A New Type of Loop Antenna with Plasma Core

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Abstract. A new type of loop antenna with core of fan-shaped plasma is designed. When the plasma frequency is about 4 times of the antenna frequency, the radiated power of loop antenna is enhanced greatly. Numerical analysis shows it is the resonance of electric field between plasma and dielectric of positive permittivity, which enhances the radiated power. Furthermore, the effects of parameters of antenna core on radiation characteristics are studied.

1. Introduction
As charged particles, the plasma will affect the propagation of the electromagnetic field, and has different influences in the antenna radiation. When the plasma frequency is large than the frequency of electromagnetic wave, the permittivity of plasma is negative. Plasma column can replace metal as the guiding medium in radio frequency antennas. Such plasma antennas offer the possibility of low radar detectability and negligible mutual coupling when de-energized [1-4].

The antenna radiation will be cut off if an antenna is immersed in infinite plasma with the plasma frequency exceeding the antenna frequency [5]. However, when the thick of plasma is less than the skin depth of electromagnetic field (thin plasma layer), the radiation can be enhanced with a range of plasma density. The phenomenon of enhanced radiation from a spherical antenna covered by a plasma layer was reported first by Messiaen and Vandenplas [6], In addition, Effects of plasma parameters on antenna radiation are given by numerical and experimental studies [7-9]. Studies show the inductive plasmas compensate the capacitvity of the near-field of dipole antenna and enhance the radiation power [10].

For the loop antenna operating in the ionosphere and magnetosphere of the Earth, the presence of plasma will affect the radiation characteristics of the antenna. The impedance of loop antenna in magneto plasma is investigated and the near-field of the loop antenna is given [11-13]. The plasma can also be applied in the core of loop antenna, studies shows the plasma column can increase the receiving area and enhance the reception of radiation signals [14].

In this paper, a new type of application of plasma as a dielectric of negative permittivity is presented. Through the designing of a plasma core for the loop antenna, the radiated power of the signal of a certain frequency band is enhanced. The loop antenna with plasma core has many excellent characteristics. For example, the frequency of maximum radiated power and far-field characteristics can be modified by the parameters of plasma core.
2. The model and numerical results
The small loop antenna with three turn coils is shown in Fig.1. The inner-radius and height of loop antenna is 5 cm and 1 cm, respectively. A cylinder core with radius of 4.5 cm is nested inside the loop antenna. The core of the cylinder is divided into two sectors. One sector is the plasma with half-angle of \( \theta \) and the other part is a dielectric with positive permittivity. The core is symmetrical along the x-axis. The infinite space surrounding the antenna is modeled by a vacuum layer (the thickness is of 100 cm) covered by a perfect match layer (the thickness is of 5 cm). A surface current, amplitude of 1A/m\(^2\) and frequency of 0.3 GHz, is loaded on the coil.

![Figure 1. Geometry of the loop antenna with plasma core.](image)

The calculated domain is controlled by Maxwell equations, as:

\[
\nabla \times \vec{H} = J + \varepsilon_r \varepsilon_0 \frac{\vec{E}}{\partial t} \\
\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t}
\]

(1)

As the plasma is considered as a uniform lossless isotropic medium, the permittivity of plasma can be expressed as: [15]

\[
\varepsilon = \varepsilon_p = \varepsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2}\right)
\]

(2)

Where, \( \omega \) is the frequency of the antenna radiation, \( \omega_p = \sqrt{n_0 e^2 / (\varepsilon_0 m_e)} \) is the plasma frequency, \( n_0 \) and is the plasma density. The numerical model is solved by finite element method in frequency domain.

Taken \( \varepsilon_r = 1 \) and \( \theta = 90^\circ \), at the observed point (90 cm, 0, 0), the change of antenna radiated power with plasma density is shown in Fig.2. The horizontal coordinate of plasma density is expressed by relative plasma frequency. The antenna radiated power is normalized by its radiated power without the
plasma core. Numerical results show that the radiated power of antenna increases greatly when the plasma frequency is about 4.2 times of the antenna frequency.

![Graph showing relative radiated power vs. plasma frequency ratio](image)

**Figure 2.** Change of antenna radiated power with plasma density

3. **The mechanism of radiation enhancement**

In order to analyze the mechanism of radiation enhancement, the induced electric fields in the core of loop antenna on the x-y plane are given in Fig.3. Without the plasma core (\(\omega_p / \omega = 0\)), the vector of electric field turns clockwise in the core of loop antenna. On the working condition of maximum radiated power (\(\omega_p / \omega = 4.2\)), the permittivity of plasma core is negative. So the electric field is clockwise in the vacuum and counterclockwise in the plasma. In quantity, we consider the electric field strength along a fixed closed circuit (closed dotted line in Fig.3).

\[
\oint_{c_a} \vec{E}_a \cdot dl = -\int_S \mu \frac{\partial \vec{H}_a}{\partial t} \cdot dS
\]

\[
\oint_{c_b} \vec{E}_b \cdot dl = -\int_S \mu \frac{\partial \vec{H}_b}{\partial t} \cdot dS
\]

(3)

Where, \(\vec{E}_a\) and \(\vec{E}_b\) are the electric field strength along the closed circuit in Fig.3(a) and Fig.3(b), respectively. \(\vec{H}_a\) and \(\vec{H}_b\) are the magnetic field strength in the closed circuit of Fig.3 (a) and Fig.3 (b).

As the time rate of change of the magnetic flux enclosed by the circuit is equal, induced electromotive force along the closed circuit for different plasma density should be equal, as

\[
\oint_{c_a} \vec{E}_a \cdot dl = \oint_{c_b} \vec{E}_b \cdot dl
\]

(4)

Average electric fields along the closed circuit in Fig.3 are introduced. Considering the direction of the electric field, the Eq.4 can be expressed as,
\[
\overline{E}_a \cdot L = \overline{E}_{vac} \cdot \frac{L}{2} - \overline{E}_{pla} \cdot \frac{L}{2}
\]  
(5)

The electric field in Fig.3 (b) is composed of average electric field strength in the plasma \( \overline{E}_{pla} \) and the vacuum \( \overline{E}_{vac} \). \( L \) is the circumference of the closed circuit. Eq.5 can be rearranged as

\[
\frac{\overline{E}_{vac}}{\overline{E}_{pla}} - 1 = \frac{2 \overline{E}_a}{\overline{E}_{pla}}
\]  
(6)

When \( \overline{E}_{pla} \approx \overline{E}_{vac} \), the left side of Eq.6 is approximately equal to zero. Referring to the right side of Eq.6, the average electric field strength \( \overline{E}_a \) is much less than \( \overline{E}_{pla} \) and \( \overline{E}_{vac} \).

**Figure 3.** The vector of electric field on the x-y plane for different plasma frequency: 
(a) \( \omega_p / \omega = 0 \), (b) \( \omega_p / \omega = 4.2 \). (The scale of electric field strength in Fig.3 (b) is 104 times of that in Fig.3 (a))

The electric field in the core of loop antenna changes with the plasma density. As the directions of the electric fields in plasma and vacuum are opposite, when the average electric field strength in plasma is closed to that of vacuum, the radiated power will be enhanced largely. The characteristics of radiation enhancement are similar to the resonance between the inductance and the capacitance in electric circuit. Without the plasma core, the loop antenna is a magnetic dipole along the z-axis. When the resonance happens, the distribution of electric field in Fig.3 (b) is similar to that of an electric dipole along y-axis. And the far-field pattern of loop antenna is same as that of the electric dipole along y-axis.

4. **Influence of parameters of plasma core on antenna radiation**

When the resonance between the plasma and positive dielectric happens, the radiation characteristics of loop antenna are determined by the antenna core. So, the structural parameters of core are changed to study the relation between the parameters of antenna core and the radiation characteristics.

4.1. **Effect of positive permittivity of dielectric**

Given \( \theta=90^\circ \) and change the positive permittivity of dielectric. The variations of antenna radiated power with plasma frequency for different relative permittivity are shown in Fig.4. Numerical results show the resonance frequency and maximum radiated power increase with the relative permittivity.

Taken the interface of plasma and dielectric as a flat, the core of antenna can be seen as a series of two flat capacitors. One medium is the plasma with a negative permittivity, and the permittivity of the other medium is positive. The capacitance is proportional to the permittivity, as
The capacitance of the dielectric in the core increases with the positive relative permittivity. According to the mechanism of radiation enhancement, it is necessary to increase the inductivity of plasma to satisfy the resonance condition. So the plasma density for maximum radiated power increases. The results show a way to modify the maximum radiated frequency of loop antenna by the dielectric in the core.

4.2. Effect of the half-angle of plasma sector

A taken vacuum as the dielectric ($\varepsilon_r = 1$), and change the half-angle of plasma sector. Simulation results show the frequency of maximum radiated power increases with the half-angle, and the radiated power reaches maximum value when the half-angle of plasma sector is 90° (Fig. 5).

Reference to the characteristics of parallel plate capacitors, the capacitance is inversely proportional to the separation between the plates, as

$$C \sim \frac{1}{d}$$

With the increase of the half-angle of the sector, the separation between the two sides of the plasma sector increases and the inductivity of the capacitor with the medium of plasma decreases. Correspondingly, the sector of vacuum decreases while the capacitance of the capacity with the medium of vacuum increases. So, the plasma frequency is increased to improve the inductivity and form the resonance phenomenon.
Figure 5. Influence of half-angle of plasma sector on antenna radiation.

In particular, when $\theta \neq 90^\circ$, the asymmetrical structure between dielectric and plasma will cause the directional radiation pattern. For the condition of $\omega_p/\omega=3.9$ and $\theta=75^\circ$, the far-field pattern of loop antenna is shown in Fig.6. The radiation of electromagnetic field in the positive direction of x-axis is more effective.

Figure 6. The far-field pattern of loop antenna near the maximum radiated power.

5. Conclusion
Through the resonance of electric field between plasma and dielectric in the core, the radiated power of loop antenna is enhanced. The frequency of maximum radiated power can be modified by the positive permittivity of dielectric. And directional radiation pattern can be achieved by changing the shape of plasma sector. This phenomenon extends the cognizance of resonance between the inductance and the capacitance in electric circuit. It also expresses a broad application prospects in other fields, such as, signal generation, signal processing and plasma diagnostics.
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