Indian Journal of Pure & Applied Physics
Vol. 56, March 2018, pp. 238-247

Study of monopole plasma antenna parameters

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Received 30 May 2017; accepted 3 November 2017

This paper is aimed to investigate the plasma antenna parameters to help the optimization of plasma antenna dimensions (length and radius of plasma antenna). Five different configurations of plasma antenna have been simulated with the help of high frequency structure simulator (HFSS 13.0). The observations have been made on variation in antenna parameters like resonance frequency, directivity, gain and radiation pattern with the radius and length of the plasma column. The results of the study indicate that plasma column of radius r< 1.5 cm shows better performance in the sense of directivity and gain than the plasma column of radius r> 0.5 cm. In addition, tunability of the plasma antenna has been studied with respect to the resonance frequencies. Moreover, simulation results have been matched with experimental results, e.g., directivity and radiation patterns, providing more interesting results which cannot be measured due to experimental restrictions.

Keywords: Plasma antenna, Antenna parameters, Monopole antenna, Resonance frequency, Antenna and communication

1 Introduction

Nowadays plasma antenna has become a well known and scientifically accepted antenna device. Previously it has been shown that plasma antenna can be used similar to a metallic antenna[1-7]. The plasma antenna has different domain of properties and multidimensional applications over the conventional antenna which requires its investigation in detail. The plasma antenna has plasma as a conducting element which has interesting properties, i.e., electrically controllable appearance, density variation, conductivity variation and reconfigurable structure. These properties of plasma make plasma antenna applicable in various fields where the metallic antenna is not appropriate[8-10]. The plasma antenna is efficient and generates sufficiently low noise so as to be useful for narrow band high frequency and very high frequency communication[11]. It is observed that radiation pattern of a plasma antenna can also be changed for different purposes by changing plasma parameters[12]. The different resonance frequencies for a single plasma antenna have been obtained[13]. Additionally, it has also inspired a great interest due to its potential advantages over the conventional antennas. It has the ability to turn "OFF" and turn "ON" by supplied power for plasma production. It can also be re-tunable for different frequencies, electrically reconfigurable, reducing radar cross section and unwanted effects in electronic warfare. A number of remarkable findings have been patented and several industries and organizations have expressed interest in the applications of plasma antenna technology to their products and services such as Motorola (application of plasma switched antenna for mobile phones), CSIR (use of plasma switched antenna for radio telescope array), CEA technologies (use of plasma antenna for RADAR applications), plasma antennas limited Oxford (solid state plasma antennae), Marklend technologies, etc.

Vast literature is available however both in experiments or theoretical/simulations which show that the plasma antenna is a re-tunable antenna. That means it can be re-tuned for different operating frequencies without making any change in their mechanical structure while just by changing electrically operated parameters (applied voltage, pressure, gas, etc) for a particular mechanical structure of antenna. Therefore the present study is focused to study the re-tunabilty of a plasma antenna with the help of simulation models for different configurations of plasma antenna. In addition we need to find antenna parameters on the observed resonance frequencies at which plasma antenna can be re-tuned, using electromagnetic software high frequency structure simulator (HFSS)[14]. Moreover one of the important issues is addressed in this paper which is related to choice of appropriate length and diameter of the plasma antenna (plasma tube).

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2 Theory and Method

For the simulation study we have to understand the basic theory of plasma antenna. The used plasma is weakly ionized cold plasma produced by glow discharge. The thermal motions of ion's are neglected. Fluid model is accepted so the plasma is treated as fluid.

For the weakly ionized plasma in which the collision frequency is higher than the wave frequency ($\vartheta_m \gg \omega$) the conductivity can be calculated by the formula is written below[6]:

$$\sigma = e^2 N_e / m_e \vartheta_m \qquad \text{... (1)}$$

Here e is the electronic charge, N_e is the electron density, m_e is the mass of an electron and ϑ_m is the electron neutral collision frequency.

According to analysis[2], the plasma density for the surface wave sustained plasma is found from a power balance equation in which the power absorbed per unit length by the plasma from the surface wave at position z along the plasma column $P_a(z)$ is balanced by the power per unit length lost to the walls from the plasma $P_l(z)$ by the migration of electron-ion pairs at Bohm velocity (u_B) hence $P_a(z)$is given by:

$$P_a(z) = -dW_p(z)/dz = a(z)W_p(z) \qquad \text{... (2)}$$

where $a(z)$ the attenuation coefficient and $W_p(z)$ is the wave power at axial position of z. The attenuation coefficient may be determined from the dispersion relation for the surface wave, with allowance being made for losses via collisions[5]. Hence:

$$a(n) = C\vartheta_m/(N_e - N) \qquad \text{... (3)}$$

where C is constant and $\vartheta_m = \vartheta_m(p)$ is the electron-neutral collision frequency for momentum transfer, N is a characteristic number density at a plasma frequency corresponding to the radio frequency of the source of ω frequency, modified by dielectric constant ε_g of the insulator (glass) surrounding the plasma as follows:

$$N = N_e - N_{eg} \qquad \text{... (4)}$$

where

$$N_e = (m_e \varepsilon_0 \omega^2)/e^2 \qquad \text{... (5)}$$

And N_{eg} is correction term:

$$N_{eg} = (m_e \varepsilon_r \omega^2)/e^2 \qquad \text{... (6)}$$

Now putting above values of N_e and N_{eg} in Eq. (4) we get:

$$N = (m_e \varepsilon_0 \omega^2/e^2) - (m_e \varepsilon_r \omega^2/e^2) \qquad \text{... (7)}$$

$$N = (m_e \varepsilon_0 \omega^2/e^2) - \left(m_e \varepsilon_0 \varepsilon_g \omega^2/e^2\right) \qquad \text{... (8)}$$

$$N = \omega^2\left(1 - \varepsilon_g\right)(\varepsilon_0 m_e/e^2) \qquad \text{... (9)}$$

If the antenna is excited at the base of the column (z =0) by input power of W_{p0} watts and corresponding density, $N_{e0} \gg N$, then combination of Eqs (2) and (3), it gives:

$$N_{e0} = P_a(p)\left(W_{p0}\right)^{1/2} \qquad \text{... (10)}$$

where

$$P_a(p) = (2C\vartheta_m(p)/k(p))^{1/2} \qquad \text{... (11)}$$

where, $P_a(p)$ is a constant for a given working pressure. The plasma density is in the approximately linear fashion along the antenna. Since surface wave does not propagate for $N_{e0}<N$ and the condition $N_{e0} = N$ defines the top end of the antenna. Antenna length can be decided as:

$$l = (N_{e0}h_0/N) - h_0 \qquad \text{... (12)}$$

where h_0 is a characteristics length of plasma antenna. Substituting for N_{e0} from Eq. (10) and generally $l \gg h_0$, Eq. (12) may be written as:

$$l = B(p)(W_{a0})^{1/2} \qquad \text{... (13)}$$

where

$$B(p) = (2/Ck(p)\vartheta_m(p))^{1/2} \qquad \text{... (14)}$$

Equation (13), therefore, shows that for a given working pressure the electric length of plasma antenna should increase as the square root of the input power.

The complex dielectric constant of the plasma can be given as[15]:

$$\varepsilon_p = 1 - \left(\omega_{pe}^2/\omega(\omega - i\vartheta_m)\right) \qquad \text{... (15)}$$

where ω_{pe} is the plasma angular frequency:

$$\omega_{pe} = (N_e e^2/m_e \varepsilon_0)^{1/2} \qquad \text{... (16)}$$

Assuming a time harmonic wave with an $e^{i\omega t}$ time dependence is propagating in the $+z$ direction has the form:

$$E(z) = kE_0 \exp(-\gamma z) \quad \text{... (17)}$$

For the special case of negligible collisions, $\vartheta_m = 0$, the corresponding propagation constant is:

$$\gamma = ik_0\left(\omega_{pe}^2/\omega^2\right)^{1/2} \quad \text{... (18)}$$

The behaviour of wave into plasma depends on propagation constant which is different in three cases. When $\omega > \omega_{pe}$ the γ is imaginary so wave propagates, for the condition $\omega < \omega_{pe}$ then γ is real means wave which is an evanescent wave and for the condition of $= \omega_{pe}$, $\gamma = 0$ and this value of ω is called the critical frequency (ω_c) which defines the boundary between propagation and attenuation of the EM wave. Plasma behaves as a dielectric medium with negative dielectric constant for frequencies above the plasma frequency. In the case, plasma transmits electromagnetic waves with the dispersion relation[15]:

$$\omega^2 = \omega_{pe}^2 + \gamma^2 c^2 \quad \text{... (19)}$$

where c is the velocity of light. For frequencies below the plasma frequency, plasma cannot transmit EM waves. At plasma-dielectric interface, surface wave propagates along the interface. The given basic theory of plasma antenna will help us to design of antenna which is given in the next section.

3 Design of Antenna

To design a plasma antenna on electromagnetic software (HFSS), it requires some plasma parameters like plasma conductivity, plasma density, and plasma permittivity. These parameters of plasma have been calculated theoretically by the formulas as given in the section 2. These parameters are as follows, plasma electron density[9] is chosen to be n_e~ 10^{16} m^{-3} and the collision frequency[9] v_m~ 4×10^8 Hz. Hence from Eq. (1) the plasma conductivity is $\sigma = 22.5$ S/m^3 and from Eq. (16) the plasma frequency is $\omega_p = 30\times10^6$ Hz.

Simulation study is presented for an experimentally established plasma antenna[9]. Experimental setup of a plasma antenna is shown in Fig. 1 which consist a 30 cm long glass tube with a radius of 1.5 cm. The tube is evacuated by a combined rotary and diffusion pumps and then filled with argon gas to working pressure (0.05 mbar). A plate of aluminum with a diameter of 12 cm and thickness of 2 cm is mounted at one end of the glass tube as ground plate. A capacitive coupler mounted above the ground plate, used to couple signals into the plasma because direct contact with plasma is not possible. The initial breakdown takes place inside the tube in the gap between coupler and ground plate by CW (continuous wave) RF generator of power up to 100 W. A 30 cm long plasma column is formed by surface wave in the glass tube.

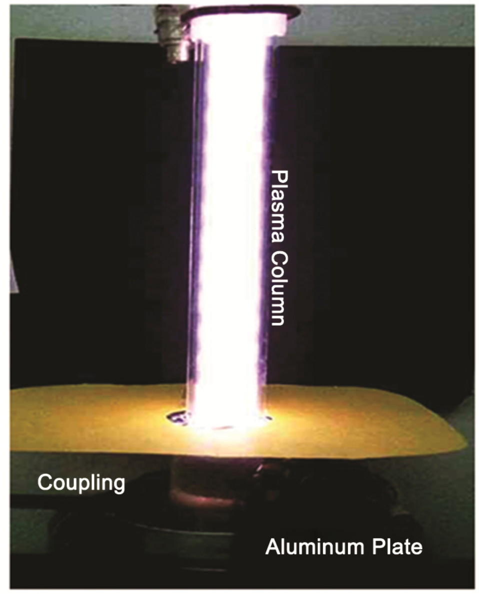

Fig. 1 — Experimental setup of monopole plasma antenna of 1.5 cm radius and 30 cm length.

A plasma antenna of similar parameters and configuration to experimental antenna described above is simulated and shown in Fig. 2, it consists a glass tube of 30 cm long and 1.5 cm in radius, the tube filled with the plasma medium and as mentioned in above approximations that density of plasma is uniform in whole tube, an aluminum ground plate of 12 cm in diameter and a thickness of 2.0 cm is designed at the one end of the glass tube and a port as a source assigned in between the plasma column and ground plate. An air volume object is designed as a radiation boundary infinitely far from the antenna.

Furthermore to find out the effect on antenna parameters and resonance frequencies with respect to variation in length and radius of plasma tube, we also simulate four different configuration of this antenna without changing any plasma parameter. The two of them have same length 30 cm but different radius of 1.00 cm and 0.50 cm shown in Fig. 3 and Fig. 4, respectively, and the other two have same radius

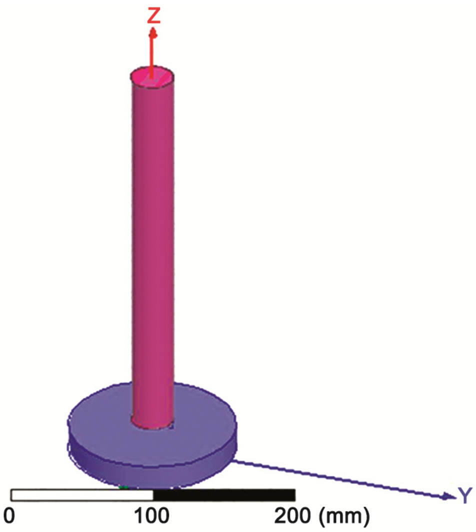

Fig. 2 — Plasma Antenna model of 1.5 cm radius and 30 cm length.

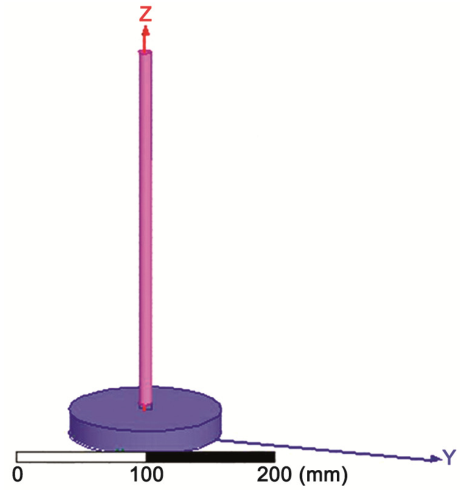

Fig. 4 — Plasma Antenna model of 0.5 cm radius and 30 cm length.

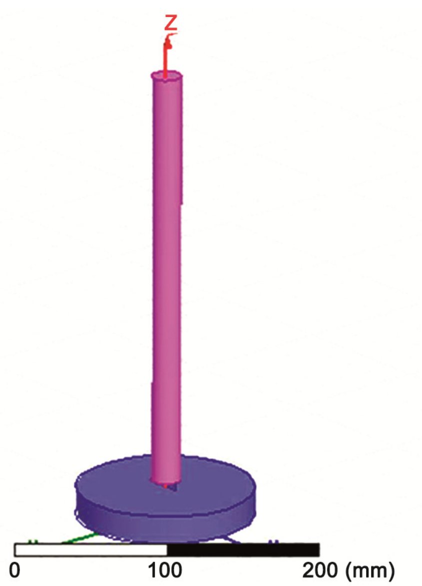

Fig. 3 — Plasma Antenna model of 1.0 cm radius and 30 cm length.

1.5 cm but different lengths of 20 cm and 10 cm shown in Fig. 5 and Fig. 6, respectively.

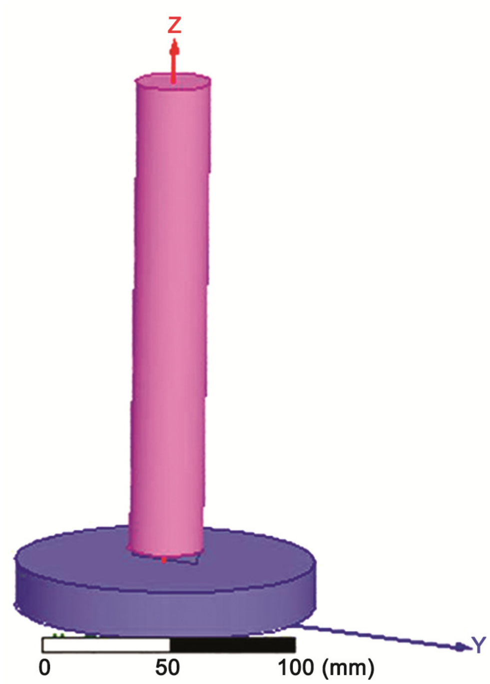

Fig. 5 — Plasma Antenna model of 1.5 cm radius and 20 cm length.

4 Results

After the simulations of different configurations of plasma antenna as mentioned in earlier section we find the different antenna parameters (*S*-parameter, radiation patterns, directivity and gain) for each plasma antenna separately. The detail of each parameter is given below in subsections.

4.1 *S*-parameter

S-parameter describes the input-output relationship between ports (or terminals) in an electrical system. The *S*11 parameter represents how much power is reflected from antenna on a certain frequency. Any frequency at which *S*11 has minimum value is called resonance frequency of the antenna and at that frequency antenna will transmit maximum power[16]. In this paper, we find *S*-parameter for all the configuration of plasma antennas over the frequency range from 0.001 GHz to 2 GHz.

The *S*-parameter for plasma antenna of 1.5 cm in radius and 30 cm in length is shown in the Fig. 7. The

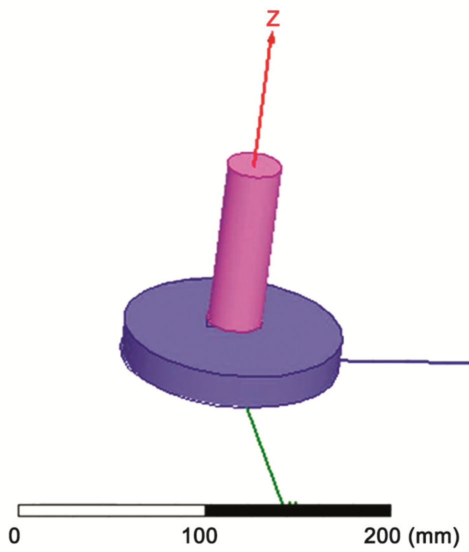

Fig. 6 — Plasma Antenna model of 1.5 cm radius and 10 cm length.

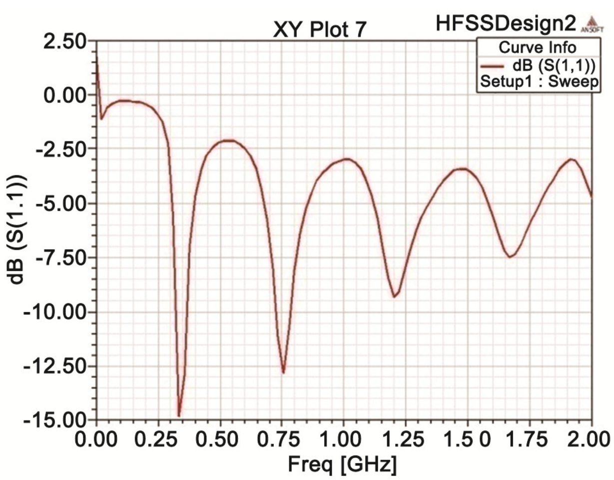

Fig. 7 — *S*-parameter for plasma antenna of radius 1.5 cm and length 30 cm.

resonance frequencies for this configuration of the antenna are 0.330 GHz, 0.750 GHz, 1.200 GHz and 1.700 GHz and the return losses corresponding to these resonance frequencies are -14.85 dB, -12.76 dB, -09.29 dB and -07.46 dB, respectively. The *S*-parameter for plasma antenna of 1 cm in radius and 30 cm in length is shown in Fig. 8. The resonance frequencies for this configuration of the antenna are 0.330 GHz, 0.750 GHz, 1.200 GHz and 1.700 GHz and the return losses corresponding to these resonance frequencies are -18.20 dB, -23.89 dB, -13.69 dB and-16.07 dB, respectively. Moreover the *S*-parameter for plasma antenna of 0.5 cm in radius and 30 cm in length is studied and results are shown in Fig. 9. The resonance frequencies for this configuration of the antenna are

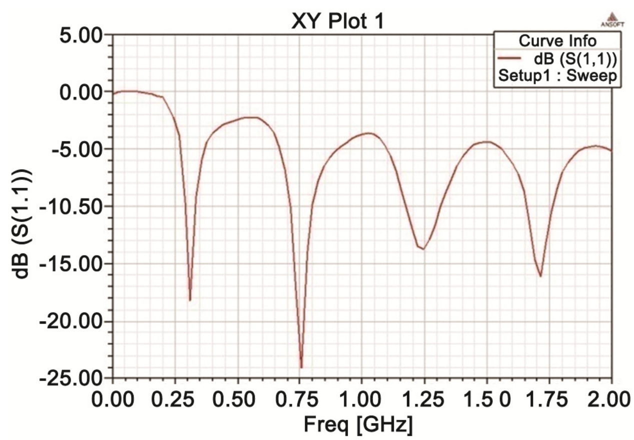

Fig. 8 — *S*-parameter for plasma antenna of radius 1.0 cm and length 30 cm.

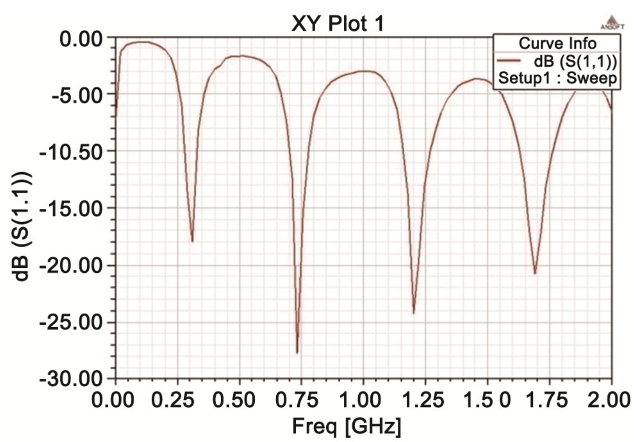

Fig. 9 — *S*-parameter for plasma antenna of radius 0.5 cm and length 30 cm.

0.330 GHz, 0.750 GHz, 1.200 GHz and 1.700 GHz and the return losses corresponding to these resonance frequencies are -17.84 dB, -27.70 dB, -24.22 dB and -20.73 dB, respectively. The resonance frequencies and corresponding return loss obtained for the above three configurations are given in the Table 1.

Figure 10 is the result of the study of the *S*-parameter for plasma antenna of 1.5 cm in radius and 20 cm in length. The resonance frequencies for this configuration of the antenna are 0.440 GHz, 1.100 GHz and 1.800 GHz and the return losses corresponding to these resonance frequencies are -19.60 dB, -09.07 dB and -07.87 dB, respectively, while Fig. 11 shows the *S*-parameter for plasma antenna of 1.5 cm in radius and 10 cm in length. For this configuration obtained resonance frequencies and corresponding return loss are shown in Table 2. Furthermore the resonance frequency for this configuration of the antenna is 0.800 GHz and the

Table 1 — Resonance frequencies with corresponding return loss for plasma antennas of radius 1.5 cm, 1.0 cm, 0.5 cm at constant length 30 cm.

S. No.	Resonance frequency (GHz)	Return loss for radius 1.5 cm (dB)	Return loss for radius 1.0 cm (dB)	Return loss for radius 0.5 cm (dB)
1	0.330	-14.85	-18.20	-17.84
2	0.750	-12.76	-23.89	-27.70
3	1.200	-09.29	-13.69	-24.22
4	1.700	-07.46	-16.07	-20.73

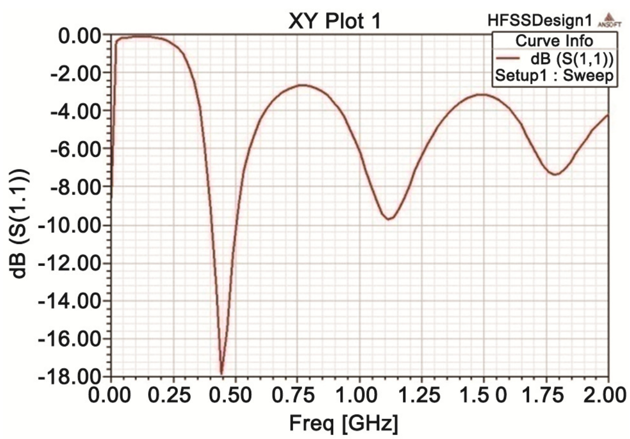

Fig. 10 — *S*-parameter for plasma antenna of radius 1.5 cm and length 20 cm.

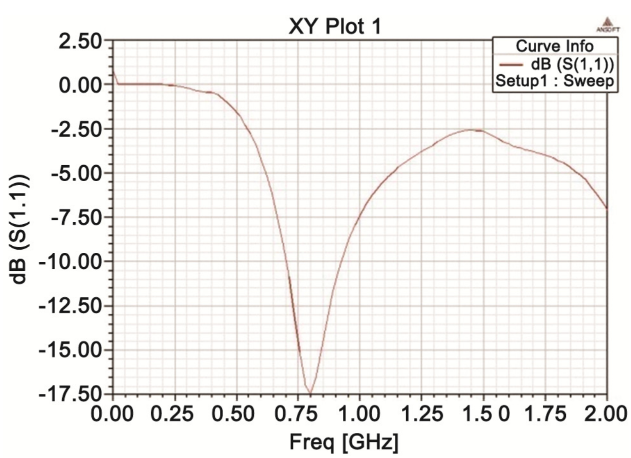

Fig. 11 — *S*-parameter for plasma antenna of radius 1.5 cm and length 10 cm.

return losses corresponding to the resonance frequency is -17.64 dB.

4.2 Radiation patterns

The radiation pattern is an important property of an antenna. In general the power received at a point by a receiving antenna is a function of the position of the receiving antenna with respect to the transmitting antenna. At a constant radius from transmitting antenna, graph of the received power is called the power pattern which is a spatial pattern. The special pattern of the electro-magnetic field is called field pattern. A cross section of this field pattern in any particular plane is called "radiation pattern" in that plane[17,18].

Radiation patterns corresponding to the all configurations of plasma antennas at all the observed resonance frequencies have been studied. The radiation patterns are simulated in both the planes (azimuthal and elevation). It has been estimated that radiation pattern in azimuthal plane for all the configurations are symmetric around the axis but elevation pattern are different. Therefore only elevation patterns are shown in results.

Radiation patterns for three plasma antenna of radius 1.5 cm, 1.0 cm and 0.5 cm at constant length 30 cm are shown in Fig. 12, Fig. 13 and Fig. 14, respectively. Figure 12(a-d) is radiation patterns for plasma antenna of radius 1.5 cm and length 30 cm at the resonance frequency 0.330 GHz, 0.750 GHz, 1.200 GHz and 1.700 GHz, respectively. Figure 13 (a-d) is radiation patterns for plasma antenna of radius 1.0 cm and length 30 cm at the resonance frequency 0.330 GHz, 0.750 GHz, 1.200 GHz and 1.700 GHz, respectively. Figure 14(a-d) is radiation patterns for plasma antenna of radius 0.5 cm and length 30 cm at the resonance frequency 0.330 GHz, 0.750 GHz**,** 1.200 GHz and 1.700 GHz, respectively.

The radiation patterns of plasma antenna of radius 1.5 cm and length 20 cm are shown in Fig. 15(a-c) for the frequencies 0.440 GHz, 1.100 GHz and 1.800 GHz, respectively. However for the plasma antenna of radius 1.5 cm and length 10 cm, one resonance frequency is observed, i.e., 0.800 GHz, the radiation pattern is estimated which is shown in the Fig. 16.

Table 2 — Resonance frequencies with corresponding return loss for plasma antennas of radius 1.5 and length 20 cm.

S. No.	Resonance Frequency (GHz)	Return loss (dB)
1	0.440	-19.60
2	1.100	-09.97
3	1.800	-07.87

4.3 Gain and directivity

Directivity and gain are the antenna parameters, which can be estimated by the maximum radiation and the signal strength in a particular direction. The gain of the antenna is closely related to directivity. However there is the only difference between gain

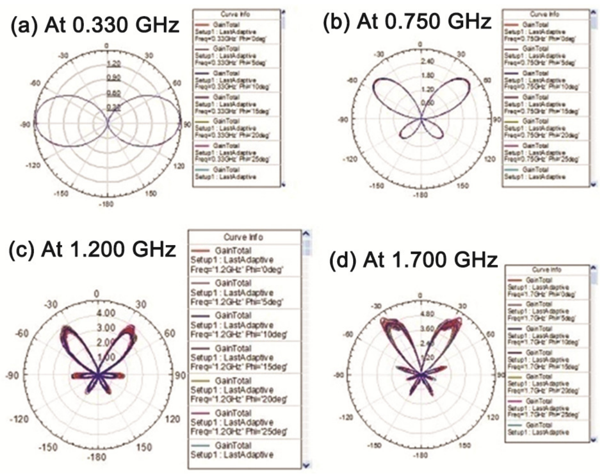

Fig. 12 — Radiation pattern for plasma antenna of radius 1.5 cm and length 30 cm in elevation plane.

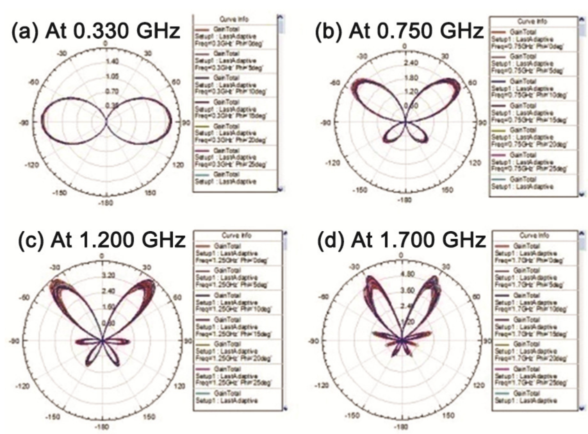

Fig. 13 — Radiation pattern for plasma antenna of radius 1.0 cm and length 30 cm in elevation plane.

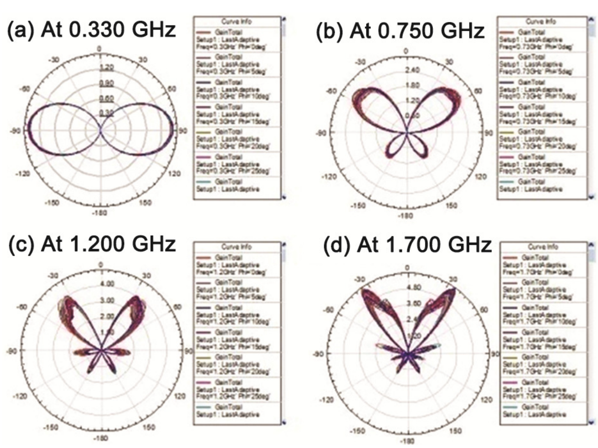

Fig. 14 — Radiation pattern for plasma antenna of radius 0.5 cm and length 30 cm in elevation plane.

and directivity that directivity is based entirely on the shape of the radiated power pattern but gain taken into account antenna efficiency as well as its directional capabilities. Higher gain in one direction means lower gain in other directions. High gain antennas allow longer range in one direction, but need to be pointed accurately. Low gain antennas have lower range, but can transmit or receive signals in wider span of directions[17,18]. We also find directivity and gain for each configuration of plasma antenna at obtained resonance frequencies. Directivity for three plasma antennas of radius 1.5 cm, 1.0 cm and 0.5 cm and same length 30 cm are shown in the Table 3. Plasma antenna of radius 1.5 cm and length 30 cm has directivity 1.48, 2.50, 3.75 and 5.14, plasma antenna of radius 1.0 cm and length 30 cm has directivity 1.52, 2.63, 3.62 and 5.94 and plasma antenna of radius 0.5 cm and length 30 cm has directivity 1.41, 2.43, 3.77 and 5.47 corresponding to resonance frequencies 0.330 GHz, 0.750 GHz, 1.200 GHz and 1.700 GHz, respectively.

Gains for three plasma antennas of radius 1.5 cm, 1.0 cm and 0.5 cm keeping the constant length of 30 cm are shown in the Table 4. Plasma antenna of radius 1.5 cm and length 30 cm has gain 1.50 dB, 2.62 dB, 4.07 dB and 5.58 dB, plasma antenna of radius 1.0 cm and length 30 cm has gain 1.54 dB, 2.78 dB, 3.91 dB and 5.44 dB and plasma antenna of radius 0.5 cm and length 30 cm has gain 1.43 dB, 2.57 dB, 4.04 dB and 5.93 dB corresponding to resonance frequencies 0.330 GHz, 0.750 GHz, 1.200 GHz and 1.700 GHz, respectively. Directivity and gain for plasma antenna of 1.5 cm in radius and 20 cm in length are shown in Table 5. This antenna has directivity 1.66, 2.84 and 5.45 and gain 1.68 dB, 3.05 dB and 6.09 dB corresponding to resonance frequencies 0.440 GHz, 1.100 GHz and 1.800 GHz, respectively. Plasma antenna of 1.5 cm in radius and 10 cm in length has directivity 1.60 and gain 1.71 dB corresponding to resonance frequency 0.800 GHz.

So far we have shown the results of simulation study of plasma antenna, for better understanding of the plasma antenna, it is required to discuss the all antenna parameters simultaneously. Hence the next section is focused on discussion on the results.

5 Discussion

From the results it is clear that the S-parameter for the plasma antennas of different radius (1.5 cm $<r<$ 0.5 cm) and constant length (l = 30 cm) having equal resonance frequencies, however there return losses corresponding to resonance frequency are slightly

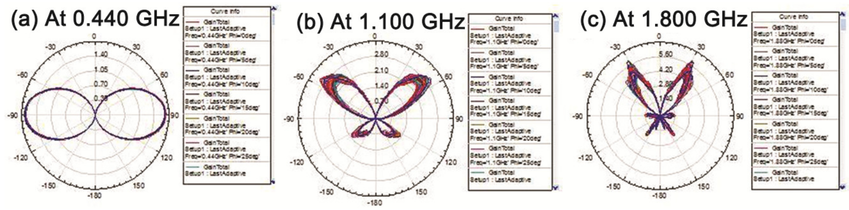

Fig. 15 — Radiation pattern for plasma antenna of radius 1.5 cm and length 20 cm in elevation plane.

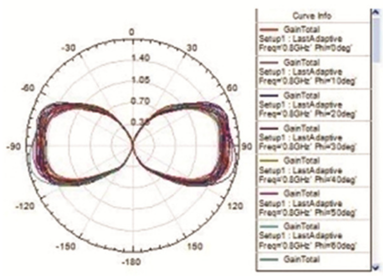

Fig. 16 — Radiation pattern for plasma antenna of radius 1.5 cm and length 10 cm in elevation plane at resonance frequency 0.800 GHz.

Table 3 — Resonance frequencies with corresponding directivities for plasma antennas of radius 1.5 cm, 1.0 cm and 0.5 cm at constant length 30 cm.

S. No.	Resonance Frequency (GHz)	Directivity For radius 1.5 cm	Directivity For radius 1.0 cm	Directivity For radius 0.5 cm
1	0.330	1.48	1.52	1.41
2	0.750	2.50	2.63	2.43
3	1.200	3.78	3.62	3.77
4	1.700	5.14	4.94	5.47

Table 4 — Resonance frequencies with corresponding Gains for plasma antennas of radius 1.5 cm, 1.0 cm and 0.5 cm at constant length 30 cm.

S. No.	Resonance Frequency (GHz)	Gain For radius 1.5 cm(dB)	Gain For radius 1.0 cm (dB)	Gain For radius 0.5 cm (dB)
1	0.330	1.50	1.54	1.43
2	0.750	2.62	2.78	2.57
3	1.200	4.07	3.91	4.04
4	1.700	5.58	5.44	5.93

Table 5 — Resonance frequencies with corresponding directivity and gain for plasma antenna of radius 1.5 cm and 20 cm in length.

S. No.	Resonance Frequency (GHz)	Directivity	Gain (dB)
1	0.440	1.66	1.68
2	1.100	2.84	3.05
3	1.800	5.45	6.09

different. But S-parameter for plasma antenna of different length (30 cm $<l<$ 10 cm) and constant radius (r = 1.5 cm) are having totally different resonance frequencies for each length of plasma antenna. The radiation patterns at each observed frequencies (0.330 GHz, 0.750 GHz, 1.200 GHz and 1.700 GHz) are also equal for the plasma antennas of different radius (1.5 cm $<r<$ 0.5 cm) at constant length (l = 30 cm). It means, at 0.300 GHz frequency, antenna radiates maximum power at θ=90º and θ=270º or in the perpendicular to the axis of antenna and minimum power at θ=0º and θ=180º or in the parallel to the axis of antenna. Therefore, it is clear that at this resonance frequency, radiation patterns are non-directional in the azimuthal plane and directional in elevation plane so the antenna is considered as Omni-directional antenna. It has been seen that the radiation patterns founded from the simulation at the operating frequency 0.330 GHz as shown in the Fig. 12(a) is similar as the radiation patterns has been observed in the experimental study. The radiation patterns at 0.750 GHz frequency are directive and different from radiation patterns at 0.330 GHz. At this frequency antenna radiates maximum power at θ=50º and θ=310º in the elevation plane. The radiation patterns at 1.200 GHz frequency are more directive than radiation patterns obtained at 0.750 GHz. At this frequency in the elevation plane, antenna radiates maximum power at θ=35º and θ=325º in the elevation plane. The radiation patterns at 1.700 GHz frequency are more directive than radiation patterns obtained at 1.200 GHz. At this frequency antenna radiate maximum power at θ=30º and θ=330º in the elevation plane. Radiation pattern for plasma antenna of length 20 cm and radius 1.5 cm at resonance frequency 0.440 GHz is omni-directional while at 1.100 GHz and 1.800 GHz are getting directive and more directive, respectively. Radiation pattern for plasma antenna of length 10 cm and radius 1.5 cm at resonance frequency 0.800 GHz is also omni-directional.

Furthermore the results for return loss are explained in following. Figure 17 shows relation between resonance frequency and return loss for the three plasma antennas of different radius (1.5 cm $< r <$ 0.5 cm) and constant length (l = 30 cm). This shows that a plasma antenna of radius 0.5 cm has better return loss then the antennas of radius 1.5 cm and 1.0 cm of same length 30 cm at the same resonance frequencies. Therefore our study suggests that a plasma antenna with r =0.5 cm radius provides better antenna properties than r >0.5 cm one of same length (l =30 cm) and same plasma parameters. In addition thin radius of the plasma tube can also reduce the power consumption of plasma antenna.

Figures 18 and 19 show the relation between directivity and gain with resonance frequency for the same three antennas, from these it is also clear that no appreciable effect observed on directivity and gain of the plasma antenna with respect to radial variation of plasma tube. But it is observed that at lower resonance frequencies all the plasma antennas are Omni-directional however at higher resonance frequencies these get directed. Directivity and gain further increase on moving towards higher resonance frequencies.

The effects on antenna parameters due to variation in length of plasma column/antenna by changing the operating parameters are also explained. Initially we calculate the L/λ ratio (L is length of antenna and λ is wavelength of resonance frequency) for three antennas at each resonance frequency. The calculations suggest, for the plasma antenna of length L = 10 cm and radius r = 1.5 cm, at resonance frequency 0.800 GHz the L/λ ratio is calculated as 0.04. Now for the plasma antenna of length L = 20 cm and radius r = 1.5 cm, corresponding to resonance frequencies 0.440 GHz, 1.100 GHz and 1.800 GHz the L/λ ratio is calculated as 0.04, 0.12 and 0.20, respectively. While for the plasma antenna of length L = 30 cm and radius r = 1.5 cm, corresponding to resonance frequencies 0.330 GHz, 0.750, 1.200 GHz and 1.700 GHz the L/λ ratio is calculated as 0.04, 0.12 and 0.20 and 0.28, respectively. It can be concluded from the mentioned discussion that the length of antenna is increased the probable number of resonance frequencies also increases as well as the resonance frequencies changes with the change in the length of antenna in order to uphold the L/λ ratio. It is well known that the L/λ ratio determines the performance of an antenna, in the terms of directivity and gain. Therefore as the value of L/λ increases the performance of antenna also increases.

Furthermore, the results at the lower resonance frequency for plasma antenna of radius 1.5 cm and length 30 cm are matched with the experimental study of plasma antenna of same configurations[9]. The radiation patterns in azimuthal plane for both the antennas are symmetric around the axis of plasma

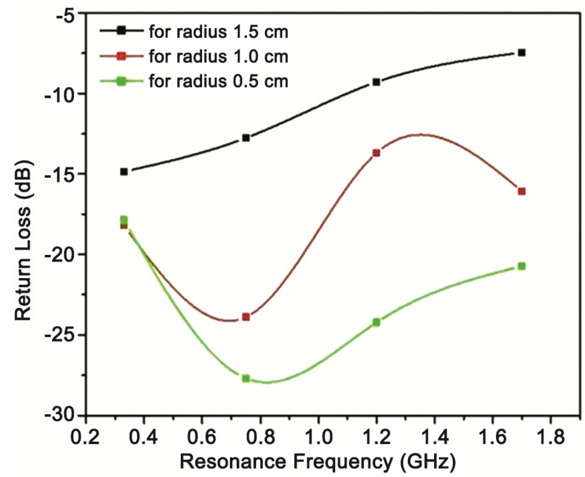

Fig. 17 — Relation between resonance frequency and return loss.

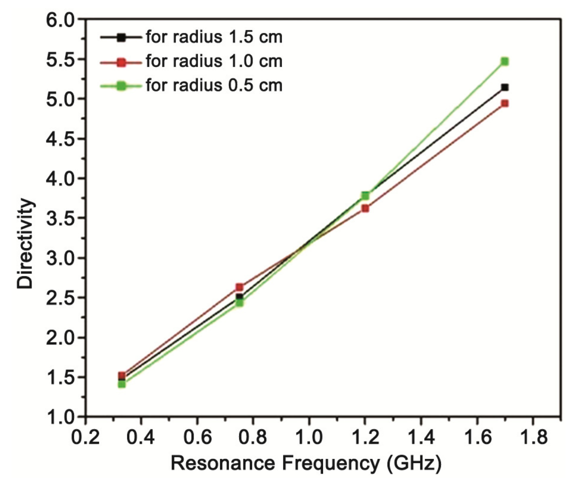

Fig. 18 — Relation between resonance frequency and directivity.

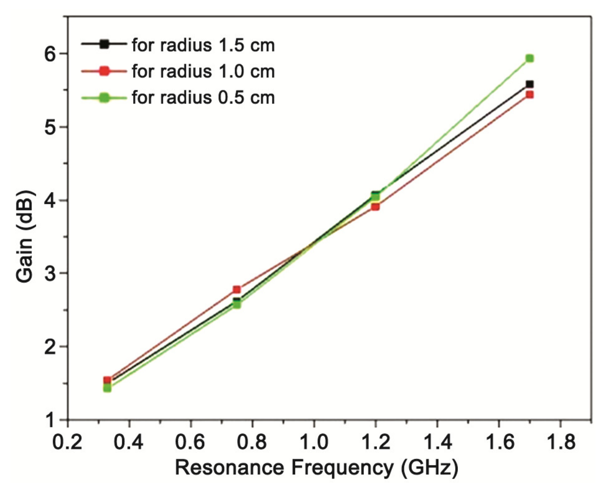

Fig. 19 — Relation between resonance frequency and gain.

antenna and in elevation plane both the antennas radiate maximum radiation in the direction perpendicular to the antenna axis and minimum radiation parallel to the antenna axis. Therefore the radiation patterns are quite similar for experimental and simulated plasma antennas. Directivity of the antenna in the experiment is calculated as 1.75 while in the simulation study it is obtained as 1.48. However the small difference in the radiation patterns and also in the directivities might be due to the simulation limitations.

6 Conclusions

The simulation study was conducted for different configurations of monopole plasma antenna using HFSS software. Antenna parameters of such antennas were investigated. Resonance frequencies and radiation patterns are quite similar for three plasma antennas of constant length ($l = 30$ cm) of different radius (r = 0.5 cm, 1.0 cm and 1.5 cm). However the antenna parameters get changed when the length of plasma column (l = 10 cm, 20 cm and 30 cm) is changed at keeping constant plasma column radius (r = 1.5 cm). It is quite interesting that directivity and gain for all configurations of plasma antennas vary with respect to resonance frequencies. For plasma antenna of radius (r = 1.5 cm) and length (l = 30 cm) directivity increases from 1.48 to 5.14 and gain from 1.50 dB to 5.58 dB, for plasma antenna of radius (r = 1.0 cm) and length (l = 30 cm) directivity increase from 1.52 to 4.94 and gain from 1.54 dB to 5.44 dB, for plasma antenna of radius (r = 0.5 cm) and length (l = 30 cm) directivity increase from 1.41 to 5.47 and gain from 1.43 dB to 5.93 dB, while resonance frequency changes from 0.300 GHz to 1.700 GHz. For plasma antenna length (l = 20 cm) of antenna and radius (r = 1.5 cm), directivity and gain also increase on higher resonance frequencies from 1.66 to 5.45 and from 1.68 dB to 6.09 dB, respectively. Plasma antenna of length (l = 10 cm) and radius (r = 1.5 cm) has only one resonance frequency, i.e., 0.800 GHz, directivity and gain corresponding to this are 1.60 and 1.71 dB, respectively.

Thus our study reveals that a plasma antenna of radius r = 0.5 cm has better performance in the sense of directivity and gain with compression to plasma antennas of radius r = 1.5 cm and 1.0 cm at constant length (l = 30 cm) of plasma column. It is also noticed that directivity, gain and radiation pattern can be controlled by operating frequencies and length of plasma antenna. This study may help to optimize the plasma antenna design for industrial applications of plasma antenna as well as its broad application in wireless communication.

Acknowledgment

Authors are thankful to the members of the Department of Physics, Dr. Harisingh Gour Central University for their help and support at every stage of research. We are also thankful to the Institute for Plasma Research (IPR) Gandhinagar, India for providing the valuable information and UGC for funding support.

References

1 Mosin M & Zakrzewski Z J, *J Phys D: Appl Phys*, 24 (1991) 1025.
2 Borg G G, Harris J H, Miljak D G & Martin N M, *Appl Phys Lett*, 74 (1999) 3272.
3 Borg G G, Harris J H & Martin N M, *Phys Plasmas*, 7 (2000) 2198.
4 Hargreave M, Rayner J P & Cheetham A D, *11th International Conference on Plasma Physics*, Sydney, Australia, (2002) 388.
5 Rayner J P, Whichello A P & Cheetham A D, *IEEE Trans Plasma Sci*, 32 (2004) 269.
6 Alexef I, Anderson T & Paramswaran S, *IEEE Trans Plasma Sci*, 34 (2006) 166.
7 Zheng L, Cao L & Zhang Z, *Propand EM Theory*, ISAPE, (2008) 222.
8 Kumar R & Bora D, *Plasma Sci Technol*, 12 (2010).
9 Kumar R & Bora D, *J Appl Phys*, 107 (2010) 053303.
10 Abbasi M M & Asadi S, *Microwave Opt Technol Lett*, 59 (2017) 806.
11 Kumar R & Bora D, *J Appl Phys*, 109 (2011) 063303.
12 Sianpoush V & Shokri B, *Waves in Random Complex Media*, 26 (2016) 328.
13 Kumar P & Kumar R, *Int J Eng Technol Manag Sci*, 4 (2016) 256.
14 http://www.ansys.com/Products/Simulation+Technology/Electronics/Signal+Integrity/ANSYS+HFSS.
15 Anderson T, *Plasma antennas*, (Artech House: London), 2011.
16 Kumar V, Mishra M & Joshi N K, *Progs EM Res Lett*, 24 (2011) 17.
17 Kraus J D & Marhefka R J, *Antennas for all applications*, 3rd Edn, (Tata McGraw-Hill Edition: India), 2003.
18 Balanis C A, *Antenna theory: Analysis and design*, 2nd Edn, (Wiley Edition: India), 1938.