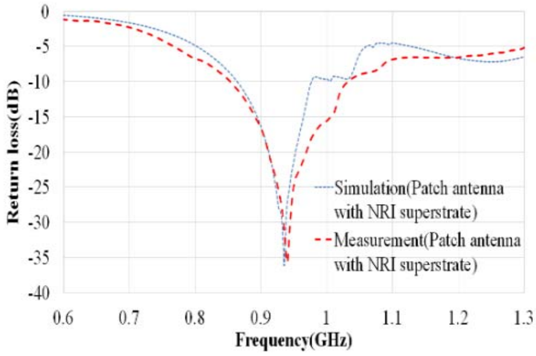


Figure 14. Comparison of sim.and test returnloss loss results for of the proposed antenna with NRI superstrate

7. Conclusions

This article proposed a negative refractive index superstrate based high-gain patch antennafor RF energy harvesting application. The NRI region of the nested SRR-strip line unit cell is well beyond the desired frequency range 770 MHz to 1070 MHz, of which the radiation from the antenna and the free space is converged. The antenna proposed is directional which the required feature for the desired application is andthe gain is increased significantly by 82.29%. Also observed that there is a degredation in impedence bandwidth due to high quality factor characteristic ofsuperstrate layer on to the patch antenna, however it is well within the desired bandwidth of GSM 900, hence the proposed antenna is suitablefor the application at this band.

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