Gain Enhancement of Microstrip Patch Antenna using Low Loss Negative Refractive Index Metamaterial Superstrate

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***Abstract*—A novel microstrip patch antenna (MPA) based on planar negative refractive-index metamaterial is proposed. It is demonstrated that the proposed nested split ring resonator (SRR) structure metamaterial yields an effective refractive index that equal to negative value over the frequency range of 770 MHz to 1070 MHz The negative refractive index structure is applied as a superstrate to a C-shaped microstrip patch antenna. The simulation results show that the gain is effectively improved by 2.64 dB (119 %) after the incorporation of negative refractive index metamaterial superstrate. The results illustrated that the gain of the proposed antenna is enhanced over the desired frequency band 935 MHz to 960 MHz. The air gap between the antenna and superstrate was also studied by applying the theory of Fabry-Perot (F-P) resonant cavity to obtain the optimum air gap of 55 mm to achieve the maximum gain.**

***Index Terms*—C-Shaped Patch Antenna; Gain; Nested Split Ring Resonator; Negative Refractive Index, Radio Frequency Harvesting System.**

I. INTRODUCTION

Currently, batteries are the main energy source for portable devices. However, it consists of several drawbacks such as limited battery life often needs maintenance. Recently, energy harvesting technique is one of the alternative sources which can help to solve the use of limited life of batteries in certain applications.

Source of energy harvesting include kinetic, radio frequency, piezoelectric and thermal energy which are the suitable source for the energy harvesting. Among the various techniques of energy harvesting, Radio Frequency and Piezoelectric are the most popular energy harvesting techniques for low power application. In RF energy harvesting system, antenna is the vital component. The microstrip antennas are widely used due to its inherent characteristics such as low profile and low cost. In spite of several of its advantages, they also suffer from few drawbacks such as low gain and narrow bandwidth which limits their application. In order to overcome the limitations of microstrip patch antennas numerous techniques are proposed such as low permittivity and thick substrate [1], stacking of microstrip element [2], truncating and slotting the microstrip patch antenna [3] to improve the bandwidth of the antenna.

In recent years, metamaterials have shown tremendous potential on the performance enhancement of the antenna. It can use 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 1968, Veselago [4] explored the properties of isotropic media where both the permittivity and the permeability are simultaneous negative will exhibit unusual physical properties such as negative refraction. The propagation vector k, electric field, E and magnetic field, H vector of these materials form a left handed set of vectors which are opposite to the commonly known right handed material. Therefore, these materials also known as the left-handed materials (LHM). In 2000, Smith [11] successfully made the first left-handed metamaterial prototype using split ring resonator (SRR) and thin wire (TW).

Enoch [5] proposed that the gain of the antenna can be enhanced through the use of near zero refractive index metamaterial. He exploited the thin wires structure to make the metamaterial place on a dipole antenna to enhance the gain. Various structures have been proposed In the recent years such as Omega -shape, S -shape [6], Fishnet -shape [7], Labyrinth –shape [8], the combination of modified square rectangular Split Ring Resonator (SRR) and the Capacitance Loaded Strip (CLS) [9], triangular–shape [10] and all of them exhibit the properties of NRI. Due to the special properties of NRI metamaterial, a large number of researches have been done by using it to enhance the microwaves device such as antennas and the filter [9], [11]–[14].

In this paper, the design of a C-shaped patch antenna with 4 layer of low loss nest structure SRR NRI superstrate for gain enhancement is presented. The nested SRR is proposed by Yong Liu [15] in 2013. To the best of author’s knowledge, the nested SRR hasn’t been used before to improve the antenna gain. The proposed antenna is designed for RF energy harvesting system at downlink radio frequency band of GSM 900. The objective of the work in this paper, is to increase gain of the antenna by using the NRI superstrate layer and the impedance bandwidth to cover the desired frequency band.

The paper is organized as follows: the proposed antenna design and configuration is described in Section 2, design of NRI superstrate discussed in Section 3, analysis on the proposed antenna discussed in Section 4, methodology presented in Section 5, the results and analysis are summarized in Section 6 and the conclusion or summary of research work presented in Section 7.

II. ANTENNA DESIGN AND CONFIGURATION

The configuration of proposed patch antenna with NRI superstrate is illustrated in Figure 1. The structure contains 3 components, which are C-shaped patch antenna, air gap and the NRI superstrate. Figure 2 depicts the patch antenna configuration. It is a C-shaped patch on one side and defective ground plane on the other side of FR 4 substrate printed with a thickness of 1.6 mm, permittivity of 4.7 loss tangent of 0.025 and conductivity of 5.9 × 10^7. The optimized dimensions of the antenna structure are shown in Table 1.

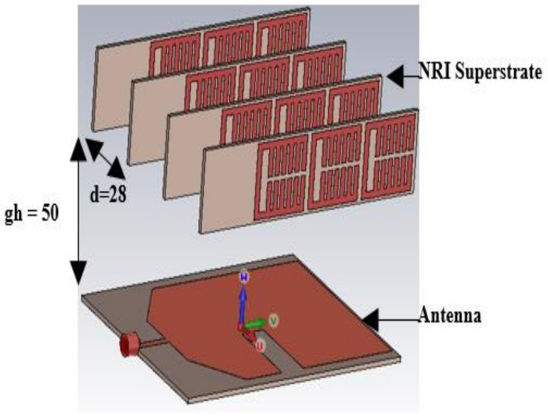

Figure 1: Configuration of proposed antenna with NRI superstrate

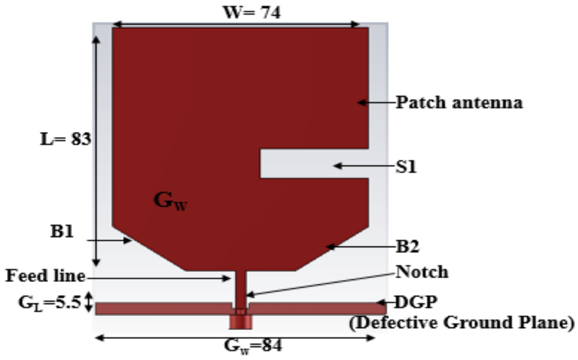

Figure 2: Configuration of C- shaped patch antenna

The patch antenna illustrated in Figure 2 consists of 2 bevels and a horizontal slot which is denoted by *B1*, *B2* and *S1*. The function of the horizontal slot and the two bevels are to control the resonant frequency and impedance bandwidth of the antenna. In addition the defective ground plane at the back of the substrate also contributes to enhance the impedance bandwidth of the antenna. The width *(W)*, length *(L)*, effective dielectric constant (ε_{eff}) and effective length (ΔL) of the patch antenna is determined using Equations (1), (2), (3) and (4) obtained from [16].

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

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

Table 1
Optimized dimensions of the patch antenna

Basic Configuration	Patch antenna						Feed Line		Ground Plane	
Variable	W	L	B1, B2		S1					
			W	L	W	L	W	L	G_W	G_L
Dimension (mm)	74	83	21	15	31.4	10	2.93	15	84	5.5

Normalized extension of ΔL is given by:

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

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

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

III. DESIGN OF NRI SUPERSTRATE

The configuration of the proposed NRI unit cell is illustrated in Figure 3 which is the combination of the nested SRR and strip line.

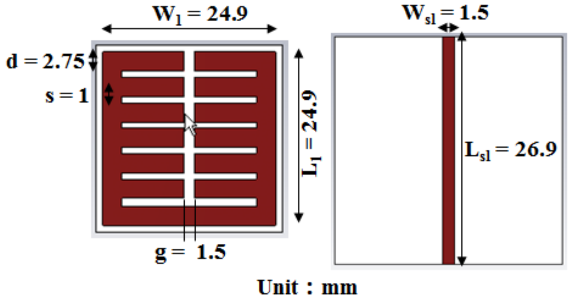

Figure 3: Configuration of unit cell (a) SRR (b) Strip line

The length of the unit cell substrate (FR 4) is 35 mm, and the properties are the same as used for antenna substrate. The nested SRR has the dimensions of 24.9 mm in width (*w)* and length (*l)*. In addition, the thickness of the nested SRR is 2.75 mm and the width of the split is 1.5 mm.

Negative refractive index metamaterial superstrate in this paper is realized by combining the periodic strip wires and the nested SRR structures as shown in Figure 3. It consists 4 layers of NRI superstrate with 3 x 1 nested SRR and strip wire. Nested SRRs produces the negative magnetic response so it exhibits negative permeability µ and array of strip lines will provide negative 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 this research work, a standard retrieval algorithm [17] is used to retrieve the constitutive effective parameters of unit cell. These parameters are extracted from the scattering parameters and all the results obtained are shown in the Figure 4 to Figure 7. Figure 4 illustrate reflection phase of the unit cell and antenna. The real and imaginary parts of the, permittivity, permeability and refractive index are shown in Figures 5, 6 and 7 respectively. According to the retrieved result shown in Figure 5 and 6, the nested SRR-strip line structure has the property of negative permittivity and permeability around 947 MHz and the frequency region of negative refractive index is from 774 MHz to 974 MHz. which is well within the desired frequency band.

In general, the analysis of NRI superstrate for gain enhancement of antenna is based on the effective near zero negative refractive index *n*. By analyzing the reflection and transmission properties of the NRI superstrate, the refractive index obtained is shown in Figure 7. It can be observed that the refractive index is close to zero around 947 MHz where the EM wave can be concentrated around the normal of the NRI slab.

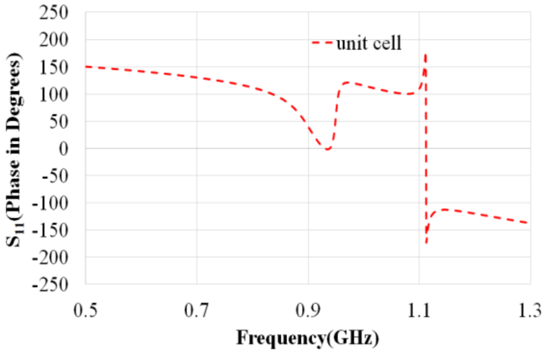

Figure 4: Results of the phase of reflection coefficients for the antenna ground plane and the unit cell.

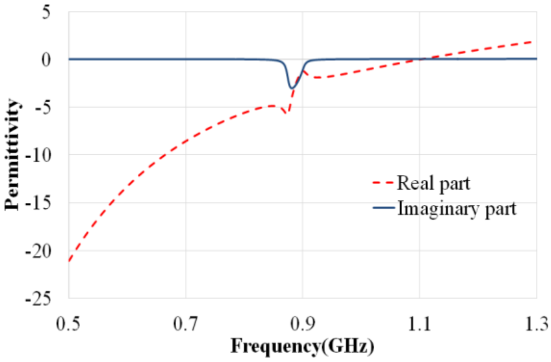

Figure 5: Results of real and imaginary parts for permittivity of the unit cell

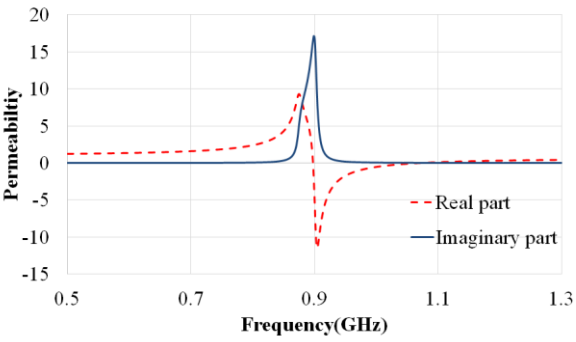

Figure 6: Results of real and imaginary parts for permeability of the unit cell

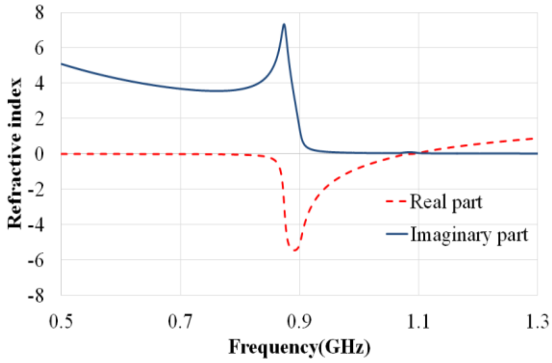

Figure 7: Results of real and imaginary parts for refractive index of unit cell

IV. ANALYSIS ON THE PROPOSED ANTENNA

In this section, the overall structure and the air gap between the antenna and the NRI superstrate layer are discussed based on the theory of Fabry Perot 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 reflection phase values of the NRI superstrate and antenna ground planes. The resonant condition is given by Equation (5), obtained from [20].

$$h = (\varphi_{NRI} + \varphi_{GND})\frac{\lambda_o}{4\pi} + \frac{\lambda_o}{2}N, N = 01,2,3.... \qquad (5)$$

where the φ_{NRI} is the reflection phase of the NRI superstrate, φ_{GND} is the reflection phase of the antenna ground plane and it is equal to π for a full ground plane, h is the height of the air gap and λ_o is the free-space wavelength. It is observed that the reflection phases φ_{NRI} of the NRI unit cell and antenna ground plane φ_{GND} are approximately equal to -27 degree and 128 degree respectively at the center (947 MHz) down link radio frequency of GSM 900 band. The cavity height h between antenna and the NRI superstrate was calculated using Equation (5), obtained a value of 44.3 mm and is almost matches with the simulated result 50 mm. The maximum gain of the antenna can be achieved by using the resonant height of the F-P cavity.

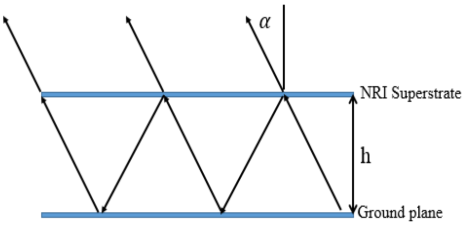

Figure 8: F-P resonant cavity composed of a ground plane and a superstrate

V. METHODOLOGY

Full-wave 3D electromagnetic simulation software, Computer Simulation Technology (CST) Microwave Studio is used in design and simulation of the proposed antenna which is based on Finite Integration Technique (FIT). First the C-shaped patch antenna was designed and simulated to obtain the desired performance at GSM 900 band. Secondly, the SRR unit cell is designed and simulated using the frequency domain solver in CST which is more suitable for electrically small structure. All the parameters of the SRR are optimized to achieve a low loss NRI nested SRR unit cell. After that, NRI superstrate is introduced onto the C-shaped patch antenna and the air gap between the antenna and NRI superstrate is optimized based on the theory of Fabry-Perot. 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 using parametric optimization in CST at the desired frequency band.

VI. RESULTS AND DISCUSSION

The results obtained with and without NRI superstrate are discussed in this section. The radiation patterns for both antennas in E-plane are shown in Figures 9, 10 and H-plane are in Figures 11, 12. From the observation, the gain improvement of the C-shaped antenna is 2.65 dB after the incorporation of the NRI superstrate. The Half power beam width (HPBW) for E-plane is narrowed down from 83.8 degree to 77.2 degree, and in H-plane, the HPBW narrowed down to 110.6 degree. On the other hand, the main lobe direction of the antenna also changes from backward direction to forward direction as depicted in Figures 9 to 12.

Figure 13 illustrate that the gain comparison of the proposed antenna over conventional patch antenna in the desired frequency band 935 MHz to 960 MHz. This clearly indicates that the NRI superstrate effectively working in this frequency band.

There is some trade-off of performance where there is degradation on the impedance bandwidth as shown in the Figure 14. The impedance bandwidth of the proposed antenna decreased from 273 MHz to 120 MHz after the incorporation of the NRI superstrate, even then it is much higher than the desired band width. The resonant frequency is slightly shifted to the lower frequency and the return loss still remains the same.

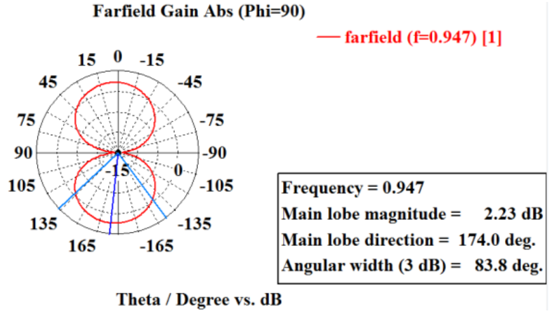

Figure 9: Polar form of E plane gain radiation pattern of conventional patch antenna

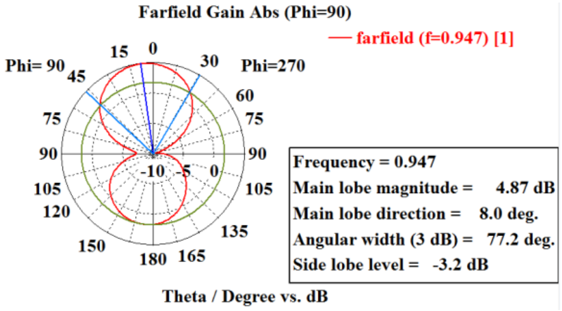

Figure 10: Polar form of E plane gain radiation pattern of C- shaped antenna with NRI superstrate

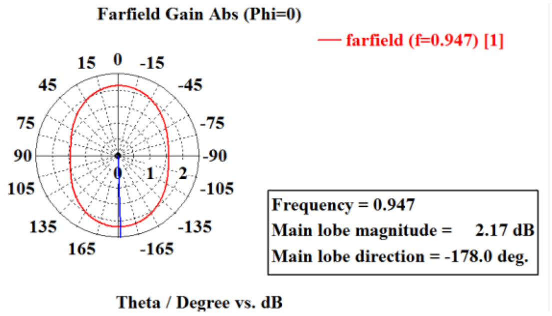

Figure 11: Polar form of H plane gain radiation pattern of C-shaped antenna

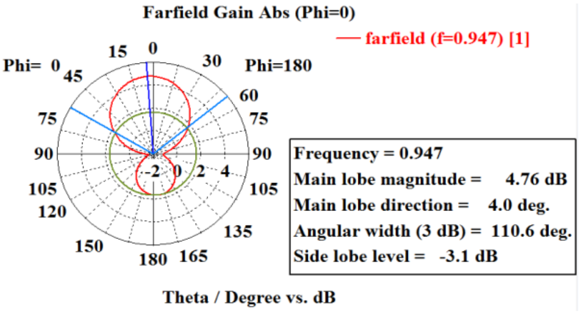

Figure 12: Polar form of H plane gain radiation pattern of C-shaped antenna with NRI superstrate

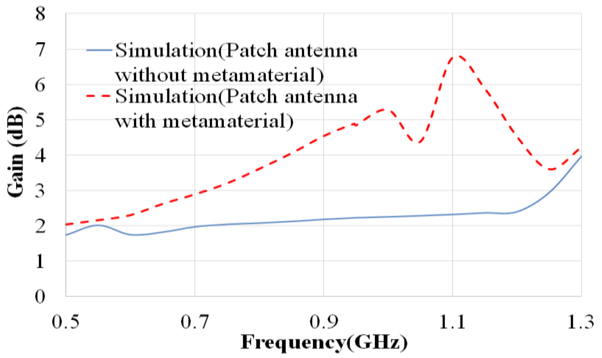

Figure 13: Comparison of the gain of C shape antenna and C- shape antenna with NRI superstrate

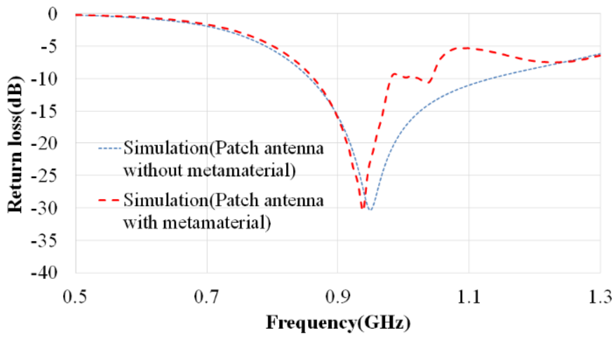

Figure 14: Comparison results of return loss of proposed antenna with and without superstrate

Summary performance of the proposed antenna is shown in Table 2.

Table 2
Performance summary of results

Results	Parameters	Antenna type	
		C-shaped Patch antenna	C-shaped Patch antenna with NRI superstrate
Simulation (at 947MHz)	Impedance Bandwidth (MHz)	273 MHz	120 MHz
	Return loss (dB)	-30.3	-30.4
	Gain(dB)	2.23	4.87

VII. CONCLUSION

The gain of the proposed antenna is successfully enhanced through the incorporation of the NRI superstrate onto the patch antenna. A gain of 2.65 dB improvement was achieved. There is a decrease in bandwidth from 273 MHz to 120 MHz. However, it is still well within the requirements of the desired impedance bandwidth. The main lobe direction of the antenna changes from the back side to the front side of the antenna. On the other hand, the HPBW of the antenna with NRI superstrate is narrowed down to 77.2 degree from 83.8 degree. These results indicate that the NRI superstrate acts as a lens which is high transmission medium and focus the EM to normal direction of the antenna. The air gap between C-shaped patch antenna and the NRI superstrate layer is also studied and the optimized air gap for maximum gain is at 50 mm. From the result and analysis, we conclude that the proposed antenna is suitable for RF Energy Harvesting System applications.

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