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Simulation of plasma filled hemispherical cavity as dielectric resonator antenna

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Abstract. Plasma antennas are becoming an increasingly interesting research topic because of their uncommon characteristics. They are highly configurable, can be turned on and off rapidly, and exhibit lower thermal noise compared to metal antennas. In recent years, research has been conducted on cylindrical plasma columns sustained by DC, RF or microwave field, and their application as leaky wave antennas or as regular monopole antennas.

Dielectric resonator antennas (DRA) with high dielectric permittivity are known for their small size and excellent operating characteristics for modern mobile communications (WiMAX, LTE). Hemispherical dielectric resonator antennas are characterized by simple shape, high radiation efficiency and wide bandwidth. Hemispherical DRA with a low density weakly ionized plasma as dielectric material will combine the positive features of plasma and dielectric antennas, and is particularly interesting, as antennas of this type have not been studied yet. The hemispherical plasma antenna is simulated with Ansoft HFSS in the microwave S-band. Obtained radiation pattern and bandwidth show the advantages of hemispherical plasma antennas for future communication technology.

1. Introduction

Using a dielectric material as a resonator antenna has been studied extensively and has become more common in recent years [1]. Dielectric resonator antennas are characterized with high efficiency (typically 95-99%), small dimensions and low manufacture cost. They can be produced in almost any form and size, and can be excited by microstrip lines, slots and coaxial probes. Materials with dielectric permittivity of 2-100, as well as layered dielectrics have been studied theoretically and experimentally as resonator antennas with high success.

Low-temperature plasma has been studied and considered an adequate replacement for metal in antennas because of its low thermal noise, instant turn-on, and configurable radiation pattern. The applicability and efficiency in the RF range as leaky-wave antennas has been demonstrated in many experiments [3]. Operation of the cylindrical plasma antennas with plasma column sustained by surface waves as resonant antennas in the microwave S-band is still under research [4].

A hemispherical plasma resonator antenna with a low density weakly ionized plasma as dielectric material will combine the positive features of plasma and dielectric antennas. The main goal of our research is to study plasma as a substitute to dielectrics in a hemispherical DRA and to achieve a realistic model through computer-aided simulations.

2. Methods of simulation

The operation of the plasma resonator antenna depends on the relative permittivity of plasma. Plasma permittivity is evaluated as:

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega(\omega - j\nu)} \quad , \tag{1}$$

where ω_p stands for plasma frequency, ω is the angular frequency of the microwave signal, and ν is the frequency of elastic collisions between electrons and neutrals. Formula for plasma frequency is:

$$\omega_p = \left(\frac{ne^2}{\varepsilon_0 m_e} \right)^{1/2} \quad , \tag{2}$$

where n is the plasma density, e – electron charge, m_e - electron mass, ε_0 - vacuum dielectric constant. Considering the relation between (1) and (2), it is clear that dielectric permittivity of plasma depends on electron density and the collision frequency.

In this research we assume that the hemisphere is filled with argon gas at low pressure of p = 3 Pa. Taking into account our experimental results for cylindrical plasma antenna [4], we estimate that a microwave signal with about 10 W of power could sustain plasma with electron density of $7.5*10^{17}$ m^{-3} inside the cavity. In this case, the complex permittivity of plasma will be ε = -4 + j0.004.

Hemispherical DRA offer analytical solution [2] for resonant frequencies and antenna radiation pattern. However, formulas for calculating resonant frequencies of hemispherical DRA are inapplicable for the plasma antenna because of the negative permittivity. For this reason, the plasma cavity is computer-simulated as a hemispherical resonator antenna with unknown properties. The software used is Ansoft HFSS, which allows simulation of materials with negative permittivity.

The plasma antenna design is described in figure 1. The exciting element consists of a microstrip line (1) fed by a lumped port (2). The dielectric substrate is sandwiched between the microstrip and the ground plane (3). Substrate thickness is 0.6 mm with ε_r = 3. The plasma antenna (4) with radius of 13 mm is placed above the circular slot (5) in the ground plane, and is excited by the loop element embedded in the microstrip (6). The loop element has inner radius of 5.0 mm. The radiation domain is a sphere with radius of ~5λ.

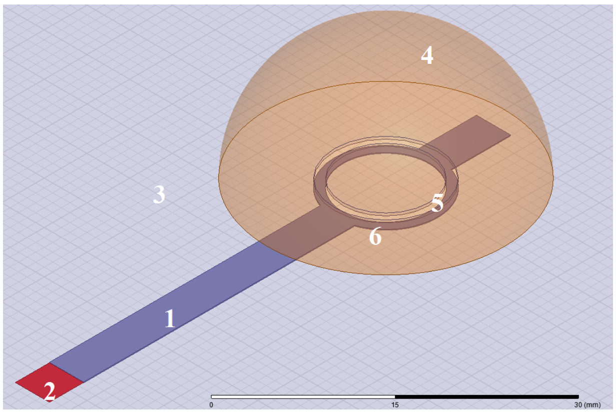

Figure 1. 3D model of hemispherical resonator plasma antenna.

During investigations, several methods for slot excitation were examined with results showing that circular slot above a loop element is the most efficient. The microstrip line length is designed for optimal VSWR.

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3. Results

To better clarify the obtained results, the plasma resonator antenna is compared to a dielectric resonator antenna. A simulation is performed with a regular dielectric material with $\varepsilon_r = 9$ inside the hemispherical cavity. As expected, HEM_{11} mode (figure 2) is excited in the dielectric antenna at 3.5 GHz, radiating in vertical direction. In this case, results for electromagnetic field configuration and radiation pattern confirm known theoretical models on hemispherical DRA [1].

Substituting the dielectric with plasma with permittivity of $\varepsilon = -4 + j0.004$, the S_{11} parameter remains the same, but different distribution of electromagnetic fields inside the cavity is obtained. Results (figure 3) show that TM_{01} mode is excited with vertical and radial components of electric field while magnetic field has azimuthal dominant component. Radiation of the plasma antenna is similar to monopole antenna over ground plate. The resonant frequency is 3.5 GHz, which is a common band for the WiMAX and LTE standards in wireless communications. Operating frequency and antenna bandwidth depend on the value of negative permittivity (figure 4), and, consequently, on plasma density inside the cavity.

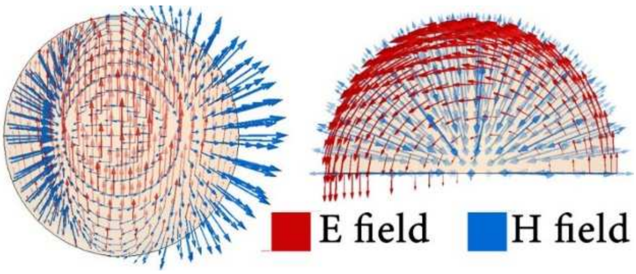

Figure 2. HEM_{11} mode at 3.5 GHz resonance frequency inside ordinary dielectric hemispherical resonator antenna.

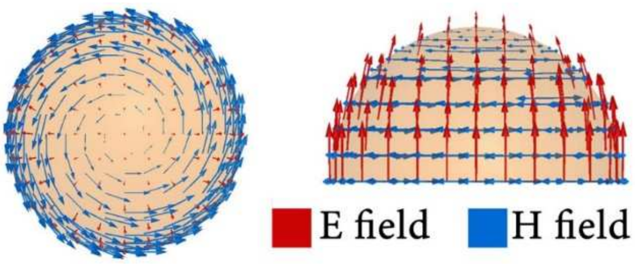

Figure 3. TM_{01} mode inside plasma hemispherical resonator antenna at 3.5 GHz resonance frequency.

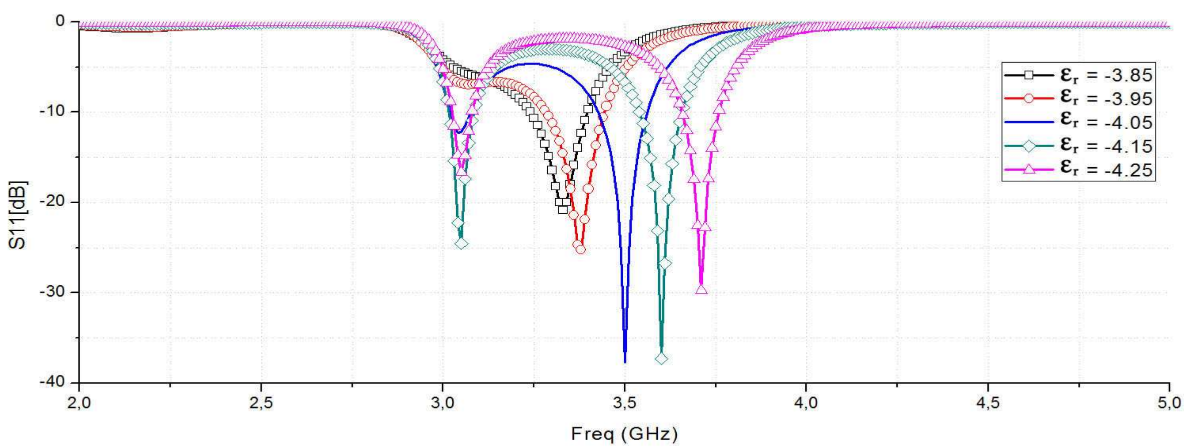

Figure 4. Dependence of S_{11} parameter on operating frequency of plasma antenna at various values of plasma permittivity. Operating mode is TM_{01}.

As shown in figure 4, small variance in permittivity of plasma results significant deviation of resonant frequency, which allows dynamic frequency tuning. The best result at 3.5 GHz is obtained with permittivity ε_r = -4.05 with VSWR of 1.02. The bandwidth of about 150 MHz is sufficient for WiMAX and LTE operation.

Radiation pattern of hemispherical plasma antenna (figure 5) shows relatively high gain of 5 dBi and omnidirectional profile. Wave attenuation in the plasma resonator antenna is very low, which leads to high efficiency, close to 100%, like in dielectric resonator antennas. The radiation pattern shape of hemispherical plasma antenna is similar to the radiation pattern of a wire monopole antenna over finite (with radius ~5λ) and over infinite ground plane.

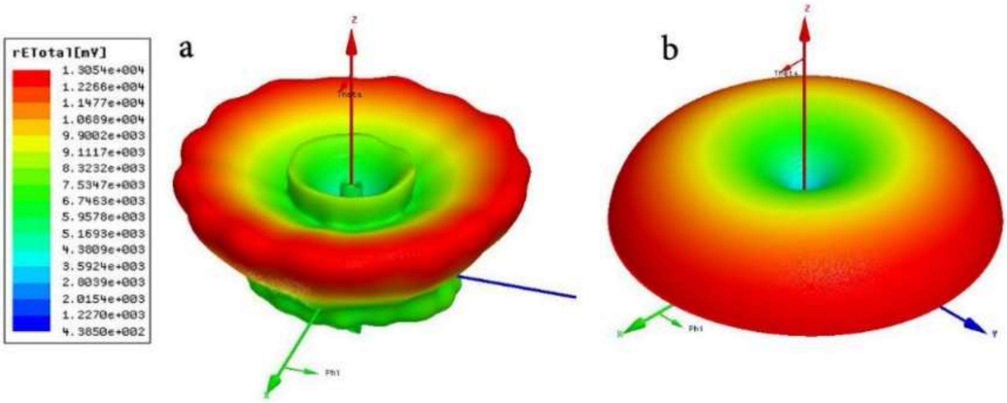

Figure 5. Plasma antenna 3D radiation model over finite (a) and over infinite ground plane (b).

4. Conclusion

Plasma resonator antenna with hemispherical shape is investigated with an EM simulator. Obtained radiation pattern is similar to radiation pattern of a monopole antenna. Plasma antenna is characterized by high efficiency and configurability. Plasma density can be used to dynamically tune resonant frequency and antenna bandwidth. Plasma density needs high precision control to achieve optimal operating characteristics.

The plasma resonator antenna is a possible candidate for demanding 5G modern communications. It is compact, efficient, with low noise, and quick response, and within the reach of current technology. Compared to equivalent DRA, plasma antennas possess the unique properties as instant turn-off and frequency tuning. Further development of the research is aimed towards experimental verification of the simulation results.

Acknowledgements

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