Modeling and Experimental Measurements of a Tunable Microstrip Resonator using Plasma Discharges

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***Abstract*—In this paper, we suggest the use of a cold plasma as tunable material inside a microstrip resonant cavity. Plasma dielectric constant can indeed be moved to values below 1 to tune its resonant frequency. DC plasma analysis were conducted and integrated into classic electromagnetic solvers to investigate tuning abilities. Numerical simulations are consistent with experimental results and make this original tuning techniques viable for high power applications.**

***Index Terms*—Cold plasma, tunable resonator, microstrip, DC voltage, 3D modeling.**

I. Introduction

Due to a growing demand for multiband system, frequency reconfigurability is a fundamental need for today's microwave circuits. Frequency tuning can be achieved using integrated lumped elements (PIN diodes, varactors, ...) or tunable materials (liquid crystals, ferroelectrics, ...), [1]. However, these solutions usually concede power handling issue.

In this context, integrated plasma discharges in microwave circuit offer a promising alternative. Plasmas can indeed withstand massive microwave power. Besides, their microwave response can be controlled to emulate different values of dielectric constant (smaller than 1 and negative). Such a versatility can offer many applications, for example power limitation [2], radiation [3], stealth [4], or frequency tuning, which is considered here. Frequency tuning using plasma discharges has been proposed by considering plasma as a lumped microwave component [5] in planar circuits. In this paper, we suggest the use of plasma as a tunable material integrated into a microstrip resonator. Provided adequate control, the plasma dielectric constant can be tuned from unity to zero and enable frequency agility of a microstrip resonator.

We computed numerical simulations to characterize the non-uniform plasma dielectric permittivity. A prototype has been developed to validate the concept of a plasma based tunable microstrip resonator. Finally, S parameters of the whole resonator were simulated and compared with experimental measurements.

II. Theoretical Approach

A. Theoretical Background

A plasma is a globally neutral ionized gas. In this study, we specifically consider non-magnetized low pressure non-equilibrium plasma (cold plasma), which means only electrons have enough energy to ionize the gas and the degree of ionization δ (ratio of free-moving electrons to the total amount of particles) is usually below 10^{-3}.

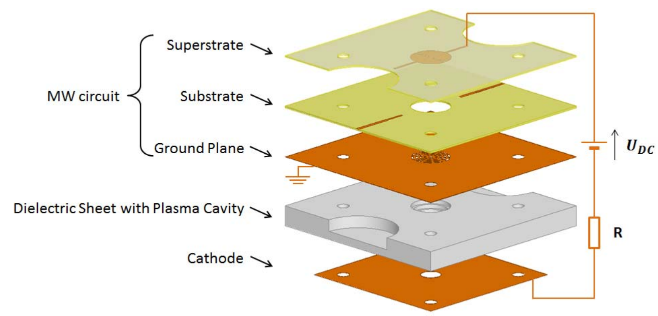


Fig. 1. Exploded view of the considered system with DC electrical connections between electrodes. Superstrate edges were round-cut to solder SMA connector at the end of the microstrip

A cold plasma can be represented by its relative permittivity ε_p which is derived from the Drude model [6]:

$$\varepsilon_p(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu)}, \quad \omega_p^2 = \frac{e^2 n_e}{m_e \varepsilon_0} \tag{1}$$

where ν, ω_p, e, n_e, m_e, and ε_0 are the electron collision frequency which represents the electromagnetic losses, the plasma angular frequency, the Coulomb charge, the electron density, the mass of electron and the vacuum permittivity, respectively. From (1), it is clear that when ω_p is slightly larger than ω the real part of ε_p takes values between 0 and 1.

B. Design of a plasma based tunable microstrip resonator

As mentioned previously, the main principle of our tunable microstrip resonator consists in modifying the dielectric constant between its conductors. We therefore consider a microwave system composed of a 1 cm radius circular microstrip resonator whose gas-filled cavity height is 813 μm. A plasma is then ignited between the patch and the ground plane to change the dielectric permittivity inside the cavity (typically $0 < \varepsilon_p < 1$) and achieve frequency tuning. Note that a superstrate was added to uphold the patch above the cavity.

To minimize losses, ν must be much smaller than ω in (1). Considering for example argon, the gas pressure must be reduced to $P = 2$ Torr ($\simeq 2.67$ mbar) in order to obtain an electron collision frequency $\nu \approx 3$ GHz (using BOLSIG+, [7]) which is ten times smaller than ω. At this pressure, DC plasmas reach medium electron densities (10^9 cm$^{-3} < n_e <$

10^{12} cm^{-3}). Plasma ignition however requires around 800 V at 2 Torr in a 813 μm cavity, when the two microstrip conductors acts as electrodes. Hence, we suggest the solution depicted in Fig. 1 to lower the breakdown voltage.

An extra 1 cm thick step-shaped cavity and a hollow cathode were added below the microwave circuit to increase the inter electrode distance to 1.1 cm. In this case, the plasma supply current is delivered through the microstrip line and the cathode (see Fig. 1) which reduces the breakdown voltage to values between 200 V and 300 V. We also notice from Fig. 1 that a 0.5 cm radius hole is drilled through the cathode plane. The additional cavity central hole is gradually drilled from 0.5 to 1 cm to fit the resonator radius and enhance the plasma diffusion. Likewise, a slotted grid is designed to enable plasma diffusion above the microstrip ground plane. It is composed of a central hole of diameter 2 mm and four radial layers of holes. The distance between two holes is 1 mm and the angular opening of the outer holes was limited to 20° not to excite extra microwave resonances on the ground plane. Two outer slots were also added to the patch to lower its natural frequency to 4 GHz. Given the gas pressure and the geometry from Fig. 1, plasma dielectric permittivity is indeed more flexible at these frequencies.

III. Plasma and microwave numerical modeling

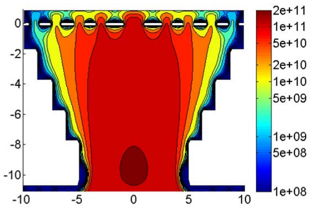
In the light of the difference between electron and ion mobility, a homogeneous plasma region cannot be stable: thus a sheath is necessarily created between any plasma and its surrounding medium to balance this difference. In our case, the plasma contact area is complex (mainly due to the slotted ground plane) which suggests a strong non uniform electron density distribution inside the cavity.

To understand the impact of a non uniform plasma inside the resonator cavity, simulations based on fluid dynamics, electrostatics, and Maxwellian particle distribution were conducted using our in-house software GDSim (*Glow Discharge SIMulation*) developed by Boeuf et al. [8]. The derived profiles of n_e were then included in a full-wave electromagnetic simulation with commercial software Ansys HFSS.

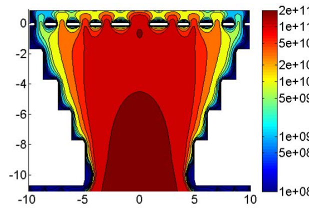
A. Plasma ignition and diffusion numerical modeling

The simplified simulated geometry comprised the microstrip resonator electrode, the microwave cavity, the slotted ground plane, the step-shaped cavity, and the cathode. The superstrate was not included as it do not have direct contact with the plasma. Axial symmetry was assumed and the mesh surrounding the slotted grid was denser (30 μm compared to 400 μm elsewhere) to best represent the plasma diffusion and avoid overestimating the sheath thickness. The series resistance R was set to 680 Ω to allow large current variations, and thereby higher n_e.

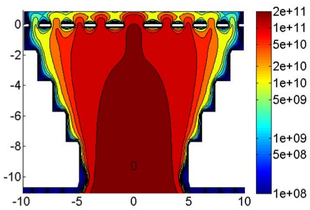
Fig. 2 exhibits several electron density distributions inside both the plasma and RF cavities for different values of U_{DC}. As expected, the electron density is not uniform between the ground plane and the microstrip line. Higher excitation voltage leads to higher electron density and thus larger expected tuning



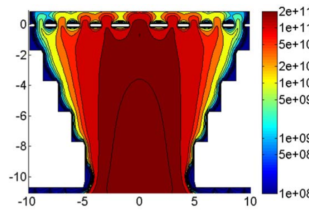
(a) $n_e^{max} = 3.14 \times 10^{11}$ cm^{-3}



(b) $n_e^{max} = 4.47 \times 10^{11}$ cm^{-3}



(c) $n_e^{max} = 6.01 \times 10^{11}$ cm^{-3}



(d) $n_e^{max} = 8.30 \times 10^{11}$ cm^{-3}

Fig. 2. Simulated electron density for different values of supply voltage, (2a) $U_{DC} = 400$ V, (2b) $U_{DC} = 450$ V, (2c) $U_{DC} = 500$ V, (2b) $U_{DC} = 550$ V. Views were zoomed for clarity and do not represent the entire simulated region.

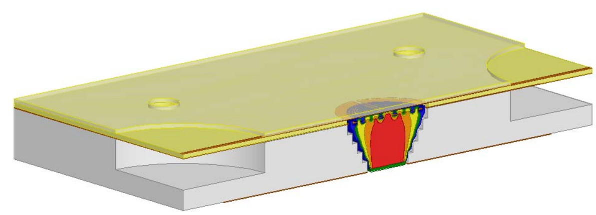


Fig. 3. Schematic of the simulated system in Ansys HFSS with a 5-layers representation of the plasma for $U_{DC} = 400$ V.

ability. We can also notice that high density plasma hardly reaches the outer holes of the ground plane; this phenomenon was also observed experimentally.

B. Full-wave simulation including plasma model

From the 2D-axisymmetric models from Fig. 2, several isocontours of electron density have been extracted. Each contour has been extrapolated to fit the non-axisymmetric ground plane (basically a local sweep around each hole) and imported into Ansys HFSS.

As the number of simulated plasma layers increases, the required mesh becomes denser and leads to very large computational resources. The plasma model was hence restricted to a five layers geometry which is depicted in Fig. 3.

Between two isocontours the plasma electron density is assumed uniform. Plasma electrical properties have been computed using (1) to define new materials with dispersive dielectric constant and bulk conductivity to represent plasma losses. Full-wave analysis from 3.5 GHz to 5 GHz have been conducted.

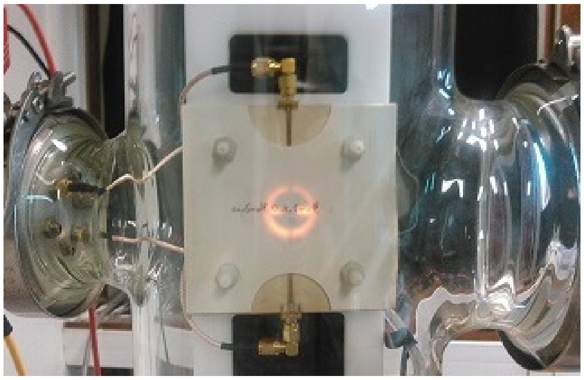


Fig. 4. Picture of the resonator inside the glass jar with plasma (top view).

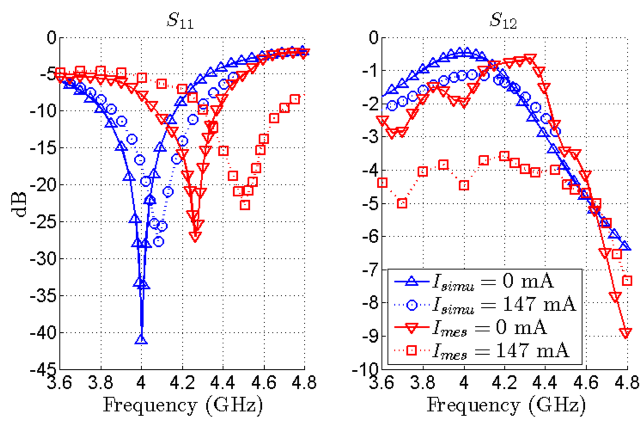


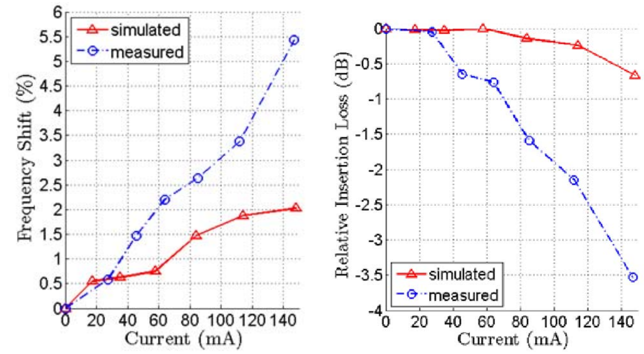
Fig. 5. Simulated (solid line) and measured (dotted line) S parameters for different values of supply voltage U_{DC}.

IV. Numerical and Experimental Results

A prototype has been designed to confirm the tunability of a plasma based microstrip resonator. The whole system is presented in Figure 4. A bias tee has been mounted outside the glass jar to bring DC current to the discharge cavity without overloading the Vector Network Analyser (VNA). U_{DC} was generated using floating potential and the ground plane was connected to earth through the VNA.

The simulated and measured S parameters are presented in Fig. 5 for different values of I_{DC}. We first see that the measured resonant frequency without plasma, when $I_{DC} = 0$ mA, is different from the simulated one which is found to be $f_{mes} = 4.26$ GHz. This deviation is likely due to experimental issues such as substrates misalignments or small variations of their dielectric constant. Though, highly excited plasma, when $I_{DC} = 147$ mA, leads to a 231.1 MHz measured frequency shift, which corresponds to a tuning range of 5.43 %. Note that, in this case, the measured relative insertion loss was strongly reduced by -3.53 dB at resonance.

To better characterize the frequency tuning range, different plasma configurations were considered for U_{DC} varying from 0 V to 550 V. Fig. 6 summarizes the simulated and measured frequency shift of the plasma based microstrip resonator and the relative insertion loss at the resonant frequency for different values of input current. In both cases, a roughly linear current-dependent behaviour is observed and confirms that a simple tuning control can be achieved.



(a) (b)

Fig. 6. Simulated and measured (6a) frequency shift and (6b) relative insertion loss obtained for different values of current.

However, the simulated tuning range seems limited, compared to measurements, and hardly reaches few percent. This mitigation is mainly attributed to the plasma model. First, we think that numerical results can be improved by considering more plasma layers. Besides, the 3D extrapolation likely underestimates the electron diffusion in regions right above the ground plane (between holes) which narrows the resulting plasma dielectric permittivity range inside the cavity and thus limits the resonator tuning ability. To the best of our knowledge, it is still the first time that realistic 3D plasma models were included in full-wave simulations of integrated microwave circuit.

V. Conclusion

In this paper, we have implemented a plasma discharge inside a microstrip resonant cavity to tune its frequency. DC plasma simulations were held to understand and characterize the electron density diffusion through a slotted plane. The resulting non uniform plasma models were used to investigate tuning abilities of such a resonator with commercial electromagnetic software. Numerical predictions are consistent with experimental results. A 5.43 % tuning range was experimentally achieved. We believe this value can be improved by designing more sophisticated diffusion grid or considering more efficient gases, such as neon or xenon.

Acknowledgment

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