Exotic radiation from a photonic crystal excited by an ultrarelativistic electron beam

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We report the observation of an exotic radiation (unconventional Smith-Purcell radiation) from a one-dimensional photonic crystal. The physical origin of the exotic radiation is direct excitation of the photonic bands by an ultrarelativistic electron beam. The spectrum of the exotic radiation follows photonic bands of a certain parity, in striking contrast to the conventional Smith-Purcell radiation, which shows solely a linear dispersion. Key ingredients for the observation are the facts that the electron beam is in an ultrarelativistic region and that the photonic crystal is finite. The origin of the radiation was identified by comparison of experimental and theoretical results.

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Radiations from moving charged particles have attracted much interest in various research fields of physics and materials science. The radiations, which include Synchrotron radiation, Cherenkov radiation, transition radiation, and so on, can serve for a coherent source of radiation, beam diagnostic, particle detection, and a probe of a specimen [1]. Among them, Smith-Purcell radiation (SPR) [2] is a promising candidate to make a compact free-electron laser of arbitrary frequency. In SPR, coherent radiation is emitted from an electron beam scanning just above a diffraction grating. There, the most important thing is that the output frequency is widely tunable by changing the period of the grating [3–13].

So far, SPR has been studied in diffraction grating. However, as shown recently, SPR also occurs in photonic crystals (PC) [14–18], i.e., multidimensional periodic dielectric structures. When we consider a PC as a converter from an electron beam to propagating radiation, various features inherent in the PC will arise by exciting highly confined radiation modes, or in other words, photonic band (PB) modes of PC. Direct excitation of PB modes may result in exotic radiation, which has never been observed in diffraction gratings. One example of such exotic radiation caused by an electron beam interacting with a PC was theoretically predicted by Luo *et al.* [19]. There, the Cherenkov effects reveal a strange directivity depending on the frequency of observed radiation. It should be stressed that PB modes can be controlled by changing various parameters of the PC. Since the radiation is strongly modulated by PB modes, it can be used to probe them.

In this study, we report the experimental observation of exotic radiation from a PC induced by an electron beam in a standard arrangement of SPR. The exotic radiation, which hereafter is called unconventional SPR, is completely different from conventional SPR. Conventionally, SPR shows linear dispersion in frequency-momentum space and has narrow-band characteristics on the dispersion lines. On the other hand, the unconventional SPR shows the dispersion curves of PB modes with a certain parity and has broadband characteristics on the curves. Since the PB structure extends throughout entire frequency-momentum space, a variety of PB modes can be utilized. To observe unconventional SPR, key ingredients are ultrarelativistic velocity of the electron beam, the broken translational invariance of a finite-sized PC and, and the formation of PBs. The radiation is identified by using carefully prepared samples and by excellent agreement of the radiation spectrum with a refined theory of SPR that takes into account the finiteness of the sample. The unconventional SPR is versatile in physics and applications. It can be a probe of PC or a radiation source of broadband. However, of primary importance is that the unconventional SPR is a new regime of the SPR, which cannot be understood within the conventional theory of SPR and is highlighted by using PC.

Let us recapitulate conventional SPR mechanism briefly. We used the coordinate system shown in Fig. 1. Light of frequency ω emitted by an electron traveling with velocity v along the x axis has a wave vector $(k_x, \pm\Gamma, k_z)$, with the x

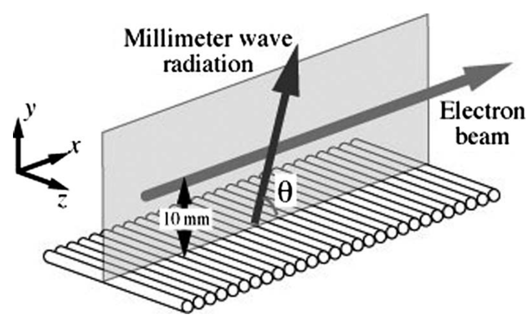

FIG. 1. Experimental geometry. The electron beam is in the x direction 10 mm above the photonic crystal. Cylinders for which data are given in Table I are arrayed with axes in the z direction. The intensity of millimeter-wave radiation is measured as a function of (θ, ω) at the far-field observation point in the xy plane.

TABLE I. Characteristics of PC samples.

Sample	Substance of PC	Dielectric constant of cylinders	Number of cylinders	Diameter of cylinders	Distance between cylinders	ϵ_{eff}	Slope of u_1
1	PTFE	2.05	14	3.1 mm	6.2 mm	1.14	$0.92c$
2	PTFE	2.05	28	3.1 mm	3.1 mm	1.35	$0.78c$
3	Fused quartz	4.41	28	3.0 mm	3.0 mm	1.79	$0.59c$
4	Aluminum		28	3.0 mm	3.0 mm		

component given by $k_x=\omega/v$ and the z component k_z being arbitrary. By energy conservation, $\Gamma=\sqrt{(\frac{\omega}{c})^2-k_x^2-k_z^2}$. Since $v<c$, Γ is pure imaginary, meaning that the emitted light is evanescent and decays with constant $|\Gamma|$ with distance from the trajectory. In other words, the line $\omega=vk_x$, called the v line, lies outside the light line $\omega=ck_x$. When we observe far-field SPR within the xy plane, k_z can be set to zero. A one-dimensional PC having a periodicity d in the x direction then produces SPR by giving a Umklapp shift [20] of the integer multiple of $\frac{2\pi}{d}$ to the x component of the wave vector of initial light. Using the same symbol k_x to represent the x component of SPR, we may say that the initial light on the v line is Umklapp shifted to the new v lines of dispersion $\omega=v(k_x+n\frac{2\pi}{d})$, n being an arbitrary integer. We shall call these lines v_n lines. The light on the v_n line thus has the y component of the wave vector given by $\Gamma_n=\sqrt{(\frac{\omega}{c})^2-(\frac{\omega}{v}-n\frac{2\pi}{d})^2}$. It reaches a far-field observation point as an SPR signal when this Γ_n is real, i.e., when the frequency ω of the radiation on the v_n line is inside the light cone. This can always happen for a v_n line with positive n. In the PCs shown in Fig. 1, PB modes have their band structure in (k_x,ω) space. When the v_n line crosses a PB dispersion curve, corresponding peaks appear in the SPR spectrum. This is conventional SPR involving a PC [14,15,18].

The experimental setup is depicted in Fig. 1. A short-bunched electron beam of 150 MeV from a linear accelerator at the Laboratory of Nuclear Science (LNS), Tohoku University traveled in the x direction above a PC. The macro and micro pulse widths were 2 μs and 0.67 ps, respectively. The average beam current was 1.4 μA. The cross section of the beam was about 10×12 mm^2. The distance between the trajectory and PC surface was kept constant at 10 mm throughout the experiments. The velocity of the electrons was $v=0.999\,99c$. With this ultrarelativistic v, the decay constant $|\Gamma|$ is very small, being ω/c times 4.47×10^{-3}. The millimeter wave from the PCs was collected by mirrors and detected by a helium-cooled Si bolometer. The spectrum of the emitted light was analyzed by a Martin-Puplett-type Fourier-transformation spectrometer. The resolution of the spectrometer was 3.75 GHz. Stray light from the vacuum chamber containing the sample was blocked and the Si bolometer was electrically shielded. The ratio between signal and noise in this study was better than that in Ref. [18].

We used four samples, which are monolayers of arrayed 14 or 28 cylinders of polytetrafluoroethylene (PTFE), fused quartz or aluminum (see Table I). The samples were all PCs with diameter and periodicity in the millimeter range and having periodic in the x direction with z-directed cylinder axes. Samples 1, 2, and 3 were dielectric cylinders, whose effective dielectric constants ϵ_{eff} [21] of the monolayer became larger in this order. Sample 4 was a monolayer of metallic cylinders, a PC of perfect conductors in the millimeter wave region.

The radiation signals were collected by sweeping (θ,ω) in the xy plane of Fig. 1. By varying θ in the angle range $60°<\theta<110°$ and using the relation $k_x=(\omega/c)\cos\theta$, we obtained a radiation intensity map in the (k_x,ω) space. Figure 2 shows the radiation intensity maps for (a) sample 2 and (b) sample 3. Because $v\simeq c$, the v line overlaps with the light line. Conventional SPR signals, which show a nonmonotonic intensity change by the PB effect, can be clearly seen along the lines v_1 and v_2 [18]. A series of strong signal lines can also clearly be seen in Fig. 2 off v_n lines, referred to as unconventional SPR. The signals show up along the straight, with slopes definitely smaller than that of the light line. These lines are marked as u_n in both (a) and (b). The slope of u_1 in sample 3 is clearly smaller than that in sample 2. In sample 1, for which data are not given here, line u_1 further approaches v_1 line. Thus, the larger the effective dielectric constant of the monolayer is, the smaller their slopes become. The evaluated values of the slopes are shown in Table I. Unconventional SPR was not observed in sample 4 of metal cylinders (data not shown).

Taking into account the general tendency between effective dielectric constant and PB frequencies, it is reasonable to assume that unconventional SPR accompanies the excitation of those PBs that are quasiguided modes with a quantized wave vector component in the thickness direction (y direction in our case) [22]. The conventional theory of SPR, however, predicts only signals on the v_n lines because periodicity is assumed to be infinite. In reality, the v_n lines should have a certain width in the (k_x,ω) space, because wave number k_x is defined only approximately and has a blurring of order π/L_x, being L_x the PC length. As is obvious in Fig. 2, however, the blurring is too small to explain the signals off the v_n lines. Therefore, a naive evaluation of the finite-size effect within the conventional theory fails to reproduce the experimental features. To explain the signals off the v_n lines, therefore, we need to incorporate explicitly the finiteness of the PC length. In order to justify the assumption, we performed improved theoretical calculations in which finite effects of the sample were taken into account [23,24], in contrast to conventional SPR theory, and compared with the observation.

The results obtained by the improved theory are shown in Fig. 3. Figures 3 show superposed intensity maps of the radiation spectra and PB diagrams of the quasiguided modes

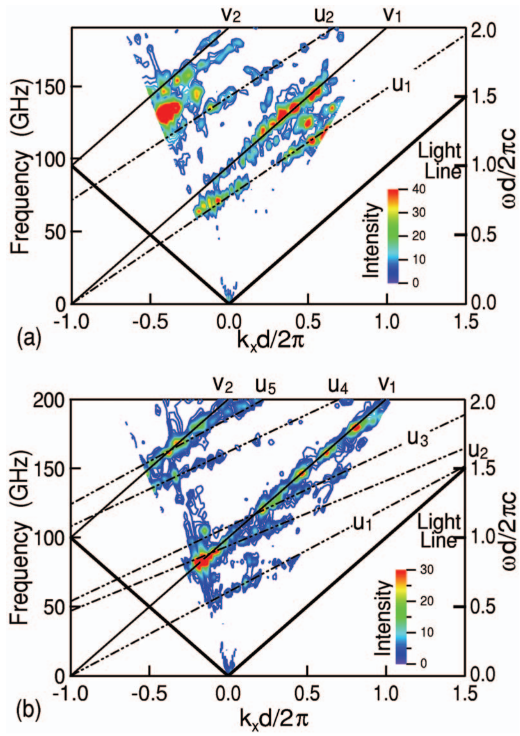

FIG. 2. (Color) Intensity maps of radiation observed in the *xy* plane for sample 2 (a) and sample 3 (b). The ratio of signal to noise was 5%. Thick solid lines with slopes $\pm c$ are the light lines forming the boundary of the light cone. Two v_n lines, marked as v_1 and v_2, are drawn parallel to the light line. Dotted lines u_1-u_5 indicate the lines on which unconventional SPR appears.

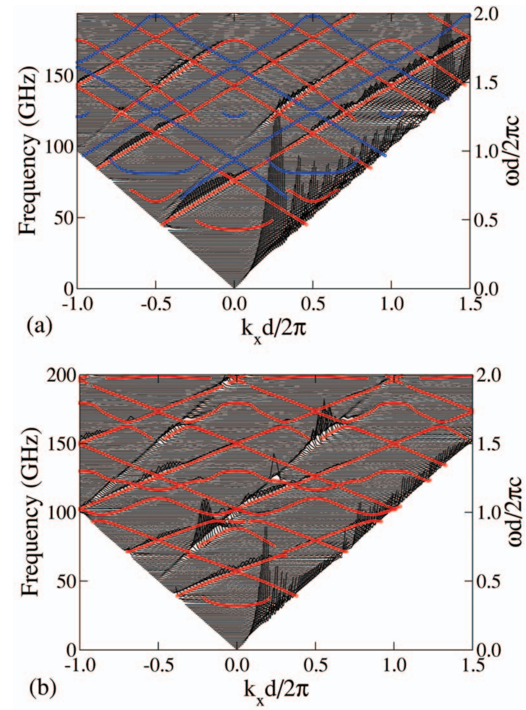

FIG. 3. (Color) Bird's eye views of calculated intensity maps of radiation observed in the *xy* plane for sample 2(a) and sample 3(b). The boundaries of the map are the light lines of slope $\pm c$. The quasiguided PBs of even (odd) parity with respect to the mirror plane $y=0$ are also shown by red (blue) lines in (a). In (b) only the even-parity modes are shown.

[25]. Figures 3(a) and 3(b) both have unambiguously unconventional signals u_1-u_5 that appear in Fig. 2. The slopes and intensity in Fig. 3 reproduced well the experimental results shown in Fig. 2. Strong signals having a Fabry-Perot oscillation are seen along the light line and correspond to light propagation in the x direction. They are strong because the v line is almost the same as the light line when $v \sim c$. Since angle θ is bounded as $\theta > 60°$, the signals in the forward direction $\theta = 0°$ are out of range in our experimental setup. The agreement between the theory and experiments is quite well, except the strong signal at $(k_x, \omega) = (-0.4 \times 2\pi/d, 130\ \text{GHz})$ in Fig. 2(a).

Besides, in Fig. 3, it is remarkable that the unconventional signals appear exactly along the dispersion curves of quasiguided PBs. Each of the quasiguided PBs has a definite parity with respect to the mirror plane $y=0$ of the monolayer and is shown by either red (even parity) or blue (odd parity) lines in Fig. 3. In Fig. 3(b), only the quasiguided PBs of even parity are shown. As is obvious in Fig. 3(a), only the even parity modes participate in unconventional SPR. This statement is indeed reconfirmed by Fig. 3(b) of sample 3, which has a PB structure much more complicated than that of sample 2.

In order to further understand unconventional SPR, it is crucial that only mirror-symmetric PB modes produce the signals. As mentioned before, in the ultrarelativistic region, the decay constant $|\Gamma|$ is very small. This implies that the evanescent light of the electron beam behaves as a plane-wave propagating in the x direction, with polarization in the y direction and, most importantly, with amplitude practically constant in the y direction. Thus, the experimental situation is essentially such that a y-polarized plane-wave light of k_x enters the finite-size PC from the edge. It is well known in light transmission that any PBs of frequency ω can be excited regardless of the coincidence of their wave vectors with k_x. This is because k_x is no longer conserved owing to the broken translational invariance of the finite-size PC. Also, selective excitation of quasiguided PB modes occurs, depending on the matching of the symmetries between incident light and modes to be excited. In our case, the even-parity PB modes participate because the y-independent incident light is mirror symmetric with respect to the plane $y=0$.

Gathering up all discussion presented above, we conclude that the observed signals reported in this study originate from truly direct excitation of PB. If PB is absent, like as in diffraction grating or in the PC composed of perfect conductor cylinders, the unconventional SPR is also absent. This is the main reason why the unconventional SPR was not observed in sample 4. This process, the generation of propagating light from an electron beam, is clearly different from that in the conventional SPR. Though the unconventional SPR is similar to an ordinary (plane-wave) light diffraction by PC, it is remarkable that the unconventional SPR shows broadband characteristics, which enable us to probe the PB structures at a sweep of the electron beam. This provides a striking contrast to the plane-wave light diffraction, in which the relevant frequency is fixed. Moreover, the incident plane-wave does not yield the conventional signals along the v_n lines.

It should be noted that our PC samples have lattice constants of several millimeters, and thus resultant radiation is in the millimeter wave region. One of the key ingredients of unconventional SPR is the usage of dielectric substances instead of metallic ones. A metal in this region can be regarded as a perfect conductor, which does not support PBs. So far, several groups have reported millimeter-wave SPR from metallic diffraction gratings [5,6,9]. They were all conventional signals. However, if the gratings are downsized so that SPR of the visible or ultraviolet range is generated, we would observe unconventional SPR caused by excitation of the PBs of the surface plasmon.

In conclusion, exotic radiation (unconventional SPR) due to direct excitation of PBs was observed from finite-sized PCs. The evanescent light induced by an electron beam with ultrarelativistic velocity enters from the edge of the dielectric PC and is converted into propagating light. A selective mode excitation occurs depending on the matching of symmetries between incident evanescent light and PBs. The process by which the unconventional SPR is generated is different from that of conventional SPR. The spectrum of the unconventional SPR is widely tunable by changing various parameters of the PC. Accordingly, the unconventional SPR also opens up a possibility of probing the PB structures with high accuracy.

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