Electrodynamic Modes Interaction in Clinotron Cavity with Double-Periodic Grating

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Abstract

The hybrid bulk-surface modes excited in a waveguide with double-periodic grating have been considered. Such modes appear due to Electrodynamic interaction of the bulk modes with surface-wave resonator modes (i.e., leaky spoof surface plasmon polariton of an open grating). The potential for the effective generation of the THz radiation in a Clinotron by the excitation of the hybrid modes has been demonstrated.

1 Introduction

Electrodynamic (ED) interaction of resonant modes in a cavity was revealed in [1]. This phenomenon consists in specific behavior of two resonant modes of a cavity when varying one of its parameters, namely: their resonant frequency dependences have no crossing when approaching degeneration frequency point, but repel each other instead and exchange their spatial structures. That phenomenon takes place in such a cavity where degeneration of its resonant modes is possible and may be removed by an inhomogeneity which is weak but affects both degenerated modes [1]. ED modes interaction has been also revealed in open resonators with the help of a new spectral theory of open ED structures developed by V.P Shestopalov and his collaborators [2,3]. This theory is based on the rigorous methods of electromagnetic wave diffraction by opened ED structures [4], which enabled studying of complete spectrum of OR resonant frequencies, including specific spectral points named as Morse points of dispersion equation [2,3]. Just around these points ED interaction of resonant modes takes place. Surface-wave resonator with a regular periodic grating is used in vacuum electron devices, named as resonant BWO and its modification named as Clinotron [5]. Recently, we discovered a possibility of ED modes interaction of a new type: ED interaction between bulk mode of Clinotron cavity containing double-periodic grating and the mode of its surface-wave resonator [6-8]. In the paper we briefly describe results of theoretical and experimental investigation of that phenomenon.

2 Theory of the Hybrid Bulk-Surface Modes

It is well known that eigen modes of an open double-periodic grating may contain leaky wave, i.e., the energy of the eigenmode is transmitted via both surface harmonic and outgoes into free space via radiating harmonic [5-9]. This can be seen from the dispersion shown in Figure 1 where dotted curve corresponding to the open grating appears not only in the pure surface area. The placing upper reflector above the grating form a closed waveguide which in its turn possess bulk eigenmodes. Near points of the intersection of leaky and bulk modes, the ED mode interaction occurs as it is seen in Fig. 1.

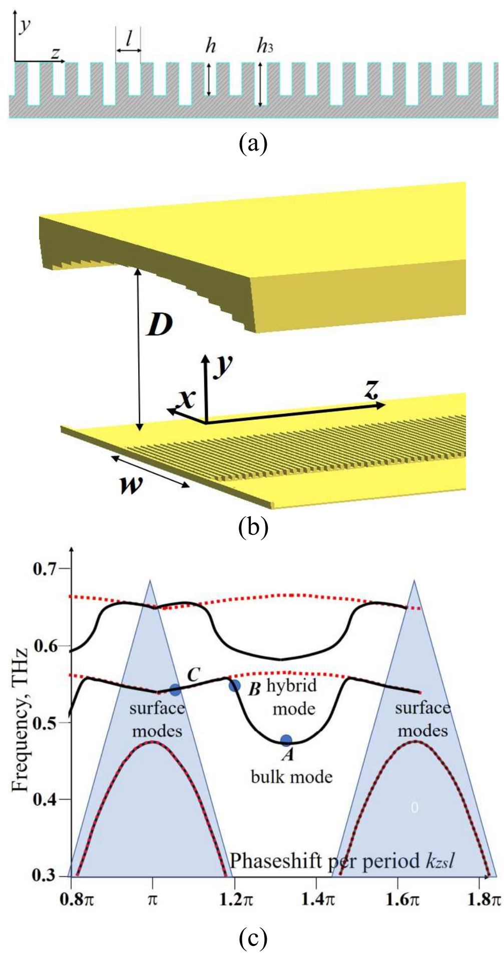


Figure 1. (a) The sketch of double-periodic grating; (b) 3D waveguide and (c) the dispersion of the closed (solid curves) and open (dashed curves) waveguides containing the double-periodic grating. The grating's parameters are as follows: small period l=70 μm, regular groove heght h=90 μm, every 3rd modified groove heght h_3=120 μm.

Physically this mode interaction can be explained by the reflection of the leaky wave from the upper wall with further resonance excitation of the spoof surface plasmon polariton (SSPP) on the grating [6, 9]. This resonance excitation is demonstrated in Figure 2 as absorption of the plane wave incident on the double- periodic grating. Near the mode interaction area, the eigenmode becomes hybrid bulk-surface mode (HBSM).

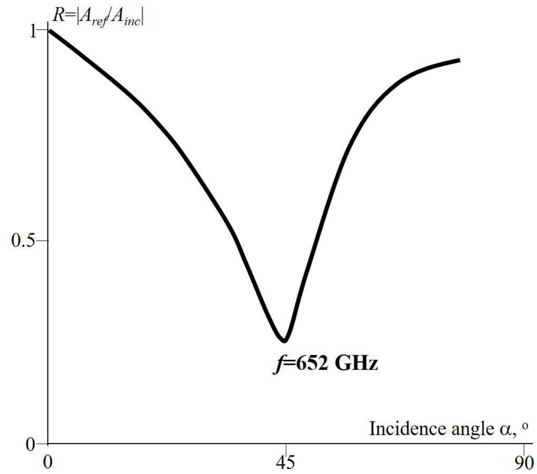


Figure 2. Reflection factor of the plane wave vs. angle of incidence.

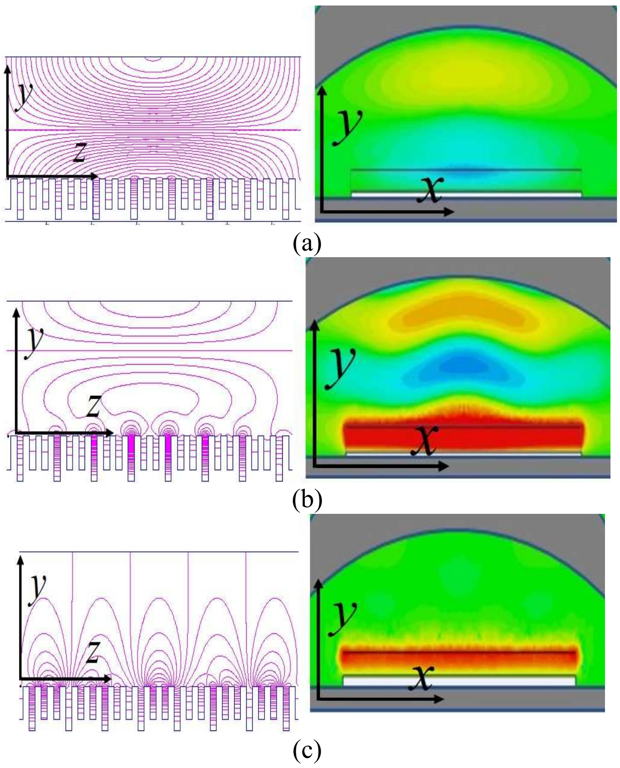


Figure 3. RF field patterns of the modes designated as (a) *A*; (b) *B* and (c) *C* in the Figure 1. The left side is the distribution in the y-z plane and the right-side ones correspond to the x-y plane.

Unlike pure bulk or pure surface modes which RF field patterns are shown in Figure 3, the HBSM contains both surface and bulk harmonics transferring the RF energy. The energy transfer may either coincide or be in opposite direction. When the energy transfer in opposite directions equals by the absolute values for surface and bulk harmonics, the group velocity becomes zero [7].

The 2D PIC simulations using MAGIC2D and MAGIC3D [12] proved that the HBSMs are very promising for generation of the sub-THz radiation in a Clinotron [5, 6]. The RF field pattern in the "hot" case is shown in the Figure 4 where one can see that the mode contains both bulk and surface waves and the angle of the bulk harmonic is in very good agreement with the dispersion. Both 2D and 3D PIC simulations demonstrated that the output efficiency reaches up to several percents at frequencies about 0.5-0.65 THz even in the case of grating conductivity σ=1.7*10^7 S/m.

The analysis has shown that there are several reasons for this. First one is that both coupling impedance and Q-factor are quite high in the HBSM regime in contrast to the pure bulk or surface modes where only one parameter is high, whereas the second one quite low. The second reason underlies in the fact that the feedback provided by the backward bulk wave is less sensitive to ohmic losses, which usually limit severely the output performance of the THz vacuum electron devices [8, 10, 11].

The 3D consideration of the HBSM has revealed more advantageous properties. From Figure 3 one can see that the SSPP RF field distribution across the grating width is quite uniform whereas the bulk harmonic's distribution is strongly non-uniform. Since the surface harmonic is synchronous with electron beam the use of wide electron beam is quite effective in the case of the HBSM. The additional argument for use of wide electron beams is that higher transverse modes with several variations across a grating have much lower Q-factor than the fundamental mode. This fact strongly mitigates the mode competition.

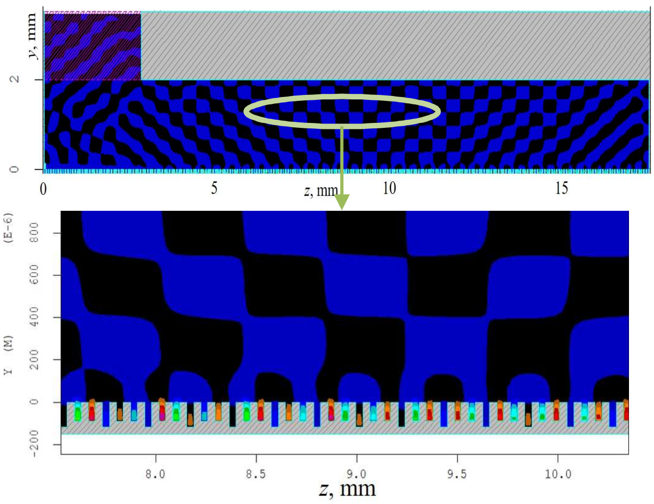
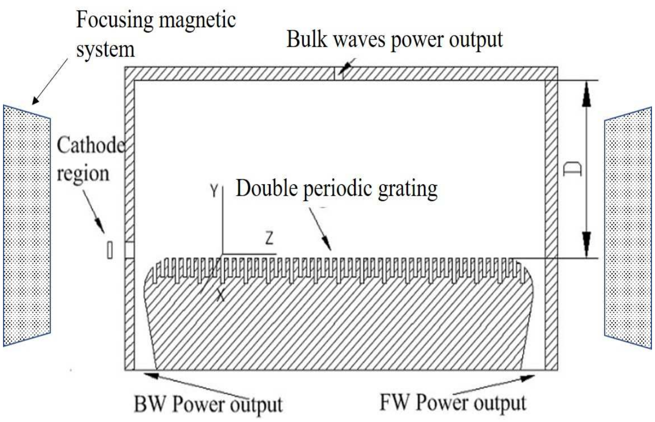


Figure 4. 2D RF field pattern obtained during "hot" PIC simulations for the electron beam with the accelerating voltage *U*=17.8 kV and current *I*=200 mA. The oscillation's frequency is 0.628 THz.

3 Experimental Study of HBSM Excitation

The experiments for the study of the hybrid bulk-surface wave oscillations have been carried out for the 0.1 THz and oscillator and amplifier [7]. The experimental prototype shown in Figure 5 contains three radiation outputs: 2 different directions (forward – FW, backward – BW) of the surface wave and 1 direction of the bulk radiation.

It operated with accelerating voltage of 2-4 kV and beam current up to 150 mA and demonstrated frequency tuning range of 92-100 GHz with power 1-2 W. The measured frequency versus wavenumber is plotted on the dispersion diagram along with 2D cold calculation in Figure 6. As follows from the dispersion, the radiating harmonic angle of the hybrid mode at D=0.8 mm is 0-15° that in a good agreement with the enhanced signal at output in the upper wall and in the output corresponding to the forward wave.



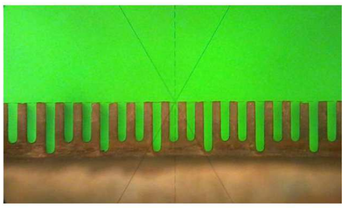


Figure 5. The sketch of the experimental prototype and photo of the fabricated double-periodic grating (period l=280 μm, regular groove heght h=600 μm, every 3[rd] modified groove heght h_3=680 μm.

The oscillations corresponding to the HBSM on the dispersion were well detected from the slot in the upper wall intended for the bulk wave identification, that additionally confirms the HBSM excitation.
The current activity in IRE NAS of Ukraine includes the development of the experimental prototypes for generation of the THz radiation.

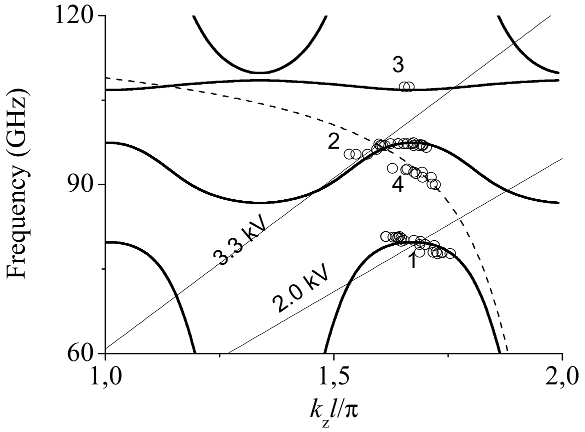


Figure 6. The measured frequency of the 0.1 THz oscillator versus wavenumber together with the 2D cold dispersion.

4 Competition of the HBSMs with Field Variations Across a Grating Width

As it was mentioned above, due to low diffraction Q-factor of higher transverse modes with several variations across a grating n_x>1 they don't compete with the fundamental transverse mode with uniform RF field distribution along a grating n_x=1. However, since hybrid modes in a ridged waveguide are not orthogonal, there is a possibility of interaction of modes with different n_x. Therefore, the ED mode interaction becomes more complicated since additionally to the mode interaction with the same n_x (2D effect) there is the ED mode interaction due to 3D configuration. Since the considered structure is symmetric, the modes interacting with the fundamental n_x=1 are with odd n_x. The dispersion which takes into account only modes with n_x=1 and n_x=3 is shown in Figure 7.

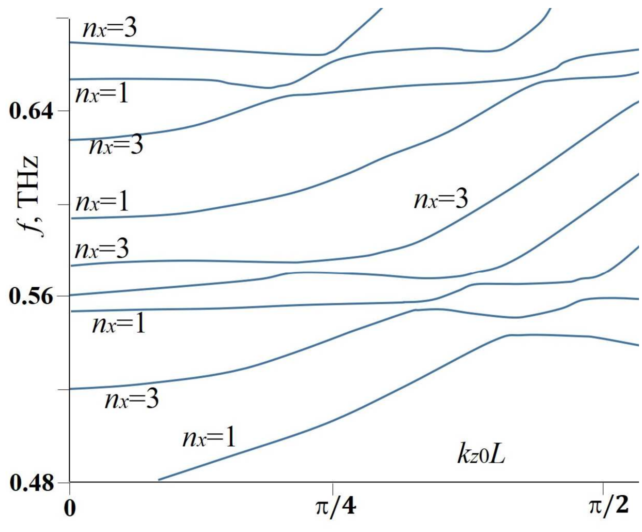


Figure 7. The dispersion of the 3D waveguide shown in Figure 1 containing the same double-periodical grating. The grating width w=2 mm.

Obviously, taking into account more modes with n_x=5,7 would essentially complicate the analysis and should be studied further in details. However, the diffraction Q-factor rapidly decreases with n_x and preliminary analysis has showed that the zones of mode interaction of n_x=1 with $n_x \geq 5$ are narrow and they don't essentially deteriorate the output performances of the fundamental oscillations during their excitation by the wide electron beam.

The exchange of the spatial structure between the modes with n_x=1 and n_x=3 and between n_x=3 and n_x=5 is shown in the Figure 8 when approaching ED mode interaction areas on the 3D dispersion.

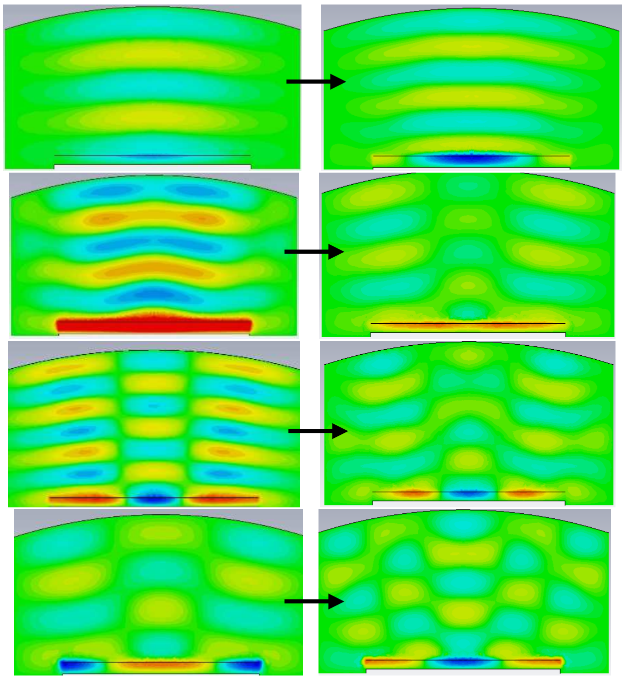


Figure 8. RF field patterns of the interacting hybrid bulk-surface modes with n_x=1, n_x=3 and n_x=5 in the x-y plane.

5 Summary

The considered structure of double-periodic grating placed in the 3D ridged waveguide exhibits variety of possible ED mode interaction cases including coupling of the bulk and surface waves with variations across a grating width. Appearing due to this ED mode interaction modes are identified as the hybrid bulk-surface modes (HBSM). Preliminary theoretical and experimental study demonstrated high potential of the electron beam-wave interaction in the THz range via HBSM excitation.

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