Capacitive Coupling Return Loss of a New Pre-ionized Monopole Plasma Antenna

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***Abstract*—Plasma antenna has unique properties like low RCS and variable impedance; however, previous plasma antenna uses 500 MHz RF power to generate a plasma column, which is limited in energy efficiency and bandwidth. Here we introduce a new type of plasma antenna that generates plasma column with pre-ionization from a DC high voltage, and signal is coupled to the plasma antenna via capacitive coupling. This device greatly increases the overall energy efficiency and bandwidth of the plasma antenna. The electron density of the plasma is nearly constant in entire length, and is tunable in some degree by the DC current. Two plasma antenna of 1m and 60 cm have been built and tested against same length metal antenna, the results are similar. Positive gain can be achieved at X-band. This device also shows a few obvious resonance lines where signal are absorbed strongly by the plasma. Return loss and radiation pattern of such antenna is reported.**

***Index Terms*—plasma antenna, adaptive antenna, smart antenna, stealth, radar cross section, ionization, radar**

I. Introduction

Plasma antenna [1-11] is a general term which represents the use of ionized gas as a conducting medium instead of a metal to either transmit or reflect a signal to achieve radar [2-5], or stealth [6,7], or communication purpose[11-13]. For the purpose of ordinary communication antenna, signals rely on surface wave propagation along the plasma positive column to transmit signal [1]. For the purpose of electromagnetic reflection, plasma is used as a conductive reflector if the incoming wave frequency is lower than the characteristic plasma frequency. Plasma antenna originates back from the eighties, and various ingenious ways has been devised to achieve such purpose. Plasma can be generated by UV laser irradiation, or by laser initiated pre-ionization followed by high voltage breakdown to form the main conducting channel [4], or by simply using commercial fluorescence tube to serve as reflector [5,6], or by much more expensive electron beam generated plasma [7-9]. There were also exotic methods like explosion generated plasma antenna for fusion research. The more commonly accepted form of plasma antenna was the works of Borg. et al. [11-13], which was intended as a RF communication antenna. That plasma antenna was constructed out of a commercial fluorescence light tube filled with low pressure Ar gas with minor amount of mercury. When switched on by a pulsed RF power, the plasma conducts and transmit signal like a metal antenna, when it is off, there is only minor reflection from the glass tube, hence a very low RCS.

Previous experiments of Borg et al. have demonstrated plasma antenna for HF (3-30 MHz) and VHF (30-300 MHz) communication with similar efficiency (30-50%) and radiation pattern of a metal whip antenna. That antenna was pumped by a 500 MHz, 10~100W RF signal to generate plasma from the bottom of a 1” fluorescent tube, and the length of the plasma column is proportional to the square root of the pump power. To create a 100 cm long plasma column, about 100 W of RF power is needed, and the plasma density is a function of length. Such design has the advantage of total zero RCS when the antenna is not energized, and a high plasma density from pulsed RF pumping, but the bandwidth of such antenna is limited to the pumping RF frequency. The cost of pumping RF generator is also high. The overall energy efficiency is low. The efficiency of existing 100W-1KW class RF amplifiers is usually less than 40% for they are generally driven by a TWT, so the overall system energy efficiency is low.

Here we report a new concept of pre-ionized DC plasma to serve as plasma antenna. The plasma is generated by a DC high voltage, and plasma density of this design is roughly uniform throughout most of the antenna, also the bandwidth is not restricted by the pumping RF frequency. The power needed to generate the plasma is much lower than previous case, and power supply is much cheaper as well. Section II explains the principle of plasma antenna, section III describes the structure of the plasma antenna and the capacitive coupling device, section IV presents the return loss measurements of a 1 m long end capacitive coupling plasma antenna and its comparison with an ordinary metal whip antenna, section V presents radiation pattern and gain of a 60 cm long plasma antenna, and finally the conclusion.

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II. Principle of Plasma Antenna

Plasma is a collection of ionized positive ions and free moving electrons; usually the ionization degree is very low, less than 1 %. Plasma can be generated by electron impact ionization, photo-ionization, or simply heating the gas, the first method being the most energy efficient one. Once plasma is formed, a sheath is set up automatically between the electrode and plasma to maintain the energy and particle balance. Region outside the sheath is called the positive column, where uniform plasma exists, whose density and dimension is determined by the balance between ion diffusion to the surrounding wall and the ion generation mechanism.

Plasma is a dispersive medium. The reflective index of uniform plasma under low electron-neutral collision rate assumption is as follow:

$$n^2 = \varepsilon_r = 1 - \frac{\omega_P^2}{\omega(\omega - jv)} = 1 - \frac{\omega_P^2}{\omega^2 + v^2} - \frac{v}{\omega}\frac{\omega_P^2}{\omega^2 + v^2}$$

$$\omega_{Pe} = \left(\frac{n_e e^2}{m_e \varepsilon_0}\right)^{\frac{1}{2}}, \quad f_{Pe} = \frac{\omega}{2\pi} \approx 9000\sqrt{n_e}\,Hz$$

Where ω_{pe} is characteristic plasma frequency, n_e is electron density in cm^{-3}, and v is the electron-neutral collision frequency. The plasma in this experiment is a low-temperature non-equilibrium plasma, which means the electron temperature is higher than the ion temperature.

Basically, plasma is a high pass filter. The signals coupled to the positive column travels along its axial direction via surface waves, which means, the signal causes fluctuations of density along the positive column surface, and it decays as it travels.

III. Structure of DC Pre-ionized Plasma Antenna

Two plasma antenna of 1m and 60 cm length were built. The plasma antenna is constructed from 12 mm outer diameter 10 mm inner diameter glass tube, and inside is filled with Ne gas at 2~5 Torr (fig.1). On both side of the tube are two hollow cathode type cylindrical electrodes. Two wires for DC bias current connect these electrodes to a high voltage power supply. When first turned on, the applied voltage has to exceed the breakdown voltage of roughly 1.5 KV (for 1m antenna), then the discharge turn into current control mode at a fixed voltage drop of ~900V. The discharge current ranges from 5-30 mA at the same voltage drop. The diameter of the positive column is about 5 mm. The plasma density in the tube is estimated to be about $0.8 \times 10^{12} cm^{-3}$, which can be adjusted in small degree by the DC conduction current. The plasma frequency is about 8 GHz from another microwave transmission experiment.

A 20GHz network analyzer is connected to two copper foils that couple the signal to the positive column of the plasma antenna. The copper foils are 3 cm wide. Two coupling locations were tested, at the bottom end and at the center of the tube (figure 2), but only the end coupling case is presented here.

From the comparison of the two plasma antenna, we know the cathode fall (sheath) voltage is about 150-200 V, and the voltage drop across the positive column is about 5 V/cm. Increasing the DC current does not change the positive column voltage drop, it only increases sheath voltage.

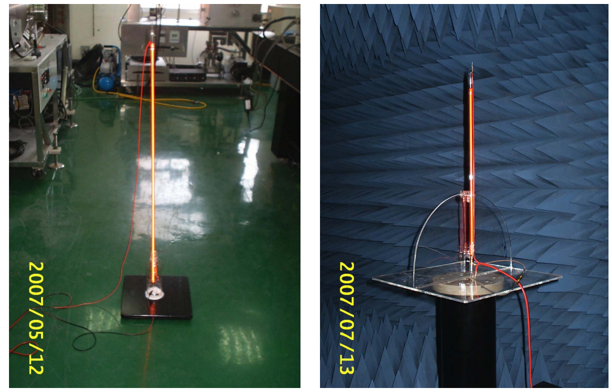

Figure 1. Picture of the 1m plasma antenna on the left, and 60 cm antenna on the right inside a 3x3x6 m anechoic room...

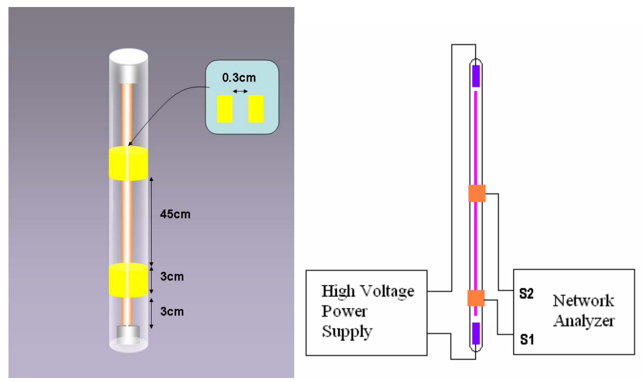

Figure2. Illustration of the arrangement for coupling signal to the antenna. A copper foil is attached to the bottom of the positive column, and connected to the S1 port of the network analyzer. Another copper foil located at the center of the antenna is connected the S2 port.

IV. Return Loss of the End Capacitive Coupling 1m Plasma Antenna

Following are series of return loss measured from port 1 position of the plasma antenna under different DC bias current. In theory, the incident signal with frequency less than the plasma frequency should be reflected back as if in collision with a metal. However, because in reality the plasma density distribution is a strong function of plasma column radius, plus the capacitive coupling mechanism affects the input impedance of plasma antenna considerably, the actual results are quite complicated and are frequency dependent.

Figure 3(a) is the return loss of a retractable metal antenna of 1 m length. We can see a very strong coupling at 10 GHz due to length effect. Figure 3(b) is the return loss of the 1m plasma antenna when the plasma is not switched on. The two coupling peaks are effects of the combined capacitance between the cupper foil and the glass tube, together with the capacitance between the cupper foil and the bottom electrode. Figure 3(c) is the return loss when the plasma is switched on, 5 mA is the minimum current that can sustains more or less uniform visible plasma. Compared with figure 3(b), we can see many new lines appear between 4-10 GHz, and the strong coupling around 18 GHz at figure 3(b) disappears.

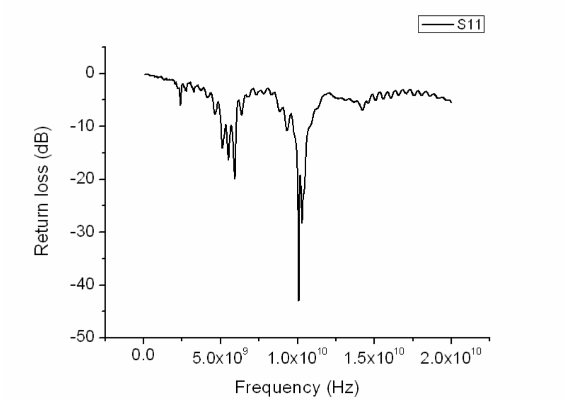

Figure 3(a) The return loss from port 1 of a 1m metal antenna.

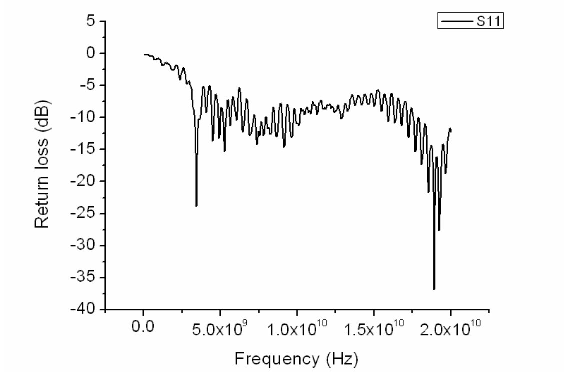

Figure 3(b) The return loss from port 1 of the 1m plasma antenna when there is no plasma.

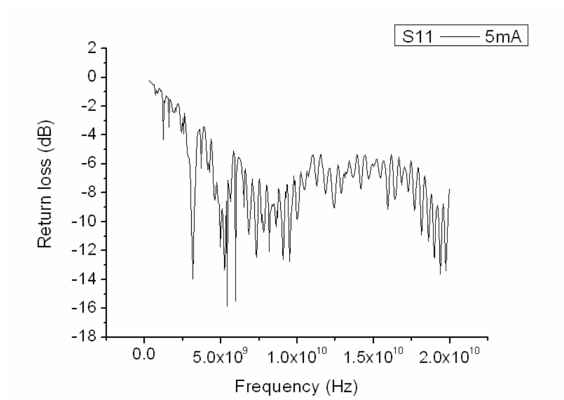

Figure 3(c) The return loss from port 1 of 1m plasma antenna at 5 mA conduction current.

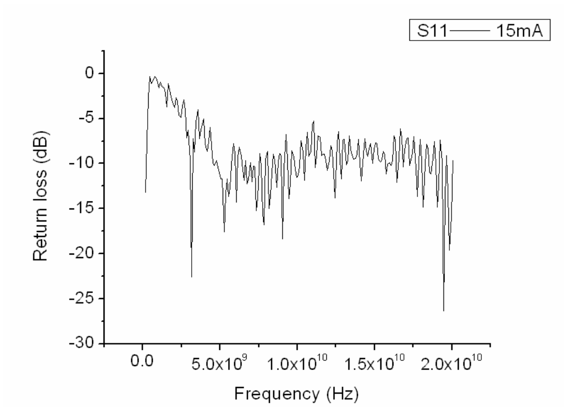

Figure 3(d) The return loss from port 1 of 1m plasma antenna at 15 mA plasma conduction current.

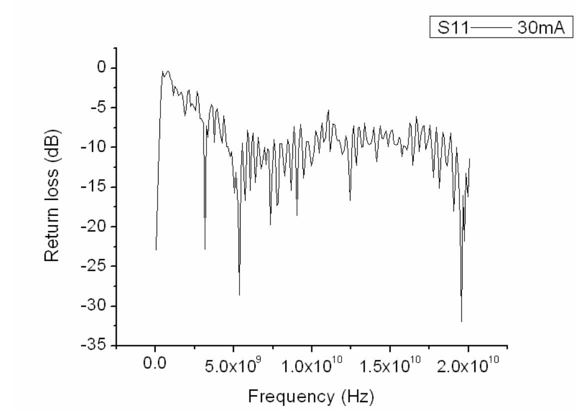

Figure 3(e) The return loss from port 1 of 1m plasma antenna at 30 mA plasma conduction current.

Figure 3(d) is the return loss at 15 mA bias current. A strong coupling line at very low frequency appears, another one is around 2.5 GHz, and the one on 18 GHz seems reappeard but shifted a bit upwards in frequency. Figure 3(e) is the return loss at 30 mA bias current, which is the largest current that can sustain stable plasma. The strong coupling at very low frequency enhances, and a new strong coupling around 5 GHz appears.

V. Return Loss, Radiation Pattern and Gain of a 60 cm Plasma Antenna

A 60 cm plasma antenna is tested in a standard 3x3x6m anechoic chamber for its radiation pattern and gain. The length of 60 cm is limited by the quite zone of the anechoic chamber.

First the return loss of the end capacitive coupling 60 cm plasma antenna is measured, and there exists three distinctive peaks where plasma makes a difference: 4.2, 18.3, and 19.2 GHz (figure 4(a)).

Figure 4(b) is the radiation pattern when the antenna is positioned vertically. The zero degree direction is facing the receiving antenna, and 180 degree direction is where there is a DC current wire taped to the glass tube. The radiation pattern does not show expected directionality due to the shielding of the DC wire, this may due to the twisting of the wire. On the other hand, there exist many side lobes that changes with respect to frequency and direction of the antenna.

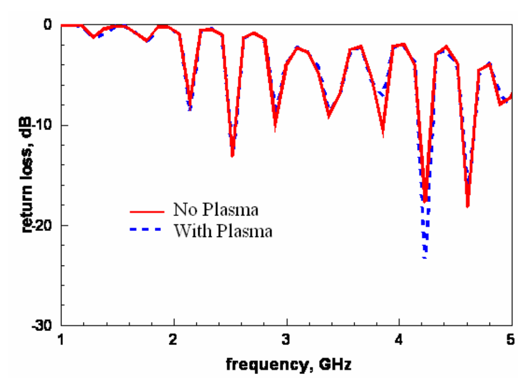

Figure 4(a) The return loss from port 1 of the 60 cm plasma antenna at 30 mA plasma conduction current.

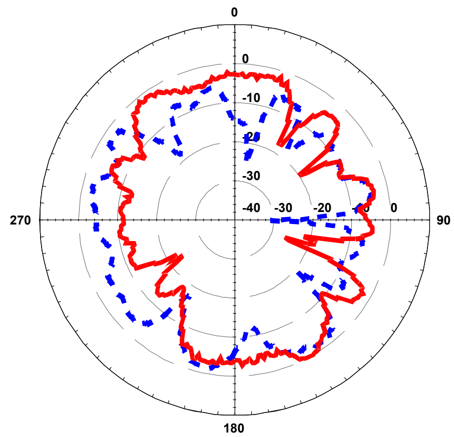

Figure 4(b) The E-plane radiation pattern of the 60 cm plasma antenna at 4.2GHz. Red curve is co-polarization; blue curve is cross-polarization. .

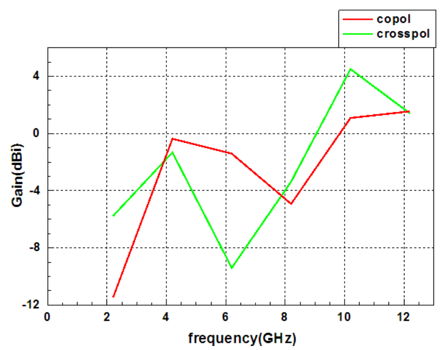

Figure 4(c) The gain versus frequency curve of the 60 cm plasma antenna when positioned vertically. Red curve is co-polarization; green curve is cross-polarization. .

Figure 4(c) is the gain versus frequency curve. We can see the antenna exhibits positive gain at X-band, with maximum gain around 4 dBi, which is similar to a retractable metal antenna of the same length.

VI. Conclusion

A new type of DC biased plasma antenna has been demonstrated. Because this plasma antenna does not rely on RF pumping power to generate plasma, therefore there is no upper operation frequency limit, and it considerably improves the bandwidth from previous device's VHF into GHz range. The over all energy efficiency also improves, since only 27 W of DC power is required to sustain the plasma infinitely. The antenna shows positive gain at X-band, with complicated radiation patterns. There are also obvious resonant lines in the return loss.

In present design, the input signal is going to drop mostly on the glass wall instead of the plasma, because the glass wall, the space between the wall and the plasma, and the plasma itself form three capacitances in series. The dielectric constant of glass at high frequency is close to a constant (~4.7), where as the dielectric constant of a plasma varies with frequency, especially so at the cross over point of the characteristics plasma frequency.

Generally speaking, the higher the input power, the more effective should the plasma antenna be. Ordinary metal antenna is limited in power handling due to heating resulted from increase of the Drude model collision resistance at high frequency and high power, on the contrary, higher input power will create stronger disturbance on the plasma surface, and may be the signal power can be used in the plasma production process as well. The best merit of plasma antenna is no doubt its stealth capability. The plasma can be pulsed on and off even with a DC bias voltage, and the decay time (0.5-200μs) is a function of the plasma density, gas species, and gas combinations. The reliability of a plasma antenna can match that of a metal antenna if carefully tuned. For the purpose of using plasma as a reflector of microwave radar, Alexeff et al. [6,7] had proved a parabolic reflector consists of plasma tube array basically has the same radiation pattern as a metal grid reflector.

Further investigation on the exact plasma density distribution in the radial direction and the propagation constant of surface wave is clearly necessary in order to better control the radiation pattern and other characteristics of such plasma antenna. .

Acknowledgment

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