Topic number: no. 5

MODELLING RESONANT MICROWAVE STUCTURES FOR ELECTRON DENSITY PROBES

N. StJ. Braithwaite, V. Samara, M. D. Bowden

Dept Physics & Astronomy

The Open University

MK7 6AA, UK

n.s.braithwaite@open.ac.uk

This paper reports results from a finite element model of a simple hairpin resonator. This structure has been shown to be an effective tool for localized measurements of electron density in low-pressure plasmas [1-3]. The hairpin is typically 20-30 mm in length so that its quarter wave resonance occurs around 3 GHz in vacuum/air. Microwave excitation is coupled to the hairpin by a one or two turn grounded-loop termination of a coaxial feed, as shown in Fig. 1. The resonance shifts to lower frequencies in a liquid dielectric and to higher frequencies when immersed in plasma. The resonance can be understood in terms of modes guided by the hairpin, which acts as a portion of twin-wire transmission line, with an effective length that includes the bend right up to the mid point. For use in low-density plasmas the transmission line model can be extended to incorporate the effect of a positive space-charge sheath around the hairpin, treating it as an electron-free ($\varepsilon_r = 1$) layer [2]. It is observed that the resonance in air can be shifted to lower frequency by positioning dielectric material between or beside the open ends of the hairpin; placing dielectric around the loop has little or no effect. At resonance the transmission line model indicates a voltage node and current anti-node at the loop end, hence the insensitivity to dielectric in this region; at the open end the electric field, and hence sensitivity to dielectric, is maximum.

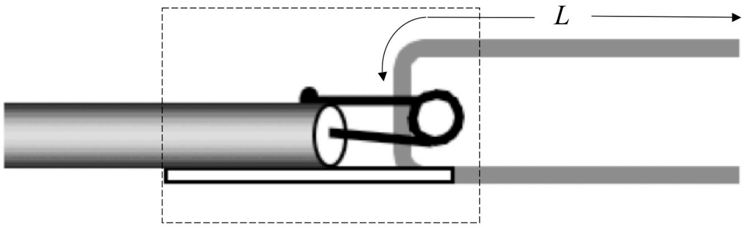

Fig. 1 Hairpin structure that resonates in vacuum when excited at $f = c/4L$; in a dielectric medium the resonance shifts by $\varepsilon_r^{-1/2}$. The dashed box marks the region of a deposition shield.

Other observations are less easily reconciled by the simple model. For instance: (i) if the sides of the hairpin are not parallel the resonance always occurs at a frequency below the `ideal' case; (ii) in a practice one observes a rich spectrum of resonances, only a few of which are related to the hairpin and its surroundings; (iii) when used in a deposition environment the probe ceases to function if conducting material is allowed to accumulate. To understand these observations a finite element approach has been used; the results are described below.

(i) The full electromagnetic solution for a hairpin structure with parallel and non-parallel sides, has been found – Fig.2 shows the fundamental resonance for various configurations of the hairpin. Consistent with observations on the bench, whether convergent or divergent, a non-parallel hairpin resonates at a lower frequency than a parallel one.

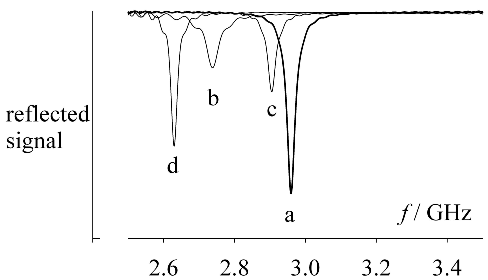

Fig. 2 Resonance curves for a hairpin in vacuum/air: (a) parallel sided; (b) convergent –3°; (c) divergent +3°; (d) divergent +5°.

(ii) In defining the solution space and the boundary conditions for the finite element model significant physical structure is defined in the vicinity of the hairpin, including the dimensions of the co-axial feed and the path length of the outer system boundary. The electromagnetic solution is sensitive to the choices made for these details, which then become imprinted in the overall impedance spectrum of the hairpin. This is directly analogous to the effect of the real environment when a hairpin probe is deployed inside the vacuum chamber of a plasma source for the measurement of its density. The specific resonance of the hairpin can be identified using effect (i). The shift in resonance that occurs between operation in a vacuum, f_o, and a plasma f_r is related to plasma density by [2, 3] : $n_e / 10^{16}\ m^{-3} = [\ (f_r / GHz)^2 - (f_o / GHz)^2]/0.85$.

(iii) Thin film deposition onto the hairpin itself is not a problem but the deposition of conducting material around the loop impedes proper function so preventing its operation as an electron density probe. The solution is to shroud the coupling loop in a dielectric shell (Fig. 1). The finite element model finds the shell to have little effect when clean but when metalized there is a shift in the fundamental resonance. As shown in Fig 3, the resonances in vacuum and plasma are shifted by the same amount so the normal analysis [2, 3] is correct at least to first order.

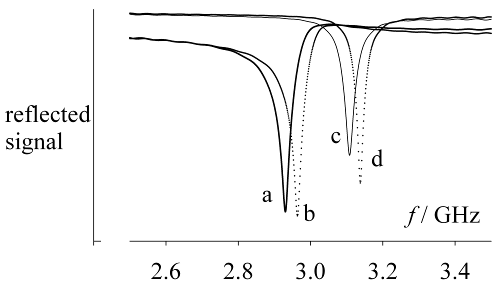

Fig. 3 Resonance curves for a hairpin: in vacuum/air (a) without and (b) with a metallized shroud; in plasma at $10^{16}\ m^{-3}$ (c) without and (d) with a metallized shroud.

References

[1] R. L. Stenzel 1976 *Rev.Sci.Instrum*. **47**, 603.
[2] R. B. Piejak, V. Godyak, R. Garner, B. M. Alexandrovich and N. Sternberg 2004 *J. Appl. Phys* **95**, 3785.
[3] R. B Piejak, J. Al-Kuzee, and N. St J. Braithwaite 2005 *Plasma Sources Sci. Technol.* **14**, 734.

Acknowledgement:
This work is supported by the UK EPSRC grant EP/E003885/1