Eigen Surface Modes of Filamentary Plasma Structures

Stiliyan Lishev, Antonia Shivarova, and Khristo Tarnev

***Abstract*—Calculated spatial distributions of the eigen surface modes guided by free-localized filamentary plasmas are presented. The plasma structures considered are those of surface-wave-sustained discharges in the gas pressure range between 10 and 200 torr.**

***Index Terms*—Filamentary plasma structures, surface waves, surface-wave-sustained discharges.**

AS THE experiments [1] show, the self-organization of surface-wave-sustained discharges in the gas pressure range between diffusion-controlled discharges [2] and atmospheric-pressure discharges [3] results in their contraction into free-localized plasma structures of the filament type. These few filaments are gas-discharge channels extending along the gas-discharge tube and positioned in the out-of-center region of its cross section, equidistantly in the azimuthal direction. The contraction of the discharge poses the question about the kind of surface modes guided by such a filamentary structure and the spatial distribution of their wave field, a problem that has been treated recently [4], [5] by covering not only plasma filaments but also the other plasma structures (plasma rings and dipole structures) which appear [1] at the different stages of the discharge contraction.

The current study is completely focused on the discharge contraction into filamentary structures and presents computationally generated images of the electromagnetic field configuration of the surface waves guided by such type of plasma structures.

The results (Fig. 1) presented here are obtained by employing the 2-D model developed in [5] for the description of the spatial distribution of the surface wave field in plasmas with an arbitrary (given) distribution of plasma density over the discharge cross section. The gas-discharge conditions chosen are as follows: a microwave ($f \equiv \omega/2\pi = 2.45$ GHz) argon discharge at gas pressure $p = 20$ torr with a fixed ratio $\nu/\omega = 0.25$, where ω and ν are, respectively, the wave frequency and the elastic electron-neutral collision frequency for momentum transfer. The filamentary structure considered consists of 4 filaments as shown in Fig. 1. The filaments extend along the discharge length, in the z-direction. In the cross section of the discharge [the $(x{-}y)$-plane in Fig. 1] a Gaussian distribution of the plasma density in each filament is assumed according to the experimental results in [6]. The positions of the center of the filaments and their width (being the same for all of them) are also according to the experiments [1]: filaments with a diameter of 4 mm located within a radius of 1 cm. The filaments are completely isolated from each other: Even the low-plasma-density contours $n_{\mathrm{e}} = 0.01 n_{\mathrm{cr}}$ (where n_{cr} is the usual critical density) close on themselves around each filament (Fig. 1).

The spatial distribution of the wave-field components shown in Fig. 1 is obtained as a numerical solution of the wave equations written for the axial electric (E_z) and magnetic (H_z) field components. The two-dimensional variation of the plasma density—the azimuthal one in addition to the radial one—couples the equations for the E_z- and H_z-fields determining the lowest order eigenmode of the filamentary structure as a hybrid wave, with all six field components E_z, E_r, E_φ, H_z, H_r, and H_φ [Fig. 1(a)–(f)] being present in the configuration of the wave field. Therefore, the filamentary structure as a whole defines a unique eigen surface mode. Recall that the lowest order eigenmode of a plasma column [1], which can be considered as a single filament, is an azimuthally symmetric surface mode.

The maxima in the distribution of the electric field components [Fig. 1(a)–(c)] are on the $(n_{\mathrm{e}} = n_{\mathrm{cr}})$-contours showing that these contours guide the wave propagation. These maxima result from the effect [2] of resonance absorption of the surface waves due to their transformation into volume plasmons. The highest peaking of the E-field is that of the E_r-field component, like in the case of the azimuthally symmetric surface mode of a plasma column [2]. The obtained higher amplitudes of the E_z- and E_r-field on the outward side of the $(n_{\mathrm{e}} = n_{\mathrm{cr}})$-contours confirm the conclusion that the wave is an eigenmode of the whole filamentary structure. Indeed, a superposition of the fields of waves that would be guided separately by each filament would result in a higher amplitude values on the inward sides of the $(n_{\mathrm{e}} = n_{\mathrm{cr}})$-contours.

Fig. 1 shows two types of spatial distributions of the field components. The maxima of E_z-, E_r-, and H_φ-field components lie on the lines connecting the center of the structure with the center of each filament. Integration of these field components over the azimuthal coordinate results into a (non-zero) background field. The E_φ-, H_z-, and H_r-field components have maxima on both sides of the center of each filament. Moreover, these two peaks are opposite in phase. Averaged over the azimuthal coordinate, these field components are zero.

Manuscript received November 27, 2007. This work was supported by DFG-Project 436 BUL 113/144/0-1.

S. Lishev and A. Shivarova are with the Faculty of Physics, Sofia University, 1164 Sofia, Bulgaria (e-mail: ashiva@phys.uni-sofia.bg).

K. Tarnev is with the Department of Applied Physics, Technical University—Sofia, 1000 Sofia, Bulgaria.

Digital Object Identifier 10.1109/TPS.2008.917773

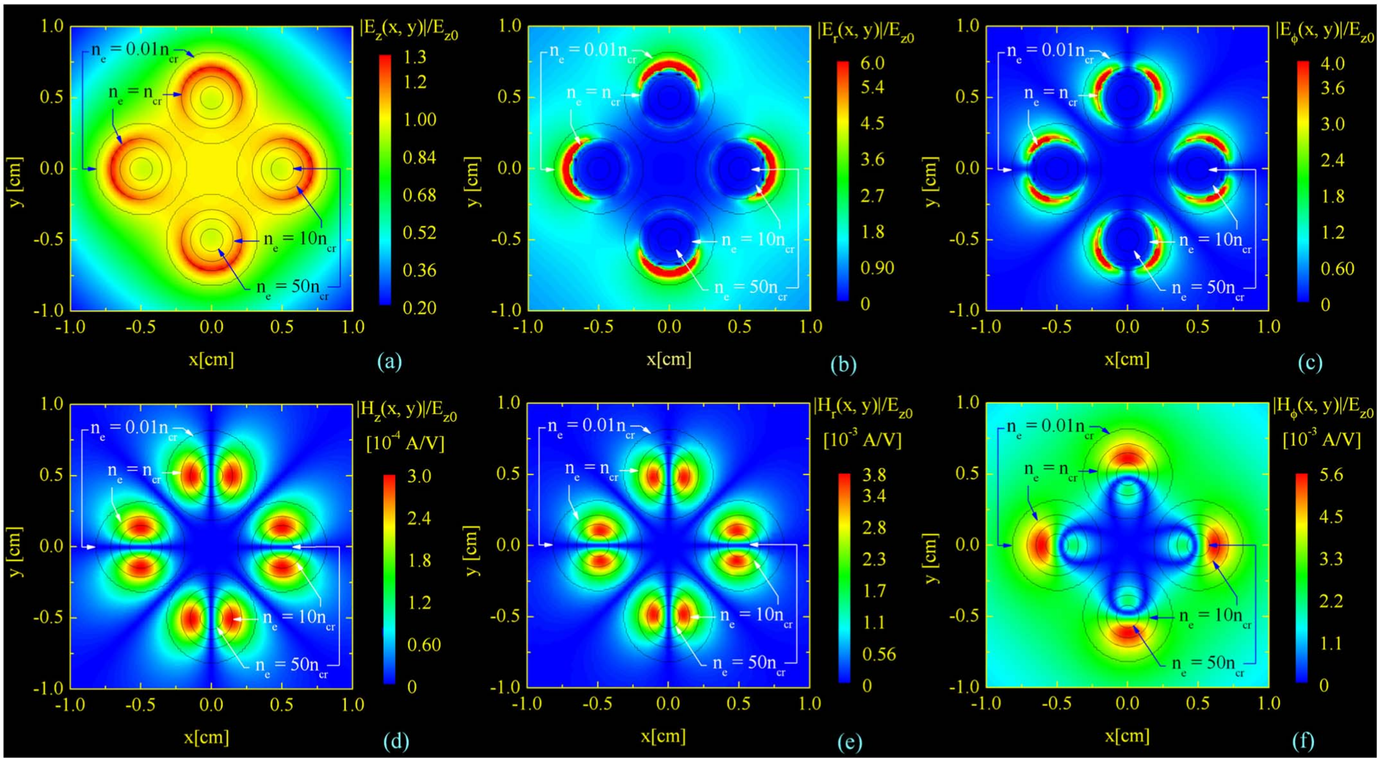

Fig. 1. Calculated color plots of the spatial distribution of the (a) E_z, (b) E_r, (c) E_φ, (d) H_z, (e) H_r, and (f) H_φ field components of the eigen surface mode of a filamentary structure consisting of four filaments. Normalization to $E_{z0} = E_z(r = 0)$ where $r = 0$ is the geometrical center of the whole structure. The distribution of the plasma density n_{e} in the filaments is presented by the black curves on the figures.

Thus, the field of the wave could be presented as an azimuthally symmetric background field completed by the E_z-, E_r-, and H_φ-field components and azimuthal variations of all the field components superimposed on it. The azimuthal variations have their maxima in the region of the filaments. They decay fast with the increase of the radius, and far away from the filamentary structure the azimuthally symmetric background field predominantly determines the total field distribution. This is in accordance with measurements [7] of the field distribution outside the gas discharge tube of a filamented surface-wave-sustained discharge at 915 MHz.

In conclusion, the images of the field configuration of the surface waves guided by a filamentary plasma structure show that the wave is a hybrid one, with a background azimuthally symmetric field, and it is an eigenmode of the filamentary structure as a whole.

REFERENCES

[1] N. Djermanova, D. Grozev, K. Kirov, K. Makasheva, A. Shivarova, and T. Tsvetkov, "Self-organization of surface wave sustained discharges in the pressure range from 10 to 200 Torr," *J. Appl. Phys.*, vol. 86, no. 2, pp. 738–745, Jul. 1999.

[2] H. Schlüter and A. Shivarova, "Travelling-wave-sustained discharges," *Phys. Rep.*, vol. 443, no. 4–6, pp. 121–255, May 2007.

[3] Y. Kabouzi and M. Moisan, "Pulsed microwave discharges sustained at atmospheric pressure: Study of the contraction and filamentation phenomena," *IEEE Trans. Plasma Sci.*, vol. 33, no. 2, pp. 292–293, Apr. 2005.

[4] S. Lishev, H. Schlüter, A. Shivarova, and K. Tarnev, "Spatial distribution of the wave field of filamented high-frequency discharges," *Plasma Process. Polym.*, vol. 3, no. 2, pp. 142–146, 2006.

[5] S. Lishev, A. Shivarova, and K. Tarnev, "Spatial distribution of the wave field of the surface modes sustaining filamentary discharges," *J. Appl. Phys.*, vol. 103, no. 1, p. 013 304, Jan. 2008.

[6] M. Moisan and J. Pelletier, *Physique des Plasmas Collisionnels: Application aux Décharges Haute Frequénce*. Les Ulis, France: EDP Sci., 2006.

[7] E. Castaños Martinez, K. Makasheva, and M. Moisan, 2007. Private Communication.