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Design of a Tunable Subwavelength Plasma-Based Resonator for Electrically Small Antenna Applications in L-band

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***Abstract*—A preliminary study of the design of an electrically small plasma-based resonator using a localized surface plasmon resonance (LSPR) above 1 GHz is presented. Such a resonator is intended to be used to develop an electrically small antenna with frequency agility. This resonator consists of a plasma discharge confined in a hemispherical glass shell 3 cm in diameter on a ground plane. From 1 to 1.5 GHz, the plasma electron density required to achieve the LSPR must be between 0.5×10^{11} and 1.4×10^{11} cm^{-3}. Plasma losses are taken into account in this study and provide information on the required gas pressure. Typically for neon gas, the working pressure must be around 50 mTorr. A practical implementation using a miniature inductively coupled plasma (mICP) source is finally discussed.**

***Index Terms*—antennas, electrically small antennas, epsilon negative material, localized surface plasmon resonance, plasma antennas, plasma devices.**

I. INTRODUCTION

Reducing the size of radio communication systems is a major contemporary challenge. In particular, a lot of effort is put forward to develop electrically small antennas (ESAs). ESAs are defined as antennas with an electrical size ka of less than 1, where k is the free space wave number, and a the minimum radius of a sphere that circumscribes the antenna [1]. Reducing the electrical size of an antenna has a significant impact on its performances as shown by several theoretical limits [2]–[4]. Miniaturization techniques have thus been proposed to develop efficient ESAs [5].

Among these miniaturization techniques, the use of a negative permittivity resonator coupled to an electrically small dipole was proposed in 2006 [6], [7]. For instance, the ESA proposed by Stuart *et al* consists of a subwavelength homogeneous hemispherical ε-negative resonator on a ground plane fed with a coaxial probe. It is numerically shown that for a relative permittivity around -2, a localized surface plasmon resonance (LSPR) can arise [8]. This resonance leads to a significant enhancement of the radiated electromagnetic field that could be used for antenna applications. As suggested by the authors of [6] and [7], such a negative permittivity resonator could be obtained with plasma discharges at microwave frequencies.

Plasma discharges are globally neutral mixtures of electrons, ions, and neutrals. They have already shown promising features to design stealth, tunable and steerable antennas [9]–[11]. For a low pressure, non-equilibrium, and non-magnetized plasma, its complex relative permittivity can be calculated using the Drude model:

$$\varepsilon_p(\omega) = 1 - \frac{{\omega_p}^2}{\omega(\omega + i\nu)}, \text{ with } \omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}} \qquad (1)$$

where ν, ω_p, e, n_e, m_e, and ε_0 are respectively the electron collision frequency, the plasma angular frequency, the Coulomb charge, the electron density, the electron mass, and the vacuum permittivity. It is clear from (1) that the real part of the dispersive relative permittivity can be negative. According to this model, it only depends on the electron density n_e and the collision frequency ν at a given wave angular frequency ω. The electron density is mainly controlled by the power delivered to the discharge, the gas type, and the pressure, while the collision frequency depends on the type of gas and its pressure.

Recently, a plasma-based ESA has been demonstrated in the low UHF band [12]. It consists of a small coaxial probe placed above a ground plane and surrounded by a hemispherical glass shell that confines an inductively coupled plasma discharge. It has been shown that the plasma allows impedance matching and frequency agility from 310 to 390 MHz by controlling the power delivered to the plasma discharge. Meanwhile, significant radiation enhancement up to 20 dB at 300 MHz has been obtained when compared to the case without discharge. In [13], the authors demonstrated that a cylindrical subwavelength plasma discharge could be used to enhance the electromagnetic field radiated by an electrically small elliptical dipole antenna. However, such an implementation does not allow an effective integration of the antenna with the plasma source. Colón Quiñones *et al* also presented an experimental validation of a plasma resonator supporting a LSPR in the Ku band using laser-induced plasma [14]. Still, this technology does not allow yet the creation of a stationary plasma for antenna applications.

In this paper, we present a preliminary study to develop a plasma-based resonator for ESA applications between 1 and 1.5 GHz. Its main purpose is to determine the key parameters of the plasma discharge to obtain the LSPR above 1 GHz. Then, we propose a practical implementation of this resonator that takes into account the problem of plasma ignition and sustainment.

II. PLASMA REQUIREMENTS

This section aims to define the plasma parameters, electron density and collision frequency, required to obtain the LSPR of a plasma discharge between 1 and 1.5 GHz.

As plasma is a gaseous medium, it should be confined in an enclosure. To mimic the original ESA concept from Stuart *et al*, we choose to confine the plasma in a hemispherical dielectric shell laying on a ground plane. The glass shell diameter is fixed to $2a = 3$ cm to ensure an electrical size ka of less than 0.5 between 1 and 1.5 GHz. It consists of a dielectric layer with a thickness of 1.4 mm and a dielectric constant of 4.6 as it will be shown in the next section.

In order to evaluate the required plasma electron density, one has to study the LSPR of the plasma-based resonator. Assuming spherical symmetry and homogeneity of the plasma discharge, the original resonator can be viewed as an electrically small plasma hemisphere on an infinite ground plane. According to image theory, this problem is equivalent to a plasma sphere in free space. The resonant behavior of this spherical plasma is finally studied as a scattering problem using Mie theory [12], [15].

The Mie model consists of a lossy homogeneous plasma sphere in a glass shell illuminated by a linearly polarized plane wave. Numerical results from Mie analysis are used to determine the required electron density corresponding to the resonant frequency of the LSPR. To do this, we consider the scattering efficiency Q_{sca} that determines how much an incident radiation is scattered by an object in all directions relatively to its electrical size, that is to say to the frequency if we assume its size constant [16]. For a given electron density, it is assumed that the resonant frequency f_0 of the LSPR occurs when Q_{sca} is maximum.

Fig. 1 shows the scattering efficiency Q_{sca} as a function of the frequency for three different values of electron density considering a collisionless plasma, $\nu = 0$ sec^{-1}. We observe that changing the electron density leads to a shift in the resonant frequency of the LSPR. For example, for $n_e = 6 \times 10^{10}$ cm^{-3}, the resonance is at $f_0 = 1.05$ GHz. According to (1), it corresponds to a real part of the relative permittivity of -3.36 for the plasma discharge. This value is different from -2 due to the electrical size of the plasma sphere and the dielectric glass shell that modifies the resonance condition [17]. We also observe that the smaller the electrical size of the resonator, or the frequency, the higher the magnitude of the scattering efficiency at resonance is. Finally, this curve also shows the frequency agility of the plasma resonator. Indeed, by changing the electron density n_e of the plasma discharge, it is possible to change its resonant frequency f_0.

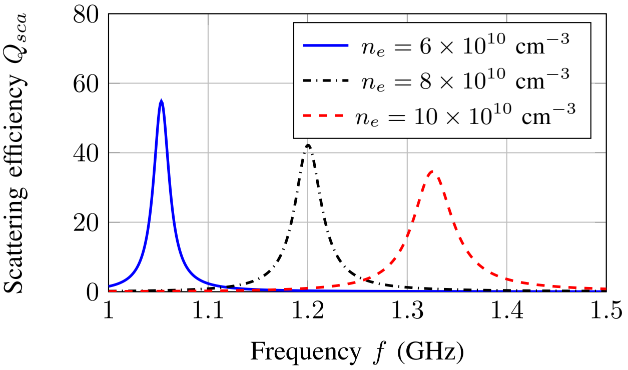


Fig. 1. Scattering efficiency Q_{sca} as a function of the frequency f for three values of electron density n_e considering $\nu = 0$ sec^{-1}.

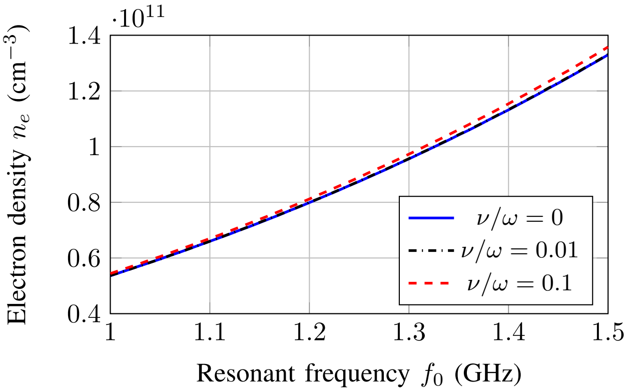


Fig. 2. Electron density n_e required for LSPR as a function of the resonant frequency f_0 for three values of collision frequency ν.

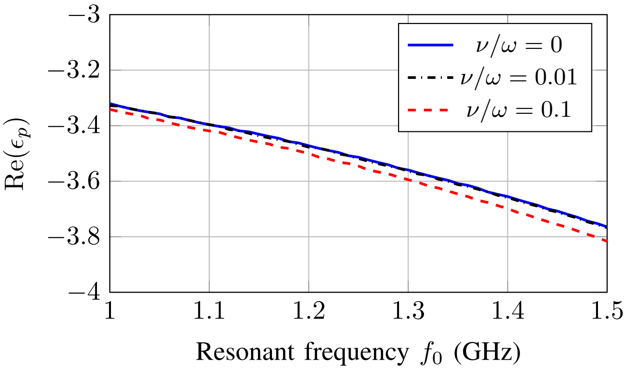


Fig. 3. Real part of the relative permittivity of the plasma Re(ϵ_p) required for LSPR as a function of the resonant frequency f_0 for three values of collision frequency ν.

From these results, it is possible to compute the electron density required to obtain a given resonant frequency f_0 of the LSPR as shown in Fig. 2. Three cases are presented for different plasma losses, namely $\nu/\omega = 0$, $\nu/\omega = 0.01$, and $\nu/\omega = 0.1$. We notice that the required electron density varies between 0.5×10^{11} and 1.4×10^{11} cm^{-3} to obtain a resonant frequency between 1 and 1.5 GHz.

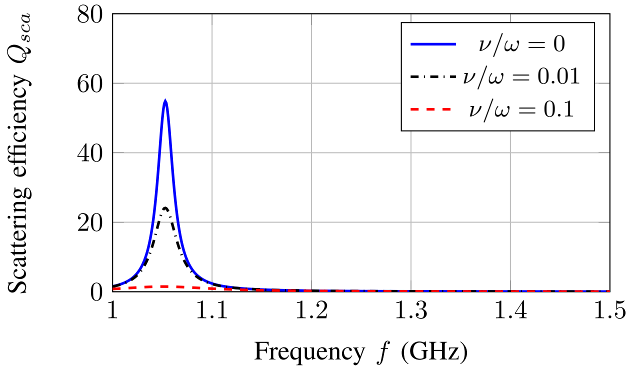


Fig. 4. Scattering efficiency Q_{sca} as a function of the frequency f for three values of collision frequency ν considering $n_e = 6 \times 10^{10}$ cm^{-3}.

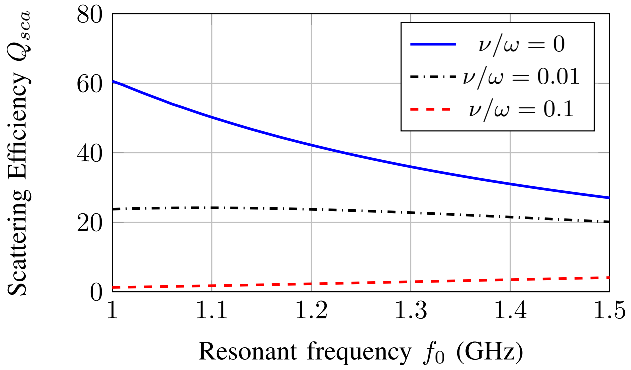
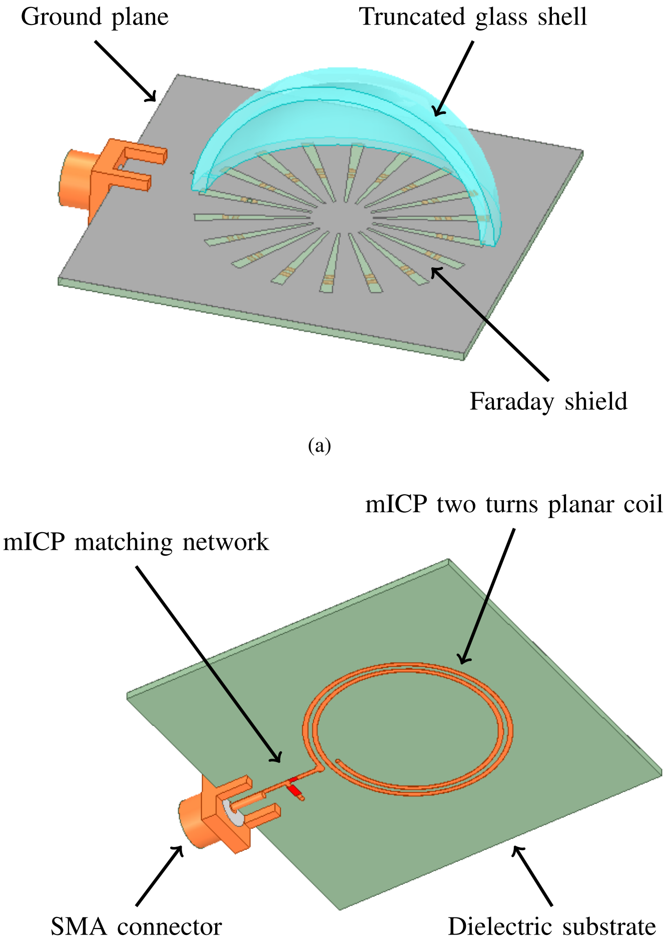


Fig. 5. Scattering efficiency magnitude at resonance as a function of the resonant frequency f_0 for three values of collision frequency ν.

Fig. 3 presents the corresponding required real part of the relative permittivity of the plasma as a function of the resonant frequency f_0 according to (1). Between 1 and 1.5 GHz, the required value for $\mathrm{Re}(\epsilon_p)$ slightly varies with the resonant frequency and, therefore, the electrical size ka of the resonator [18]. As long as the ratio ν/ω remains lower than 0.1, the resonance condition is almost unchanged. However, plasma losses have a greater impact on the magnitude of the LSPR.

Fig. 4 shows the scattering efficiency as a function of the frequency for three values of collision frequency and considering $n_e = 6 \times 10^{10}$ cm^{-3}. It is observed that the increase in the collision frequency results in a decrease in the quality factor of the LSPR. The magnitude of the scattering efficiency as a function of the resonant frequency for three values of collision frequency is also presented in Fig. 5. When $\nu/\omega = 0.1$, there is clearly a significant decrease in Q_{sca} due to plasma losses.

From this preliminary study it can be seen that the plasma electron density n_e must be between 0.5×10^{11} and 1.4×10^{11} cm^{-3} to obtain the LSPR between 1 and 1.5 GHz. Since plasma losses have a significant impact on the LSPR, the collision frequency ν has to be reduced. For this study, $\nu/\omega = 0.01$ is targeted, that is to say ν is between 63×10^6 and 94×10^6 sec^{-1} from 1 to 1.5 GHz, respectively.



(a)

(b)

Fig. 6. Design of the subwavelength plasma-based resonator: (a) top view and (b) Bottom view.

III. DISCUSSION ON PRACTICAL IMPLEMENTATION

The collision frequency in a plasma discharge depends mainly on the type of gas and its pressure. For our application, neon is an interesting candidate since its collision frequency is relatively low. It can be roughly approximated using the following formula [19]:

$$\nu = 1.2 \times 10^9 P \tag{2}$$

where P is the gas pressure in Torr. For neon gas, the condition $\nu/\omega = 0.01$ then corresponds to a pressure of 50 mTorr (around 6.66 Pa) at 1 GHz. The thickness and material of the shell have been designed to withstand such a pressure difference stress. It consists of a boroscilicate glass with a 1.4 mm thickness and a dielectric constant of 4.6.

Regarding the electron density requirement, a plasma source must be designed to ignite and sustain a plasma with an electron density between 0.5×10^{11} and 1.4×10^{11} cm^{-3} at a pressure around 50 mTorr. Such plasma discharges have already been obtained with miniature inductively coupled plasma (mICP) sources [20], [21]. A mICP source consists of a microstrip coil printed on a dielectric substrate and powered by a generator of a few hundred MHz with less than 10 W. In the inductive coupling mode, the time-varying magnetic field created by the coil induces an electric field in the plasma discharge. This electric field moves the electrons that will collide other species and sustain the discharge [22].

In order for the mICP source to supply the plasma discharge through the ground plane required for our hemispherical resonator in our application, electrically small radial slots are machined in the ground plane. Practically, the operation of the coil is not purely inductive and capacitive coupling is present. The slots are machined to design a Faraday shield that also helps in reducing the capacitive coupling. A series capacitance and a parallel capacitance are used to tune the ICP coil at resonance with a 50 Ω coaxial line [21].

Finally, Fig. 6 shows a schematic of the proposed design. Such an implementation allows to separate the plasma source with the plasma discharge operating as an electrically small resonator. For antenna applications, a possible electromagnetic coupling of this resonator would be to insert a small coaxial probe through the center of the Faraday shield [12].

IV. CONCLUSION

A tunable electrically small plasma-based resonator using a localized surface plasmon resonance (LSPR) between 1 and 1.5 GHz has been studied. Such a resonator may be interesting for developing electrically small antennas with frequency agility.

As shown by this preliminary study, the final plasma-based resonator must be confined in a hemispherical glass shell 3 cm in diameter above a ground plane in order to obtain an electrical size of less than 0.5. The simulated electron density required for the plasma is between 0.5×10^{11} and 1.4×10^{11} cm^{-3} for having LSPR from 1 to 1.5 GHz, respectively. Finally, to reduce plasma losses and their impact on the quality factor of the LSPR, it is proposed to consider a neon gas at a pressure of 50 mTorr (around 6.66 Pa).

Currently, our work is focused on the realization and characterization of this L-band plasma-based resonator by considering an implementation using a miniature inductively coupled plasma (mICP) discharge.

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