

## Grating transition radiation: A source of quasimonochromatic radiation

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(Received 16 April 1999)

We have observed transition radiation at optical wavelengths, emitted by 3–13-MeV electrons interacting with a diffraction grating. Near the direction of specular reflection we observed broadband radiation with the same properties as optical transition radiation from a flat surface. In addition, at large angles with respect to this direction and for low angles of incidence of the electrons on the grating surface, we observed the emission of quasimonochromatic radiation. This *grating transition radiation* may offer an alternative method for production of quasimonochromatic radiation in the far-infrared to mm wavelength range.

[S1063-651X(99)13211-2]

PACS number(s): 41.60.-m, 42.25.Fx, 42.79.Dj

In recent years, promising results have been achieved in obtaining strong radiation sources in the far-infrared to mm range using transition radiation and the Smith-Purcell effect [1–3]. Transition radiation occurs when charged particles cross the interface between two media of different dielectric properties [4]. Figure 1(a) shows schematically optical transition radiation (OTR) produced by relativistic electrons hitting a flat surface. The maximum of the OTR intensity scales [5] with  $\gamma^2$  while the opening angle diminishes as  $1/\gamma$  ( $\gamma$  being the Lorentz factor). For relativistic electrons, transition radiation is a rather strong radiation source. However, it is emitted as a broadband continuum. At relativistic energies ( $\gamma \geq 30$ ) stacks of foils have successfully been used to obtain quasimonochromatic radiation in the x-ray domain [6]. At low electron energies the use of multilayer structures may be envisaged [7,8]. At optical wavelengths, however, the attenuation of the radiation inside the radiator becomes a severe limiting factor and transparent structures are needed such as, e.g., SiO<sub>2</sub> aerogels [9].

An alternative technique is based on the Smith-Purcell effect [10], shown schematically in Fig. 1(b). In this case the radiation emitted by an electron passing close and parallel to a diffraction grating has a wavelength  $\lambda$  dependent on the angle of observation  $\eta$ ,

$$-n \frac{\lambda}{D} = \beta^{-1} - \sin \eta, \quad (1)$$

where  $D$  is the grating period,  $\beta = v/c$  the reduced electron velocity, and  $n$  the order of diffraction. Smith-Purcell radiation is a rather intense source in the far-infrared to millimeter range, and is quasimonochromatic if observed in small solid

angles. The intensity decreases exponentially with increasing distance of the electron trajectory from the grating surface, the characteristic interaction range being of the order of  $\beta\gamma\lambda/4\pi$  [11,12]. Therefore, Smith-Purcell radiation is not very efficient for electron beams of diameter larger than  $\gamma\lambda$ , in contrast to transition radiation where all electrons interact with the radiator. In both cases, coherence effects can further increase the intensity [1–3].

In an attempt to overcome the limitations inherent to

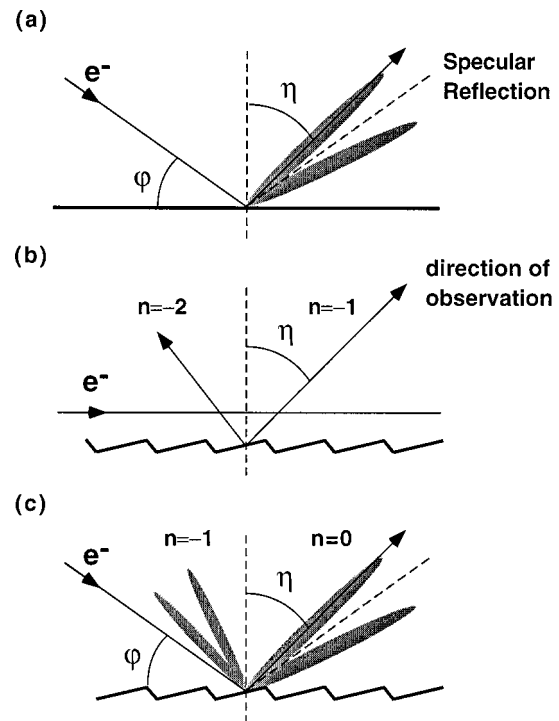


FIG. 1. Radiation of a fixed wavelength  $\lambda$  generated by relativistic electrons. (a) Transition radiation. (b) Smith-Purcell effect. (c) Grating transition radiation.

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Smith-Purcell radiation (i.e., the limited interaction range) and to transition radiation from flat surfaces (i.e., the broad spectral distribution), we investigated transition radiation from a diffraction grating as shown schematically in Fig. 1(c). As in the case of other radiative processes involving periodic media [5,6], waves of a given frequency  $\omega$  with wave vectors  $\kappa$  obeying  $\omega = \kappa \cdot \mathbf{v}$  are diffracted by the grating surface. Those diffracted waves, which are propagative, constitute the grating transition radiation. For a certain wavelength  $\lambda$ , we expect successive orders of diffraction  $n, n+1$  being emitted at angles  $\eta_n$  and  $\eta_{n+1}$  satisfying

$$\sin \eta_{n+1} - \sin \eta_n = \frac{\lambda}{D}. \quad (2)$$

The angular distribution of this grating transition radiation (GTR) then consists of several OTR-like lobes spaced according to Eq. (2) and modified by the diffraction coefficients characteristic for the grating profile. Conversely, GTR emitted at a certain angle  $\eta$  will not be monochromatic. When the zero order of diffraction is propagative, it is emitted at all wavelengths in an angular range of the order of  $1/\gamma$  around specular reflection, as OTR from a flat surface. From the calculations of Smith-Purcell radiation [11,12], and in analogy to optics [13], we know that the diffraction coefficients are strongly modified at certain angles of observation for which another order of diffraction becomes propagative (the so-called Wood-Rayleigh anomalies). For example, we expect a reduction in GTR intensity observed in first order of diffraction  $n = -1$  when the zero order is propagative. From Eq. (2) we obtain that this is the case for angles  $\eta_{-1} < \eta_c$  with  $\sin \eta_c = 1 - \lambda/D$ .

The experiments have been carried out in the optical range 400–700 nm. Several optical gratings were mounted on a rotating frame and the radiation was detected at a fixed angle of observation  $\theta$  with respect to the electron beam in a so-called constant deviation mounting. In this geometry we have

$$\eta = \frac{\pi}{2} - \theta + \varphi. \quad (3)$$

Figure 2 schematically shows the experimental setup. The gratings could be rotated around an axis perpendicular to the incidence plane, simultaneously changing the incidence angle  $\varphi$  and the observation angle  $\eta$ . The radiation was observed in the incidence plane (angle  $\zeta = 0$  in Fig. 2) and also out of plane ( $\zeta = 3.8^\circ$ ) at two fixed angles  $\theta = 90^\circ$  and  $\theta = 120^\circ$ . We used a linear polarizer and a set of interference filters between 400 and 700 nm, with equal bandwidths  $\Delta\lambda = 10$  nm. The radiation was detected using a Peltier-cooled intensified CCD camera. The full aperture of the optical system was 23 mrad. All data were corrected for the transmission of the quartz window of the vacuum chamber, the transmission of the optical filters, and the objective, as well as for the spectral response of the CCD. The data are displayed as intensities, i.e., energy radiated per frequency interval  $\Delta\omega$ .

We used two lamellar gratings with a symmetrical rectangular profile of either 1800 or 2000 l/mm, and two blazed gratings with 2000 l/mm and blaze angles of  $7.3^\circ$  or  $12.4^\circ$ , respectively. The gratings were ruled in a 100- $\mu\text{m}$  SiC layer

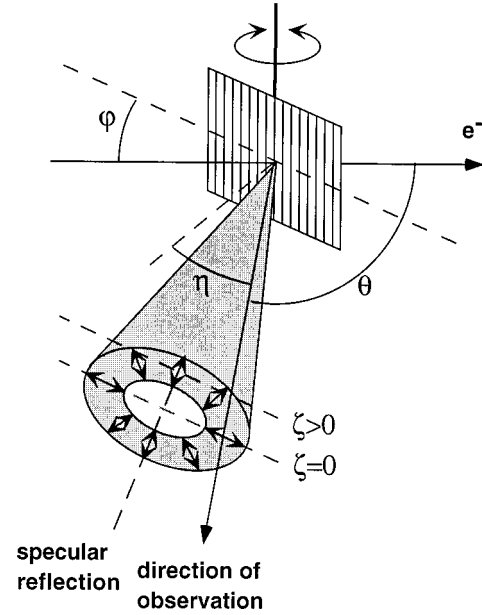


FIG. 2. Experimental setup. The radiation cone indicates the  $n = 0$  distribution and corresponding polarization.

deposited on a  $50 \times 50 \times 10\text{-mm}^3$  graphite block and aluminized on the surface to ensure a high reflectivity. The  $50 \times 50\text{-mm}^2$  surfaces of the lamellar gratings were divided into two parts. Only one half was etched, leaving the second half as a flat surface for conventional OTR measurements. Figure 3 shows the intensity observed at  $\theta = 120^\circ$  as a function of the incidence angle  $\varphi$  using the 2000-l/mm-blazed grating with a blazing angle of  $12.4^\circ$ . The zero order of diffraction was observed as broadband radiation close to specular reflection with only minor differences in the intensities for the different wavelengths, as for OTR.

The GTR measurements in first diffraction order  $n = -1$  at  $\lambda = 400$  nm [cf. Fig. 3(a)] illustrate the important reduction in intensity at angles  $\varphi < \varphi_c$  corresponding to the Wood-Rayleigh anomaly. The narrow line at angles  $\varphi \geq \varphi_c$  stands out against the lobes. The intensity cutoff is not sharp due to the 10-nm bandwidth of the interference filters and the acceptance angle of the camera. At increasing wavelengths only narrow lines at decreasing angles  $\varphi$  were detected because of the even more drastic reduction in the lobes at angles  $\varphi < \varphi_c$  [cf. Fig. 3(b)]. Note that these quasimonochromatic GTR lines are of larger intensity than the OTR-like radiation near specular reflection.

The experiments were repeated at different electron energies in the range 3–13 MeV. Figure 4 shows the energy scaling of the peak intensities observed for  $\lambda = 550$  nm. The  $n = 0$  intensity shows the same  $\gamma^2$  dependence as OTR from a flat surface. The intensity of the  $n = -1$  peaks near the “cutoff” angles  $\varphi_c$  did not increase with increasing energy, but remained almost constant. This is due to the fact that for  $\lambda \approx D$  the cutoff angles  $\eta_c$  (viz.  $\varphi_c$ ) are located at rather large distances from the minima of the GTR distribution compared to the characteristic angle  $1/\gamma$ , and the corresponding  $n = 0$  OTR-like distribution does not increase very much with increasing electron energy.

At 7.5 MeV we measured the polarization of GTR using a

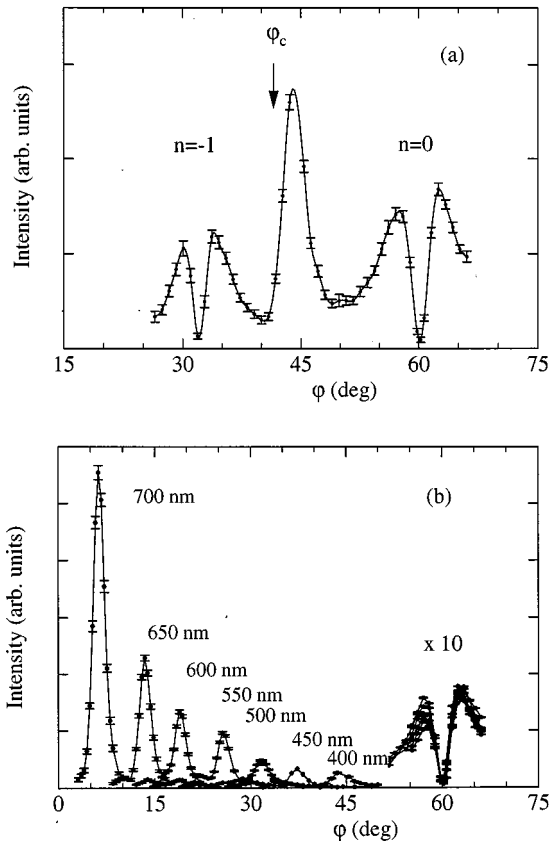


FIG. 3. Intensity observed at a fixed angle  $\theta=120^\circ$  (i.e.,  $\eta = \varphi - 30^\circ$ ). The electron energy is 5 MeV and the grating period 500 nm. (a)  $\lambda=400$  nm. (b) Measurements with filters of different wavelengths superimposed. The lines are guides to the eye. The zero-order contributions in (b) have been increased by a factor of 10.

linear polarizer in front of the CCD. The results obtained with the 1800-l/mm grating are summarized in Fig. 5. Most of the measurements were carried out in the incidence plane, perpendicular to the grating surface (i.e.,  $\zeta=0^\circ$  in Fig. 2).

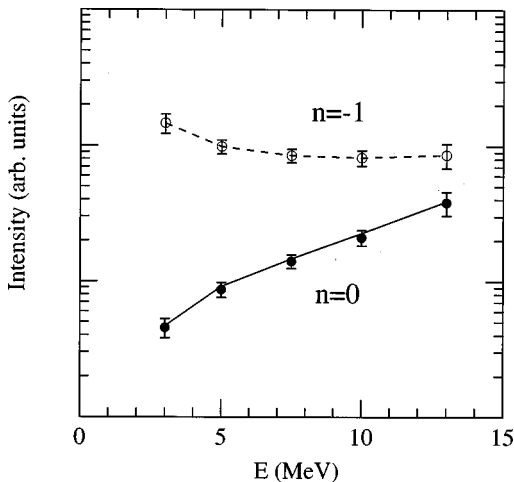


FIG. 4. Energy dependence of the intensity maxima observed at  $\theta=90^\circ$  and  $\lambda=550$  nm. Solid circles: GTR,  $n=0$ , intensity maxima near specular reflection; solid line: OTR; open circles: GTR,  $n=-1$ , peak maxima near cutoff angles  $\varphi_c$ ; dashed line: guide to the eye.

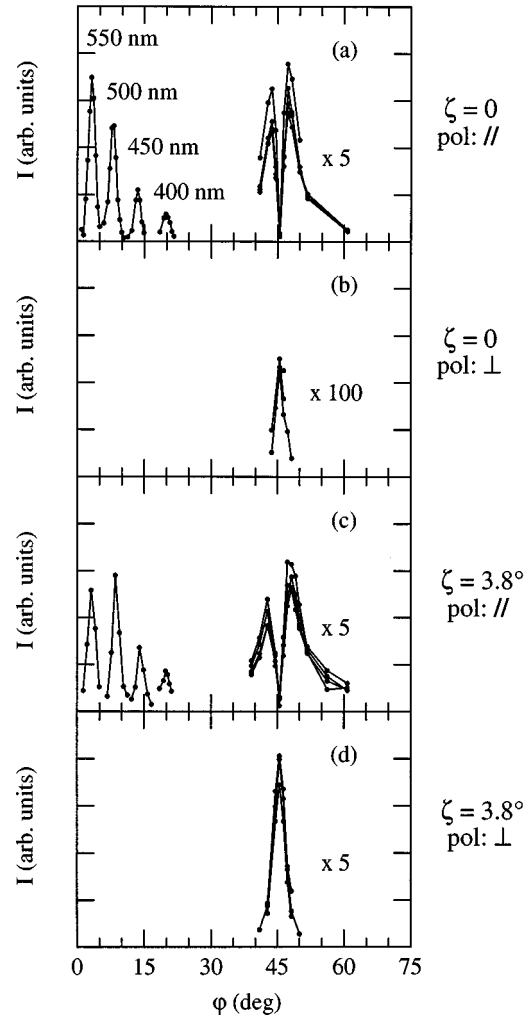


FIG. 5. GTR intensity  $I$ , observed at  $\theta=90^\circ$  using a linear polarizer and interference filters. (a) and (b) in plane ( $\zeta=0$ ); (c) and (d) out of plane ( $\zeta=3.8^\circ$ ). The direction of linear polarization is defined with respect to the incidence plane (cf. Fig. 2). The lines are guides to the eyes. The zero-order contributions have been increased by arbitrary factors for the sake of better visibility.

Figures 5(a) and 5(c) show both the  $n=0$  and  $n=-1$  GTR intensities, which were almost completely polarized in the observation plane, like the OTR observed from the flat surfaces. The residual perpendicular polarization can be attributed to the divergence of the electron beam and the acceptance angle of the optical system. The same polarization would also have been expected for pure Smith-Purcell radiation.

After tilting the optical bench to an angle of  $\zeta=3.8^\circ$  ( $\approx 1/\gamma$  at 7.5 MeV) above the incidence plane, there was no essential change in the parallel components. For the perpendicular components the situation was different. For  $n=0$  a strong peak appeared at the position of the minimum in the parallel component, analogous to OTR [cf. Fig. 5(d)]. For  $n=-1$  the position of this peak is located at angles  $\varphi$  well below the cutoff angle  $\varphi_c$  and the intensity of the perpendicular component was below our detection limit.

In conclusion, grating transition radiation produced by electrons hitting an optical grating has been observed. GTR in a zero order of diffraction was observed near specular

reflection, similar to conventional transition radiation from a flat surface. The  $n = -1$  contributions were observed far from the direction of specular reflection according to Eq. (2). We observed a considerable intensity of the  $n = -1$  contributions when the corresponding zero-order radiation was evanescent. At 5-MeV electron energy and long wavelengths, these quasimonochromatic lines were of higher in-

tensity than OTR from a flat surface. Extrapolating these results to the far infrared and millimeter wavelengths indicates that GTR produced by low energy ( $<10$  MeV) electrons may be an interesting quasimonochromatic radiation source in this spectral range.

The authors would like to thank the staff of the Gent linear accelerator for their technical support and assistance.

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