Generation of Subterahertz Superradiance Pulses Based on Excitation of a Surface Wave by Relativistic Electron Bunches Moving in Oversized Corrugated Waveguides

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The first experiments on the observation of short pulsed superradiant (SR) emission with the excitation of a surface wave by a relativistic electron bunch moving in an oversized corrugated waveguide were performed. Subterahertz SR pulses with a central frequency of 0.14 THz, an ultrashort duration of 150 ps, and an extremely high peak power of 50–70 MW were generated. The experiments were based on a theoretical consideration including the quasioptical approach and direct particle-in-cell simulations.

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In recent years, significant progress has been achieved in the generation of high-power ultrashort microwave pulses by electron bunches extended in the wavelength scale [1–4]. From a general point of view, the mechanism of pulse production used in these experiments can be considered [5] as a classical analogy of the superradiance effect originally studied in optics [6,7]. In microwaves, typical for superradiance, coherent emission from the entire volume of the active medium (i.e., an extended electron bunch) occurs due to the development of microbunching and slippage of the wave with respect to electrons caused by the difference between the group velocity of the electromagnetic wave and the translational velocities of the particles. At the present stage, microwave superradiant (SR) pulses with the highest peak power were obtained for the Cherenkov mechanism in the case of electron interaction with the backward wave propagating in slow-wave structures (SWS). Progress in these studies has enabled the creation of a new type of generator capable of producing uniquely short (under 0.2–1 ns) electromagnetic pulses at superhigh peak powers exceeding 1 GW in the millimeter waves (Ka band) and 3 GW in the centimeter waves (X band) [2,3].

It should be noted that, in experiments [2,3], an electron bunch interacts with a synchronous spatial harmonic of the lowest TM-polarized volume mode of a periodically corrugated waveguide with a small oversize factor $D/\lambda \approx 1$ (D is the mean diameter and λ is the radiation wavelength). However, in the shorter wavelength bands, the use of single-mode SWS becomes much more complicated due to strict requirements for transportation of the high-current electron bunches and increase of the Ohmic losses. For these reasons, a strong reduction of the SR pulse peak power to a level of 5–10 MW was observed in the previous experiments [4] conducted in the subterahertz band.

An obvious method for the generation of high-power radiation in the subterahertz and, especially, in the terahertz wave bands is to implement oversized slow-wave structures where evanescent surface waves [8–14] can be formed. Specific features of SR emission with the excitation of surface waves in planar SWS were studied in Ref. [14] within the frame of a quasioptical approach. In this Letter, such an approach has been extended on the Cherenkov SR in a cylindrical corrugated waveguide with the finite curvature of walls. The performed analysis allowed us to conduct the first experimental observation of SR emission with the excitation of a surface wave by relativistic electron bunches. In these experiments, the peak power of 0.14 THz SR pulses reached 50–70 MW, which strongly exceeds the value obtained in the previous subterahertz experiments [4] with single-mode SWS. Comparing the suggested method with other possible schemes of terahertz sources, we should mention that Cherenkov SR generators are significantly more compact than free-electron lasers [15] or sources employing coherent spontaneous radiation from undulators [16]. On the other hand, laser-based terahertz sources [17] typically generate single-period picosecond pulses (video pulses), while in our case as in Refs. [15,16] the generation of multiperiod subnanosecond pulses (radio pulses) with a substantially higher spectral density takes place.

Let us describe the Cherenkov SR from an electron bunch that moves rectilinearly with the velocity $\nu_0 = \beta_0 c$ along the guiding magnetic field $\vec{H}_0 = H_0 \vec{z}_0$ in a cylindrical oversized waveguide [Fig. 1(a)] with a shallow sinusoidal corrugation $r(z) = r_0 + r_1 \cos \bar{h} z$, where r_0 is the mean waveguide radius, d is the period, $r_1 \ll d$, r_0 is the amplitude of corrugation, and $\bar{h} = 2\pi/d$. As shown in Ref. [10], the most efficient excitation of a surface wave occurs in the vicinity of Bragg frequency $\bar{\omega} = \bar{h} c/2$ (π-mode regime). In these conditions, within a quasioptical approach, the radiation field in an oversized cylindrical waveguide can be represented as a sum of two

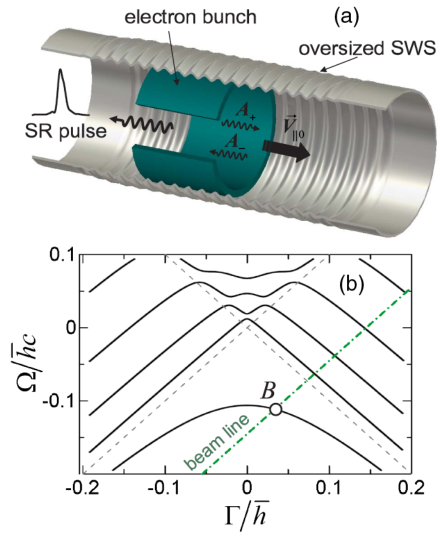

FIG. 1. (a) Model used for the theoretical analysis and PIC simulations of the SR pulse generation by an extended electron bunch moving in a periodically corrugated oversized waveguide. (b) Dispersion characteristics of a corrugated waveguide. The resonance point B corresponds to the backward surface wave excitation.

counterpropagating TM-polarized wave beams with the azimuthal component of the magnetic field in the form

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

$|2k\partial A_\pm/\partial z| \gg |\partial^2 A_\pm/\partial z^2|$, where $k = \bar{\omega}/c$. In the case of the axial symmetric mode excitation, the electric field has both longitudinal $E_z = -\mathrm{Re}[(i/kr)\partial(rH_\varphi)/\partial r]$ and radial $E_r = \mathrm{Re}[(i/k)\partial H_\varphi/\partial z]$ components. To describe mutual coupling of the wave beams (1) on the corrugation, we use the well-known method [18] in which the corrugated cylindrical surface is replaced by a regular cylindrical waveguide with a virtual surface magnetic current. As a result, we obtain a system of two parabolic equations where we have also included the factor of excitation of the copropagating partial wave A_+ by the high-frequency electric current induced in the electron bunch:

$$\begin{aligned}
&\frac{\partial A_+}{\partial z} + \frac{\partial A_+}{c\partial t} + \frac{i}{2k}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(rA_+)}{\partial r}\right) \\
&\quad = i\alpha\delta(r-r_0)A_- + \frac{iI_0}{\bar{\omega}S_b}f(z-v_0t)\frac{\partial}{\partial r}[\psi(r)J], \\
&-\frac{\partial A_-}{\partial z} + \frac{\partial A_-}{c\partial t} + \frac{i}{2k}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(rA_-)}{\partial r}\right) \\
&\quad = i\alpha\delta(r-r_0)A_+,
\end{aligned} \qquad (2)$$

where $\delta(r)$ is the Dirac delta function. The amplitude $J = (1/\pi)\int_0^{2\pi}\exp(-i\theta)d\theta_0$ of high-frequency current arising due to microbunching can be found from the electron motion equations

$$\begin{aligned}
&\left(\frac{\partial}{\partial z} + \frac{1}{v_0}\frac{\partial}{\partial t}\right)^2\theta = \frac{e}{mc^2\gamma_0^3\beta_0^3}\mathrm{Re}\left(\frac{i}{r}\frac{\partial(rA_+)}{\partial r}e^{i\theta}\right), \theta|_{Z=0} = \theta_0 + \xi\cos\theta_0, \\
&\theta_0 \in [0, 2\pi), \qquad \xi \ll 1, \qquad \left(\frac{\partial}{\partial z} + \frac{1}{v_0}\frac{\partial}{\partial t}\right)\theta\Big|_{Z=0} = k(\beta_0^{-1} - 1).
\end{aligned} \qquad (3)$$

In Eqs. (2) and (3), $\theta = \bar{\omega}(t - z/c)$ is the phase of electrons relative to the partial wave A_+, $\alpha = \bar{h}r_1/4$ is the coupling parameter, r_0 is the normalized mean waveguide radius, I_0 is the electron current, $\gamma_0 = (1-\beta_0^2)^{-1/2}$ is the relativistic mass factor, and $S_b = \int_0^{r_0} r\psi(r)dr$ is the effective beam cross section. The functions $\psi(r)$ and $f(z - v_0t)$ define the unperturbed radial and longitudinal bunch profiles, respectively.

In the absence of the electron beam ($I_0 = 0$), presenting the solution of Eq. (2) as $A_\pm \propto J_1(g_\pm r)\exp i(\Omega t - \Gamma z)$, we obtain the dispersion equation:

$$g_+g_- = 4\alpha^2k^2\frac{J_1(g_-r_0)J_1(g_+r_0)}{J_0(g_+r_0)J_0(g_-r_0)}, \qquad (4)$$

where $g_\pm = \sqrt{2k(\Omega/c \mp \Gamma)}$ are the transverse wave numbers. In Fig. 1(b), the dispersion curves of normal waves given by Eq. (4) are plotted for the following parameters of the SWS: a mean radius of 3.75 mm, a corrugation period of 0.825 mm, and a corrugation depth of 0.36 mm. The dispersion curve lying below the light lines $\Omega = c\Gamma$ and $\Omega = -c\Gamma$ (dashed lines) corresponds to the slow surface wave. In fact, it represents the modified TM_{01} mode of a regular waveguide. Other dispersion curves correspond to fast volume modes and their space harmonics.

Based on Eqs. (2) and (3), we simulated the excitation of the surface wave by a hollow cylindrical electron bunch with an electron energy of 300 keV, a total current of 2 kA, a bunch duration of 500 ps, a mean injection radius of 3.3 mm, and a width of 0.2 mm. For the given electron energy, the radiation frequency at the resonance point B [see Fig. 1(b)] is 0.14 THz and corresponds to the oversize factor of $D/\lambda \approx 3.5$. It should be noted that at point B the electron bunch excites the backward surface wave with the group velocity directed opposite to the electron motion. As a result, most of the radiation is emitted in the $-z$ direction

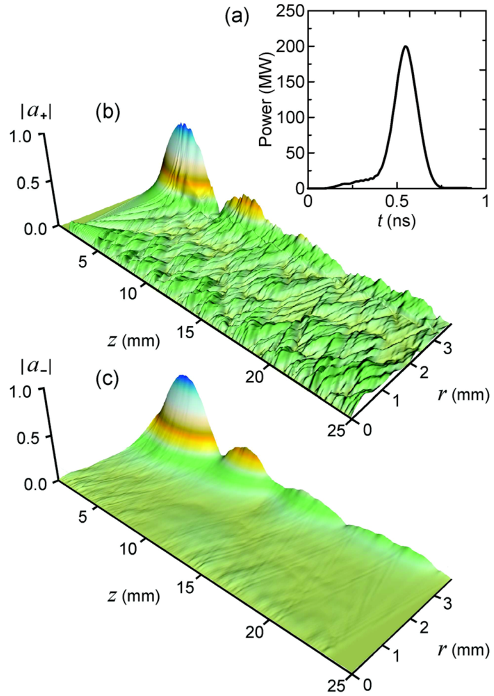

FIG. 2. The SR pulse temporal profile (a) and the instant spatial structures of the partial waves $A_{\pm}(r, z)$ which correspond to the formation of a surface wave (b),(c).

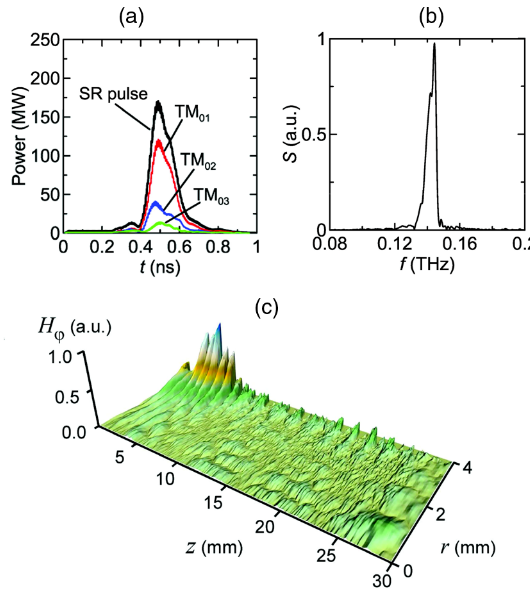

FIG. 3. The results of 3D direct PIC simulations of the subterahertz Cerenkov SR with parameters close to the experimental values: (a) SR pulse and its expansion over waveguide modes, (b) radiation spectrum, and (c) spatial distribution of the H_φ component of the radiated field inside the interaction space at the time 0.4 ns.

and has the form of a short SR pulse with a peak power of ~200 MW and a pulse duration of ~200 ps [Fig. 2(a)]. The SR pulse formation is illustrated by Figs. 2(b) and 2(c), where the instant spatial structures of the partial waves are presented. One can see that, due to the formation of the evanescent surface wave, the amplitudes of both of the partial waves A_+ and A_- exponentially decay with distance from the corrugation located at $\rho = \rho_0$.

For a more detailed analysis of Cherenkov SR, direct 3D particle-in-cell (PIC) simulations were carried out using CST STUDIO SUITE [19] at the parameters indicated above. Figures 3(a) and 3(b) demonstrate the emission of a 160 MW/200 ps SR pulse with a center frequency of 0.14 THz. The transverse structure of the radiation field corresponds to an axially symmetric surface wave [Fig. 3(c)], which can be represented as a combination of several in-phased TM_{0n} modes of a regular waveguide [Fig. 3(a)]. Thus, for a rather high oversize factor $D/\lambda \approx 3.5$, PIC simulations confirm the validity of the theoretical model given by Eqs. (2) and (3), where only the excitation of axially symmetric modes is taken into account. At larger values of the oversize factor and the same injection current density, the peak power of SR pulses increases. At the same time, the excitation of nonsymmetric rotating modes takes place.

Based on a theoretical analysis, experiments on the observation of the subterahertz SR pulse generation were performed. The principal scheme of the experimental setup is shown in Fig. 4. A high-current RADAN-303 [20] equipped with an energy compression unit was used as the source of electrons. Bunches were formed in a magnetically insulated coaxial diode which utilized a cold explosive emission cathode. A typical accelerating voltage pulse with a duration of 1 ns and an amplitude of −350 kV is presented in Fig. 5(a). A voltage prepulse that initiates the explosive emission provided the low-inertial operation of a sharp-edged graphite cathode [21]. As a result, the beam current reaches ~2.2 kA with a rise time of ~300 ps [curve (1) in Fig. 5(b)]. The electron current 1.8 kA at the SWS input [see the beam reprint in Fig. 5(c)] was slightly lower [curve (2) in Fig. 5(b)] due to some losses in the coaxial microwave reflector installed at the cathode edge of the SWS. This reflector with a beam tunnel width of 0.3 mm collimated the beam by cutting off the electrons having high transverse velocities. For the beam transportation through the reflector tunnel, precise tuning of the magnetic field (adjustments in the H-field force line profile) was used. This was achieved by varying the ratio of acting magnetic fields in the accelerating gap and inside the SWS

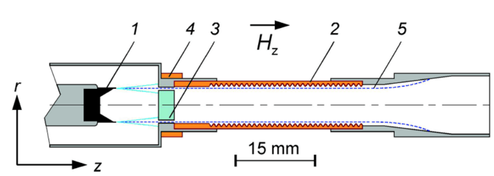

FIG. 4. Principal scheme of the experimental setup for subterahertz SR pulse generation. 1, graphite cathode; 2, SWS; 3, reflector; 4, copper ring; and 5, electron trajectories.

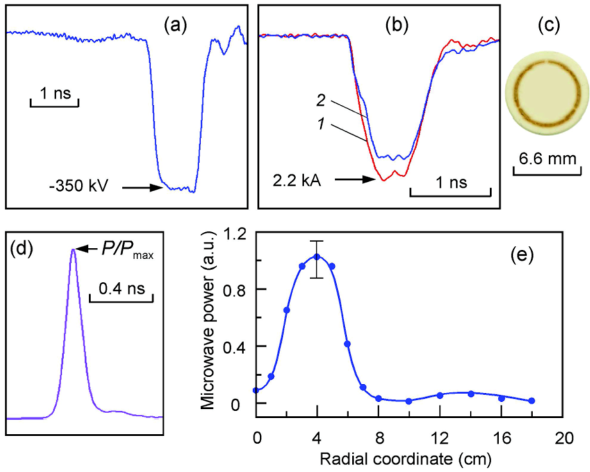

FIG. 5. The results of experiments: (a) waveforms of the accelerating voltage pulse; (b) beam current pulses before [curve (1)] and after the collimation [curve (2)]; (c) beam current reprint at the SWS input; (d) envelope of the subterahertz SR pulse recorded by the detector; (e) directional pattern of the radiation at a distance of 0.9 m from the output horn.

by an adjustment of the beam injection time relative to the magnetic field pulse. In fact, we use the difference between characteristic times of pulsed magnetic field diffusion through a thin steel wall of the accelerating area and through the massive SWS made of copper.

A typical oscilloscope trace (detector signal) 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. 5(d). Frequency measurements using a set of cutoff waveguide filters show that the pulse spectrum has a central frequency in the interval 0.13–0.15 THz. The directional pattern of radiation [Fig. 5(e)] measured at a distance of 0.9 m from the output horn with an aperture diameter of 30 mm corresponds to the preferential excitation of the TM_{01} mode, which is in good agreement with the simulations [Fig. 3(a)].

The peak power of generated SR pulses was estimated by integrating the detector signal over the directional pattern. Taking into account the reduction of detector signals with an increasing frequency of measured radiation (in the studied subterahertz band, it is at least 3 times less than in the Ka band [4]), we obtained the lower estimation of the peak power of superradiant pulses of 50–70 MW. Good pulse-to-pulse reproducibility (not worse than 15%) of the SR peak power value was also confirmed in measurements by the response of the laser pulse gauge IMO-2.

An additional confirmation of the high level of radiated power was obtained in experiments where, after the focusing of the radiation in a gradually convergent receiving horn with a minimum radius of 3.5λ, the appearance of ozone was detected. In the absence of visible light, it may be interpreted as the initial stage of an incomplete air breakdown. It should be noted that the development of the air breakdown for a pulse duration of 150 ps with a rise time as short as 100 ps even in the case of multielectron initiation requires an electric field at least of 180–200 kV/cm (see Refs. [4,21]). Simple calculations show that, in the case of the TM_{01} wave excitation, to achieve such intensities of the radial component of the electric field, the radiated power should exceed 70 MW.

Thus, in this Letter, we generalized the quasioptical model [14] to describe peculiarities of the Cherenkov superradiance of an electron bunch in oversized cylindrical periodically corrugated waveguides. Based on the theoretical consideration, experiments were performed where 0.14 THz SR pulses with a duration of 150 ps and an extremely high for the subterahertz band peak power of 50–70 MW were generated. The further increase in the peak power of SR pulses can be achieved by increasing the oversize factor and, correspondingly, the total current of the electron bunch. In this case, for stabilization of the azimuthal structure of the radiation field, it is promising to use the SWS in the form of cylindrical waveguides with two-dimensional corrugation [22].

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