International Journal of Engineering Works
Kambohwell Publisher Enterprises
ISSN: 2409-2770 Vol. 2, Issue 12, PP. 93-98, Dec. 2015
www.kwpublisher.com

A Negative Refractive Index Metamaterial Structure for Antenna Gain Enhancement

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Abstract— A microstrip patch antenna over which a 6 layer of metamaterial superstrate with the negative refractive index is proposed for the enhancement of gain over the conventional patch antenna The negative refractive index (NRI) property of superstrate covers the frequency range from 774 MHz to 974 MHz. The superstrate is placed 55 mm above the microstrip patch antenna. The function of the properties of negative refractive index is to gather the EM wave radiated from the antenna and the free space toward the normal direction of the antenna. An electromagnetic simulation software CST is used to study the characteristics of this metamaterial and the designe for the proposed antenna. The simulated result indicates that the gain of the proposed antenna is increased by 87.6% (2.32dB), in the desired frequency band 935 MHz to 960 MHz is also increased. Therefore, the gain of the antenna is effectively enhanced based on the negative refractive index metamaterial.

Keywords— ***n***egative refractive index, metamaterial, microstrip antenna, gain

I. INTRODUCTION

Due to the application of wide spread radio frequency spectrum for wireless communications, the power levels of radio frequeny signals has been increased. Recently Radio Frequency Energy harvesting technique is emerged as one of the environmental energy sources, which form an alternative energy source to complent the existing low power energy sources. Furthermore, RF energy harvesting has attracted the attention of many researchers to utilize on low power devices such as wearable device and electronic sensors etc. Antenna is the major component of energy harvesting system and the patch antenna is widely use due to its favourable features of low cost and easy to fabricate. However, it has drawbacks such as low impedance bandwidth and gain. Consequently, in recent years various types of techniques have been proposed to overcome this problem[1].

This Research work is funded by Ministry of Higher Education Malaysia Grant No. is FRGS/2/2013/ ST02INTI/ 02/01.

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For applications requiring high gain and broadband, array antennas had been widely used. The problem arising here is that need a complicated feeding network which makes difficulty in design and fabrication of array antennas. One of the advanced solutions for patch antennas performance enhancement is introducing the NRI metamaterial superstrate on to the patch antenna.

Forty years ago, Veselago [2] predicted that material which consists of negative permittivity, ε and permeability, μ simultaneously will exhibit some unusual properties such as negative refractive index. Furthermore, the propagation vector, k, electric (E) and magnetic field (H) vector of these materials form a left handed set of vector which are opposite to the commonly known right handed material. Therefore, these materials can called left-handed (LHM) or negative refractive material (NIM) [3]. Furthermore, the frequency range where consists of negative permittivity and permeability can control structure of the unit cell [4]. Finally, Smith successfully made the first left-handed metamaterial in which both ε and μ were negative [5]. Different structures have been proposed in the recent studies; such as Omega, S [6], Fishnet [7], Labyrinth [8], and triangle [9] shapes; all of them exhibit the properties of NRI. Due to the special properties of NRI metamaterial, many researcher have been interested in investigating the properties of this artificial material and several of them used this material property to improve the performance of the microwaves device such as antennas and the filters [10]–[14].

In this article, a study has been made to analyze and discuss the properties of the NRI structure for the desired frequency band of GSM 900. In addition, the performances of the antenna with and without the NRI structure are also analyzed and discussed. The NRI superstrate structure used in this study is a combination of Triangular split ring resonator (TSRR) and strip line. According to the our research, TSRR hasn't used for gain enhancement of microstrip antenna.

This paper is organized as follows: section II of this article described the antenna configuraton, design and simulation study of NRI unit cell in section III, proposed antenna structure in section IV, methodology in section V, discussion on results in VI and paper is concluded in section VII.

II. ANTENNA CONFIGURATION

The configuration of proposed patch antenna with NRI superstrate is shown in Fig. 1. It consists of three layers which are patch antenna, air gap and the NRI superstrate. The patch antenna consists of three components; bevel shape, and ring slot, and defective ground plane. The configuration of patch antenna is shown in Fig. 2. Bevel shape, ring slot of patch are printed on one side and the defective ground plane printed on the other side of FR 4 substrate. with thickness of 1.6 mm. The permittivity of 4.7, conductivity of 5.9×10^7 S/m and loss tangent of 0.025 is chosen for substrate. The optimized dimensions of proposed patch antenna is shown in Table.1.

The patch antenna illustrated in Fig.2 consists of two bevels and ring slot which are denoted by B1, B2 and S1. The function of the ring slot and the two bevels are used to control the resonant frequency and impedance bandwidth of the antenna. The defective ground plane at the back of the substrate is used to enhance the impedance bandwidth of the antenna. The width, length, effective length and effective dielectric constant of the patch antenna was determined by (1), (2), (3) and (4)[1]:

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

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

Normalized extension of ΔL is given by

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

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

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

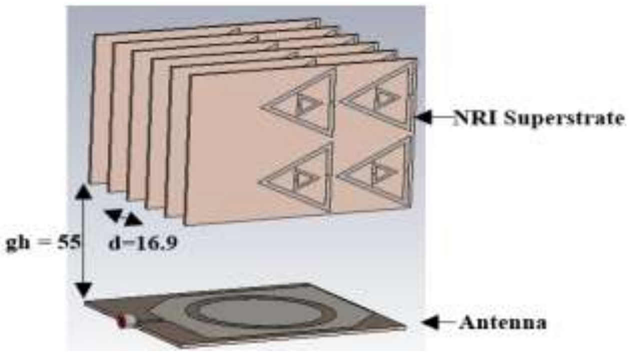


Figure 1. Configuration of proposed microstrip antenna with NRI superstrate

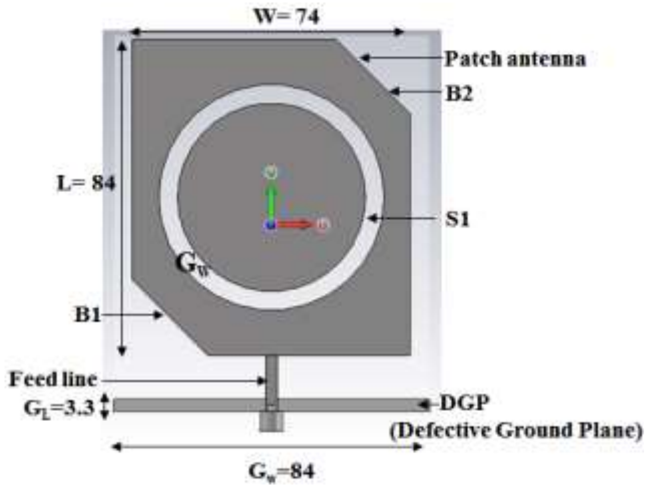


Figure 2. Configuration of patch antenna

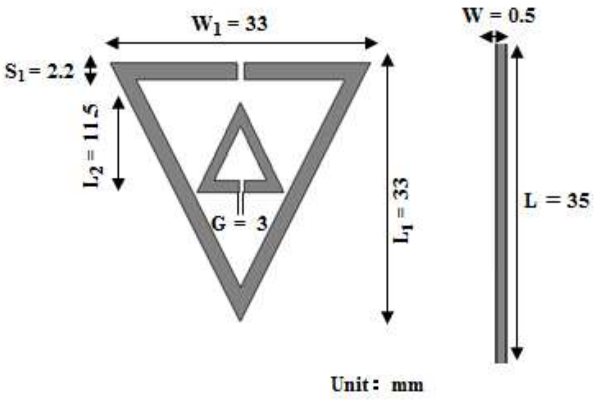
TABLE I. DIMENSIONS OF THE PATCH ANTENNA

Basic Config.	Patch antenna						Feed Line		Ground Plane	
Variable	W	L	B1		B2					
			W	L	W	L	W	L	G_W	G_L
Dimension (mm)	74	84	20	20	20	20	2.93	15	84	3.3

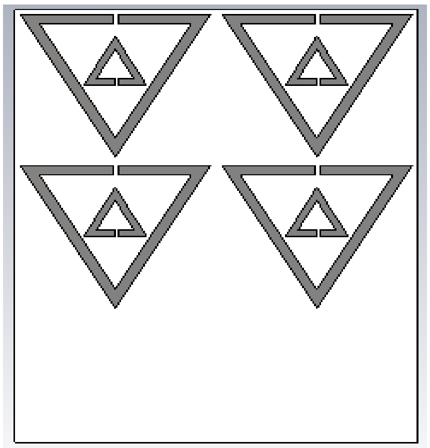
III. THE DESIGN AND SIMULATE OF THE NRI UNIT CELL

The NRI metamaterial superstrate is realized by etching the periodic triangular shaped unit cell on one side of the dielectric-slab and the other side is the strip line. The configuration of the triangle unit cell and the strip line with the optimized dimensions are shown in Fig. 3(a). It is realized by two triangular shaped in opposite direction and one strip line behind the triangular shaped structure. Fig. 3(b) is the geometry of proposed NRI superstrate with 6 layers is used in the design. This consists of 2 × 2 unit cells that are placed 55 mm above the patch antenna. The periodic structure which includes unit cells and strip lines printed on the surface of FR 4 substrate. The characteristic of unit cell substrate is same with antenna substrate, and the size of the it is 100 mm × 70 mm. The distance between unit cell and the dielectric substrate is 1 mm and the spacing between each unit cell is 2 mm.

ISSN: 2409-2770



(a)



(b)

Figure 3. (a) Configuration of TSRR unit cell (b) Geometry of proposed NRI superstrate

In 1998, Pendry *et al.*[15] proposed that the array of metal wires has the property of negative ε below the plasma frequency and it opens new possibilities for GHz devices. Metals consist of some response to electromagnetic radiation (EM) radiation due to the plasma resonance at the electron gas [15] and it can be described by the equation (5)

$$\varepsilon_{eff} = 1 - \frac{w_p^2}{w^2} \tag{5}$$

where ω_p is the plasma frequency and w is the frequency of the unit cell structure, the effective permittivity will approach to zero when the ω is very close to the ω_p.

After that, the effective permeability of the structure also can be calculated by the equation (6)

$$\mu_{eff} = 1 - \frac{Fw^2}{w^2 - w_o^2 + iw\Gamma} \tag{6}$$

Where F is represents the fractional area of the unit cell occupied by the interior split ring, Γ is the dissipation factor, $\omega_o = 1/\sqrt{LC}$ is the resonant frequency of the unit cell. Furthermore, refraction index n is defined by the equation (7)

$$n = \sqrt{\mu_{eff}\,\varepsilon_{eff}} \tag{7}$$

Based on the Equation (7), the negative refractive index can be obtained when the both μ_{eff} and ε_{eff} are negative. The near zero refractive index metamaterial can be used to gather the wave radiated from the antenna toward the normal direction of the antenna as demonstrated by Enoch *et al.* [16]. On the other hand, Wu *et al* [6] has experimented that the gain of the antenna can be enhanced by using negative refractive index metamaterial.

A standard retrieval algorithm is used based on the work by D. R. Smith [17] where effective constitutive parameters are extracted from the scattering parameters.

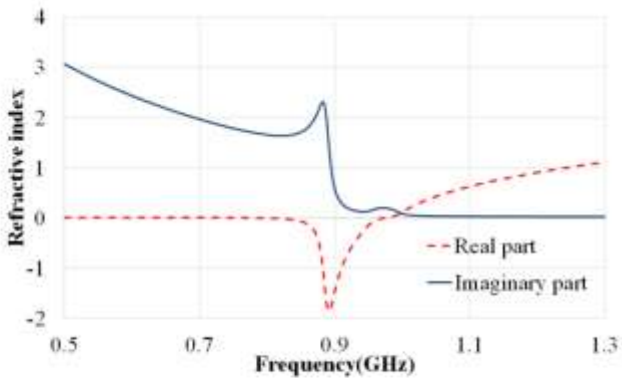


Figure 4. Results of real and imaginary parts of refractive index of unit cell

It can be observed from Fig.4, the refractive index of the unit cell is negative within the frequency range of 774 MHz to 974 MHz and approach negative one at 947 MHz.

IV. ANALYSIS ON THE STRUCTURE OF THE PROPOSED ANTENNA

In this section, the overall structure and the air gap between the antenna and the NRI superstrate layer will be discussed based on the theory of Fabry-Perot (F-P) resonant cavity. The proposed antenna with NRI superstrate and the air gap between them can be considered as an F-P resonant cavity antenna and cavity height. The cavity height h is proportional to the sum of the electromagnetic (EM) reflection phase values of the NRI superstrate and antenna ground plane. The resonant condition is given by A. P. Feresidis [18].

$$h = (\varphi_{NRI} + \varphi_{GND})\frac{\lambda_o}{4\pi} + \frac{\lambda_o}{2}N,\ N = 0,1,2\ldots. \tag{9}$$

where the φ_{NRI} is the reflection phase of the NRI unit cell, 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 Fig. 5 the reflection phase φ_{NRI} of the NRI unit cell is 75 degree at the frequency of 947 MHz and the reflection phase φ_{GND} of the antenna approximately equal to 69 degree at 947 MHz. Furthermore, the cavity height h between antenna and the NRI superstrate was obtained by equation (9) which is equal to 63.2 mm. This is a close to 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.

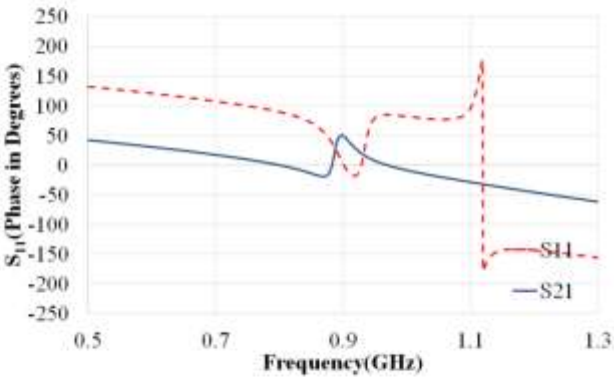


Figure 5. Results of phases of reflection and transmission coefficients for the unit cell.

V. METHODOLOGY

The proposed antenna is designed using a full-wave 3D electromagnetic simulation software Computer Simulation Technology (CST) Microwave Studio, which is based on Finite Integration Technique (FIT) approach. First, a patch antenna is designed and simulated to obtain the desired performance at down link radio frequency of GSM 900 band. Next, the triangular split ring resonator (TSRR) unit cell is designed and simulated by using frequency domain solver in CST environment. All the parameters of the TSRR are optimized to achieve a low loss NRI TSRR 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, 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 at the desired frequency band.

VI. RESULT AND ANALYSIS

The results of proposed antenna gain, radiation characteristics and bandwidth are presented and discussed in this section. The results are obtained using EM simulator Computer Simulation Technology (CST). The comparison on gain versus frequency of the proposed and the conventional patch antenna is shown Figure 6 the results indicates that the proposed FP antenna has improved well gain 91.4% (2.42 dB) characteristics in the desired band. when compared with conventional patch antenna.

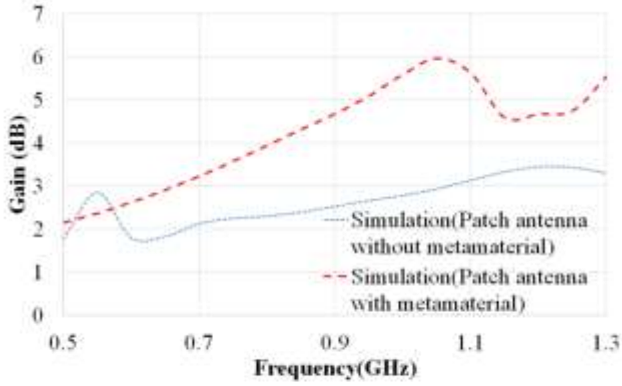


Figure 6. Comparison of the gain for propsed antenna with and without NRI superstrate

The results of the radiation characteristic for antenna with and without NRI superstrate in 3D, E plane and H plane are presented in Figure 7 to Figure 12. The results in 3D, both E- and H-planes at resonance frequency of 0.947 GHz show 2.42 dB, 2.42 dB and gain improvement 2.29 dB for the proposed antenna. In addition, the main direction of the antenna change from backside to front side of the antenna and the half power beam width (HPBW) of the antenna decreased from 82.9º to 71.7º as shown in Figure 9 and Figure 10. Furthermore, through the observation of H plane radiation pattern of the antenna which shown in Figure 11 and Figure 12, the main lobe direction of the antenna also change from backward direction to forward direction which show the effect of the NRI superstrate.

The results of return loss for the proposed antenna with with out NRI structure is shown in Figure 13. The use of TSRR and strip line NRI superstrate, the bandwidth of the overall structure is decreased but it is still well cover the desired frequency band of 935 MHz to 960 MHz. The reason behind to decrease of impedance bandwidth by using NRI superstrate is that the proposed NRI superstrate resonant structure is with high Q so the impedance is decreased. In addition, return loss of the proposed patch antenna also increase from -31.83 dB to -27 dB due to NRI superstrate.

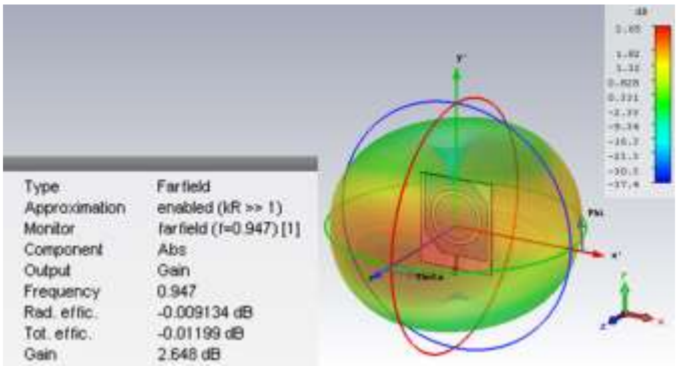


Figure 7. Polar form of E plane gain radiation pattern of proposed NZRI superstrate with antenna

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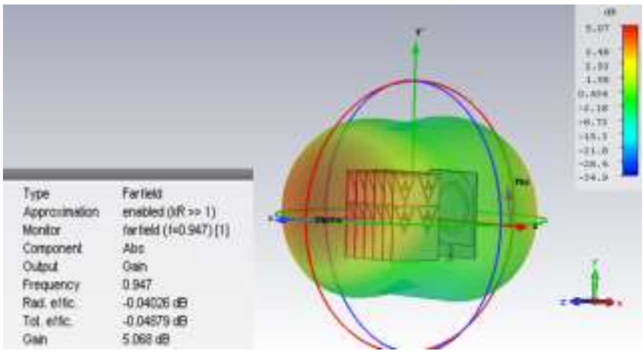


Figure 8 Polar form of E plane gain radiation pattern of proposed NRI superstrate with antenna

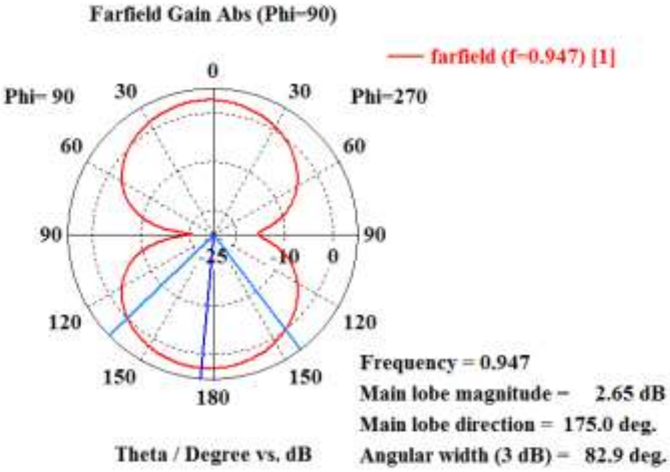


Figure 9. Polar form of E plane gain radiation pattern of patch antenna

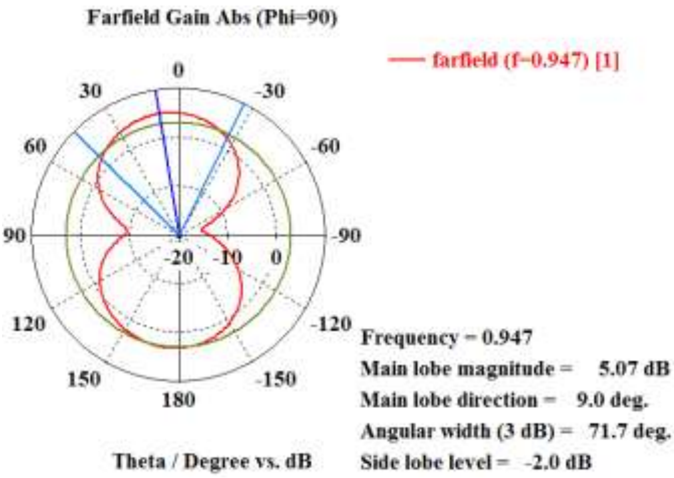


Figure 10. Polar form of E plane gain radiation pattern of proposed NRI superstrate with antenna

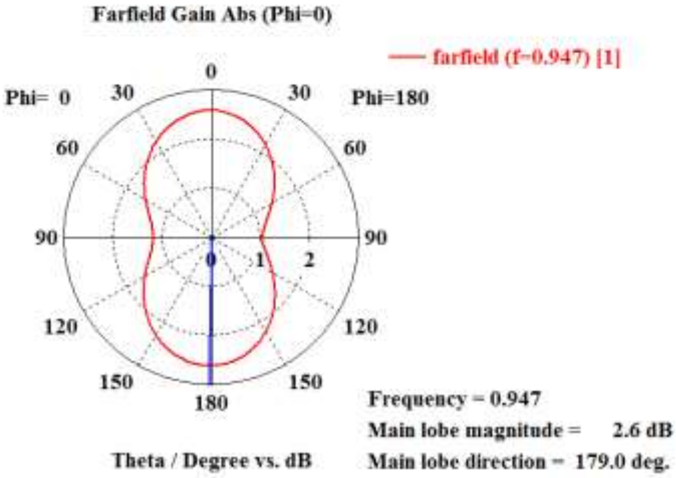
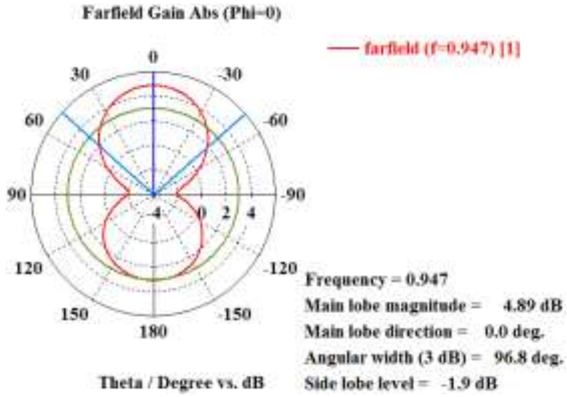


Figure 11. Polar form of H plane gain radiation pattern of patch antenna



Fighure 12. Polar form of H plane gain radiation pattern of proposed NRI superstrate with antenna

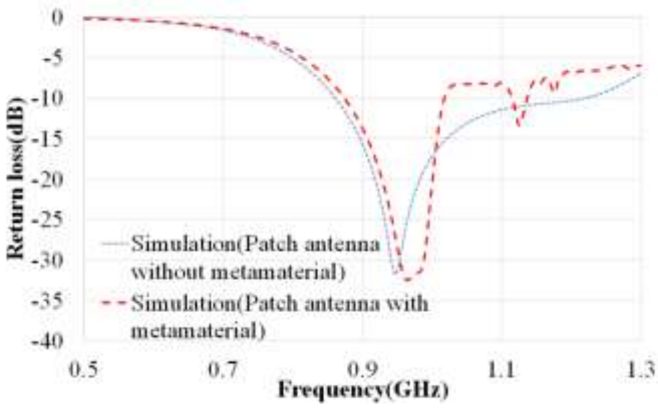


Figure 13. Comparison results of returns loss of the proposed antenna with and withot superstrate structure

Table II shows summarized performance of the antenna with and without the NRI superstrate.

TABLE II. SUMMARY OF THE SIMULATION RESULT

Results		Antenna type	
Simulation (at 947MHz)	Parameters	Patch antenna	Patch antenna with NRI superstrate
	Impedance Bandwidth (MHz)	356	144
	Return loss(dB)	-31.83	-27
	Gain(dB)	2.648	5.068

CONCLUSION

This article proposed the negative refractive index superstrate based high-gain rectangular microstrip antenna. The negative refractive index region of the triangular unit cell is within the required frequency range of 774 MHz to 974 MHz, of which the radiation from the antenna and the free space is converged. As a result, it improves the antenna's gain significantl, and is increased by 2.42 dB in this research work. It is also observed that there is degredation in impedence bandwidth due to superstrate layer on to the patch antenna, however the impedance bandwidth is well within the desired bandwidth of the downlink radio frequency band of GSM 900, hence the proposed antenna is suitable for RF energy harvesting at this band.

ACKNOWLEDGMENT

We would like to acknowledge and thank the Ministry of Higher Education Malaysia for funding this project under the Fundamental Research Grant Scheme (FRGS);Grant No: FRGS/2/2013/ ST02INTI/ 02/01.

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