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Simulation of Wave Propagation in Plasma-Metamaterial Composites Based on Plasma Parameters and Metamaterial Structures

Ahmad Nazri Dagang[1,*], Avinaash Harikrishnan[1], Nor Azwan Mohamed Kamari[2]

[1] Faculty of Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
[2] Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

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ABSTRACT

Metamaterial is a left-handed medium used in antenna design to overcome the typical design's larger size and untunable nature. Because of its design with a high permittivity dielectric substrate and some deformation, the wireless sector may be able to solve this difficulty. Metamaterial antennas have a five-fold reduction in size, a higher bandwidth, a wider scanning angle, good beam performance, and electronically controlled targeting. Metamaterials antennas also improve antenna parameters such as frequency generation, gain, and bandwidth. This research aims to suggest the best metamaterials structure for improving antenna performance using plasma as a base. This study used 12 types of plasma with varying plasma frequencies and collision frequencies with four metamaterials structures: 1D-split ring structure, Symmetrical structure, Omega structure, and S structure. Computer Simulation Technology (CST) Studio Suite was used to design and simulate each structure with a sequence of plasma. At frequencies ranging from 1 GHz to 20 GHz, parameters including return loss, gain, radiation pattern, and Voltage Standing Wave Ratio (VSWR) are used to assess an antenna's performance. Due to its electromagnetic qualities, the 1D-split ring construction has a better omnidirectional figure and VSWR value of 1.0039 dB. When all criteria were considered, the best results were obtained when using a 1D-split ring structure of the Plasma 9 (plasma frequency of 3.58528 $x10^{11}$ rad/s and collision frequency of 1.3349 $x10^{9}$ 1/s) produces an efficient return loss, high gain, better VSWR and a better omnidirectional figure among the four structures evaluated.

1. Introduction

This research focuses on the study of wave propagation in plasma and metamaterial composites. Plasma as metamaterials is a left-handed media that applications are to overcome typical designs that are larger and untunable. Furthermore, antenna design not only minimizes the size of the antenna but also provides high directivity, tuneable frequency, and high performance to solve those issues. Metamaterials antennas have a few characteristics that could be adjusted to catch signals from any direction. Metamaterials have unique features such as negative refractive index, high

* *Corresponding author.*
E-mail address: nazri.dagang@umt.edu.my

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chirality, artificial magnetism, and electromagnetic cloaking [1,2], which allow them to be used in wireless communication, imaging, and radar systems. Metamaterials are artificial materials with electromagnetic properties found nowhere else in nature, such as negative electrical permittivity and magnetic properties. Conductivity, permeability, and permittivity are three key factors that determine an electronic material's electromagnetic properties [3]. Seismic protection, super-lens, enhanced antenna, sensor, sound filters, cloaks, magnetic resonance imaging (MRI), and phase compensator are a few of the applications for metamaterials in the industry. Previous metamaterial research has focused on using metamaterial antennas in medical applications. In order to improve the performance of an ultrawideband antenna, modified split ring resonators (SRRs) with small planar wideband negative index metamaterial were used. Left-handed metamaterials (LHM) array unit cell is set on materials. LHM was built by modifying square SRRs, resulting in a stable negative refractive index with negative permeability and permittivity, which means it significantly impacts antenna performance in terms of the transmission coefficient, efficiency, and low loss. The antenna reaches from 3.1 GHz to 10.71 GHz with impedance bandwidth (-20 dB), whichever covers the whole ultra-wideband (UWB) [4]. A central patch through a common feedline was connected to the antenna consisting of square-shaped concentric rings. One of the antennae in the array is used in transmission mode while others are in receive mode. Antenna arrays exhibit 2-13 GHz covering the frequency range with average radiation gain and efficiency improvement of 4.8 dBi and 18% [5]. From recent research, at higher frequencies by using the unit cell parameters, the design achieves a significant impedance bandwidth of 8.47 GHz (S_{11} = −10 dB, 72.56 GHz ~ 81.03 GHz), and a minimum return loss of −40.79 dB at 76.89 GHz, which clearly indicates good impedance matching to 50 Ω [6]. At lower frequencies, for microstrip antenna based on metamaterial, it shows a suitable gain for short and medium wireless communication systems of about 1 dBi, 1.24 dBi, 1.48 dBi, 2.05 dBi, and 4.11 dBi at 403 MHz, 433 MH, 611 Mz, 912 MHz, and 2.45 GHz, respectively [7].

Plasma is an ionized gas in the fourth state of matter, it contains free-moving charged particles such as electrons, positive and negative ions. Plasma contains free charge carriers and attains electrical conductivities, which causes it to be electrically conducting while it is neutral. Plasma is also used as a tuneable material in antenna applications. Microwave device is one of the applications using plasma tenability. Conventionally based on phase shifter array antenna was used in telecommunication and aerospace systems. Electron density value depends on the plasma source which controls its permittivity, while electron collision frequency control by gas pressure which involves in plasma electromagnetic losses. Radio Frequency (RF) is a good choice for plasma creation, it can work at low pressure, high densities, create homogenous and stable plasma [8,9]. A productive negative permeability by utilizing 3D arrays of SRR fabricated on thin substrates produced by metamaterials. SRRs at 1.5 GHz excite when the microwave energy on these materials, thus the low-pressure gas was break-down and produced a steady-state plasma. Since the negative permeability is lost when the plasma effectively short circuits the SRRs. SRRs are included within the metamaterials in the second set, separated from plasma, and shown to be immune to plasma interference. The separated SRRs maintain negative permeability properties at the frequency of 1.9 GHz [10,11].

Antenna design is now a must for wireless communication applications. Antenna designs must be appropriately directed to receive a signal. It uses a high-permittivity dielectric substrate, a shorting well, shorting pins, and some deformation in its design. Furthermore, antenna design not only minimizes the antenna size such as microstrip patch type [12,13], but also provides high directivity, tuneable frequency, and high performance to solve challenges such as appropriately directing to receive signal. There is no ringing effect in the plasma antenna as it allows extremely short pulses, which a metal conductor does not allow. When there is a sudden change in input a burst of electricity flows through the metal conductor for a short time, which is the ringing effect. Plasma antenna also has fast transmission ability. For example, by using a plasma semiconductor antenna, the electromagnetic waves produced can be focused to form a beam that travels faster than a wave when certain diodes are activated. This wastes electromagnetic energy and produces unwanted electromagnetic waves. Metamaterials antenna boosts antenna parameters such as generating multiband frequency and enhancing gain and bandwidth. Metamaterials antenna has no moving parts and consists of hundred features tuneable to catch signals from any direction [14-16].

This research uses Computer Simulation Technology (CST) Studio to propose alternative metamaterial architectures employing plasma. Analyse and compare the antenna performance in terms of return loss, gain, and radiation pattern, as well as explore antenna performance for the negative permeability and permittivity for various plasmas. This study will employ four different metamaterial structures, including a 1D-split ring structure, a symmetrical structure, an Omega structure, and an S structure, as well as 12 different plasmas, labelled Plasma 1 – 12, each with its own plasma frequency and collision frequency. These materials will be simulated in CST to determine return loss, gain, and radiation pattern, allowing the optimal structure to be selected to improve antenna performance.

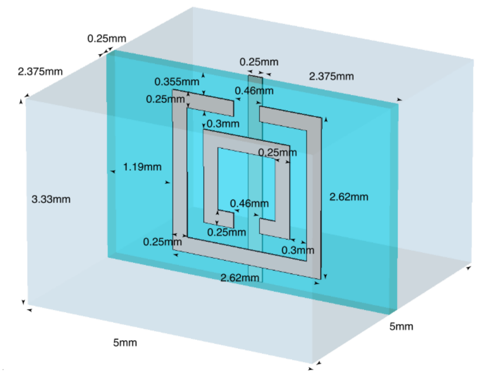
2. Methodology

2.1 CST Studio

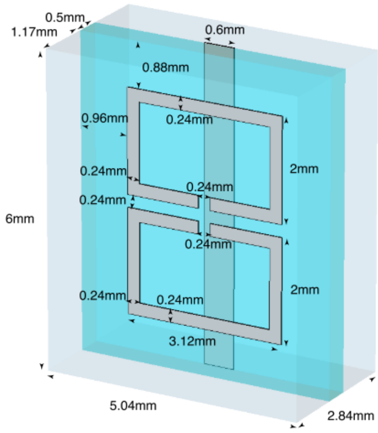
This study used CST Studio Suite software for all the simulations involved. This software is an electromagnetic field solver for applications across the EM spectrum which contains a single user interface. CST Studio Suite is a high-performance 3D EM analysis software package for designing, analysing, and optimizing electromagnetic (EM) components and systems. Electromagnetic field solvers for applications across the EM spectrum are contained within a single user interface in CST Studio Suite. The solvers can be coupled to perform hybrid simulations, enabling the flexibility to analyse whole systems made up of multiple components efficiently and straightforwardly. A plasma metamaterials unit cell is designed and simulated using CST. Based on the CST results, a study on different plasma metamaterials in terms of antenna performance can be done.

2.2 Metamaterials Structure as Antenna

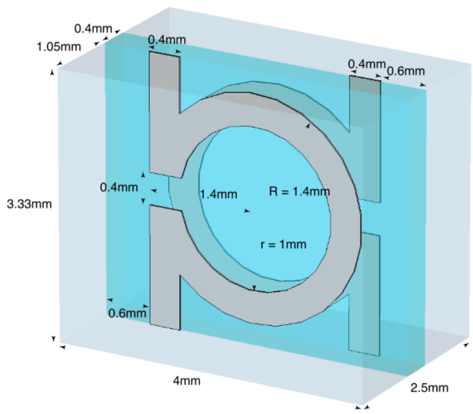
Four different structures were used in this study, which are 1D-split ring structure, symmetrical structure, omega structure and S structure. Metamaterial is a composite made up of SRR and tiny wire strips with a distinctive design. The form and distribution of complex patterns found in them, not the underlying physical features, determine the uniqueness of DNG material's electromagnetic properties. The structures used to design in CST software are shown in Figure 1. In the x-y plane, 2D metamaterials are helpful and relatively isotopic consistent, but their assembly structure is complex. 1D structures are simpler to build and produce. Furthermore, the 1D variant features large rod spacings and can reduce the electric plasma frequency [17]. Figure 1(a) shows the unit cell dimension for a 1D-split ring structure. When a large inductor and capacitor are incorporated into the construction, the free space wavelength at the resonance frequency is more significant than the unit cell dimension, resulting in a substantially dispersive magnetic permeability around the resonance frequency. When the free space wavelength and length scales defining the unit cell are disconnected, the tiny spreading in the effective permittivity of the structure is decreased. The magnetic activity in this structure leads to the concentrated field energy into the smallest volume in the structure [18-20]. 1D-split ring structure is selected to be used as it is the most common and basic structure applied by the previous researchers, and it is also most of the metamaterial exhibiting negative magnetic permeability. The symmetrical structure of unit cell dimensions is shown in Figure 1(b). Omega structure is one-dimensional metamaterials with three connected omega rings printed back-to-back, and reverses on two sides of a dielectric substrate. It is a stable structure, easy to fabricate compared to the original 1D-split ring geometry [21]. The omega structure of the unit cell dimension is shown in Figure 1(c). S structure is an overlapping negative permittivity and negative permeability which reacts over the frequency band of 2.6 GHz. This structure is able to lower the negative permittivity frequency band to the level of the negative permeability frequency band resulting in overlapping occurs. S structure is able to stand alone, which does not need an additional rod [22]. The S structure of the unit cell dimension is shown in Figure 1(d).



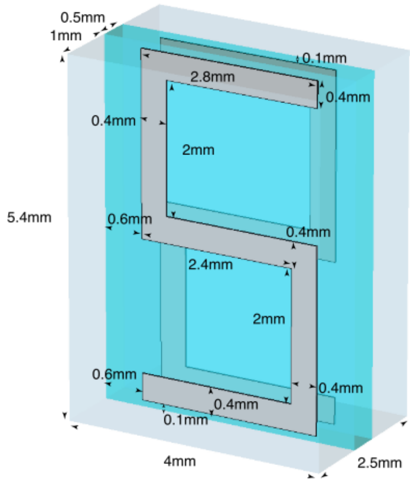
(a) 1D-Split Ring structure



(b) Symmetrical-Ring structure



(c) Omega Structure



(d) S structure

Fig. 1. Metamaterial structures used in this study, composing 4 types of unit cell structures i.e., 1D-Split Ring Resonator, Symmetrical Ring, Omega and S structures [17]

2.3 Plasma Parameters Design

Plasma metamaterials can be included in the CST simulation data by creating a database using low-pressure electrical discharge at actual values as a reference. Plasma is designed using the plasma frequency and collision frequency. In this study, 12 different plasma properties were used, each having a different collision frequency and plasma frequency. The list of plasma frequencies and collision frequencies employed in this investigation is presented in Table 1. The setting values were the assumption based on the previous calculations results of typical glow discharge [23]. The glow discharge experiment and the Drude model calculation based on prior works [24] were used to find these values. The Drude dispersion model describes the dielectric behaviour of plasma material, determined by the plasma frequency and the collision frequency. The dielectric constant of the Drude dispersion model is given by Eq. (1) below.

$$\varepsilon = \varepsilon_0 \left[\frac{\varepsilon_\infty - \omega_p^2}{\omega(\omega - \mathrm{jv})} \right] \tag{1}$$

where ε_∞ is the relative dielectric constant at infinite frequency (ε_∞ = 1), *w* is EM wave frequency and w_p is the plasma frequency.

Table 1
List of Plasma Frequency and Collision Frequency of Plasma

Plasma Number	Plasma Frequency PF (rad/s)	Collision Frequency CF (1/s)
Plasma 1	3.5853×10^{10}	1.3349×10^{9}
Plasma 2	3.5853×10^{10}	1.3349×10^{10}
Plasma 3	3.5853×10^{10}	1.3349×10^{11}
Plasma 4	3.5853×10^{10}	1.3349×10^{12}
Plasma 5	3.5853×10^{11}	1.3349×10^{9}
Plasma 6	3.5853×10^{11}	1.3349×10^{10}
Plasma 7	3.5853×10^{11}	1.3349×10^{11}
Plasma 8	3.5853×10^{11}	1.3349×10^{12}
Plasma 9	3.5853×10^{12}	1.3349×10^{9}
Plasma 10	3.5853×10^{12}	1.3349×10^{10}
Plasma 11	3.5853×10^{12}	1.3349×10^{11}
Plasma 12	3.5853×10^{12}	1.3349×10^{12}

2.4 Antenna Simulation

The eigenmode solver is used to simulate the finished model of the unit cell. As a result, the return loss, gain, and radiation pattern will be displayed. Return loss is defined as the difference between the input and output of signal sources. Antenna losses reduce gain, which reduces antenna efficiency. The radiation pattern graphically depicts the antenna's radiated electrical efficiency. In order to simulate the metamaterial difference-based unit cell to identify the S parameter, the unit cell structure is situated between the two waveguide ports on the left and right sides of the x-axis. The internal waveguide environment is produced by labelling the y-plane as PEB and the z-plane as PMB. Lorentz model gives the eigenmode solver to define the properties of metamaterial. Eq. (2) below is valid for electromagnetic waves used to show the motion of electrons in the material. The first term on the left-hand side is inertia, the second term is loss and the third term is restoring force, whereas, in right-hand side denotes the applied electric fields. Due to these terms, electrons get polarized and start working according to electrical force and combined with the EM wave, which is out of phase, and generates oscillation [25].

$$m\frac{\partial^2 r}{\partial t^2} + m\Gamma\frac{\partial r}{\partial t} + m\omega_0^2 r = -qE \tag{2}$$

2.5 Voltage Standing Wave Ratio

The voltage standing wave ratio (VSWR) or the reflection coefficient is used to describe the power reflected from an antenna. Poor VSWR can reduce transmission quality, and catastrophic VSWR caused by coaxial cable or antenna damage can destroy the transmitter in the worst-case scenario. VSWR has a minimum value of one, no power is reflected from the antenna in this situation. All power is bounced from the antenna, and nothing is radiated when S_{11} is zero. VSWR can be calculated using CST studio software. The formula that can be used to calculate VSWR is as Eq. (3) below. Here, Γ is refer to the reflection coefficient or S_{11}.

$$\mathrm{VSWR} = \frac{1+\Gamma}{1-\Gamma} \tag{3}$$

3. Results and Discussion

3.1 Antenna Parameter

Return loss, gain, and radiation pattern are the three parameters that are used to evaluate the antenna performance. Plasma 1-12 were utilized to construct the unit cell structure, each with a different plasma frequency and collision frequency. Regarding return loss and gain, each plasma produces a distinct outcome. The minimal point of the input reflection, S_{11}, is used to calculate the return loss. All the return loss values are negative, indicating that the metamaterial feature for electromagnetic characteristics is achieved. However, in terms of peak shape, not all are acceptable.

3.1.1 1D-split ring structure

Table 2 shows the value of return loss of the 1D-split ring structure, and Figure 2 shows the peak condition for the return loss (1-20 GHz) of 1D split ring structure for Plasma 1 to 12.

Table 2
Return loss and gain results of 1D-split ring structure for Plasma 1 to 12

Plasma Number	Reflection Coefficient S_{11} (GHz, dB)	Gain (dB)
1	3.156, -69.546	-14.79
2	2.650, -67.570	-7.847
3	1.546, -75.428	-6.976
4	1.803, -76.379	-7.130
5	1.346, -32.167	7.546
6	18.309, -42.517	6.592
7	1, -47.2818	-5.918
8	1.329, -66.692	-6.202
9	15.752, -33.345	4.851
10	3.249, -15.255	-9.940
11	1.764, -21.776	-6.649
12	1, -33.739	-7.339

Based on the figure, it can be seen that Plasma 9 at a resonance frequency of 15.752 GHz, and a reflection coefficient of -33.345 dB, has the sharpest peak, indicating that it is more effective in transmitting and receiving the signal. Plasma 5 has the better gain value with 7.546 dB, followed by Plasma 6 and 9 producing 6.592 dB and 4.851 dB respectively. From the results, the plasma conditions that fulfilled the requirement for a peak for return loss are Plasma 1, 5, 9, and 10. Thus, Plasma 5 and 9 are the best conditions for a 1D-split ring structure. This shows that plasma frequency plays an important role instead of collision frequency in producing good antenna parameters. Results of the radiation pattern show an omnidirectional pattern of the radiated signal which can provide a good transmitting and receiving angle.

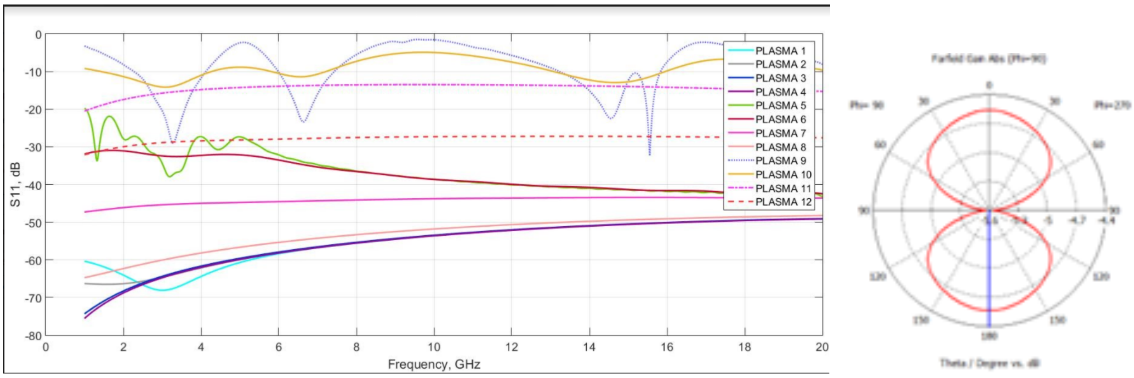


Fig. 2. Result of return loss (left) and radiation pattern (right) for 1D-split ring structure

3.1.2 Symmetrical ring structure

Table 3 shows the return loss for symmetrical ring structure, and Figure 3 illustrates the graph for return loss at 1-20 GHz for symmetrical ring structure. From the results, Plasma 9 produces the better return loss value with a reflection coefficient of -44.541 dB and 5.551 dB of gain, followed by Plasma 10 has the second good return loss, with a reflection coefficient of -29.221 dB and 7.075 dB of gain. Plasma 10 provided a better gain value of 7.075 dB, as shown in Table 3.

Table 3
Return loss and gain results of symmetrical ring structure for Plasma 1 to 12

Plasma Number	Reflection Coefficient S_{11} (GHz, dB)	Gain (dB)
1	12.474, -38.721	5.921
2	12.474, -38.720	5.921
3	12.474, -38.720	5.921
4	12.474, -38.896	5.713
5	12.115, -38.312	5.852
6	12.115, -38.592	6.164
7	12.882, -38.507	5.967
8	12.628, -38.429	5.433
9	11.513, -44.541	5.551
10	16.71, -29.221	7.075
11	13.989, -27.022	6.778
12	11.330, -35.754	5.115

Plasma 11 has the second good gain value of 6.778 dB, while Plasma 6 has the third good gain value of 6.164 dB. When the shape of the return loss peak is taken into consideration, only Plasma 9 provides a good peak and can be an effective antenna with a small bandwidth. Thus, the best condition for a symmetrical ring structure is Plasma 9. Plasma 9 also has a high plasma frequency which comes from a high-density plasma. This shows that, plasma density has an important effect on antenna performance. The radiation pattern results show a non-omnidirectional pattern of the radiated signal, which can result in unbalanced transmitting and receiving angles.

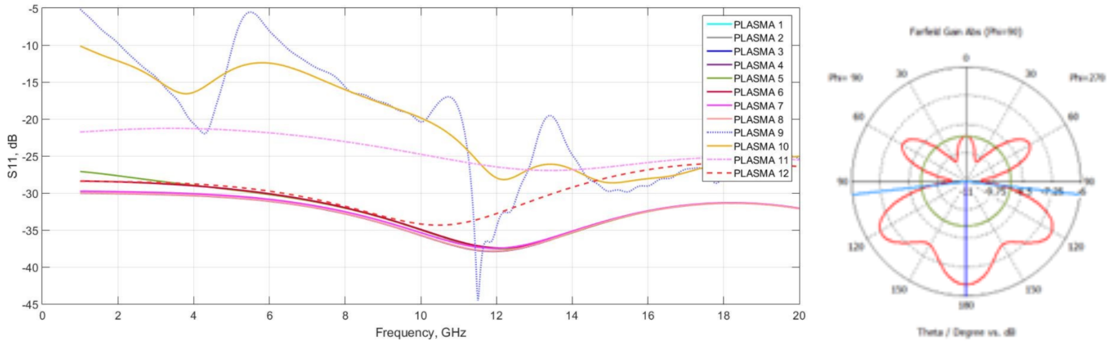


Fig. 3. Results of return loss (left) and radiation pattern (right) for symmetrical ring structure

3.1.3 Omega structure

Table 4 shows the return loss for omega structure, and Figure 4 illustrates he return loss peak change for frequency 1-20 GHz. From the results, Plasmas 5 and 6 gave the better return loss regarding reflection coefficient and valid gain values. Plasma 6 generates the better gain for omega structure, 8.082 dB but does not provide any good return loss peak. Plasmas 5 and 9 achieve gains of 8.022 dB and 6.795 dB, respectively.

Table 4
Return loss and gain results of omega structure for Plasma 1 to 12

Plasma Number	Reflection Coefficient S_{11} (GHz, dB)	Gain (dB)
1	3.612, -63.382	-12.11
2	1.440, -63.771	-13.86
3	1.660, -71.880	-6.019
4	1.809, -73.451	-6.295
5	3.977, -36.277	8.022
6	19.582, -45.573	8.082
7	1, -44.180	-6.124
8	1.082, -61.527	-6.279
9	13.201, -15.411	6.795
10	5.841, -21.319	-4.320
11	1.130, -20.324	-5.635
12	1.610, -30.650	-6.645

Figure 4 shows that the condition that met good antenna in terms of return lost peak shape are Plasma 5, 9, and 10. From these, Plasma 9 provides the most effective bandwidth at 13.201 GHz of resonance frequency and -15.411 dB of reflection coefficient. Thus, for omega structure, high plasma frequency which corresponds to high plasma density gave the best performance of an antenna. Results of the radiation pattern show a non-omnidirectional pattern of the radiated signal, which can result in an unbalanced transmitting and receiving angle.

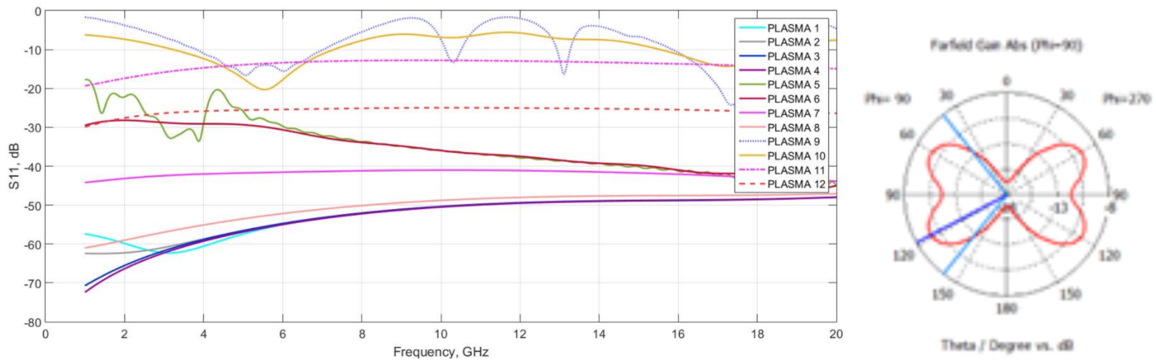


Fig. 4. Results of return loss (left) and radiation pattern (right) for omega structure

3.1.4 S structure

Table 5 and Figure 5 show that Plasma 9 has a practical return loss peak shape with a resonance frequency at 7.243 GHz and reflection coefficient at -40 dB. In addition, Plasma 9 has the best gain at 8.425 dB, followed by Plasma 10 at 8.130 dB.

Table 5
Return loss and gain results of S structure for Plasma 1 to 12

Plasma Number	Reflection Coefficient S_{11} (GHz, dB)	Gain (dB)
1	3.408, -62.697	-13.78
2	1.770, -64.295	-6.108
3	1.565, -70.190	-6.267
4	1.029, -70.988	-5.992
5	2.897, -39.837	-7.901
6	19.988, -45.602	-8.442
7	2.089, -47.551	-6.015
8	1, -61.927	-5.963
9	7.243, -40	8.425
10	7.081, -18.844	8.130
11	20, -21.339	-7.309
12	1.077, -34.066	-6.230

Thus, for S structure Plasma 9 provides the best antenna parameters. This condition could relate to the values of plasma frequency and collision frequency of Plasma 9. Good results can be obtained with lower collision frequency but at higher plasma frequency. The radiation pattern results show an omnidirectional pattern of the radiated signal, which can provide a better transmitting and receiving angles.

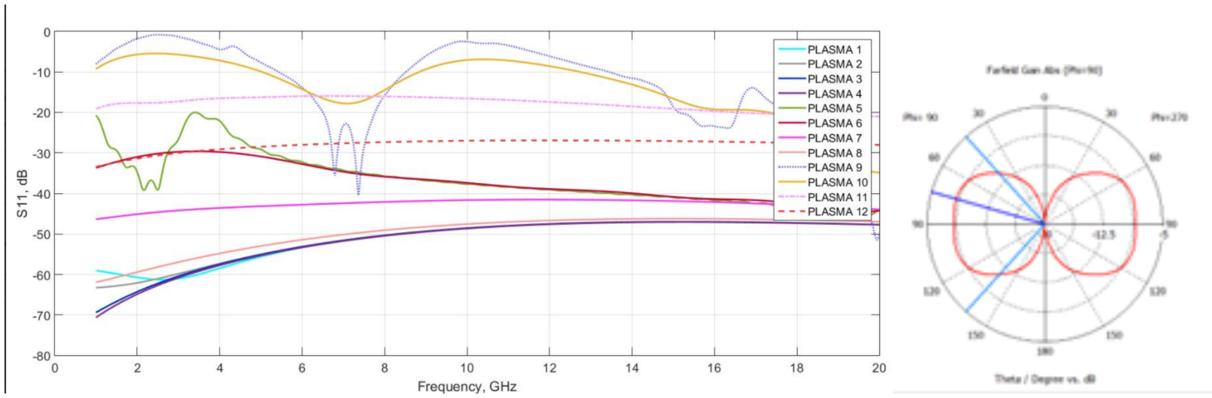


Fig. 5. Results of return loss (left) and radiation pattern (right) for S structure

3.2 Parameter Comparison

According to the simulation results, each structure has varied return loss and gain values. Those structures generate different frequencies and have unique radiation patterns. The best return loss for a 1D-split ring structure (as discussed in 3.1.1) with a reflection coefficient of -33.345 dB produced by Plasma 9 and 1.0003 dB of VSWR produced by Plasma 4. However, the VSWR value among the 1D-split ring structure is not much different. According to previous research, the 1D-split ring structure was proven to be the structure that produces the best antenna performance due to its minimal simulation time and high tuning degree [26]. Moreover, the shape of the structure itself played a crucial role in the outcome. The secondary issue that affected the return loss and VSWR value was the varied collision frequency and plasma frequency values in each plasma. In a symmetrical structure, Plasma 9 produced a good return loss (as discussed in 3.1.2) and VSWR value with a reflection coefficient of -44.541 dB and 1.0119 dB, respectively. Other than that, a good return loss for omega structure (as discussed in 3.1.3) is -15.411 dB, produced from Plasma 9 and 1.0005 dB of VSWR. Plasma 9 produces a better return loss for the S structure (as discussed in 3.1.4), where the reflection coefficient is at -40 dB, and Plasma 4 produces a good VSWR at 1.0006 dB. There are reflection coefficient values at a higher range (more than -50 dB). However, in terms of effective bandwidth, those values do not possess an acceptable peak shape and thus are not taken into account. For antenna gain, Plasma 5 has a good gain of a 1D-split ring structure with 7.546 dB, while Plasma 10 has a good gain value for a symmetrical ring structure at 6.957 dB. Plasma 6 has a better gain value of 8.082 dB in an omega structure, whereas for a S structure, Plasma 9 had a better gain value at 8.425 dB. It is reasonable to suppose that the gain is influenced by the structure design. In terms of the radiation pattern, those structures with omnidirectional patterns prove that they can provide good signal transmitting and receiving angles. The scale for the geometry of the design plays a crucial part in achieving an effective, wider band, more power, and lower beam width. A change in a design parameter can result in an increase or decrease in gain, which has an impact on antenna performance. Since a negative gain value is regarded as the worst, it cannot be interpreted as a good performance of an antenna.

4. Conclusions

The 1D-split ring structure is the best metamaterial structure for improving antenna performance since it has a better VSWR value compared to other structures. 1D-split ring structure with Plasma 9 (out of 12 types of plasma) produces a better VSWR and a good omnidirectional figure among the four structures evaluated. The second most successful structure for boosting antenna performance is the S structure, which produces the better return loss, gain value, and the sharpest peak as compared to the other structures studied. S structure with Plasma 9 produces a better return loss and gain values. Hence, each structure provides its own antenna parameters trend, which highly depends on plasma parameters. More work is needed to find an optimum condition. Better conditions can be optimized by focusing on two types of proven structures (1D split ring and S) and optimizing the plasma frequency, where plasma density will need to improve and evaluate more.

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