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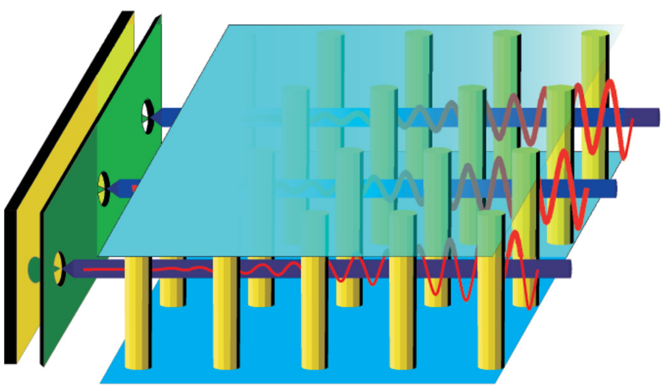

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Photonic Free-Electron Lasers

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(Invited Paper)

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Abstract: A photonic free-electron laser (pFEL) produces coherent Cerenkov radiation from a set of parallel electron beams streaming through a photonic crystal. The function of the crystal is to slow down the phase velocity of a copropagating electromagnetic wave, such that also mildly relativistic electrons (of about 10-keV energy) can emit coherent Cerenkov radiation. Starting from spontaneous emission, the feedback of the radiation on the electrons results in bunching of the electrons on the scale of the radiation wavelength, and consequently, coherent radiation can build up. The frequency of the coherent mode is set by the electron velocity and wave dispersion of the photonic crystal and can, *a priori*, be continuously varied by varying the electron energy. The scale invariance of Maxwell's equation allows operation from Gigahertz to Terahertz and possible infrared (IR) frequencies without the need to increase the electron beam energy. Therefore, the pFEL is a very attractive, compact, and coherent radiation source that has the potential to significantly enhance the power available in the THz domain.

Index Terms: Free-electron lasers, photonic crystal, slow light, light source, oscillator.

Photonic crystals are structures with a periodically varying dielectric constant that show a strong interaction with light having a wavelength comparable to this periodicity [1]. Such a crystal allows an unprecedented control of light propagation and emission [2]–[4]. A most intriguing capability of photonic crystals is to shape the local density of electromagnetic states (LDOS) inside the crystal, which, e.g., can be used to suppress or enhance spontaneous emission [3]–[5] or be used to study fundamental strong-coupling cavity quantum electrodynamics experiments [6].

Of particular interest is the emission of Cerenkov radiation by a charged particle moving through a photonic crystal [7]. For example, it was shown that, contrary to ordinary Cerenkov emission in bulk material, distinctive, particle velocity dependent, radiation patterns are generated without a velocity threshold, which can be used for, e.g., particle detection. On the other hand, electron energy loss spectroscopy enables measurement of the photonic band structure and LDOS [8], [9]. Here, a low-energy electron beam from a transmission electron microscope is sent at various positions through a photonic crystal, and electrons lose energy through coupling to the crystal eigenmodes, among others via Cerenkov radiation [9]. Recently, spontaneous Cerenkov radiation was observed from a nanostructured light well [10], where a low-energy electron beam (20–40 keV) was sent through a 700-nm-diameter hole in a 1-D photonic crystal consisting of a stack of 11 alternating metal and dielectric layers, each having a thickness of 200 nm. By changing the electron beam energy, the

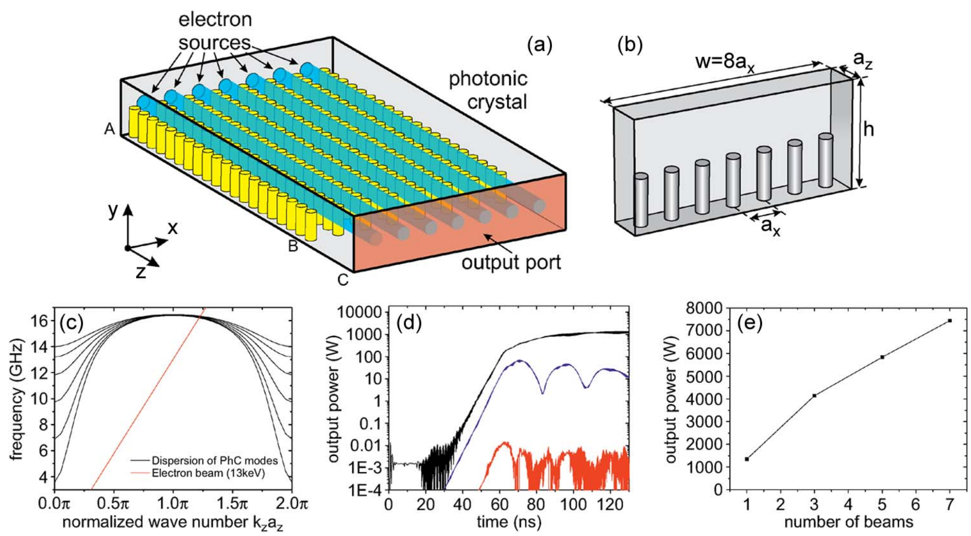

Fig. 1. (a) Schematic view of a pFEL oscillator. The photonic crystal consists of a 2-D array of round truncated posts in a rectangular waveguide. (b) Unit cell for the photonic crystal: $a_x = 4.2$ mm, $h = 8$ mm, and $a_z = 2.5$ mm. The height of the posts is 0.5 h, and the radius is 0.75 mm. (c) The band diagram calculated for the unit cell (b), showing only the lowest six modes. Also shown is the dispersion of a 13-keV electron beam. (d) Output power for the first three nonzero waveguide modes at the output port when the pFEL is pump with a single electron beam in the center. (e) Output power in the TE_{10} mode as a function of the number of electron beams. Current and voltage for each beam as in (d).

emission wavelength could be tuned from 750 to 840 nm. Due to the small current ($\leq$ 20 nA), only spontaneous radiation of about 0.2 nW was observed.

The concept of the photonic free-electron laser (pFEL) aims at the generation of coherent Cerenkov radiation from electrons streaming through straight and parallel vacuum channels in a photonic crystal [e.g., see Fig. 1(a)], which requires a sufficiently high total current and a sufficiently long crystal [10]. The pFEL allows scaling of the total current by providing many parallel electron beams without the need to increase the local current density in each individual beamlet. This not only controls the gain of the laser and allows scaling of the output power, but also, low-voltage ($\sim$10 kV), multibeam electron guns can be used that leads to compact devices, in contrast with other research [11]. Longitudinal coherence in each beamlet of a pFEL is established when the electron velocity approximately equals the phase velocity of a photonic crystal eigenmode, which possesses a longitudinal electric field component. This electric field component bunches the electrons on the scale of the radiation wavelength, thus providing longitudinal coherence in a way similar to the bunching in free-electron lasers [12], [13] and microwave tubes [13]. Transverse coherence is achieved by engineering the photonic crystal to provide coupling between neighboring channels, i.e., the electron beamlets communicate with each other through a common electromagnetic field. In this way, the bunching within the beamlets is phase locked, and despite the extended transverse interaction area, a coherent transverse field is developed, similar to the way supermodes are developed in coupled diode laser arrays [14].

Most pFEL devices use a photonic crystal similar to Fig. 1(a) with the unit cell shown in Fig. 1(b) [15]–[17]. The device of Fig. 1(a) allows multiple electron beams to propagate through the photonic crystal. The photonic crystal consists of a 2-D array of half-height cylindrical metal posts in a metallic rectangular waveguide. The half-height posts maximize the field strength of the resonant spatial harmonic at the position of the electron beam while, at the same time, maintaining a large tuning range [15] [see Fig. 1(c)]. A resonator is formed by a flat metallic mirror at location A and the partial reflecting mirror formed by the transition of the photonic crystal into an empty waveguide at location B. Alternatively, by tapering either the height of the posts or tapering the transverse distance between the posts in case of a single beam device, a low reflecting gain section can be realized [18]. Fig. 1(c) shows the band structure for the six lowest modes for the first Brillouin zone calculated from the unit cell using an eigenmode solver (CST Microwave Studio). Also shown in Fig. 1(c) is the dispersion of a 13-kV electron beam. At the intersection point, the electron velocity equals the wave phase velocity and this point defines the approximate operating frequency of the device ($\sim$16.3 GHz). Note that for these settings the interaction is at the first spatial harmonic of the Bloch eigenmodes and that the interaction is of a backward-wave type. Also, from the wave dispersion, it is expected that the laser frequency tunes up with increasing electron accelerating voltage.

A particle-in-cell (PIC) simulation code is generally used to numerically analyze the performance of pFELs [15], [18], [19]. For the example shown in Fig. 1, several electron beams are injected into the resonator by placing electron sources on the surface of mirror A [see Fig. 1(a)]. The radiation that is coupled out of the resonator propagates to the nonreflecting waveguide port at C [see Fig. 1(a)]. Here, the radiation is decomposed into eigenmodes of the port. As a preliminary result of the PIC simulations (CST Particle Studio), Fig. 1(d) shows the temporal evolution of the three lowest TE eigenmodes of the port when the pFEL is driven by a single 13-kV, 1-A (32 A/cm^2) electron beam in the center. Initially, the output power in each mode is weak and noisy, but then, exponential growth ($\sim$1.5 dB/ns) over several orders of magnitude sets in. The fundamental TE_{10} mode is clearly dominant and saturates at a level of about 1.4 kW, and the mode suppression is then at least 20 dB. The output frequency is 15.88 GHz with a full width half maximum (FWHM) of 50 MHz. When the number of electron beams is increased from 1 to 7 by turning on two adjacent beams until all available electron beam channels are occupied, we observe an almost linear increase in output power of the fundamental TE_{10} mode, as is shown in Fig. 1(e). The center frequency, FWHM width, and mode suppression remain unchanged when the total beam current is increased from 1 to 7 A [19]. This preliminary result illustrates the possibility to scale the power of a pFEL by adding more electron beams in parallel, while maintaining a single coherent output mode, even when the output waveguide is strongly overmoded. A similar, single electron beam version that can be used to generate frequencies around 1 THz was studied in [15], where an output power of 75 mW was predicted using an 11.6-kV, 4-mA (200 A/cm^2) electron beam. In order to be compatible with current state-of-the-art cathode technology, this device requires electron beam compression and a high magnetic field ($\sim$0.8 T) for electron beam guiding, while only 0.2 T was used in the above example. Using multiple beams should greatly diminish the required electron density in a single beamlet, thereby simplifying electron gun design and beam guiding.

The scale invariance of Maxwell's equations [1] allows a direct translation of these results to different spectral regions. From the scale invariance it follows that the eigenmodes of the photonic crystal, and in particular the phase velocity, remain the same when the crystal is scaled down by a factor while the frequency of the mode is simultaneously increased by the same factor. Hence, the same electron beam energy is required to be resonant with the respective crystal eigenmodes, e.g., the 13-kV electron beam in the above example would produce 1.6 THz of radiation when the photonic crystal is reduced in size by a factor 100. Indeed, single beam pFEL [15], [18] and multiple beam pFEL [16] have been considered as sources for Terahertz radiation. For example, a single electron beam (10 kV, 5 mA, and 20 μm radius) was used in a design of a backward-wave amplifier to produce a calculated gain of 12 dB at 1 THz with a 100-μW input signal [18]. A multiple beam design is presented in [16]. This paper discusses the various subcomponents, e.g., electron gun, slow-wave structure (photonic crystal), output coupler, in more detail. Simulations predict an output power of 4–6 mW over a 100 GHz bandwidth from 600 to 700 GHz using a beam voltage of 3 to 6 kV and a total beam current of 45 mA. The electron gun produces a sheet electron beam and beam scrapers are used to create a total of 4 beamlets that propagate through the slow-wave structure. The device requires a guiding magnetic field of 1.1 T. Furthermore, scaling into the infrared has essentially been successful as was demonstrated in [10], although the output remained intrinsically below threshold, and only weak and incoherent radiation was observed. This is contrary to undulator based free-electron lasers where scaling by two orders of magnitude or more by changing the period of the undulator is not feasible, and operating it at increasingly higher frequencies requires higher electron beam energies [12], [20].

Here, we have considered Cerenkov radiation as the source of coherent radiation from electrons streaming through a photonic crystal. However, other interaction mechanisms to generate coherent radiation from electrons, e.g., the cyclotron [17], [21], or Smith-Purcell [22] interaction can be used as well. The fact that a low electron beam velocity can be used in combination with power and frequency scaling characteristics makes the pFEL a versatile, compact source of coherent radiation, with a great potential to significantly enhance the available power from Terahertz sources.

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