Hairpin Probe Sensitivity for Determination of Plasma Density

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The hairpin probe is considered in this paper as an effective tool for determination of the plasma density by accurate resonance method. Multi-mode operation is considered and the unloaded Q factor of the modes is associated with the collisions in the plasma discharge. The sensitivity of the hairpin probe is investigated in details by numerical simulations with 3D simulators.

The hairpin resonator can be used as a very effective E-field probe for determination of the plasma density in low-pressure gas discharges [1]. There exist different configurations of this probe, different types of coupling between the resonator and the transmission line and different measurements schemes [2-7]. Two main modifications of the structure in "transmission" or "reflection" regimes have been reported in the literature: the transmission-type probe consists of a hairpin resonator, input loop and pick-up loop, while the reflection-type probe includes only a coaxial cable with magnetic loop at the end that feeds the hairpin structure. We use in our investigation reflection-type hairpin resonator. The main benefit of this method is that the measurements are based on determination of the resonance frequency f_{haipin} instead of any absolute measurements of E-filed magnitudes, which ensure better sensitivity, accuracy and measurement simplicity.

The hairpin probe is a quarter-wave two-wire resonator (Fig. 1a), which can be relatively easy designed for TEM-mode operation [8]. The open end of the structure has maximum of the E field of the standing wave, which makes this resonance probe enough sensitive to the changes of the dielectric parameters of the surrounding plasma medium. The opposite short end has maximum of the H field, which allows to construct quite stable and reliable coupling between the resonator and the feed coaxial cable using H-type loop probe. We investigate in this paper the possibility to use as the low-order

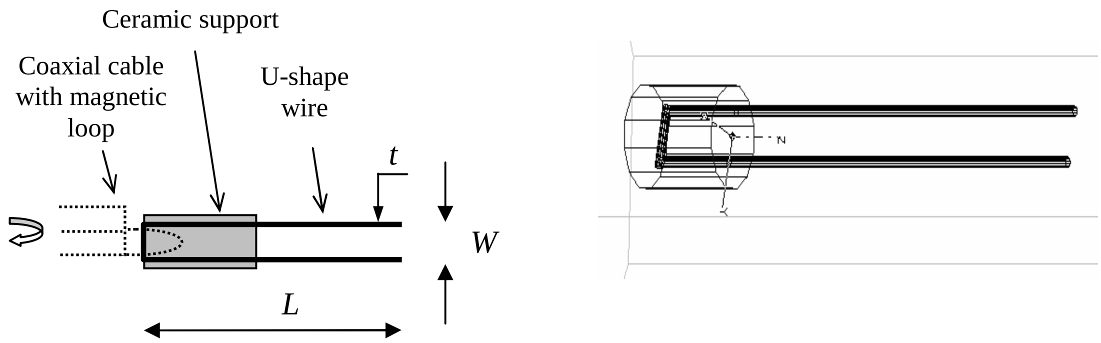

Fig. 1: a) Schematic view of the hairpin resonator wire with length *L* and cylindrical ceramic support; b) 3D model of the resonator, used in the Ansoft® HFSS simulator

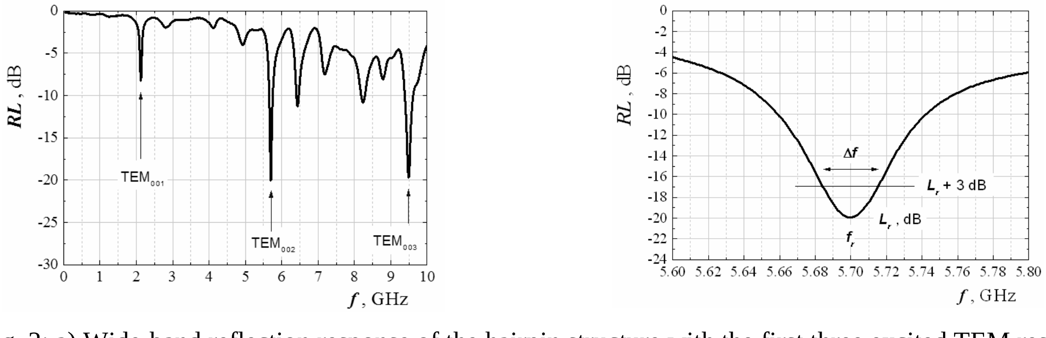

Fig. 2: a) Wide-band reflection response of the hairpin structure with the first three excited TEM resonances; b) Narrow-band response of TEM_{002} mode: $f_{hairpin}$ ~ 5700 MHz, Δf ~30 MHz, loaded and unloaded Q-factors: Q_L ~190, Q_0 ~211

resonance TEM_{01}, as well as the high-order resonances for measurement of the plasma density – Fig. 2a. Additionally, we investigate the possibility to use the information about the measured unloaded Q factor Q_0 (Fig. 2b) for determination of the collisions' parameters in the plasma.

One of the main problems, considered in the paper, is the investigation of the measurement sensitivity of this resonance hairpin probe. For this purpose, we constructed a simplified 3-D model of the hairpin resonator with a small ceramic support at the short end without introducing the coupling loop model – Fig. 1b. Then we simulate this structure for different effective dielectric constant of the plasma medium (ε_{eff} in the interval from 4 to –4). The results have been presented in 3. We can see that the measurement sensitivity is higher (the curve slope in bigger) in the interval $\varepsilon_r \subseteq (1, -1)$. Moreover, the E-field distributions in several specific points (1-4) over the plotted curve have been given (Fig. 4), which confirm the loss of sensitivity of the hairpin probe for $|\varepsilon_{eff}| > 1$. In these points (3, 4) the maximum of the E filed of the standing wave changes from the open end (when $\varepsilon_{eff} > 0$) to the short end (due to the negative sign of ε_{eff}) and the probe does not more react to the dielectric constant changes.

In the full text of the paper, we compare the simulated result with the measured data for a capacitive RF discharge with low pressure (0.1-0.01 Torr Ar).

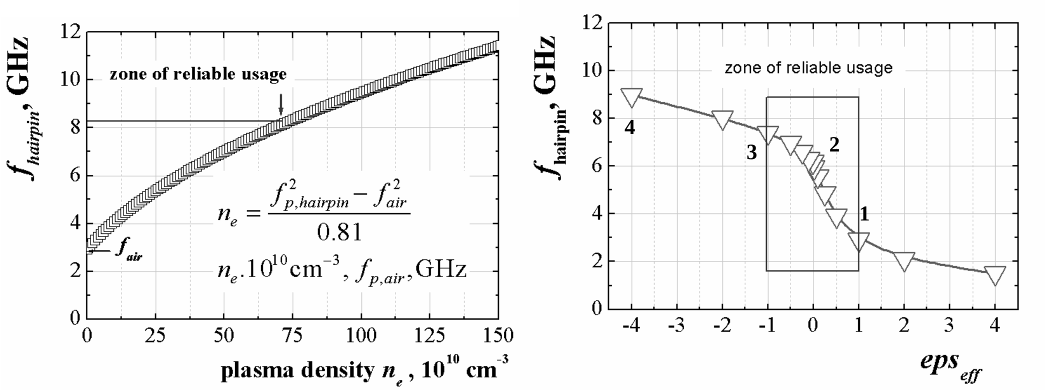

Fig. 3: a) Dependence of the hairpin resonance frequency v/s the plasma density; *b*) dependence of the resonance frequency v/s the effective plasma permittivity and simulated E-field distributions in 4 different points

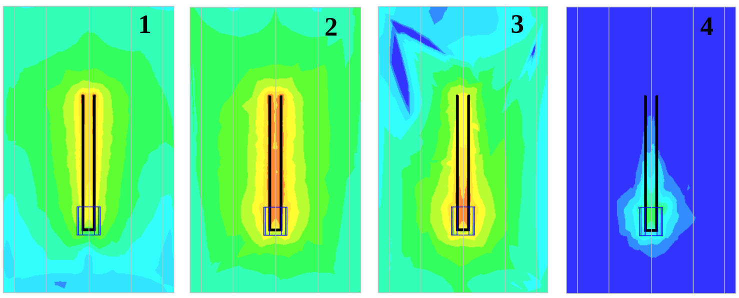

Fig. 4: Pictures of the simulated E field around the hairpin resonator in plasma with increased density (points 1, 2, 3 and 4 on Fig. 3.

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