Generation of Sub-Terahertz Surface Waves by Relativistic Electron Beams: Quasioptical Theory, Simulations and Experiments

Naum S. Ginzburg[1], A.M. Malkin[1], I.V. Zheleznov[1], V.Yu. Zaslavsky[1], A.S. Sergeev[1], I.V. Zotova[1], and M.I. Yalandin[2]

[1]Institute of Applied Physics RAS, Nizhny Novgorod, Russia, ginzburg@appl.sci-nnov.ru
[2]Institute of Electrophysics RAS, Ekaterinburg, Russia

Advancement of vacuum electronic devices into sub-THz and THz frequency ranges calls for oversized beam-wave interaction space due to the fact that that the dimensions of the beam guiding systems can not be reduced lower than the millimeter scale. Thus, in order to provide coherent THz radiation from the spatially extended beams, excitation of surface modes existing in 1D and 2D corrugated systems appears to be attractive [1,2,5,6].

In this paper, we present recent results of theoretical and experimental studies of sub-terahertz generation based on excitation of surface waves by electron beams and extended bunches. Using oversized slow-wave structures allows for a significant increase of total current and, correspondingly, radiation power. Based on superradiance of electron bunches, 150 ps superradiant pulses with a central frequency of 0.14 THz, and an extremely high peak power of 50-70 MW were obtained in the joint effort by the Institute of Electrophysics RAS and IAP RAS. We also report of the first successful experiments on the cylindrical 0.03 THz Cherenkov oscillator with a 2D corrugation conducted at IAP RAS with an output power of 1.5 - 2 MW.

Generation of Sub-THz SR Pulses Based on Excitation of Surface Waves in Oversized Waveguides

Cherenkov SR of electron bunch exciting the surface wave in an oversized 1D corrugated cylindrical waveguide (Fig. 1a) can be considered within quasi-optical approach [1]. In this case the radiation field near a shallow corrugation is presented as a sum of two counter-propagating *TM* polarized wave-beams:

$$H_\varphi = \mathrm{Re}(A_+(z,r,t)e^{i\bar{\omega}t-ikz} + A_-(z,r,t)e^{i\bar{\omega}t+ikz}), \quad (1)$$

propagation and mutual coupling of which is described by two non-uniform parabolic equations. The synchronous interaction of electrons with a forward partial waves leads to development a self-bunching and formation of powerful SR pulse.

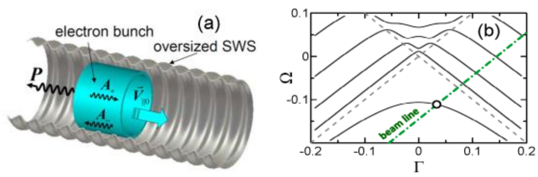

Fig. 1. (a) Scheme of SR pulse generation with excitation of a surface wave in an oversized periodically corrugated waveguide. (b) Dispersion characteristics of a corrugated waveguide and an electron beam.

Simulations show that the most optimal conditions for SR emission correspond to excitation of the backward surface wave near the Bragg frequency (π-regime, Fig.1b). For parameters of an electron bunch formed by an accelerator RADAN (electron energy of 300 keV, a total current of 2 kA, a bunch duration of 500 ps) and a corrugated waveguide with the mean radius of 3.75 mm, corrugation period of 0.825 mm, and corrugation depth of 0.36 mm the operating frequency in the resonant point is of 0.14 THz ($2r_0/\lambda \approx 3.5$). In this case the power of generated SR pulse emitted in $-z$ direction achieves ~200 MW for pulse duration of ~200 ps (Fig. 2a). As it is seen in Fig. 2b the instant spatial structure of the partial wave corresponds to formation of the evanescent surface wave with the field amplitude exponentially decaying from the corrugation.

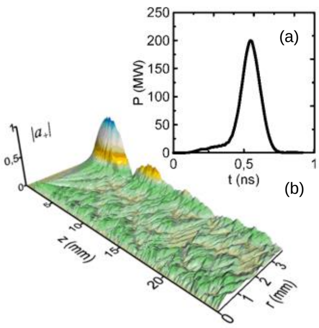

Fig. 2. SR emission with excitation of the backward surface wave: (a) generated SR pulse, (b) the structure of the forward partial wave.

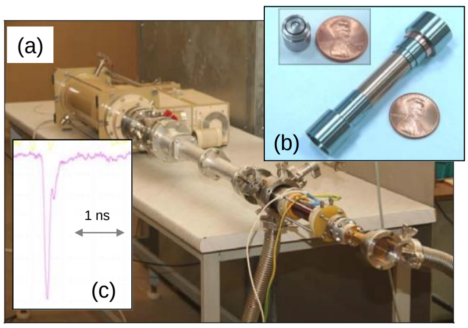

Fig. 3. Photo of the experimental set-up (a), corrugated waveguide and coaxial reflector (b) used for observation of superradiance with excitation of a surface wave. (c) Oscilloscope trace of the 0.14 THz SR pulse with duration of 150 ps and peak power up to 70 MW.

Based on a theoretical analysis, experiments on observation of the sub-terahertz SR pulse generation were carried out in IEP RAS (Ekaterinburg). Photo of the experimental set-up is shown in Fig. 3. A typical oscilloscope trace of generated SR pulses with a duration of about 150 ps and a rise time of 100 ps reconstructed in the "power-time" coordinates is presented in Fig. 3c. Frequency measurements using a set of cut-off waveguide filters show that the pulse spectrum has a central frequency in the interval 0.13-0.15 THz. The peak power of generated SR pulses was estimated by integrating the detector signal over the directional pattern and achieved of 50-70 MW, that strongly exceeds the value obtained in the previous sub-terahertz experiments [2] with single-mode waveguides.

Ka-band surface-wave oscillator based on 2D periodical corrugated structure

For spatially extended relativistic electron beams, the use of two-dimensional (2D) distributed feedback is beneficial for providing spatial coherence of radiation and can be exploited in order to increase the total radiation power in the microwave generators [3]. Such 2D feedback can be realized in planar or coaxial 2D Bragg structures (resonators) having double-periodic corrugation (Fig.4a)

$$r = \frac{\tilde{r}}{4}\left[\cos(\bar{M}\varphi - \bar{h}_z z) + \cos(\bar{M}\varphi + \bar{h}_z z)\right], \qquad (2)$$

which provides coupling and mutual scattering of the four wavebeams (Fig.4b),

$$\vec{H} = \mathrm{Re}\left[\left(\vec{x}_0(C_z^+ e^{-ihz} + C_z^- e^{ihz}) + \vec{z}_0(C_x^+ e^{-ihx} + C_x^- e^{ihx})\right)e^{i\omega t}\right]$$

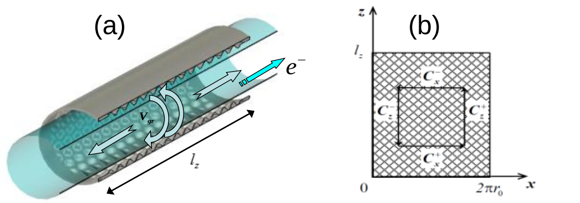

Fig. 4. (a) Scheme of an oversized SWO with 2D corrugated structure. Directions of propagation of the partial wave fluxes and tubular electron beam are shown. (b) Diagram illustrating coupling of partial waves at the 2D corrugation.

Experimental studies of free electron masers (FEMs) based on the novel feedback mechanism have been performed in Ka-band and in W-band in collaboration with the Institute of Applied Physics RAS [4]. As a result, narrow-band generation with an output power of 50 - 100 MW, which is a record for millimeter wavelength FEMs, was obtained.

At present, theoretical and experimental studies of Cherenkov masers with 2D distributed feedback are in progress [5,6]. Among relativistic masers of such type, surface wave oscillators (SWO) appear to be preferable due to the larger values of the electron-wave coupling impedance. Besides, formation of a surface mode ensures the regular field distribution along the coordinate directed perpendicularly to the corrugated surface and, thus, can solve the problem of mode selection over this coordinate. In SWOs, a 2D periodic structure can be exploited both as a slow-wave system and as a highly selective Bragg resonator simultaneously. It provides effective mode control over azimuthal coordinate.

Numerical simulations within the quasi-optical model and using 3D numerical codes show that the resulting mode to be excited in such system depends on the accelerating voltage rise time. In order to excite an azimuthally symmetric mode, this value should be small in the scale of the field excitation increment.

Experimental investigations of the SWO with 2D slow-wave structure based on the 300 keV / 100 A / 4 μs SATURN thermionic accelerator were conducted at IAP RAS [6]. The results are presented in Fig.5. Narrow-spectrum excitation of the 3rd azimuthal mode was observed.

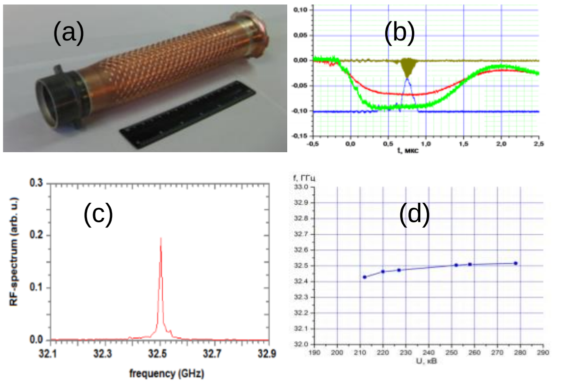

Fig. 5. Results of experimental studies of oversized Ka-band SWO based on the SATURN accelerator: (a) photograph of double periodic slow-wave structure; (b) typical oscilloscope traces of the accelerating voltage (green curve), beam current (red curve), signal from a heterodyne mixer (brown curve) and output RF-pulse (blue curve); (c) spectrum of the output radiation and (d) dependence of the radiation frequency on the accelerating voltage.

This research was performed within the framework of the state task (projects No. 0035-2014-012), and, in part, by RFBR Grant No. 17-08-01072

References

1. *Ginzburg, N.S., Malkin, A.M., Sergeev, A.S. et al.* Generation of Sub-Terahertz Superradiance Pulses Based on Excitation of a Surface Wave by Relativistic Electron Bunches Moving in Oversized Corrugated Waveguides // Phys. Rev. Lett. 2016. V.117 P.204801
2. *Yalandin, M.I., Shpak, V.G., Shunailov, S.A., et al* Generation of powerful subnanosecond microwave pulses in the range of 38–150 GHz// IEEE Trans. on Plasma Sci. 2000. V.28, Iss.5 P.1615
3. *N.S.Ginzburg, N.Yu.Peskov, A.S.Sergeev,* Dynamics of free-electron lasers with two-dimensional distributed feedback // Optics Commun., **112,** 151 (1994).
4. *A.V.Arzhannikov, N.S.Ginzburg, P.V.Kalinin, et al.*, Using Two-Dimensional Distributed Feedback for Synchronization of Radiation from Two Parallel-Sheet Electron Beams in a Free-Electron Maser // Phys. Rev. Lett. V. **117**, 114801 (2016).
5. *N.S.Ginzburg, A.M.Malkin, A.S.Sergeev, and V.Yu.Zaslavsky*, Powerful surface-wave oscillators with two-dimensional periodic structures // Appl. Phys. Lett. 100, 143510 (2012)
6. *N.S.Ginzburg, E.V.Ilyakov, I.S.Kulagin, et al.*, Theoretical and experimental studies of relativistic oversized Ka-band surface-wave oscillator based on 2D periodical corrugated structure // Phys. Rev. AB. V. **21**, 080701 (2018).