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Radiation Characteristics of a Novel μ Negative Metamaterial Spiral Resonator Antenna at the 2.4 GHz

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Abstract

A μ negative metamaterial using spiral resonator (SR) with an electromagnetically coupled (EMC) feeding system is proposed as a novel antenna structure. The proposed antenna is designed and fabricated on a FR4 dielectric substrate with a thickness of 1.6 mm and relative permittivity of 4.0 to achieve its radiation characteristic. The antenna is operated at frequency 2.4 GHz. To improve the antenna gain, a matching circuit is inserted into the feed line. The μ negative metamaterial is achieved by using a spiral resonator with spiral numbers N = 3, 5, 7, and 10. It is found that the negative imaginary part tends to shift leftward as the value of N increases. The simulation result of the proposed antenna structure with spiral number N = 3, strip width w = 3.1 mm, and gap width s = 0.5 mm provides the best performance with S_{11} = −15 dB, VSWR < 2 bandwidth of 30 MHz and gain of −0.5 dB at frequency of 2.43 GHz. The proposed antenna with matching circuit provides the antenna gain of 2.21 dB, which is better than that without the matching circuit. The dimensions of the proposed antenna are reduced by 53% compared with those of the conventional patch. Both the simulation and measurement results of the radiation characteristics of the proposed antenna show good agreement.

Keywords

Radiation Characteristics, μ Negative Metamaterial, Spiral Antenna

1. Introduction

Recently, antennas used in many modern wireless communication systems tend to have the characteristics of

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compact dimensions and light weight. A variety of antenna miniaturization approaches have been developed to improve the radiation characteristics. One technique to reduce the antenna dimension is the use of metamaterials. A metamaterial is a material that has negative properties of permittivity and permeability (Double Negative or DNG) of the dielectric [1]-[5]. However, some researchers argue that a material with single negative properties of dielectric permittivity is called an epsilon negative (ENG) metamaterial, and that with single negative properties of dielectric permeability is also called a μ negative (MNG) metamaterial [6]-[10]. A material with single negative properties of either permittivity or permeability of the dielectric cannot absorb the incident wave, so that it can eliminate the surface wave, which affects the performance of the radiation characteristic [11]. The planar antenna, as a media that can change the electric current to be electromagnetic wave, requires a structure with magnetic properties. Therefore, many research studies of planar-antenna miniaturization have been conducted involving the use of a μ negative metamaterial.

The MNG metamaterial can be composed of two shapes: a split ring resonator (SRR) and spiral resonator (SR). Bilotti *et al.* [6] [7] discussed the resonance frequency changes according to the ring number of MSRR or the spiral turn number of SR, which can be obtained by using its equivalent circuit. According to the equivalent circuit, the values of resistance, inductance, capacitance, effective impedance, and effective permeability of the MSRR and SR can be obtained. By using these values, the MNG property is obtained at a frequency range of 0.2 GHz - 0.225 GHz for N = 12, w = 0.1 mm, s = 0.1 mm, and l = 8 mm. MSRR and SR structures can reduce the dimension linearly up to $\lambda_0/30$ - $\lambda_0/40$ and $\lambda_0/65$ - $\lambda_0/250$, respectively. Huang *et al*. [12] obtained a dimensional reduction of a SR structure up to $\lambda_0/50$ and used the structure as an embedded spiral microstrip implantable antenna. Similarly, Soontornpipit *et al*. [13] also used the SR structure to design an implantable microstrip antenna to enable communication with medical implants and obtained a dimensional reduction of $\lambda_0/25$ - $\lambda_0/50$. However, the metamaterial properties with μ negative were not discussed in [12]. To observe these properties, the circuit model and the formulation in [6] [7] are used to calculate the effective permeability. The calculation result does not provide metamaterial properties with μ negative at the frequency range 0 - 3 GHz.

Moreover, Kevin fabricated a magnetic material by using a spiral structure as a substrate for applying small patch antenna; this approach can provide an adjustable reduction factor [8]. A spiral structure was used to create the substrate, while the radiator element used a conventional patch. The measurement result indicated that a reduction factor of approximately 40% - 70% can be obtained with an efficiency of 20% - 30%. The SR structure is frequently used to compose magnetic material as a substrate. However, the spiral resonator metamaterial has not been used as an antenna.

Therefore, this paper discusses the radiation characteristic of SR structure of μ negative metamaterial as a novel antenna. The discussion begins with a parametric study of the SR structure dimensions to determine the spiral turn number N, strip width w, gap width s of the single patch of the SR structure. The selected dimension of the planar antenna that provides the highest gain will be implemented for developing the proposed antenna. Furthermore, the MNG properties of the SR is obtained through the formulations in [6] [7] [14]. To enhance the radiation characteristics of the proposed antenna, the matching circuit is inserted into the feed line. Therefore, the radiation characteristic of the SR structure is investigated to function as an antenna as well as an MNG metamaterial substrate.

The background, purpose, and research methodology are described in section one. The design of the spiral resonator on metamaterial MNG and matching ciricuit to obtain a better characteristics of the radiation pattern are discussed in section two. The simulation and measurement result of the SR structure are shown in section three. Furthermore, the discussion and conclusion are presented in section four and five, respectively.

2. Design of a Spiral Resonator

2.1. SR Antenna on a MNG Metamaterial

The SR structure as a single patch of the planar-antenna with the EMC feeding system is shown in **Figure 1**. The EMC feeding system is also called the proximity coupled feeding system. The proposed antenna is composed of a two layer substrate. The first layer of substrate is a spiral resonantor (SR) patch, which has two functions as an antenna and MNG metamaterial and there is no ground plane separating the two dielectric layers. The second layer has a microstrip line as the feeding system, which is electromagnetically coupled to the antenna and ground plane.

A key attribute of the EMC feeding system is capacitive in nature of its coupling mechanism. This is in contrast

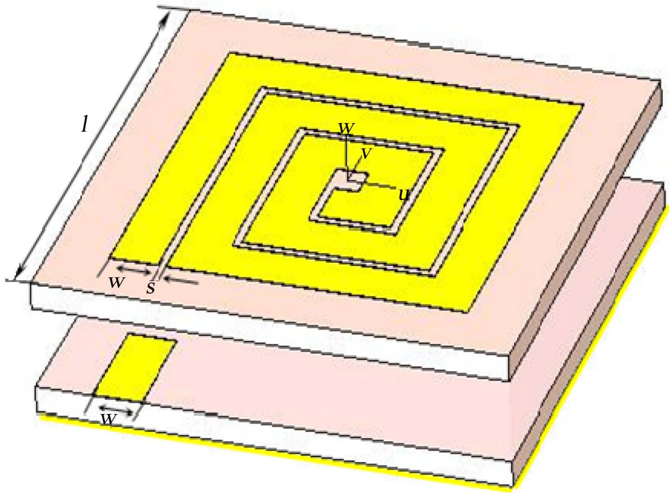


Figure 1. μ negative metamaterial SR structure as a planar-antenna.

to the direct contact methods, which are predominantly inductive. The difference in coupling significantly affects the obtainable impedance bandwidth due to the inductive coupling of the edge and probe-fed geometries limits the thickness of the material useable [15].

The SR structure dimension is defined by variables of the spiral turn number of *N*, the width of the strips of *w*, and the separation between two adjacent turns of *s*. The proposed antenna is assumed to have the constraint of the side length of the external turn of *l* which is constant. So that, the *w* and *s* values are adjusted to the *N* variations of 3, 5, 7, and 10.

The MNG metamaterial properties of the SR structure as a planar antenna for the dimensional variations can be approximately obtained by equivalent circuit models of the spiral resonator [6] [7]. The values of the inductance (L_{SR}), capacitance (C_{SR}), losses resistance in the metallic conductor (R_c^{SR}), shunt resistance due to the dissipation in the lossy dielectric (R_d^{SR}) as a function of the spiral turn number *N*, strip width *w*, and gap width *s* can be calculated by the following equations [6] [7]:

$$L_{SR} = \frac{\mu_0}{2\pi} l_{avg}^{SR} \left[\frac{1}{2} + \ln\left(\frac{l_{avg}^{SR}}{2w} \right) \right] \tag{1}$$

$$l_{avg}^{SR} = \frac{1}{N} \sum_{n=1}^{N} l_n = \frac{4Nl - \left[2N(1+N) - 3 \right](s+w)}{N} \tag{2}$$

$$C_{SR} = C_0 \frac{l}{4(w+s)} \frac{N^2}{N^2+1} \sum_{n=1}^{N-1} \left[l - \left(n + \frac{1}{2} \right)(w+s) \right] \tag{3}$$

$$C_0 = \varepsilon_0 \frac{K\left(\sqrt{1-k^2}\right)}{K(k)} \tag{4}$$

$$R_c^{SR} = \frac{\rho_c}{wt} \frac{L_{SR}}{\mu_0} \tag{5}$$

$$R_d^{SR} = \frac{1}{\sigma_d} \frac{s}{4h\left[l - (2w+s) \right]} \frac{l_{avg}^{SR}}{4l} \tag{6}$$

where:

μ_{eff} = Effective permeability of the SR structure;
Z_{eff} = Effective impedance of the SR structure;
L_{SR} = Inductance of the SR structure;

C_{SR} = Capacitance of the SR structure;
R_c^{SR} = Losses in the metallic conductor and in the dielectric;
R_d^{SR} = Shunt resistance, which takes into account the dissipation in the lossy dielectric;
$K(\bullet)$ = The complete elliptic integral of the first kind.

l_{avg}^{SR} is the average length of the spiral turn. C_0 is the per-unit-length capacitance between two parallel strips having width w and separation s.

The obtained parameters of L_{SR}, C_{SR}, R_c^{SR}, and R_d^{SR} are used to calculate the effective characteristic impedance of the SR structure, as shown in the following equation [6] [7]:

$$Z_{eff} = R_c^{SR} + \frac{R_d^{SR}}{1+\omega^2\left(C_{SR}R_d^{SR}\right)^2} + j\omega\left[L_{SR} - C_{SR}\frac{\left(R_d^{SR}\right)^2}{1+\omega^2\left(C_{SR}R_d^{SR}\right)^2}\right]. \tag{7}$$

This impedance is used to calculate the magnetic polarizability of the individual magnetic inclusion α_{mm} defined as [6] [7] [16]:

$$\alpha_{mm} = -j\omega\mu_0\frac{l^2}{Z_{eff}}. \tag{8}$$

Next, the effective permeability of the SR structure is obtained with the variation of the spiral turn number N, the strip width w, and the gap width s based on a first-order approximation of the permeability function, which is derived using the Clausius-Mosotti [6] [7] [14]:

$$\mu_{eff} = \mu_0\left(1+\frac{n\alpha_{mm}}{1-\frac{n\alpha_{mm}}{3}}\right). \tag{9}$$

2.2. Interdigital Capacitor (IDC) Parallel with a Meandered Inductor (MI) as a Matching Circuit to Enhance the Radiation Characteristics

The SR structure functions as an antenna, therefore it must be connected to the feeding system. To enhance antenna gain and bandwidth, a matching circuit is inserted in the feed line, as discussed in [17]. Two topologies were chosen, one to realize a matching from 800 MHz to 1100 MHz and another one is to realize the matching from 0.8 GHz to 2.4 GHz. The first approach was to verify the matching for a small bandwidth, and the second approach was to verify the matching throughout the entire bandwidth of the antenna. In this paper, the matcing circuit is inserted into the feed line of the proposed antenna as shown in **Figure 2**. The capacitance of the IDC and the inductance of the MI are obtained through the empirical method in [18] and the analytical approach in [19], respectively.

3. Simulations and Measurements

3.1. Simulations

The SR structure is simulated with the dimensional variation of spiral turn number N, strip width w, and gap width s. By keeping l constant, then w and s values are adjusted to the N variations of 3, 5, 7, and 10.

The MNG metamaterial properties of the SR structure with the N, w, and s variation, which will be characterized as the planar-antenna, is obtained by using Equation (1) to Equation (9), as shown in **Figure 3**.

Figure 3 shows that the MNG properties have the following characteristics: the effective permeability value (μ_{eff}) of the proposed antenna has the negative real part of at least 0.1 GHz, maintaining relatively similar value for the N variations of 3, 5, 7, and 10, and the negative imaginary part tends to shift leftward with the increasing value of N. This case shows that the negative value of μ_{eff} can be achieved at a lower frequency for larger values of N.

Furthermore, using Bilotti's work [6] [7], the SR structure is treated as a planar–antenna radiator as shown in **Figure 1** as the proposed antenna. The simulation result of the proposed antenna with variation of N, w, and s

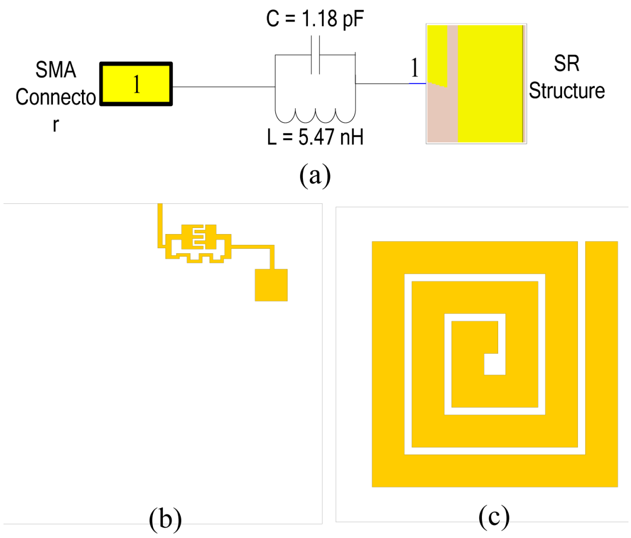


Figure 2. EMC feeding system by using the IDC parallel with MI as matching circuit: (a) circuit diagram; (b) planar diagram; (c) radiator.

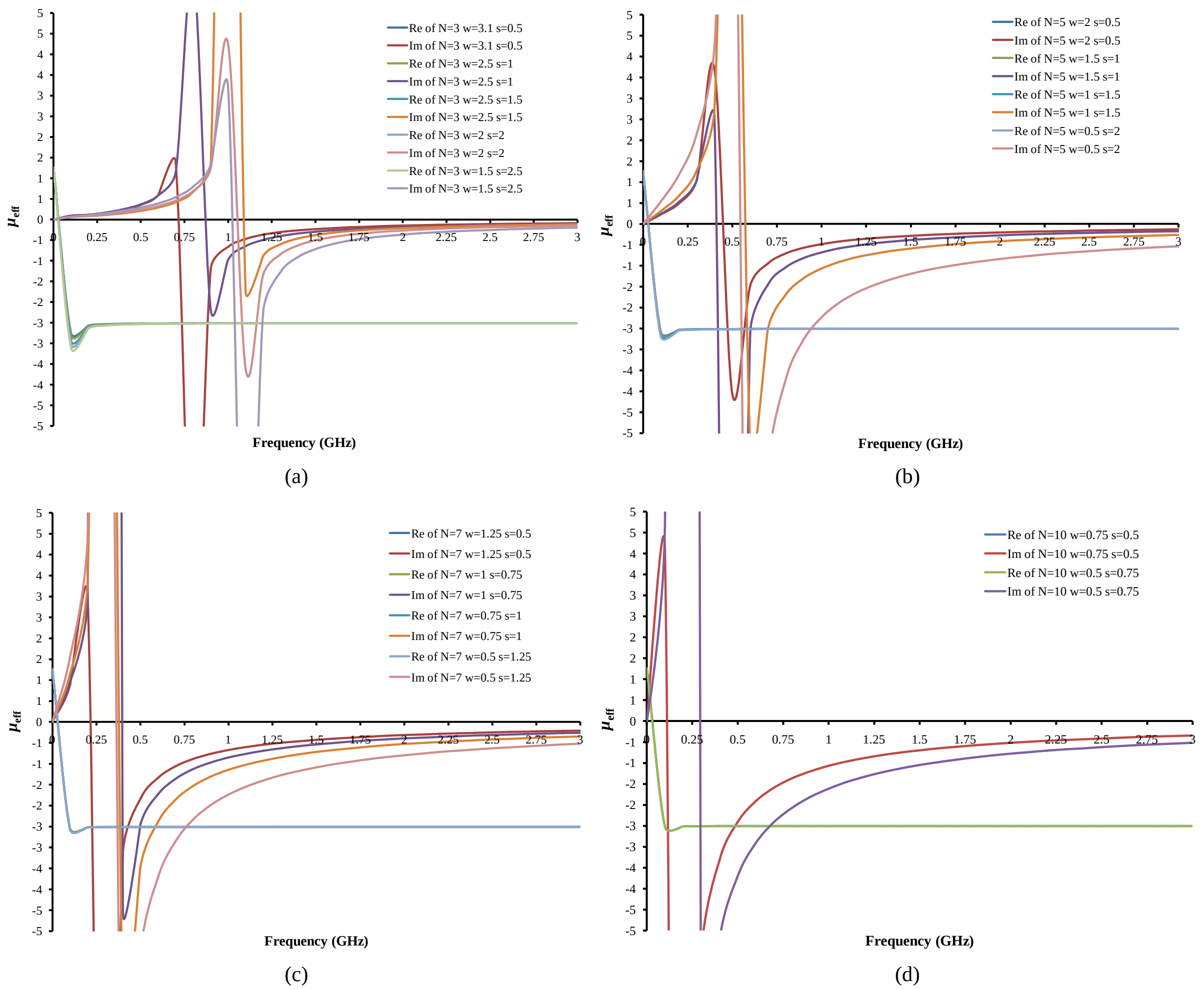
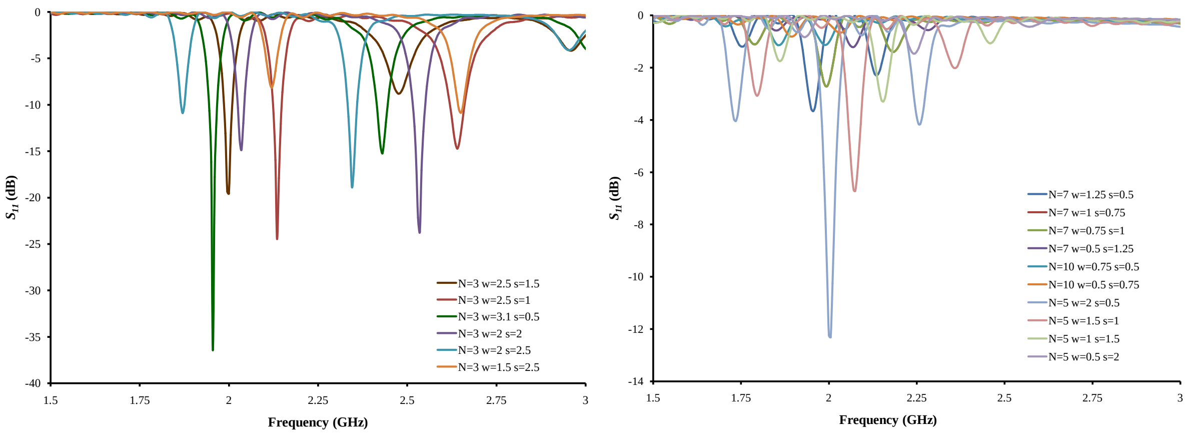


Figure 3. Effective permeability of the proposed antenna as a function of frequency: (a) $N = 3$; (b) $N = 5$; (c) $N = 7$; (d) $N = 10$.

provides the S_{11} and the realized gain are shown in **Figure 4** and **Figure 5**, respectively.

Figure 4(a) and **Figure 4(b)** show that the frequency range 2.4 GHz - 2.5 GHz occurred at the dimensional parametric variation of $N = 3$ with combinational variations of $w = 3.1$ mm, $s = 0.5$ mm and $w = 2.5$ mm, $s = 1.5$ mm, while the others are out of range and are not observed. The performance of the proposed antenna in the frequency range of 2.4 GHz - 2.5 GHz is also depicted in **Table 1**.

The radiation pattern of the proposed antenna is also characterized by the linear array approach, as shown in [20].



(a) (b)

Figure 4. The S_{11} of the proposed antenna: (a) with $N = 3$; (b) with $N = 5$, 7, and 10 and variations of w and s.

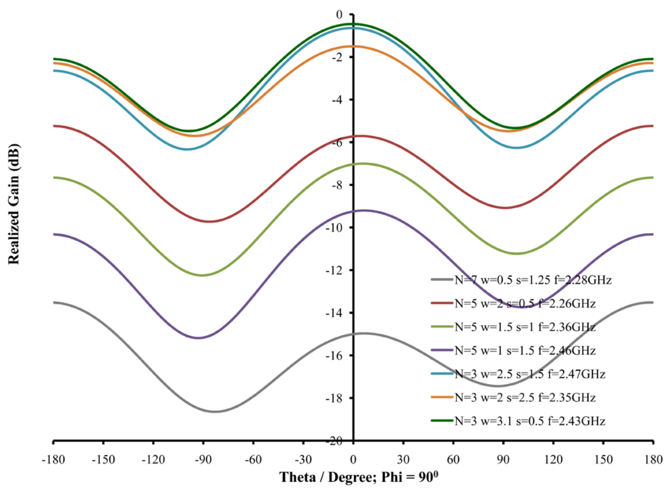


Figure 5. Realized gain of the proposed antenna with variation of N, w, and s at the frequency range of 2.0 GHz - 2.5 GHz.

Table 1. Antenna versus its dimensional parameters.

	Parameter	Frequency Range of 2.4 - 2.5 GHz	S_{11} (dB)	Gain (dB)
$N = 3$	$w = 3.1$ $s = 0.5$	2.43	−15	−0.5
	$w = 2.5$ $s = 1.5$	2.47	−9	−0.6
	$w = 2.5$ $s = 1$	out of range	not observed	not observed
	$w = 2$ $s = 2$	out of range	not observed	not observed
	$w = 2$ $s = 2.5$	out of range	not observed	not observed
	$w = 1.5$ $s = 2.5$	out of range	not observed	not observed

Moreover, the realized gain of the proposed antenna with the variation of *N*, *w*, and *s* in the frequency range of 2.0 GHz - 2.5 GHz is shown in **Figure 5**.

Figure 5 shows that the proposed antenna with $N = 3$, $w = 3.1$ mm, and $s = 0.5$ mm in the frequency range of 2.0 GHz - 2.5 GHz has the highest gain of the variations considered. The realized gain is –0.5 dB in the frequency of 2.43 GHz, with $S_{11} = -15$ dB, and VSWR = 2 bandwidth is 30 MHz. The obtained antenna gain of −0.5 dB is still low and must be improved. To increase the antenna gain, the matching circuit is inserted into the feed line, as shown in **Figure 2**. The simulation result of the S_{11} and gain of the proposed antenna with the matching circuit that is inserted in the feed line are shown in **Figure 6** and **Figure 7**, respectively.

Figure 6 shows that the proposed antenna with a matching circuit has a S_{11} of −25 dB and a VSWR = 2 bandwidth of 40 MHz, whereas the proposed antenna without the matching circuit has a S_{11} of −15 dB and a bandwidth of 30 MHz. **Figure 7** shows that the far field radiation of the proposed antenna with a matching circuit has the realized gain of 2.2 dB at the frequency of 2.45 GHz, which is much better than that without a matching circuit. To determine the dimensional reduction, the proposed antenna is compared to the antenna with a conventional rectangular patch, which is designed as shown in **Figure 8**.

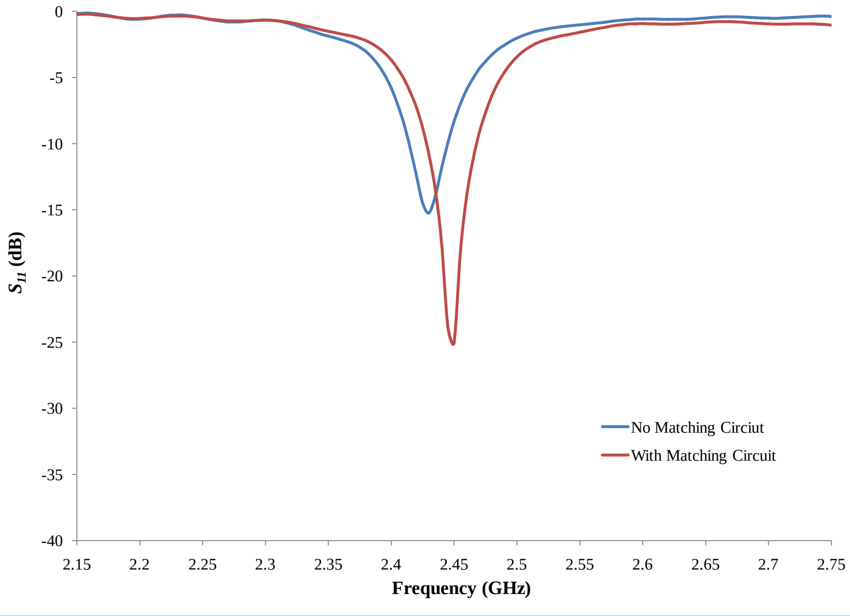


Figure 6. The S_{11} Comparison between the proposed antenna with and without the matching circuit.

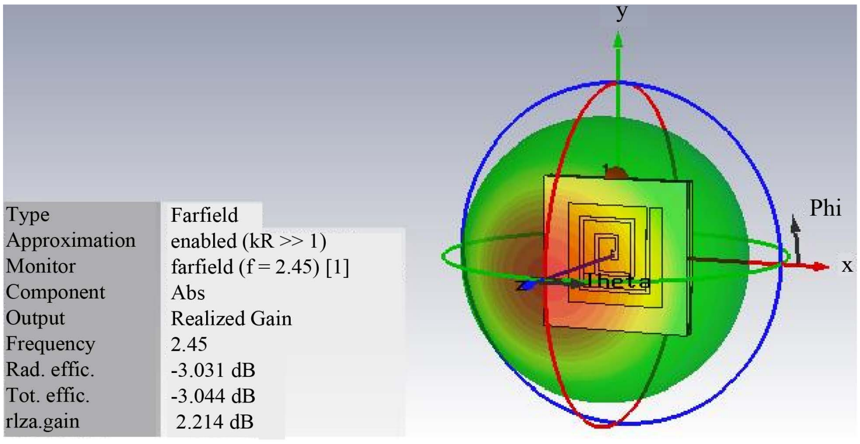


Figure 7. Realized gain of the SR structure with a matching circuit in the EMC feeding system.

The simulation result of the proposed antenna compared to the antenna with a conventional rectangular patch is shown in **Table 2**.

Table 2 indicates that the dimensional reduction of the proposed antenna is 53% compared to the antenna with a conventional patch. The radiation pattern comparison of the proposed antenna and the antenna with a conventional rectangular patch is depicted in **Figure 9**.

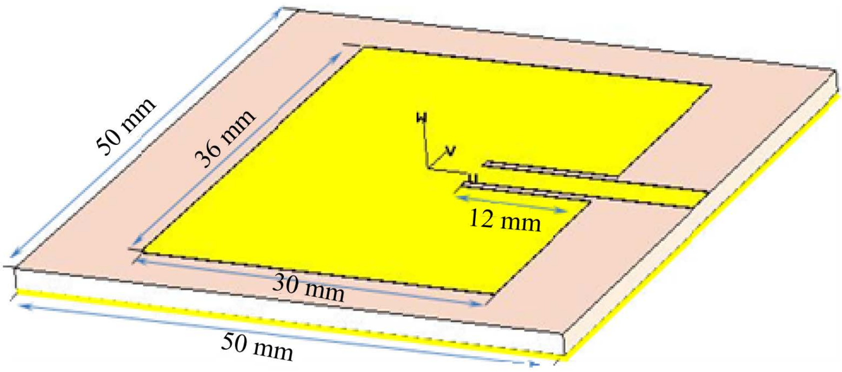
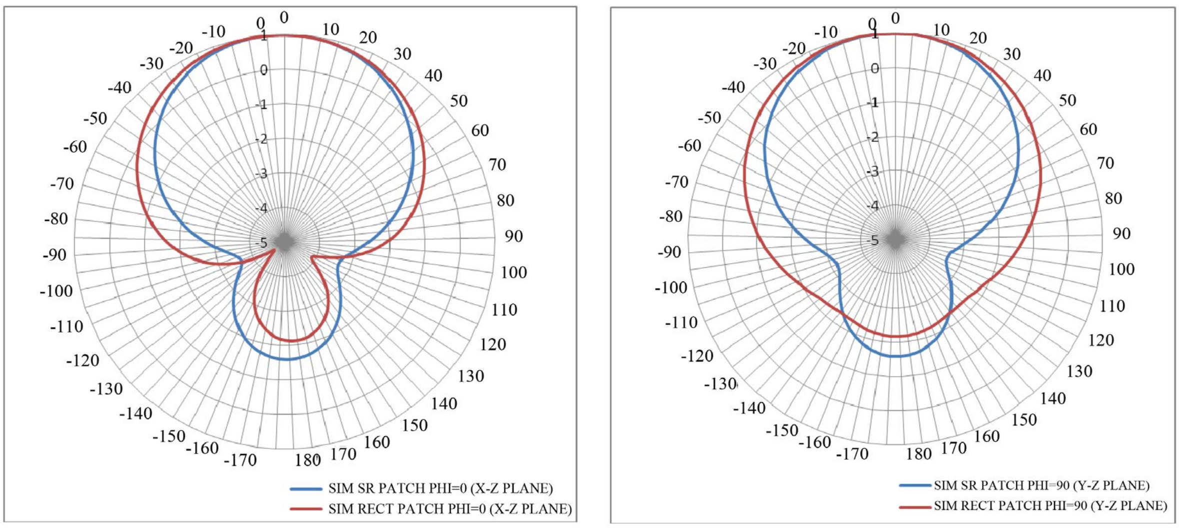


Figure 8. Planar-antenna with a conventional rectangular patch.



(a) (b)

Figure 9. Radiation pattern comparison between the proposed antenna and the conventional rectangular patch: (a) X-Z and (b) Y-Z planes.

Table 2. Comparison between the proposed antenna and an antenna with a conventional rectangular patch.

Parameter	Proposed Antenna	Antenna with Conventional Patch
Dimensions of the Ground Plane (mm)	30 × 30	50 × 50
Dimensions of the Patch (mm)	22.6 × 22.6	36 × 30
Frequency (GHz)	2.45	2.45
S_{11} (dB)	−25	−23
Bandwidth (MHz)	40	69
Gain (dB)	2.2	3.7
Dimensional Reduction of the Patch	53%	

3.2. Measurements

The simulations are validated by fabrication and characterization of the proposed antenna. The proposed antenna with a matching circuit in the EMC feeding is fabricated on FR4 substrate with thickness of 1.6 mm and relative dielectric permittivity of 4, as shown in **Figure 10**.

The radiation characteristics of the proposed antenna that measured are S_{11}, radiation pattern and bandwidth. The S_{11} comparison between the measurement and simulation results is shown in **Figure 11**.

Figure 11 shows that the measured S_{11} has good agreement with the simulation results. For convenience, the comparison between the measurement and simulation results of the proposed antenna performance, the S_{11}, bandwidth, and gain are tabulated in **Table 3**.

The radiation pattern comparison between the measurement and simulation results of the proposed antenna is shown in **Figure 12**.

Table 3. Comparison of the parameters between the measurement and simulation results of the proposed antenna at a frequency of 2.45 GHz.

Parameters	Simulation	Measurement
S_{11} (dB)	−25	−19
Bandwidth (MHz) at S_{11} of −10 dB	40	49
Realized Gain (dB)	2.21	2.0

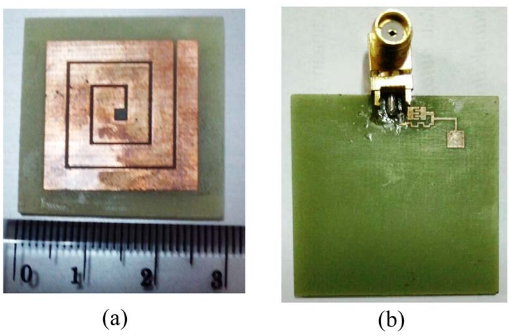


Figure 10. Fabricated proposed antenna with the SR structure: (a) radiator; (b) IDC parallel with MI in the EMC feed line.

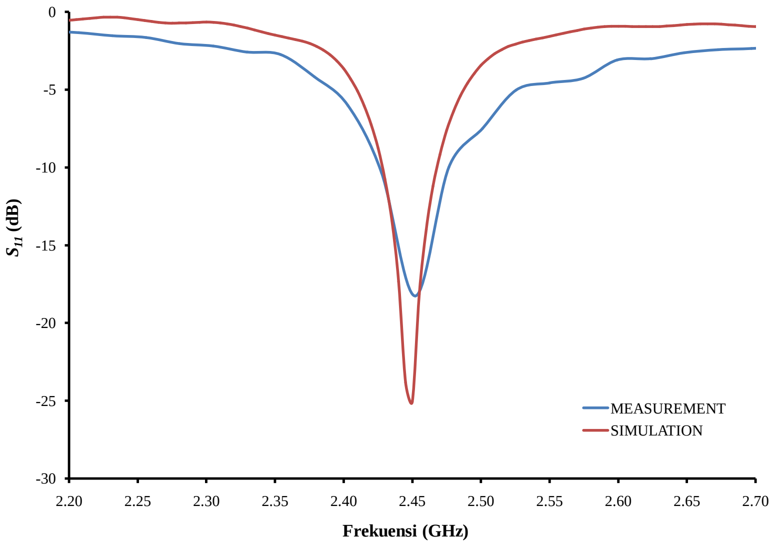
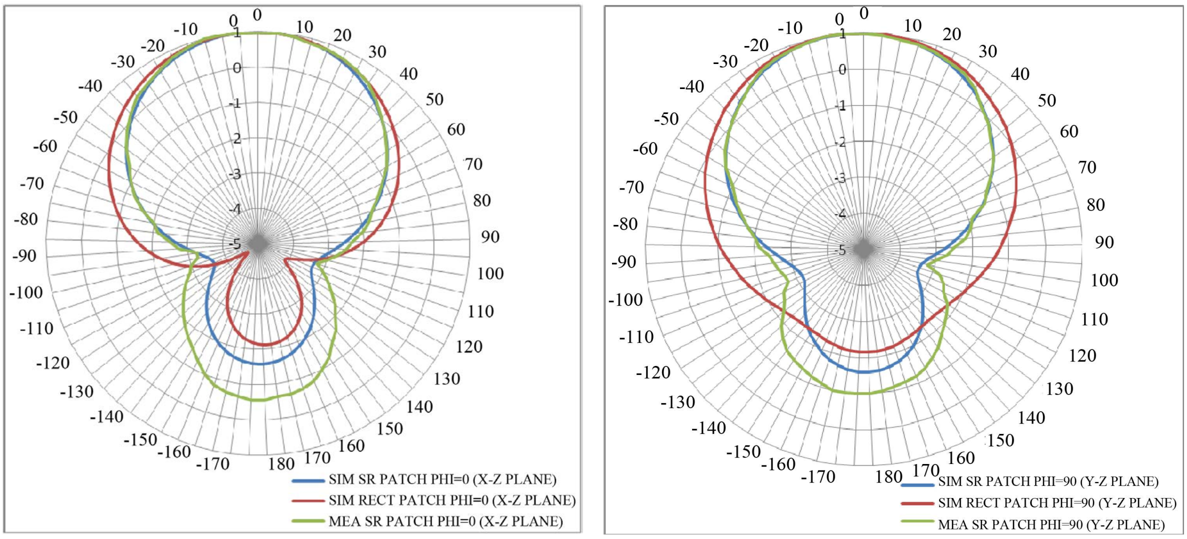


Figure 11. The S_{11} comparison between the measurement and simulation results of the proposed antenna with matching circuit in the feed line.



(a) (b)

Figure 12. Comparison of the radiation-pattern between the measurement and simulation results of the proposed antenna: (a) X-Z and (b) Y-Z planes.

Figure 12 shows that the radiation pattern for both the measurement and simulation are in good agreement, especially in the boresight direction.

4. Discussions

The main issue in the design of the microstrip antenna is the problem of the surface wave that is generated; such a surface wave significantly disrupts the antenna performance by causing an efficiency reduction and a degradation of the radiation pattern. Various methods have been used by researchers to eliminate the surface wave; one of the methods being applied is the use of a material that has a negative permittivity (ENG) or negative permeability (MNG), commonly called a single negative metamaterial. This material does not radiate the waves, as described by Kim [11]. The MNG is more properly used in the design of the microstrip antenna due to its magnetic properties, whereas the ENG, because of its electrical properties, is better suited for plasma engineering. Therefore, in this paper, only the MNG metamaterial is considered, and the ENG metamaterial is not discussed. An MNG metamaterial can be assumed as a material that is able to eliminate surface wave and is suitable for microstrip antenna design.

In his research, Billoti [6] [7] used a single SR structure to determine the resonant frequency as a function of the spiral turn number and proved that the resonant frequency decreases with increasing spiral turn number. If a structure is able to generate a resonant frequency, then the structure is able to generate a vibration of the waveform and propagate it. Therefore, the structure with a single SR shape can be assumed as a structure that can radiate and propagate waves; such a structure is called a radiator.

For many parameters of an antenna, such as the dimensions, gain, and bandwidth, compromise among these three parameters is found. In our case, the optimum value of the proposed antenna parameters is achieved for the antenna gain at 2.2 dB with a patch dimension reduction factor of up to 53%.

Having aforementioned discussions, the SR has a unique structure that can function as radiator and significantly reduce the dimension of the SR structure. Therefore, the SR structure has good prospects for development of the planar antenna applications. For future work, the SR structure will be expanded as an antennas array to obtain better characteristic of the radiation pattern.

5. Conclusion

A novel antenna using an SR structure having MNG metamaterial properties was presented. The effective permeability value (μ_{eff}) of the proposed antenna has the negative real part at least 0.1 GHz being relatively similar for spiral numbers of N = 3, 5, 7, and 10, and the negative imaginary part tends to shift leftward with increasing values of *N*. The proposed antenna showed size reduction compared with the conventional rectangular patch. Furthermore the simulation and measurement results show good agreement. Therefore, the proposed SR structure can be used as an effective antenna.

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