A MIRROR-LESS, MULTI-BEAM PHOTONIC FREE-ELECTRON LASER OSCILLATOR PUMPED FAR BEYOND THRESHOLD

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Abstract

In a photonic free-electron laser one or multiple electron beams are streaming through a photonic crystal to generate coherent Cerenkov radiation. Here we consider a photonic-crystal slab consisting of a two-dimensional, periodic array of bars inside a rectangular waveguide, with both ends tapered to provide complete transmission of an electromagnetic wave. By appropriately designing the photonic-crystal slab, a backward wave interaction at low electron beam energy of around 15 kV can be obtained. The backward wave interaction provides distributed feedback without any external mirrors being present. We numerically study the dynamics of the laser oscillator when pumped far beyond threshold with one or multiple electron beams. We show that using multiple beams with the same total current provide better suppression of higher-order modes and can produce more output power, compared to the laser pumped by a single beam of the same total current.

INTRODUCTION

The coherent emission of traditional laser oscillators is typically limited to a discrete set of emission frequencies, which is determined by the transition between bound-electron states having discrete energy levels, by the the discrete set of longitudinal modes of the resonator or by a combination of both [1]. Free-electron lasers (FELs) partly overcome this by generating coherent radiation using unbound, also called free, electrons, which have a continuous energy distribution and can therefore emit at any desired frequency [2, 3]. However, whenever an oscillator configuration is used, the emission of an FEL will again be in the longitudinal modes of the resonator. Note that the free electrons need higher kinetic energy to emit shorter wavelengths, e.g., energies of a few MeV are required to generate THz radiation, while several to tens of GeV are required to emit soft- and hard x-ray radiation.

It is therefore desirable to have a coherent radiation source based on free electrons that would be compact, continuously tunable and preferably require much lower energy electrons (compared to undulator-based FELs) to generate a specific frequency. At the same time this source should provide a feedback mechanism that does not require an external resonator. The photonic free-electron laser (pFEL) [4] is a such a light source that fulfills these requirements and has other advantages as well.

In a pFEL gain is provided by electrons streaming through a photonic crystal embedded in a waveguide as shown in Fig. 1. The photonic crystal slab considered here consists of a periodic array of metal posts placed inside a metallic waveguide that provides the vacuum required to transport the electrons. Note that this photonic crystal possesses many natural channels for the electrons to propagate through (e.g., up to seven in Fig. 1). This allows the total current to be divided over many electron beams, lowering the current density in each individual beam. This results in higher quality electron beams and easier beam transport [5] than would be possible with a single electron beam. On the other hand, when keeping the current density in the individual beams constant, increasing the number of electron beams provides a simple way of scaling the output power of the source.

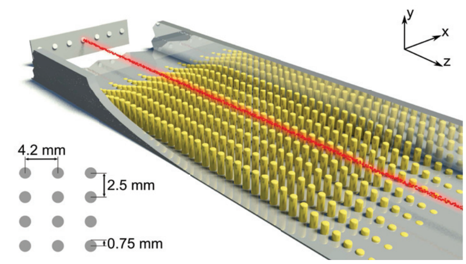

Figure 1: Schematic view of the photonic free-electron laser with a single electron beam. The red dots represent the electrons. The inset shows the orientation of the coordinate system.

When an electron beam streams through the photonic crystal, spontaneous Cherenkov radiation is emitted [6], albeit with different properties [7] compared to the emission in bulk materials. The spontaneous emission will contain Bloch eigenmodes of the photonic crystal slab that are velocity matched with the electrons for a low-order spatial harmonic. If the Bloch eigenmode has a longitudinal electric field component, then the mutual interaction between radiation field and electrons results in bunching of the electrons and hence the build-up of a coherent radiation field at the velocity-matched frequency.

The remaining part of this paper is organized as follows. We first investigate the properties of the tapered photonic crystal slab considered in this paper which includes the dispersion of the lowest order Bloch eigenmode. Then we investigate the performance of the mirrorless pFEL oscillator when pumped by a single electron beam in the center of the photonic crystal slab. This is followed by investigating the performance when the same oscillator is pumped by several electron beams and the paper concludes with a discussion and outlook.

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TAPERED PHOTONIC CRYSTAL

Because of the periodicity of the dispersion (i.e., spatial harmonics) of the Bloch modes [8], the pFEL can be operated in the so-called backward-wave regime where the group velocity is directed opposite to the phase velocity. Because of this, light generated at the downstream side of the photonic crystal travels to the upstream side, where it bunches the electron beam. Consequently, the backward wave provides feedback on the bunching and thereby creates an oscillator configuration without requiring any external mirrors. This means that the longitudinal modes induced by external mirrors are also absent and the pFEL can be continuously tuned in frequency.

To avoid that the end facets of the photonic crystal slab reflect the electromagnetic waves (and thus act as mirrors), the height of the posts that form the photonic crystal is tapered down at each of the end facets, creating a crystal as is schematically shown in Fig. 1. This photonic crystal consists of 8 rows of 40 posts, where the height of the nth post in a row is given by:

$$h_n = \begin{cases} h_0 \cos^2\left(\frac{\pi}{2}\left(\frac{n}{11}-1\right)\right) & \text{if } 1 \leq n \leq 10 \\ h_0 & \text{if } 10 < n \leq 30 \\ h_0 \cos^2\left(\frac{\pi}{2}\frac{n-30}{11}\right) & \text{if } 30 < n \leq 40 \end{cases}, \quad (1)$$

where $h_0 = 4$ mm is the full post height. The other dimensions of the photonic crystal are a post radius of 0.75 mm, a distance between post centers of 2.5 mm along the z axis and 4.2 mm along the x axis. The waveguide has a cross-section of 33.6 by 8.0 mm.

The transmission of a wave through the crystal has been numerically calculated using a frequency-domain solver (CST Studio Suite 2014). The structure shown in Fig. 1, when made out of copper, reflects only 0.4 % of the incident power at 16 GHz, the typical operation frequency of this laser. This shows that the tapers have a very low reflection. 70.4 % of the power is transmitted, so the losses in a single pass through the copper photonic crystal are 29.2 %. These calculations also show that the transmitted and reflected waves only contain the incident mode and no other modes, indicating that the photonic crystal modes and waveguide modes couple one-to-one.

The dispersion curve of the lowest order Bloch mode with non-zero longitudinal electric field for the photonic crystal of Fig. 1 is shown in Fig. 2 where the frequency (ν) is plotted versus longitudinal wavenumber, k_z, for the first (shifted) Brillouin zone. Figure 2 also shows the electron beam dispersion for the slow space-charge wave that is given by [9]

$$\nu = \frac{k_z v_{el}}{2\pi} - p\gamma^{-3/2}\nu_p, \quad (2)$$

$$\nu_p = \frac{1}{2\pi}\sqrt{\frac{e^2 n_{el}}{m_{el}\epsilon_0}}. \quad (3)$$

Here, v_{el} is the electron velocity, γ is the Lorentz factor, ν_p is the the non-relativistic plasma frequency, e, n_{el} and m_{el} are the electron charge, density and mass, respectively, ϵ_0 is the permittivity of free space and p is the so-called plasma reduction factor, which varies between 0 and 1. Figure 2 clearly shows that the laser operates in the backward-wave regime with a phase velocity in the direction of the electron velocity and a group velocity pointed in the opposite direction, i.e. towards the direction of the electron gun.

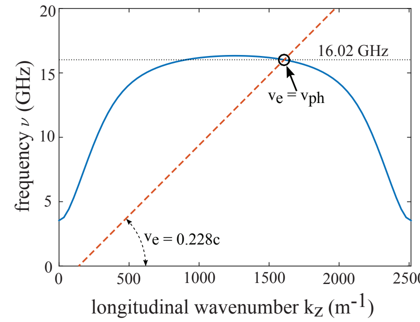

Figure 2: The calculated dispersion curve of the first Bloch mode with a non-zero longitudinal field component for the photonic crystal shown in Fig. 1 (the blue solid line) and the dispersion of the slow space-charge wave (red dashed line) for an electron beam with a $I_b = 1$ A, $E_b = 14$ keV and $p = 1$. The intersection of the two lines gives an indication of the frequency for velocity matching.

Note that in determining the operating frequency, the electron velocity inside the photonic crystal slab needs to be calculated from the kinetic energy, which is not necessarily the same as the total energy of the electron (eV_b, where e is the absolute value of electron charge and V_b is the accelerating potential of the electron gun) as the electrons will also attain potential energy when they are injected into the metallic waveguide structure that contains the metallic photonic crystal slab. Due to the periodic structure of the photonic crystal, this can not be calculated analytically. However, the average reduction in kinetic energy can be obtained from simulations that we use for studying the laser dynamics in the next section.

SINGLE BEAM PUMPING

To study the performance of the mirrorless pFEL oscillator, i.e., with a tapered photonic crystal slab as shown in Fig. 1, we perform so-called particle-in-cell (PIC) simulations [10] (CST Studio Suite 2014) to study the dynamics of the oscillator. Unless otherwise specified, the waveguide and photonic crystal are assumed to be lossless and an electron beam with zero energy spread is used (a so-called cold electron beam). The radius r_b of the electron beam is 1 mm. A guiding magnetic field of 0.5 T provides an immersed flow for the electrons and balances the radial space-charge force of the electron beam [5].

A typical output signal obtained by these simulations is shown in Fig. 3a for $I_b = 1$ A and $E_b = 14$ keV. This beam current is almost 5 times the threshold current for this device

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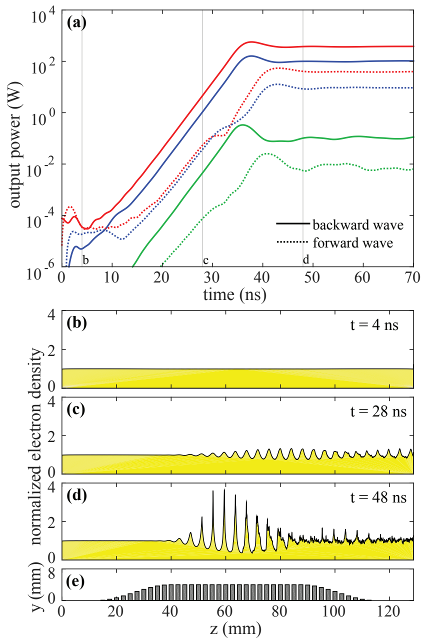

Figure 3: The power as a function of time (a) in the backward (solid lines) and forward (dotted lines) direction for the first three waveguide modes (red: TE_{10}, green: TE_{20}, blue: TE_{30}). Here, I_b = 1 A and E_b = 14 keV. The times for subfigures (b-d) are indicated by vertical dotted lines. The electron line density at various times: spontaneous emission (b), exponential growth (c) and steady state (d). A side view of the photonic crystal (e).

[11]. The output power for the three lowest order waveguide modes is shown. Note that after the tapered section the empty waveguides continues for another 13.75 mm before it ends in a matched waveguide port where the radiation is analyzed in terms of waveguide modes. Because the electron beam and therefore the gain is purely in the center of the waveguide, only modes with a strong on-axis longitudinal field are expected to couple strongly to the electron beam. Indeed, Fig. 3a shows that 99.5 % of the total power is in modes one and three and that the even modes, with zero on-axis longitudinal field, contain negligible power. The power in higher order odd modes is also negligible. Even though the pFEL only amplifies light in the backward direction, Fig. 3a shows that there is still a small amount of power leaving the crystal in the forward direction. This is caused by incomplete destructive interference of the wave in the forward (upstream) direction, due to non-homogeneous gain in the crystal. A frequency of ν = 16.047 GHz with a full width at half maximum of 0.58 MHz[1] was found. By varying the beam voltage from 13.5 kV to 15.5 kV, the frequency changed continuously from 16.02 GHz to 16.14 GHz.

[1] For the calculation of the bandwidth, the metallic parts had the properties of copper in order to obtain a realistic estimate for the bandwidth. In this case the total power was 334 W (cf. Fig. 3).

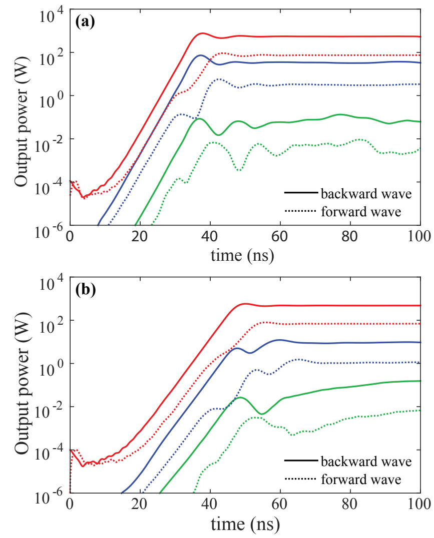

Figure 4: The output power as a function of time for the pFEL pumped with 3 (a) and 5 (b) beams. Just as in Fig. 3, shown are the backward (solid) and forward waves (dotted) for the first three waveguide modes (red: TE_{10}, green: TE_{20}, blue: TE_{30}). The total current in the beams is 1 A and E_b = 14 kV.

The dynamics can be divided into three phases that are determined by the electron bunching. Figures 3b-d show the electron line-charge density along the electron beam for the three phases. A side-view of the photonic crystal is shown in Fig. 3e to give context to the horizontal axis of sub-figures b-d. Initially, the electron beam is homogeneous and the output is dominated by spontaneous emission (Fig. 3b). Spontaneous emission into the lasing mode will start bunching the electrons and, subsequently, start the feedback mechanism that results in exponential growth (Fig. 3c). After some time the gain will saturate: the electrons slow down because their kinetic energy is transferred to the radiation field, which causes electrons and the wave to go out of phase. Finally, this effect becomes so strong that the growth will stop completely and the system reaches its steady state (Fig. 3d), i.e. the total single pass gain equals the total round-trip loss. Here, the total loss is determined by the 100 % out-coupling of the electromagnetic field from the photonic crystal.

MULTIPLE BEAM PUMPING

As mentioned before, multiple electron beams could stream through the photonic crystal. In combination with the scale invariance of Maxwell's equations [8], this can be used to maintain a certain drive current, and therefore output power, for the laser when the pFEL is scaled to operated at higher frequencies [4]. It is therefore of interest to investigate the pFEL pumped by multiple electron beams moving in parallel through the photonic crystal.

Figure 4a and b show the output power over time when pumping with the three and five most central beams, respec-

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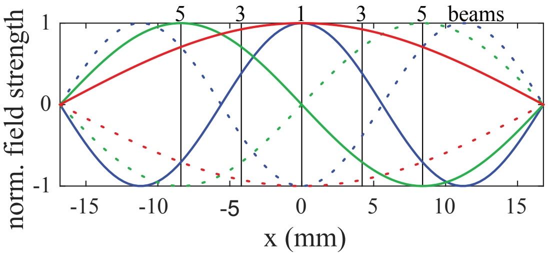

Figure 5: The empty waveguide mode profiles for the TE_{10} (red), TE_{20} (green) and TE_{30} (blue) modes. The vertical black lines show the position of the electron beams for pumping with 1, 3 or 5 beams.

tively. The same configuration is used as for the single beam simulations presented in Fig. 3 (i.e. PEC as metal and a cold electron beam) and the sum of the current in the beams is equal to 1 A. When pumped with multiple beams the pFEL behaves very similar to when pumped with a single beam. However, the multibeam pFEL does take longer to start up, which is due to the lower current per beam. Fig. 4 shows that the fraction of the power in the fundamental mode increases with the number of beams: 81 ± 3 % for one beam, 93 ± 2 % for three beams and 99 ± 1 % when five beams are used. The reason for this is that the gain depends on the field strength at the location of the electrons. The field strength of the first three waveguide modes is shown as a function of the position on the x-axis in Fig. 5. The envelope of the corresponding Bloch eigenmodes of the photonic crystal slab have a similar shape. This figure indicates that the field weighted overlap with the electron beams is highest for the fundamental mode and increases with the number of electron beams. Hence, the gain of the fundamental mode is expected to increase relative to that of the other modes, when the number of electron beams increases. For the configuration investigated, pumping with three beams gives the highest output power while five beams delivers an output with highest mode purity at the expense of a lower output power. This means that the number of pump beams can be used to optimize the tapered pFEL oscillator for maximum output power, maximum mode purity, or possibly both.

DISCUSSION AND OUTLOOK

A photonic free-electron laser oscillator without an external resonator is proposed and investigated numerically using a particle-in-cell code. In this study the metal parts are assumed to be perfect conducting and a cold electron beam is used. A backward-wave interaction provides the feedback that results in oscillator-like behavior of the pFEL. By tapering the ends of the photonic crystals, reflections at the end of the crystal can be reduced to well below the 1 % level. Keeping the total current constant at almost 5 times the threshold current, it is found that the output power and mode purity could be controlled by using multiple electron beams. It is also shown that the oscillator can be continuously tuned. Finally, using copper as metal to provide a more realistic simulation, it was shown that the dynamic oscillator behavior was very similar to the ideal case, albeit with a somewhat lower output power. Using a beam voltage of 14 kV, an output frequency of 16.0470±0.0006 GHz is found with a total power equal to 334 W.

The multi-beam performance of the pFEL oscillator suggests an interesting scaling route to increase the operating frequency to well into the THz domain, compared to the microwave frequencies investigated here. This requires the crystal to be scaled down in size by two orders of magnitude. Instead of increasing the current density in a single beam, the same total current can now be obtained by propagating many electron beams in parallel through the pFEL. Such a massively parallel set of electron beams may be produced by so-called field-emitter arrays [12]. Switching individuals beams on and off, or providing a chirp in the accelerating voltage, either in time or as a function of transverse position, may provide the source with interesting capabilities to manipulate the light produced.

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