Development of Non-Destructive Method of Plasma Critical Frequency Determination

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Abstract. This study involves a development of non-destructive method of plasma critical frequency determination by conducting an experiment to compare the characteristics of metal and encapsulated plasma in fluorescent tube. Horn antennas are used to transmit and receive radio frequency from each other. The critical frequency of plasma is the point where the plasma changes in behaviour and behave like a metal when encounter with radio frequency. The device under test (DUT) for this experiment is formed using series of fluorescent lamps with 5 mm in diameter and warm white in colour. The fluorescent lamps are arranged in a row of 20 units and act as a plasma wall between the two horn antennas with separation distance of 200 cm. The experiment was conducted with different radio frequency values transmitted by the horn antenna, starts from 2 GHz to 18 GHz. The S-parameters performance for the plasma wall and metal sheet with similar dimension were analysed and based on experimental results it is concluded that the critical frequency of plasma is approximately 7 GHz. Therefore, plasma will exhibit its metallic behavior when incoming radio frequency is lesser than 7 GHz.

INTRODUCTION

Antennas are designed to transmit or receive radio waves or electromagnetic waves that propagate through space whether in horizontal directions (omnidirectional antennas) or in particular direction (directional or beam antennas). For the transmission, a radio transmitter will supply the antenna terminal with energy in electrical current that will be transmitted in electromagnetic waves form to the receiver. While in receiver, the antenna terminal will intercept or receives the radio wave to produce electric currents to be amplified.

Commonly, antenna will be made from material that known as a good conductor such as metal. The metallic antenna will connect with the transmission line from radio transmitter to receiver current for the transmission of radio wave to another antenna. However, as the technology advanced, some researcher had tried to replace the traditional metallic antenna with other candidate such as plasma [1-3]. This is because some problems may surface to the engineers when using metallic antenna such as their non-reconfigurable behaviour and its traditional history of having known as heavy and bulky.

So as to replace metallic antenna with plasma antenna, some measurements and parameters need to be observed such as conductivity of the plasma compared to the metal. Unlike metallic antenna, plasma antenna is developed based on partially or fully from ionized gas that is as conducting material. A column full of ionized gas that will emit, reflect, and absorb free electrons is made for plasma antenna. The state when the gas is ionized is known as plasma state. Not all ionized gases can be used for plasma antenna as there are several ionized gases that chemically inert and can harm the plasma tube and electrodes. Noble gas that listed in group of 18 in periodic table are examples of ionized gas that are safe to be used as the ionized gas for the plasma antenna. Main advantages of replacing metallic antenna with plasma antenna is that plasma antenna is easier to be reconfigured electrically as the ionized gases inside the plasma antenna easily can be switched ON and OFF at any time [2].

Despite the advantages of plasma antenna, it is important to proof that plasma, have the same behaviour as metal in conductivity. To proof this, series of experiments have been made using fluorescent tube as source of ionized gas, horn antennas as transmitter and receiver for radio wave. This non-destructive method of experimental is to ensure the safety of apparatus and materials. The purpose of this experiment is to observe and determine critical frequency for the ionized gas to act as reflector for radio wave that propagate towards it. Critical frequency of an encapsulated plasma must be defined to use it as an effective antenna with respect to its metallic counterpart.

This project focuses on determination of critical frequency of plasma using a non-destructive method by setting up an experiment. Fluorescent tube that usually use as home appliances are used as the Device Under Test (DUT) in the experiment as it contains ionized gas of Helium. The fluorescent tubes are arranged in series to create a wall of plasma or plasma slab that will place between the two horn antennas.

THEORETICAL BACKGROUND

In recent years, there has been a growing interest in the characteristics of matter in a fourth and unique form known as plasma. The greater the temperature, the more freedom the material component particles have. Atoms and molecules in solid things are subjected to severe discipline and are bound to strict order. They can move in a liquid, but their freedom is restricted. In a gas, molecules or atoms move freely, inside the atoms, according to quantum physics, electrons dance in a harmonic dance around their orbits. The electrons in a plasma, on the other hand, are emancipated from the atoms and have total freedom of motion.

Atoms and molecules get a positive electric charge when some of their electrons are lost, and they are referred to as ions. As a result, a plasma is a gas made up of evenly distributed positively and negatively charged particles with a total charge of zero. A plasma is a conducting gas because free-moving electrons may transmit electric current. Distinct degrees of organization are represented by different states of matter, which correlate to different binding energy levels. The binding energy of molecules in a crystal lattice is an essential parameter in the solid state.

To transform a liquid into a gas, a specific minimum kinetic energy is necessary to break the bindings of the van der Waals forces. The kinetic energy per plasma particle must surpass the ionising potential of atoms in order for matter to change to its fourth state and exist as plasma [4]. As a result, the average kinetic energy per particle determines the state of matter. Ice melts when the temperature rises at normal atmospheric pressure, for example. If you held the temperature steady but lowered the pressure, eventually you would reach a point where the ice would undergo sublimation directly to water vapor. But usually, when the ice is being heated, the solid state of the ice will change into a liquid form under the process of melting. Melting is the process by which a substance changes from the solid phase to the liquid phase.

The liquid form of the water can be changed into a water vapor that is a gas state through a vaporization process. In this process, the water will be heated usually at certain temperatures like 100 degrees Celsius. In order to get the fourth state of matter that known as plasma, the gas will undergo a process known as the ionization process. Gas turns into plasma when heat or energy is added to it. The atoms that make up the gas start to lose their electrons and become positively charged ions. The lost electrons are then able to float freely.

Plasma is ionized of noble gases such as Helium, Neon, and Argon. Helium, neon, and argon are the three inert gases used in plasma technology, although argon is the most common because of its low cost [4]. In comparison to other substances, noble gases absorb and emit electromagnetic radiation in a simpler manner. This property is employed in discharge lamps and fluorescent lighting devices: any noble gas contained at low pressure in a glass tube that is passed through an electrical discharge will glow. Xenon emits a stunning blue hue, whereas neon generates the typical orange red colour of advertising signs [5].

Every noble has different characteristics and behavior. The higher the number of valence electrons, the higher the boiling and melting point of the atom as the Van Der Waals force of attraction between the atoms becomes stronger. Argon has a higher boiling point compared to neon as it contains more valence electrons compared to neon. Also, the ionization potential decreases with an increasing radius because the valence electrons in the larger noble gases are farther away from the nucleus and so are not held as tightly together by the atom [6].

Every gas contains free electrons under normal circumstances. They are formed by secondary cosmic radiation-induced ionization, collisions of high-energy gas atoms (or molecules), or collisions of metastable gas molecules [5]. The ionization potential for argon is higher compared to krypton as the radius between the nucleus to valence electron for argon is smaller compared to krypton. As going down the periodic table in group 18, the ionization energy keeps decreasing. For the conduction of electricity, all the gases in group 18 conduct electricity except for neon. Figure 1 represents the sample of the complete valence shell of a group of eighteen elements.

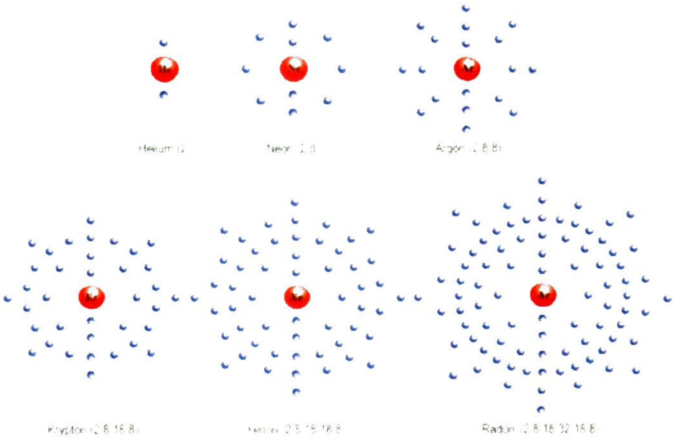


FIGURE 1. Types of Inert Gases

When working with plasma, it is important to keep in mind a few variables that can affect the plasma qualities. The general quantities that could be changed to change plasma properties to benefit application purposes such as excitation power or power injected to dielectric tube [7], pressure of gases (electron density depends on the mercury vapor pressure) [8] and type of gas and combination of gas [9].

The plasma parameters can be changed with the proper altered from three quantities that are permittivity, conductivity, and plasma frequency. These three are core parameters that must be known and comprehended when working with the plasma. The isotropic plasma is dispersive material that has complex permittivity. The permittivity under low electron-neutral collision is given by Equation (1) [10][11].

$$\varepsilon_r = 1 - \frac{\omega_p^2}{w(w - iv)} \tag{1}$$

Where ε_r is the complex plasma permittivity, ω is the operating angular frequency [rad/s], and the v is the electron-neutral collision frequency [Hz]. The ω_p is the plasma angular frequency [rad/s] and its can be calculated by using formula as shown in Equation (2).

$$\omega_p = (\frac{ne^2}{m\varepsilon_0})^2 \tag{2}$$

Where n is the electron density [m^{-3}], e is the change of electron [12], m is the electron mass [kg], and ε_0 is the free space permittivity [F/m]. From the Equation (2), the ε_0 of the plasma will very if the ω_p varies and the ω_p can be altered by changing the n as the expressed in Equation (2) [13]. In order to have the same behavior as a metal, the ω_p of plasma must be higher enough than $\omega(\varepsilon_r < 0)$.

$$\sigma = \varepsilon_0 \frac{\omega_p^2}{v} \tag{3}$$

When the ω_p is larger enough compared to the v the plasma exhibits good electrical conductivity, σ is given in the Equation (3) by varying ω_p or v will give difference value of σ and hence the characteristics of electromagnetic wave will be change [13]. If the radio frequency that is given is higher than plasma frequency, the plasma properties will behave like a dielectric. It is because the permittivity of plasma is less than unity.

One of the main goals of this study is to use an inexpensive commercial plasma source as an antenna element. The complexity of assembling the plasma tube by hand, as in [14-16] can be avoided by using compact fluorescent lamps often used in homes. Controlling the driving force, encapsulated gas type, gas pressure, and gas density gives a conventional portable plasma tube additional freedom to change plasma properties. However, this method requires more sophisticated experimental equipment, which increases the complexity and cost of making a plasma antenna. As a result, the fluorescent lamps (FL) are used as a plasma source in this study. The complication of dealing with plasma formation might be disregarded by utilizing the FL and compact fluorescent lamps (CFL) [17]. The fluorescent lamps used in the experiments are shown in Figure 2.

(a) (b)

FIGURE 2. Fluorescent Tube (FL). (a) Fluorescent Lamp (FL) Column. (b) Fluorescent Lamp 14-Watt Diameter 5 mm

To produce a plasma in a dielectric tube and regulate its state, current CFL technology just requires a simple electron ballast and a switch. In terms of noise cancellation, electronic ballasts are recognised to outperform traditional magnetic ballasts. Internal and exterior noise are decreased when electronic ballast is used. Furthermore, when employing an electronic ballast instead of a magnetic ballast, the size and weight of the magnetic ballast are irrelevant.

The FL and CFL enable fast and rapid experimental access, in addition to their low cost and great availability. With less complexity and ease, a simple plasma reflector and plasma antenna might be built. However, design improvements are required to achieve optimal performance. The FLs and CFLs with a colour temperature of 2700K were employed as plasma sources in this study [17].

Figure 3 and Figure 4 depict reflector antennas with a plasma sheet as the reflecting surface instead of a solid conductor [18]-[19]. The reflections take place within plasma, rather than at a sharp interface like a metal reflector. The reflection is assumed to occur at a "critical surface" within the plasma for the purposes of ray tracing (like the virtual reflection point when tracing rays through the ionosphere).

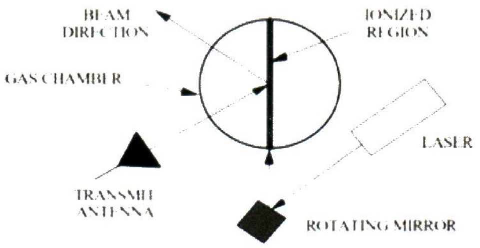


FIGURE 3. Plasma Mirror using a Laser [18]

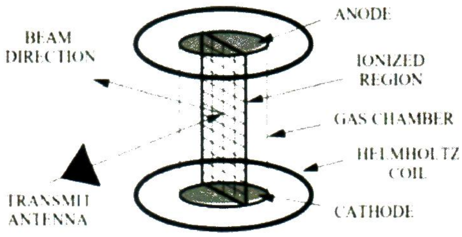


FIGURE 4. Plasma Mirror using Tube [19]

A high-quality plasma reflector must have a critical surface that is repeatable and stable across the transmission periods of interest. When the plasma is shut off, the time it takes for it to decay limits the speed at which the reflecting surface may be moved. The 10 microseconds turn-on and turn-off times have been achieved [20]. A circular cross section column with variable radial electron density, for example, can be used to scan a beam travelling through it. A helicon wave was used to stimulate the plasma to show this notion. The deflected beam had a frequency of 36 GHz, a peak density of roughly 7 x 10^{18} cm, and an insertion loss of 2 dB. The time it took to sweep a 30-degree scan was 200 microseconds, which was restricted by the plasma decay rate [21]. A comparison of radiation patterns for plasma and metal antennas has been discussed in [22]. The plasma antenna shows lower sidelobes, especially at wide angles, due to its higher surface resistivity compared to a solid conductor.

Fluorescent lamps produce light by the collision of freely accelerated electrons with atoms (usually mercury) in a hot gas (plasma). In this case, the electron is knocked to a higher energy level and falls back as it travels along the two UV emission lines (254 nm and 185 nm). The UV radiation thus generated is converted to visible light by the UV excitation of the fluorescent coating on the glass envelope of the lamp. The chemical composition of this coating is selected to emit light in the desired spectrum.

At a total pressure of around 0.3% of atmospheric pressure, a fluorescent lamp tube is filled with a gas containing low-pressure mercury vapour and noble gases. A pair of filament emitters, one at each end of the tube, are heated by a current and utilized to produce electrons that excite noble gases and mercury gas via impact ionization in the most common configuration. Only undamaged light bulbs may ionize. As a result, there will be no negative health consequences from this ionization process. Furthermore, many lamps have two envelopes, limiting the quantity of UV radiation released significantly.

The fluorescent lamp is connected to the electronic ballast in order to produce a high voltage output to start up the discharges process. Electronic ballast works in a low supply voltage but can produce high voltage output and stable the current during the fluorescent still working to avoid excessive voltage and blown up [23]. The fluorescent lamp does not need a starter as the electronic ballast can provide a working principle similar to a starter.

The part of electromagnetic spectrum that comprises static fields and these fields is up to 300 GHz. Electromagnetic spectrum also known as electromagnetic fields (EMF). The strengths of EMF that are emitted from CFLs are sparse. There are several kinds of electromagnetic fields found in the vicinity of these lamps. Like other devices they emit electric and magnetic fields in the low-frequency range that are dependent on electricity for their functions.

Plasma antennas have sparked renewed interest due to their possible benefits over conventional antennas. The plasma antenna is a radio frequency antenna that uses a plasma element rather than a metal conductor. Experiments have shown that such antennas can be efficient and low-noise, making them suitable for narrow-band high-frequency and very-high-frequency communications. The physical parameters of a plasma antenna have been investigated, and simulations of a plasma antenna have been carried out using numerical and computational algorithms. A plasma antenna is an antenna that uses ionized gas as conducting medium rather than metal to create radiation of electromagnetic wave and act as antenna [24]. Plasma antenna made up from glass tube that contains noble gas with a low atmospheric pressure. It operated as antenna when the antenna is switched on by applying bursts of pump power to the discharge vessel of the tube. The gas in the tube will ionize then it creates plasma, and the plasma will act as conducting medium and generate electromagnetic wave radiation for stealth, radar or communication purpose [4].

The advantage of plasma is firstly it is undetectable to radar. Plasma antenna signals are hard to detect and intercept because this signal is invisible above plasma frequencies. The second advantage of plasma is it is an efficient, light, and smaller antenna. Plasma antenna is more portable and lighter compared to metal antenna. This is because the antenna is replaced by gases which it lighter and will fill the glass tube shape. This makes plasma antenna become more efficient. Dynamically reconfigurable is another advantage of plasma antenna. As the power, direction, bandwidth, gain, frequency, and polarization of plasma antenna can be freely changed instated using metal antenna. Next is the possibility of having conducting elements only when useful signal needs to be transmitted. The plasma antenna can only be switched ON or be put in conducting and receiving state when the antenna needs to be used.

The plasma antenna can only operate in limited frequency which is frequency that below plasma frequency. This is one of the disadvantages of plasma antenna Research has been done that basic plasma tube has critical frequency of 7 GHz. Therefore, research needs to be done on optimizing the plasma frequency by creating more applications that operate below 7 GHz. Plasma antenna also uses more power than metal antennas. This is due to ionizing the gas in creating electromagnetic waves. In this case, other technologies need to be developed to reduce power consumption in plasma antenna operations. Next is not hundred percent of the gas in the tube becomes plasma when ionized. Perhaps research needs to be done to generate maximum plasma in the tube to get the best plasma antenna.

Plasma can be rapidly created, and it is also easy to destroy by just applying ac voltage on it as storied in previous. In other words, plasma antenna can be switched on and off at any time. Less than 200 W plasma antenna have achieved adequate illumination and half of which was radiated at 30 MHz. Besides that, plasma antenna also can permit clear long-range communication as long as 3 to 150 MHz this is due to it having very low base band noise [25]. As the pump power is applied to the antenna, it will create surface wave that propagates along the antenna. Discharged and providing the conductivity is sustain as it is necessary for the communication signal to be radiated.

METHODOLOGY

The physical shape of fluorescent bulbs was determined by their intended use. As a result, they come in a variety of forms and sizes. Fluorescent bulbs come in five different sizes that are often used in homes. Fluorescent lamp technology is improving year after year to give a wider range of possibilities for people to choose from. The tiny fluorescent light is one of them (CFL). Compact fluorescent lamps are also available in many sizes and shapes. Due to its high efficiency and compact size, CFL has become the most popular light source for energy saving. This project used fluorescent with 14 Watt and a diameter of 5 mm that is usually being used for some home applications, as shown in Figure 2(b). This fluorescent lamp can be purchased at the electrical shop. In this project, some modifications have been made to the circuit of the fluorescent lamp to avoid noise from its original structure. The circuit has been extended for the electronic ballast of the plasma tube to be taken out from its original place. This was important as the electronic ballast released its frequency that can affect the result of surface wave propagation.

Non-conductor material is an important factor that needs to be taken care of in making the bracket or holder fluorescent to prevent from affected the results. In this experiment, a bracket made from wood is used as wood known for its non-conductor characteristics. The wooden bracket will hold all the fluorescent tubes in its position so the DUT will not fall and break. These materials can be found at any hardware store. The 12 mm in thickness and 25 mm in width are the details for the bracket of plasma wall. Figure 5 shows the wooden stick used in making the plasma wall bracket.

FIGURE 5. Material for Making Bracket of Plasma Wall

This experiment took place in an anechoic chamber. The experiment was conducted using a pair of wideband horn antennas, a network analyzer, a plasma wall, and a metal sheet. The dimensions and setup for the plasma wall and metal sheet are shown in Figure 6. Each fluorescent tube is connected to electronic ballast that will regulate the current for the lamp and provide enough voltage for the fluorescent lamp to light up.

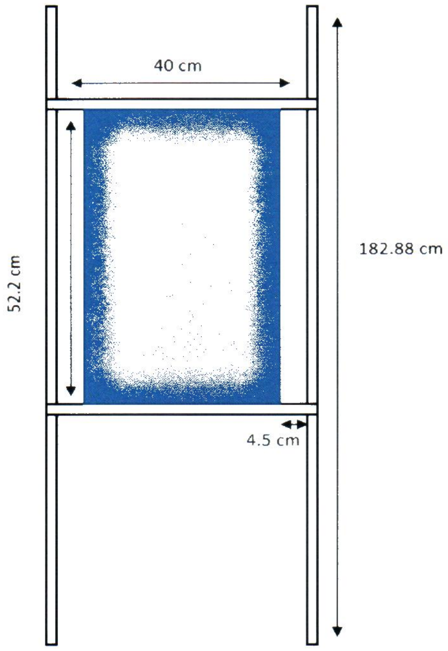


FIGURE 6. Dimensions and Setup of Plasma Wall and Metal Sheet

The plasma wall and metal sheet are placed at the centre between the pair of horn antennas. The radio wave that being transmit from one horn antenna will need to pass through plasma wall or metal sheet with distance of 100 cm before being received by another horn antenna with the same distance. Figure 7 and Figure 8 show the placement of the plasma wall and metal sheet during the experiments.

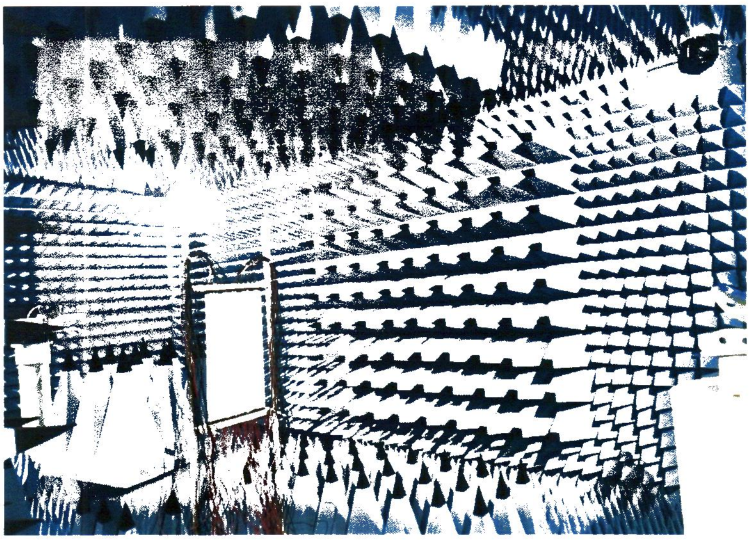


FIGURE 7. Plasma Wall Placement

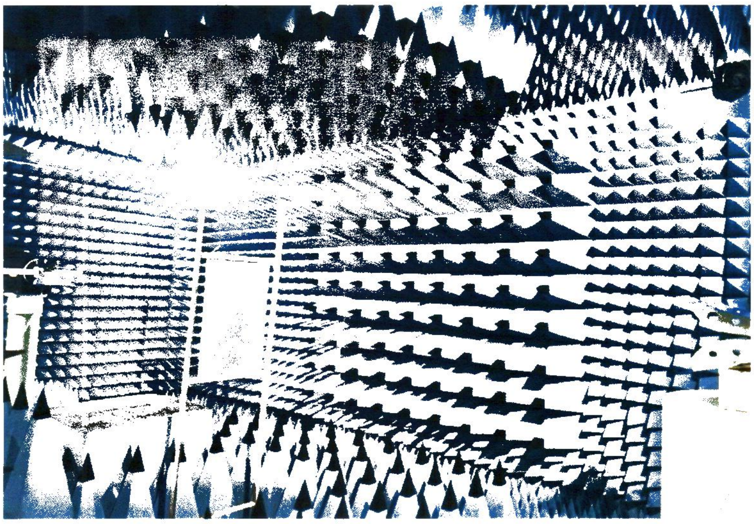


FIGURE 8. Metal Sheet Placement

These measurements were conducted in four conditions that are in free space condition, plasma wall in ON state, plasma wall in OFF state and metal sheet. The measurement starts with free space as a reference. The pair of wideband horn antenna are connected to a network analyser so the observation for radio wave frequency being transmit and receiver can be detected and analysed.

In determine the critical frequency of plasma, measurements need to be run in difference condition such as free space, presence of plasma wall in ON state and OFF state and metal sheet. These to compare all the results so an approximate result can be obtained and observe. The measurements for all the conditions that had been mentioned before will take place in isolated place that is anechoic chamber to prevent factors that can affected the radio wave from transmitter of horn antenna. The distance between both horn antennas with the DUT also constant except for free space condition as there will be no obstacle between transmitter and receiver. The results for all the measurements will be compared to observe the differences and determine the critical frequency for the plasma.

RESULT AND DISCUSSION

The experiments were conducted for broadband frequency starting from 800 MHz up to 8 GHz. However, the performance for wideband horn antennas only valid from 2 GHz to 18 GHz. To observe the performance for the horn antennas, this experiment needs to be done in a free space condition where there are no materials or obstacles between working region of wideband horn antennas. Figure 9 shows the performance of horn antennas that transmit radio waves from one to another.

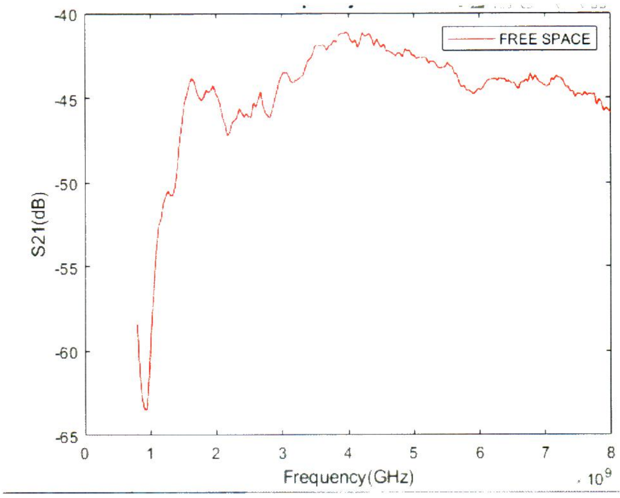


FIGURE 9. Measured Transmission Coefficient in Free Space

From Figure 9, the transmission coefficient between the horn antennas in space condition can be observed. The purpose of this experiment had been made to observe the performance for both horn antennas. Also, as the reference to compare with the results that obtained from other conditions.

As the fluorescent tube using a non-conductor material for the bracket to ensure that the plasma wall can be arranged parallelly without fall, a measurement need to be taken as to identified that the bracket of non -conductor will not be one of factor to affect the radio wave that been transmit. Figure 10 shows the transmission coefficient for radio waves that propagate pass through the empty bracket.

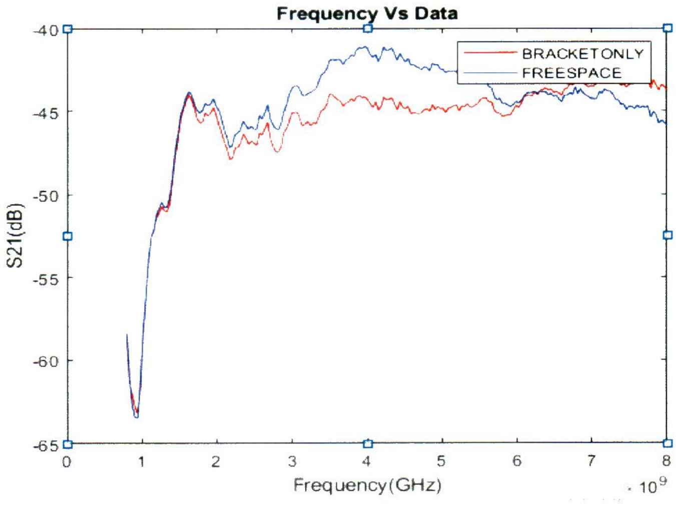
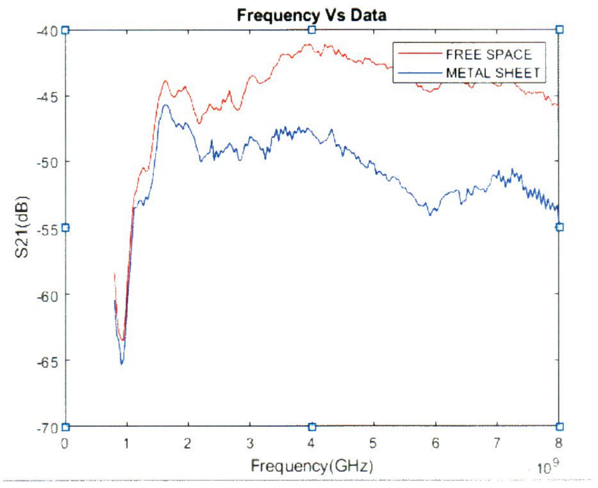


FIGURE 10. Measured Transmission Coefficient for Bracket of Plasma

Referring to Figure 10, there are slight differences in the transmission coefficient of bracket with the free spaces especially from frequency of 3 GHz to 6 GHz. These occur because of nails that been using as connector to combine the wooden bracket. Nails are made from metal that known for their conductor's behaviour. So, it is been one of the reasons that can interfere the reading for transmission coefficient for the plasma wall and metal sheet.

By placing a metal sheet at the working region of the horn antennas as shown in Figure 8, the transmission coefficient for the radio wave that passes through the metal sheet had been observed. Figure 11(a) and Figure 11(b) shows the transmission coefficient for metal sheet versus free space and metal sheet versus bracket as to differentiate between both conditions.

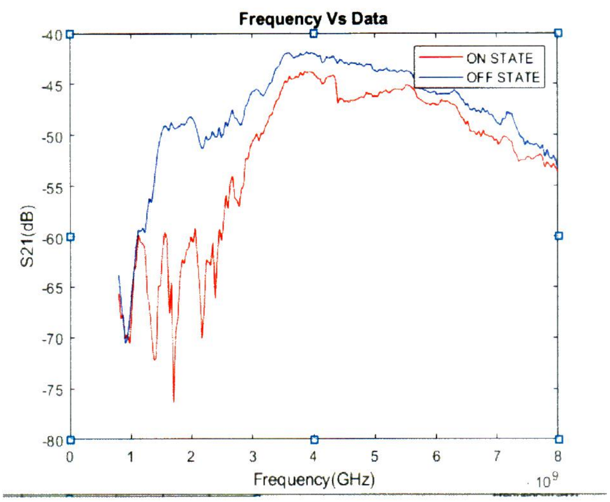


(a) (b)

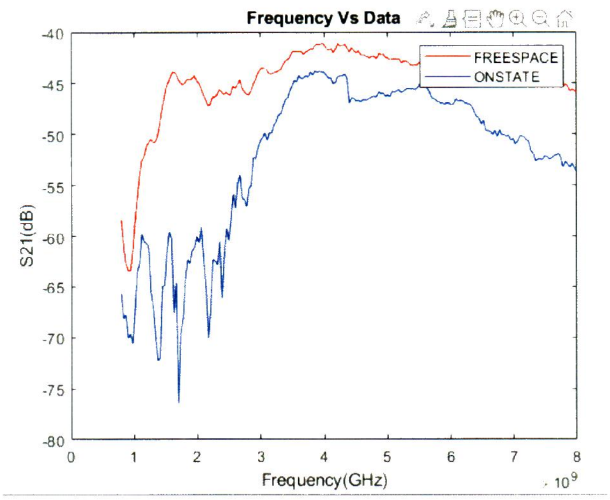
FIGURE 11. Measured Transmission Coefficient. (a) Metal Sheet versus Free Space (b) Metal Sheet versus Bracket

Figure 11(a) shows that as the frequency that being transmitted become higher, the radio wave that propagate being reflected to surrounding as they cannot pass through the metal sheet. The metal sheet suppressed the radio wave from -45 dB to be below -55 dB. For frequency between 5 GHz to 6 GHz, there are about 10 dB difference in transmission coefficient that pass-through metal sheet respect to free spaces. There is still radio wave that can pass beyond the metal sheet as its not totally covered the entire working region for the horn antennas. As for Figure 11(b), the difference for the transmission coefficient for metal sheet respect to bracket is not much from 3 GHz to 4.4 GHz compared to free space condition as there is factor that interfere the radio wave that propagate.

To observe the behavior of plasma wall, the metal sheet is replaced with plasma wall as the DUT. Figure 7 shows the placement for the plasma wall in the anechoic chamber. The measurement of the transmission coefficient was taken place in both states, ON and OFF states. Then both results were compared with the transmission coefficient of free space and bracket as shown in Figure 12.


Frequency Vs Data
ON STATE
OFF STATE
S21(dB)
-40
-45
-50
-55
-60
-65
-70
-75
-80
0
1
2
3
4
5
6
7
8
Frequency(GHz)
$\times 10^9$

(a)


Frequency Vs Data
FREESPACE
ONSTATE
S21(dB)
-40
-45
-50
-55
-60
-65
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-75
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Frequency(GHz)
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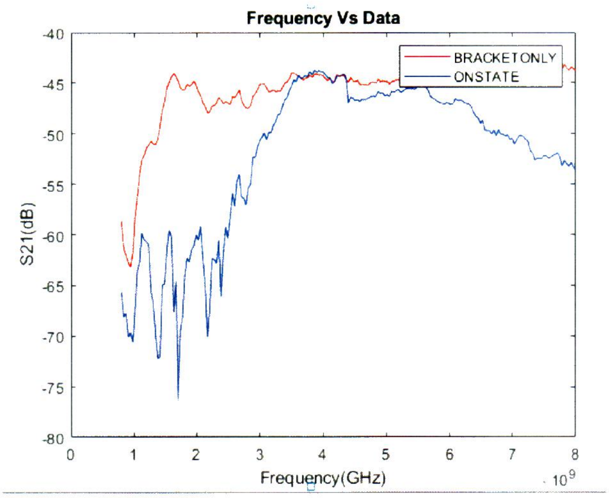
(b)


Frequency Vs Data
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ONSTATE
S21(dB)
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-55
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-65
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Frequency(GHz)
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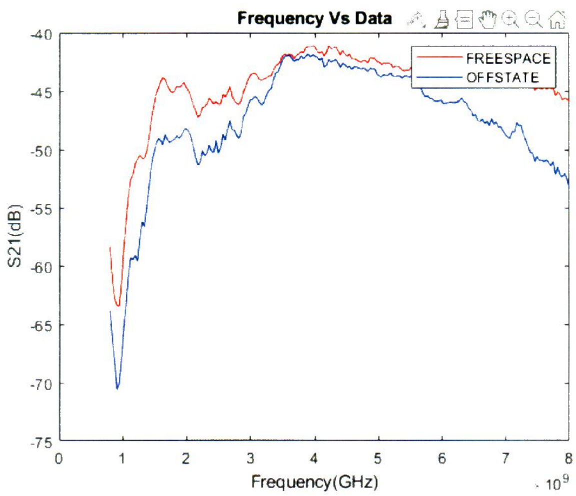
(c)


Frequency Vs Data
FREESPACE
OFFSTATE
S21(dB)
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-45
-50
-55
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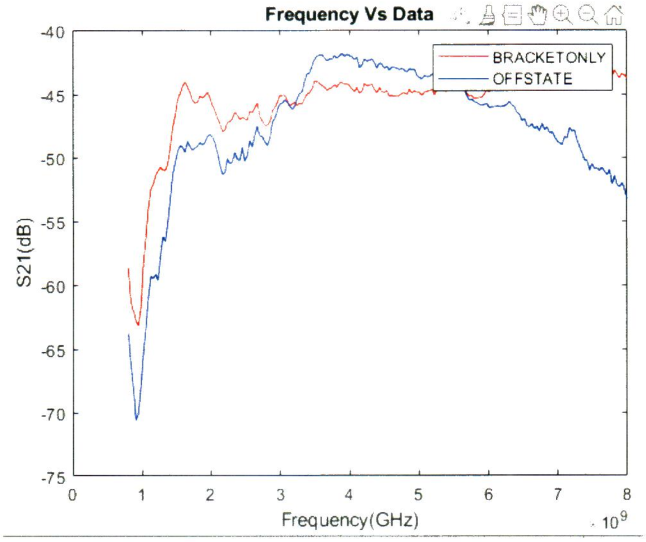
(d)



(e)

FIGURE 12. Measured Transmission Coefficient. (a) Plasma in ON State versus Plasma in OFF State (b) Plasma in OFF State versus Metal Sheet (c) Plasma in ON State versus Metal Sheet

When the plasma wall was on OFF state or not being supply with current, the reading for S_{21} for plasma wall in OFF state almost parallel with the reading of free space and bracket. This was because the ionized gas in the plasma tube does not show any reaction in ionizing. However, some factors may affect the radio wave that propagated such as nails. This was shown in Figure 12(d) and Figure 12(e).

The reading of S_{21} and transmission coefficient showed drastic change as the plasma wall was supplied with electric current. The plasma ions in the plasma tube occur by ionizing to produce electrons that can conduct electricity. As the radio wave being transmitted from transmitter penetrates through the plasma wall in ON state, at certain frequency the radio wave being reflected to the surrounding as the plasma wall acted as reflector. These can be observed in Figure 12(b) where the reading of S_{21} between free space and ON state plasma had the bigger difference in range of 2.2 GHz-2.8 GHz. Somehow in the range of 3 GHz-3.6 GHz, plasma changes its behavior from metal to dielectric. However, this experiment focused on determining the frequency for plasma to have common behavior with metal.

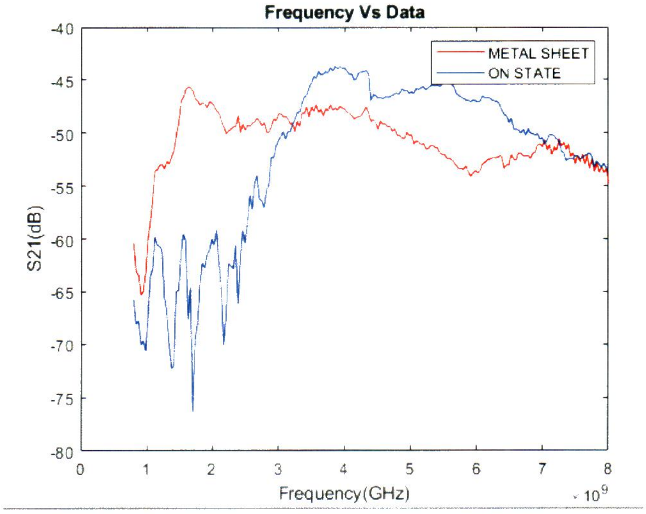


FIGURE 13. Measured Transmission Coefficient Plasma Activated and Metal Sheet

In proving that plasma had the properties of reflector where the radio wave cannot propagate through the plasma wall, the changing properties can be seen during below 3 GHz and upper 7 GHz of frequency in Figure 13. Plasma wall showed the same properties as the metal sheet in that range of the frequency.

CONCLUSION

The aim of this paper is to determine the critical frequency where plasma can act like a reflector and has similar properties as the metal, thus it can be a candidate to replace the traditional metallic element. The non-destructive method in determining the plasma critical frequency is well developed in the experiment and it is proven workable. The result in the experiments shows that at certain frequency when the radio wave was being propagated from the transmitter to receiver, the radio wave was reflected as the plasma wall changes its behavior to reflector. Based on the experimental results, it can be concluded that the plasma frequency of this experiment is approximately 7 GHz.

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