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Theoretical and Numerical Study of a Plasma-Based Frequency Tunable Microstrip Antenna

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***Abstract*—The use of a plasma microdischarge as a reconfigurable element for a frequency tunable microstrip antenna is theoretically and numerically investigated.**

***Index Terms*—microstrip antennas, reconfigurable antennas, plasma devices.**

I. INTRODUCTION

Frequency tunable antennas have been widely studied to cope with the increasing number of communication standards [1]. They usually integrate active lumped elements (e.g. PIN diodes, RF MEMS, ...) or reconfigurable materials (e.g. ferrites, liquid crystals, ...) to allow control of their instantaneous bandwidth. Most of these solutions, however, cannot be used when medium to high microwave power is involved. Therefore, the use of plasma discharges as microwave reconfigurable elements is currently investigated because of their ability to handle microwave power [2].

Reconfigurable plasma antennas usually rely on large volumes of plasma confined in glass tubes to modify their resonant frequencies or to shape their radiation patterns [3]. Despite of the recent advances in microplasmas [4], few reconfigurable microstrip devices using localized microplasmas have been proposed [5].

In this paper, we theoretically and numerically investigate the feasability of a plasma-based frequency tunable microstrip antenna.

II. COLD PLASMAS

A. Physical Characteristics

A plasma is an ionized gas, macroscopically neutral. To generate a plasma discharge, one must provide enough energy to a neutral gas so that its ionization degree reaches a level that changes its macroscopic properties from an insulator to a conducting medium.

A common way to create a plasma is to apply a voltage between two electrodes in the gas. It leads to a non-equilibrium or cold plasma where the heavy particles keep their temperature close to the room temperature while the electrons are heated enough to cause ionization by collision with neutrals.

B. Electromagnetic Model of a Homogeneous Cold Plasma

From an electromagnetic point of view, a homogeneous cold plasma can be modeled as a dielectric medium whose complex relative permittivity ϵ_p is given by [3]:

$$\begin{aligned}\epsilon_p &= \epsilon_r(1 - j\tan\delta) \\ &= \left(1 - \frac{\omega_p^2}{\omega^2 + \nu_p^2}\right)\left(1 - j\frac{\nu_p}{\omega}\frac{\omega_p^2}{\omega^2 + \nu_p^2 - \omega_p^2}\right) \quad (1)\end{aligned}$$

where ω represents the angular frequency of the electromagnetic wave interacting with the plasma, ν_p the plasma electron-neutral momentum transfer frequency, or collision frequency, and ω_p the electron plasma angular frequency defined as:

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad (2)$$

with e the electron charge, ϵ_0 the permittivity of vacuum, and m_e the electron mass.

According to Equations (1) and (2), we can see that the dielectric constant ϵ_r of a homogeneous cold plasma medium can be controlled by varying its electron density n_e and collision frequency ν_p. Besides, it is interesting to notice that, for a given angular frequency ω, the dielectric constant ϵ_r can be negative, null, or positive with a value between 0 and 1.

III. CAVITY MODEL ANALYSIS OF A PLASMA-LOADED RECTANGULAR MICROSTRIP ANTENNA

A. Description of the Cavity Model Analysis

The cavity model technique is often used to estimate the resonant frequencies of a microstrip antenna [6]. It consists in modeling the antenna as a cavity bounded by two PEC conditions above and below it, and PMC conditions along its perimeter. Here, we consider a rectangular cavity completely filled with a homogeneous cold plasma medium. Its resonant angular frequency ω_{res} for the fundamental TM$_{10}$ mode is thus given by:

$$\omega_{res} = \frac{c\pi}{L\sqrt{\epsilon_r}} = \frac{c\pi}{L\sqrt{1 - \frac{\omega_p^2}{\omega_{res}^2 + \nu_p^2}}} \quad (3)$$

If we assume that the plasma is generated so that its dielectric constant is positive (i.e. $0 < \epsilon_r < 1$), we finally obtain the following biquadratic equation for ω_{res}:

$$\omega_{res}^4 + \left(\nu_p^2 - \omega_p^2 - \frac{c^2\pi^2}{L^2}\right)\omega_{res}^2 - \left(\frac{c\pi\nu_p}{L}\right)^2 = 0 \quad (4)$$

that has four solutions, one of which is purely real and positive. This latter solution represents the resonant angular frequency ω_{res} of the cavity filled with a plasma medium.

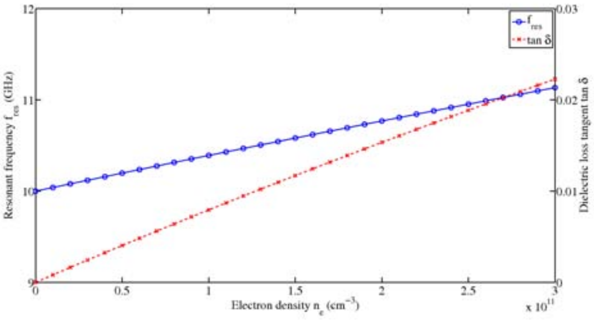

Fig. 1. Resonant frequency (TM_{10} mode) of the cavity filled with a homogeneous plasma as a function of the electron density ($\nu_p = 6.5 \times 10^9$ s^{-1}).

B. Results of the Cavity Model Analysis

In this study, we have considered a plasma discharge generated in a mix of Neon-Xenon at 5 torr which leads to an approximated collision frequency $\nu_p = 6.5 \times 10^9$ s^{-1} and a maximum electron density $n_e = 3 \times 10^{11}$ cm^{-3}.

Figure 1 presents the resonant frequency f_{res} calculated thanks to Equation (4) as a function of the electron density. We observe that the resonant frequency of the cavity increases almost linearly with the electron density. Therefore, one may theoretically control the resonant frequency of the cavity by varying the plasma electron density. However, as it is also shown in Figure 1, increasing the electron density n_e results in a larger dielectric loss tangent $\tan\delta$ of the plasma medium.

IV. NUMERICAL ANALYSIS OF A PLASMA-LOADED RECTANGULAR MICROSTRIP ANTENNA

A. Plasma-Loaded Inverted Microstrip Antenna

Several numerical simulations have been carried out with Ansys HFSS. Figure 2 shows the simulated antenna. It consists of an inverted microstrip antenna loaded by a homogeneous cold plasma. The inverted microstrip antenna is a rectangular element printed on a dielectric substrate with $\epsilon_r = 3.5$ and $\tan\delta = 0.0018$. Its dimensions are $L = 11.35$ mm and $W = 18$ mm so that it is well matched at its resonant frequency of 10 GHz. This antenna is fed with a 50 Ω inverted microstrip transmission line ($W_{line} = 3.3$ mm). Due to this inverted configuration, an air gap of 1 mm is present between the ground plane and the dielectric substrate that supports the antenna. The plasma medium is finally located in this space. It has the same length L and width W as the microstrip antenna, but its height is slightly lower ($h_{plasma} = 0.8$ mm) to take into account of the plasma sheaths that appear between the plasma discharge and the conductors of the antenna [5].

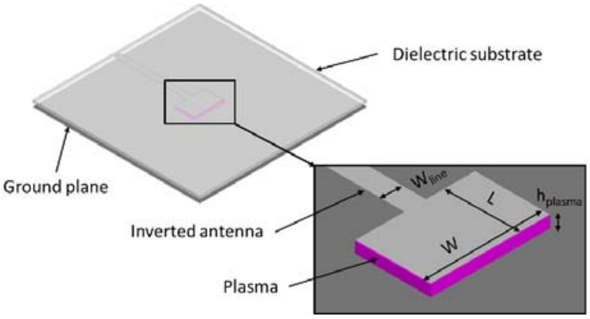

Fig. 2. Plasma-loaded inverted rectangular microstrip antenna.

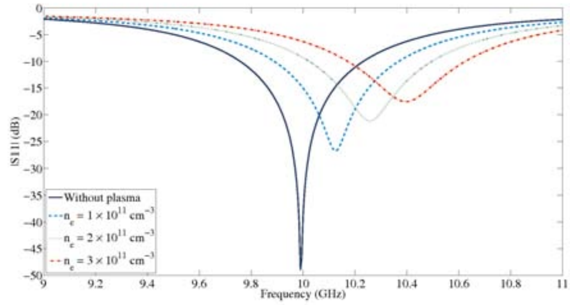

Fig. 3. Simulated $|\mathrm{S}_{11}|$ of the plasma-loaded inverted microstrip antenna as a function of the frequency and for different electron densities ($\nu_p = 6.5 \times 10^9$ s^{-1}).

B. Results of the Numerical Analysis

Figure 3 presents the simulated $|\mathrm{S}_{11}|$ parameters of the plasma-loaded inverted microstrip antenna as a function of the frequency and the electron density of the plasma ($\nu_p = 6.5 \times 10^9$ s^{-1}). We notice that the resonant frequency of the antenna increases with the electron density. A shift of 400 MHz (i.e. 4 % of the initial resonant frequency) is observed when $n_e = 3 \times 10^{11}$ cm^{-3}. This shift is lower than the one predicted by the cavity model analysis. This difference may be explained by the inverted configuration which is slightly different from the classical microstrip antenna and its cavity model.

V. CONCLUSION

We have theoretically and numerically investigated the feasability of a plasma-based frequency tunable microstrip antenna. Thorough study as well as achieved simulated antenna gain will be presented and discussed during the conference.

Current work focuses on the development and characterization of a plasma-based frequency tunable microstrip antenna.

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