VOL. 12, NO. 23, DECEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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STUDY ON THE EFFECT OF A VARIATION TYPES OF GAS, PRESSURES AND COUPLING SLEEVES ON THE PERFORMANCE OF MONOPOLE PLASMA ANTENNA

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ABSTRACT

Plasma antenna is an antenna using ionized gas instead of metal as its conducting element. Plasma can be formed by energizing glass tubes which are filled with neutral gases. The main objective of this study is to investigate the effect of different gases, pressures and materials of coupling sleeve on antenna parameters of plasma antenna. Previous studies concentrate on using commercial fluorescent tube with unknown pressure as plasma antenna, and plasma ionization method using electroded discharge. This study investigates the parameters of plasma antenna with 4 different gases (neon, argon, argon-nitrogen and argon-mercury (fluorescent lamp)), 3 different pressures (1, 5, 10 Torr) and 2 different materials (copper and aluminium) for coupling sleeve. In this research, the simulation approach was conducted. The plasma tubes with constant length and diameter but different gas, pressures and coupling sleeve were designed. Actual tubes were used and energized using Dielectric Barrier Discharge (DBD) method in order to calculate plasma parameters. DBD was used as it can improve discharge lifetime. Antenna parameters were simulated using Computer Simulation Technology (CST) software with the resonance frequency is design in a ranged from 1 GHz to 10 GHz. Simulation results show that Ar (5 Torr) with aluminium coupling sleeve has the best performance in term of return loss by having the best value at -43.69894 dB. In terms of directivity and parameters, fluorescent tube with copper coupling sleeve has the highest value compared to others, which is 3.376 dBi and 3.3 dB, respectively. The variation type of gas, pressure and coupling sleeve material gives different performance of plasma antenna.

Keywords: plasma antenna, CST, dielectric barrier discharge (DBD), coupling sleeve.

INTRODUCTION

A plasma antenna can be used for transmission and receiving system, just like normal radio antennas. When voltage applied to an antenna, electric field produced and this electric field causes current to flow in antenna [1]. Due to this current flow, magnetic field is produced. These two fields are emitted from an antenna and propagate through space over very long distances. The electron behavior of plasma antenna is totally different from that of metal antenna. In plasma antenna, its functioning concept is due to 'electrons in free space' rather than 'electrons moving freely' [2]. In plasma antenna the electronic movement is made even more easily inside, because of the electrons are in a free state compared to traditional antenna. Solid metal antenna can function because electrons can move or vibrate in the metal conductor. Besides, plasma antenna greatly reduces the effects of interference compared to metal antennas which can pick up various noises or interference that bounce of the surrounding metal objects. Plasma antenna can be design in order to allow the signals to communicate in very short pulses that is useful in many forms of digital communication and in radars. It can be deionized just after sending a pulse and this makes the signal more confidential and harder to be detected [3]. Another distinguishing feature of plasma antenna is that the gas ionizing process can manipulate the resistance. When deionized, it has infinite resistance and hence it does not react with radio frequency (RF). When ionized, it will have some resistance as it will react with electromagnetic (EM) waves. This research focuses on how different types of gases, values of pressures applied and materials used for coupling sleeve affect the antenna parameters such as return loss, gain and directivity, as well as their efficiency as a plasma antenna.

In plasma antenna, when a voltage is supplied to the discharge tube, an electric field is formed. However, a signal is transmitted in EM wave form. A magnetic field is required to produce the EM wave and to ionise the gas inside the discharge tube. Hence, a wire is coiled on the discharge tube to serve as an inductor. The coil, which is the coupling sleeve, acts as inductance that causes electromotive force to be generated by a change in the flowing of current. Previously, the effect of the number of turns of coupling sleeve on monopole plasma antenna has been investigated. This research is focused on monopole plasma antenna and its performance has been evaluated previously [4, 5]. It was shown that monopole plasma antenna with four turns of coupling sleeve has the optimum performance, but the effect of the material used for coupling sleeve was not investigated [6]. Therefore, in this research, copper and aluminum were used and their results were compared. Besides, researchers normally focused on using the ready-made tube such as the commercial fluorescent tube, which the pressure inside is unknown. The effect of pressure on the tube performance remained uncertain with the unknown pressure. Hence, custom made discharge tubes with various pressures (1, 5, and 10 Torr) were used in this research to see how pressure affects the performance of different plasma

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antennas and the results were compared with the fluorescent tube which has unknown pressure. Most of the previous studies used electrode to allow current flow into the tubes to ionize the gas inside. However, dielectric barrier discharge (DBD) method has been proved to be better than using electrode in term of increasing the life span of the lamps and it is a simplest type of electrodeless discharge [7]. Hence, DBD method was used for this study.

There are many progress in the development of plasma antenna in recent years. In 2006, there is a remarkable discovery in the operation of plasma antennas. Alexeff *et al*., [8] discovered that benefits are brought if the discharge tubes are ionised by extremely short bursts of DC instead of by AC. The exciting current is on for only 2 μs. This makes the current-driven instabilities to be not serious. Less noise is produced in this new mode of operation. Besides, the plasma density produced by the pulsed-power technique is considerably higher than that produced by the same power supplied in the steady state. A research in 2007 [9] introduced a new type of plasma antenna that generates plasma column with pre-ionization from a high DC voltage. This device greatly increases the overall energy efficiency and bandwidth of the plasma antenna. Moreover, the electron density of the plasma is also nearly constant in entire length of the plasma column. Other than that, an analysis of monopole plasma antenna using different number of turns of coupling sleeve was presented in 2013. This research used plasma antenna which were fabricated with three different gases (neon, argon and xenon) with pressure 0.5, 5 and 15 Torr. It was found that four turns of coupling sleeve gave the optimum result in each configuration [6]. In 2015, plasma antenna characteristics were investigated theoretically and experimentally on the basis of gaseous collisionality and electron density [10]. The authors investigated that in the plasma antenna, the ratio of the electron elastic collision frequency to the total number of electrons at the plasma cross section determines the antenna's internal loss and the electrical equivalent antenna length, whereas the ratio of the radio wave frequency to the total number of electrons at the plasma cross section determines the antenna's resonant frequency. These results are confirmed by experimental results of the antenna's impedance and radiation patterns. The study presented here is an extension of the above mentioned studies.

EXPERIMENTAL SETUP

The experiment is divided into three phases where each phase is correlated. In the first phase, electrical properties of the plasma antenna were measured to obtain the value of discharge current and voltage which is needed in the second phase. At the second phase, the values obtained in the first phase were input into the Glomac program to get the values of electron density and electron temperature. During the third phase, the values of electron density and electron temperature are used to calculate the values of plasma frequency and collision frequency which are required in designing the plasma antenna using CST software.

Discharge tubes

A custom-made tubes were used. The length and diameter of the discharge tubes are shown in Table-1. Each tube was filled with different type of gas and pressure. Commercial fluorescent lamp was also used with an assumption of filled mercury and its vapour pressure at 10 Torr. Length and diameter for fluorescent lamp is 15 cm and 1.5 cm respectively. Note that the length of discharge tubes were measured according to the length of the aluminium tape since only the aluminium-covered area will be lightened up. Those gases were chosen due to their cost effective, environmental friendly, and relatively easy to discharge with the selected pressures.

Table-1. Length and diameter of discharge tubes.

Gas	**Ne**			**Ar**			**Ar-N_2**		
Pressure (Torr)	1	5	10	1	5	10	1	5	10
Length (cm)	10	10	10	10	10	10	10	10	10
Diameter (cm)	1	1	1	1	1	1	1	1	1

Discharge circuit

Connection diagram for DBD is shown in Figure-1. DC power supply is connected to the electronic ballast which act as converter (from DC to AC), amplifier (increase the voltage up to few hundreds volt) and also as a controller to control the current flow. The voltage input to the discharge tube can be controlled by adjusting the value of DC voltage.

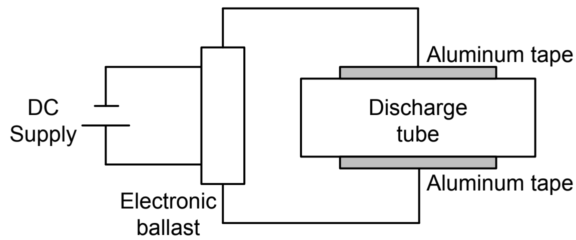

Figure-1. Diagram of the DBD discharge circuit.

Glomac programming

At the second phase, the values of current and voltage obtained in the first phase are input into the

Glomac program to get the values of electron density and electron temperature. Glomac is a computer codes to generate electron temperature, average gas density and average electron density [11]. By using the outputs from electrical properties measurement, the values of electron temperature, average gas density and average electron density can be generated. The current and voltage values obtained from electrical properties measurements with physical properties of discharge tube data such as length and radius of the tube, and other data such as type of gas and pressure were fed into Glomac programming. This software was beneficial to generate the plasma parameter such as electron temperature and electron density which needed to be used in calculations to find plasma and collision frequencies. Collision frequency and plasma frequency need to be obtained in order to simulate the behavior of plasma that will be used in CST software. Plasma frequency, ω_p, was calculated by using Eq. 1 (where n_e is the density of the ionized electrons, e and m are electron charge and electron mass respectively), while collision frequency, ν_c, can be obtained using Eq. 2 (where n is gas density, σ is collision cross section and ν_e is electron speed.). Numerically, the plasma frequency is based on the electron number density, and collision frequency is related to the electron temperature that obtained from Glomac programming. From the calculation, the values of plasma frequency and collision frequency were obtained and used as input parameters in CST software for plasma antenna simulation.

$$\omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m}} \quad (1)$$

$$\nu_c = n\langle \sigma \nu_e \rangle \quad (2)$$

CST Setting

Via CST software, the model of monopole plasma antenna is constructed using CST Microwave Studio (CST MWS). The plasma antennas were designed with the same length and diameter, which are 10 cm and 1 cm respectively. Every tube contains the same length of plasma column but different plasma parameters due to different gas fill and pressure. Each tube will be simulated by using copper and aluminium as coupling sleeve as comparison. During the third phase, the values of electron density and electron temperature are used to calculate the values of plasma frequency and collision frequency using Eq. 1 and Eq. 2. These values are required in designing the plasma antenna using CST software. After designing the model of plasma antenna, simulation is carried out to obtain the return loss, directivity and gain of the antenna using frequency range of 1-10 GHz. The example of the model of plasma antenna designed using CST software is shown in Figure-2.

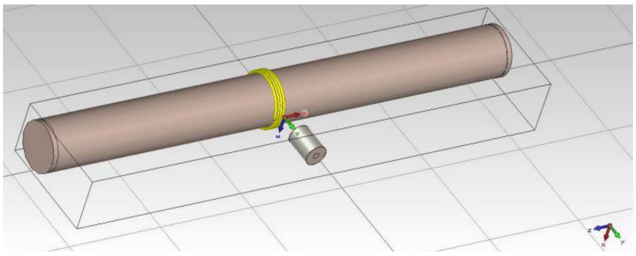

Figure-2. The complete model of plasma antenna.

RESULTS AND DISCUSSIONS

From Glomac calculation and CST simulation, antenna parameters such as return loss, resonant frequency, gain and directivity were obtained. The plasma antenna were designed and analysed in different conditions of plasma properties in order to optimize the performance of plasma antenna.

Electrical and plasma properties

The voltage needed to energize the tubes were in the range of 250-400 V (Ne, Ar, Ar-N_2) and 150-300 V (fluorescent), while current needed were 35-45 mA (Ne, Ar, Ar-N_2) and 40-50 mA (fluorescent). For lamp filled with Ne, Ar, Ar-N_2, the voltage needed is higher than Ar-Hg (fluorescent) lamp. This is due to breakdown voltage those gases are higher than mercury. Those gases are non-reactive gas, thus they need high energy to be ionized. However, discharge current for mercury lamp is higher. This can be thought due to mercury need low voltage to be discharged, thus their gas resistivity is low that can allow more current flow across the tube. Results of Glomac calculation is shows in Table-2. Higher pressure gives high electron density but low electron temperature. This can be considered due to the increase in the mean free path that decreases the electron collision probability. Thus the ionization process per unit atom will decrease and subsequently the plasma density will be reduced. Electrons receive kinetic energy when accelerated by an electric field, and in the meantime lose their energy due to collisions. Electron temperature can be determined from the difference between these two energies [12]. Hence, due to the decrease of collisions, effect of kinetic energy largely contribute to the increase of electron temperature when pressure is decreased. As shown in Table-3, in general plasma frequency and collision frequency increases when gas pressure is increased. Plasma frequency is the motion caused by the coordinated movement of many particles together that gives a collective effect. Its value directly relates with the value of electron density, the higher the electron density the higher the plasma frequency. Collision frequency increases when the gas pressure is increased is due the higher gas density that could bring higher rate of electron-atom, electron-molecule collisions.

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Table-2. Electron temperature and electron density for each condition of discharge (results from Glomac).

Pressure (Torr)	**Type of gas**	**Electron temperature** (eV)	**Electron density** (m^{-3})
1	Ne	2.833	5.27×10^{16}
	Ar	2.163	9.57×10^{16}
	Ar-N_2	2.158	1.01×10^{17}
5	Ne	0.487	2.24×10^{18}
	Ar	0.496	2.33×10^{18}
	Ar-N_2	1.572	2.60×10^{17}
10	Ne	0.482	2.14×10^{18}
	Ar	0.49	2.14×10^{18}
	Ar-N_2	1.42	3.85×10^{17}
	Ar-Hg (fluorescent)	0.971	1.52×10^{17}

Table-3. Calculated results of plasma frequency and collision frequency for each condition of discharge.

Pressure (Torr)	**Type of gas**	**Plasma frequency** (rad/s)	**Collision frequency** (s^{-1})
1	Ne	1.29×10^{10}	8.26×10^{8}
	Ar	1.74×10^{10}	1.03×10^{9}
	Ar-N_2	1.79×10^{10}	1.03×10^{9}
5	Ne	8.44×10^{10}	1.02×10^{9}
	Ar	8.61×10^{10}	3.24×10^{8}
	Ar-N_2	2.88×10^{10}	2.63×10^{9}
10	Ne	8.25×10^{10}	2.03×10^{9}
	Ar	8.25×10^{10}	6.70×10^{8}
	Ar-N_2	3.50×10^{10}	4.57×10^{9}
	Ar-Hg (fluorescent)	2.20×10^{10}	1.89×10^{9}

Simulation Results

The overall simulation results are shown in Table-4 and Table-5. Table-4 shows the return loss, directivity and gain of each type of gases, pressure with copper as their coupling sleeve while Table-5 shows the same antenna parameters when aluminum was used as their coupling sleeve.

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Table-4. Return loss, directivity and gain for each type of gas and pressure using copper as coupling sleeve.

Pressure (Torr)	Gas	Return loss (dB)	Directivity (dBi)	Gain (dB)
1	Ne	-28.61712	2.702	2.612
	Ar	-30.01453	2.680	2.575
	Ar-N_2	-21.29231	2.328	2.230
5	Ne	-29.52618	2.478	-2.508
	Ar	-37.17196	2.468	-2.822
	Ar-N_2	-22.01325	2.235	2.112
10	Ne	-20.35013	2.439	-3.632
	Ar	-20.54576	2.537	-1.872
	Ar-N_2	-24.26353	2.169	1.881
	Ar-Hg	-35.48373	3.376	3.300

Table-5. Return loss, directivity and gain for each type of gas and pressure using aluminum as coupling sleeve.

Pressure (Torr)	Gas	Return loss (dB)	Directivity (dBi)	Gain (dB)
1	Ne	-29.22372	2.701	2.578
	Ar	-30.69921	2.680	2.555
	Ar-N_2	-21.46847	2.333	2.210
5	Ne	-31.47198	2.465	-2.586
	Ar	-43.69894	2.468	-2.900
	Ar-N_2	-22.19300	2.234	2.087
10	Ne	-20.16618	2.436	-3.694
	Ar	-21.07466	2.537	-1.926
	Ar-N_2	-24.78401	2.168	1.859
	Ar-Hg	-34.33682	3.382	3.280

Return loss

In term of return loss, S_{11}, -10 dB is used as a reference to decide whether the antenna can function well as an antenna. The value of S_{11} has to be smaller than -10 dB so that the antenna is functional [13]. From Table-4 and Table-5, all of the results have values less than -10 dB, which means that every plasma antenna are functional as an antenna. They have less power loss while the signals are reflecting back. Since most of the result of using aluminum as coupling sleeve are better than that using copper as coupling sleeve, the following comparisons will be done based on the results of using aluminum as coupling sleeve. The comparisons of each gas with different pressures are shown in Figures 3, 4 and 5. Then, the best result of each gases are compared with fluorescent tube (Figure-6). For Ne and Ar, the best result of return loss belong to the discharge tubes with pressure of 5 Torr and the worst for pressure of 10 Torr. However, for Ar-N_2, the best result of S_{11} belongs to the discharge tube with pressure of 10 Torr. The sequence of the values of S_{11} for Ne and Ar is decreasing from 1 Torr to 5 Torr but increase at 10 Torr and the plot for 3 pressures are obviously different. On the other hand, the sequence for Ar-N_2 keeps decreasing from 1 Torr to 10 Torr and the plot for 3 pressures has the same shape. This phenomena indicates that gas pressure plays an important role in plasma formation. Different values of current are needed at different level of pressures. This relates to the balance in the number of electrons and the value of mean free path or average distance between collisions for a gas molecule. According to the equation of mean free path (λ) below, the gas with higher pressure has higher electron density (n_e) as shown in Table-2; hence it gives smaller value of mean free path [14].

$$\lambda = \frac{1}{n_e \sigma} \qquad (3)$$

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When the value of mean free path is smaller, the distance before a molecule to collide with another is shorter. This lowers the electron velocity and causes ineffective collision. In contrast, the gas with lower pressure has lower electron density, bigger value of mean free path, longer distance before the molecule collides with another and higher electron velocity. However, the collision is still ineffective due to the low number of electrons. Therefore, this theory explains why the optimum result for Ne and Ar is at 5 Torr and 10 Torr for Ar-N_2. The final comparison of this part (Figure-6) shows that the discharge tube filled with argon gas and pressure of 5 Torr has the best performance by having the best value of S_{11}.

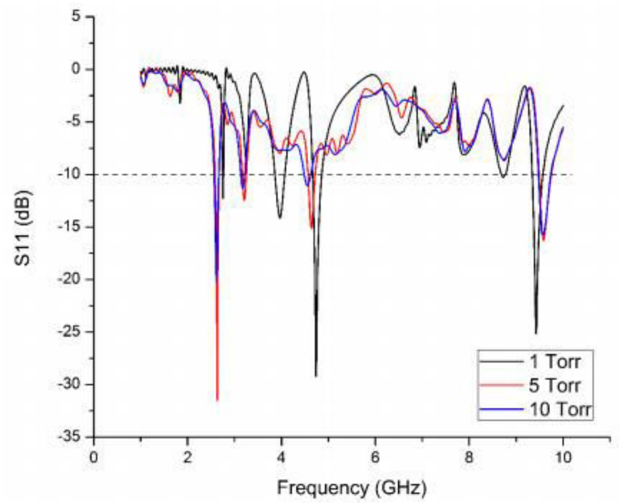

Figure-3. Comparison of Ne with different pressures using aluminum as coupling sleeve.

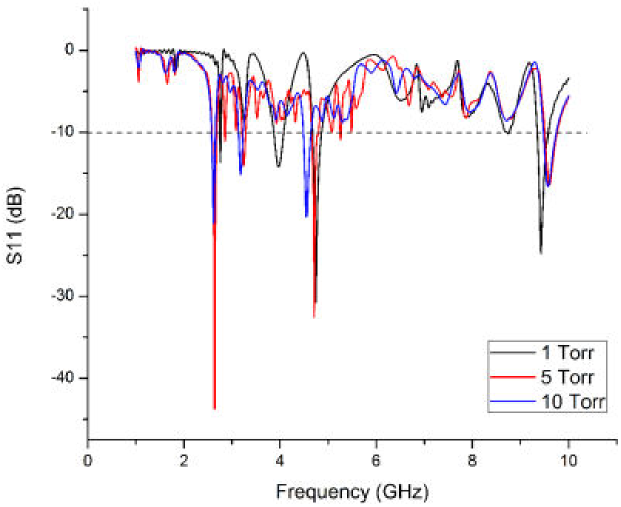

Figure-4. Comparison of Ar with different pressures using aluminum as coupling sleeve.

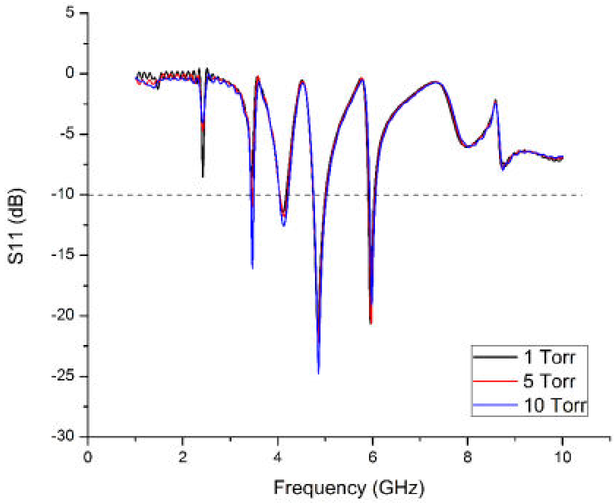

Figure-5. Comparison of Ar-N_2 with different pressures using aluminium as coupling sleeve.

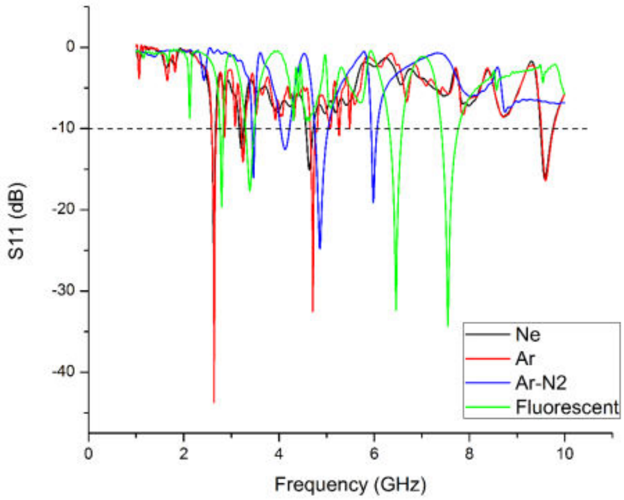

Figure-6. Comparison of the best result of S_{11} from each gas with fluorescent using aluminum as coupling sleeve.

Directivity

In term of directivity, the results of either using copper or aluminum as the coupling sleeve has no big difference, and the results of copper is slightly higher than the aluminum in most cases. Hence, the following comparisons are done by using the data of copper coupling sleeve instead of aluminum coupling sleeve. According to Figure-7, the values of the directivity of each gas are around 2 to 3 dBi. Fluorescent (Ar-Hg) has the highest value of directivity, which is 3.376 dBi compare to other three gases. This means that it can receive more "focused" signal than others. For the other three gases, they share the similarity that they have the best directivity when the pressure of 1 Torr is used comparing with the pressures of 5 Torr and 10 Torr. However, the difference of the value of directivity of fluorescent and other gases is very small. The result obtained is considered as low directivities. It also indicates that the discharge tubes behave as quarter-wave monopole antennas which typically have in the range of 2.8 dBi of directivity [15].

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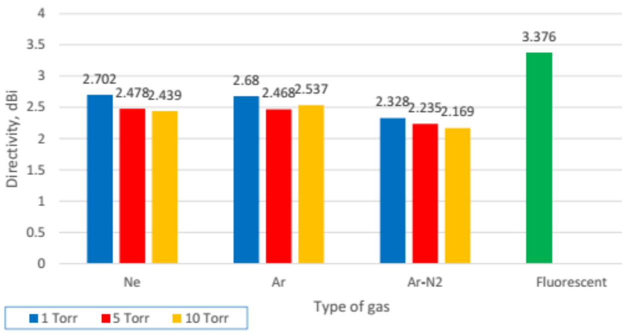

Figure-7. Comparison of the directivity of each gas with different pressures to fluorescent tube using copper as coupling sleeve.

Gain

By using the result of gain as the main perspective, the results from Table-4 and Table-5 suggest that the discharge tubes with copper as coupling sleeve have better performance than those with aluminum. Therefore, the comparison under this topic will be made by using the results of copper coupling sleeve. The comparison is shown in Figure-8. The reason why copper coupling sleeve has better simulation result than aluminum coupling sleeve is thought to be caused by the electrical conductivity of the material used as the coupling sleeve. According to the material library of the CST software, the electrical conductivity of copper and aluminum are 5.8×10^{7} S/m and 3.56×10^{7} S/m respectively. When the electrical conductivity of a metal is higher, it allows more current to flow through it, and hence it makes the magnetic field produced stronger. Results from the Figure-8 appear to suggest that fluorescent tube has the best performance among the discharge tubes with pressure of 1 Torr have better performance than those with 5 Torr and 10 Torr. Figure-8 also shows that Ne and Ar have “negative” gain when using pressures of 5 Torr and 10 Torr. A further evaluation on the results of Table-4 as well as Figures 3, 4 and 5, indicates that the gain value is related with the return loss results. In Figures 3 and 4 which are the plot of Ne and Ar, the plots of each pressure of the same gas are different. However, the plot in Figure-5, which is the plot of Ar-N_2, the three plots of the same gas with different pressures has the same shape. Due to this “negative” gain, the steps for the simulation were repeated for many times. However, same results were obtained. It is accounted to be an error or possibly due to the results of impedance miss match or the antenna is not radiating well at certain direction. Besides, from Figure-7 and Figure-8, the result of directivity and gain parameters are linear. In other words, if the directivity value is high, the value of gain is also high, or vice versa. This proves the general relation of gain, directivity and efficiency, which is *Gain = Efficiency × Directivity*. Overall, fluorescent with copper coupling sleeve has a better result. It owns the best result in terms of directivity and gain. Although fluorescent with aluminum coupling sleeve has a good result just after the result of Ar with aluminum coupling sleeve, which is the best result among all, the difference between the result of return loss of fluorescent using copper and aluminum coupling sleeve is very small. Moreover, return loss is less commonly quoted than gain and directivity in an antenna's specification sheet because gain is the one that takes into account the actual losses that occur. Therefore, via simulation, fluorescent with copper coupling sleeve serves as a better antenna comparing to other plasma antennas within the tested condition.

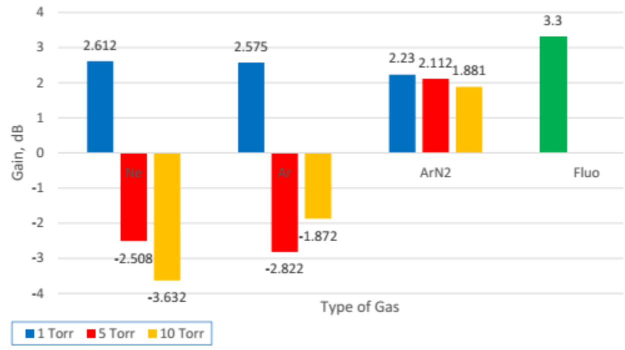

Figure-8. Comparison of the gain of each gas with different pressures to fluorescent tube using copper as coupling sleeve.

CONCLUSIONS

This simulation exposed the crucial characteristics of plasma antenna based on the different gases filled and pressures for plasma antenna as well as the materials used for coupling sleeve. Based on simulation, Ar with 5 Torr has the smallest return loss, while fluorescent has the highest directivity and gain. Overall, fluorescent with copper coupling sleeve has the better result. The simulation results showed that different level of pressures applied and different material used for coupling sleeve affect the value of return loss, directivity and gain of the plasma antenna.

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