THE PHOTONIC FEL: TOWARD A HANDHELD THz FEL

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Abstract

Low energy, slow wave, electron beam based radiation devices, like traveling wave tubes and Cerenkov free-electron lasers, have the disadvantage that the gain seriously degrades when the operating frequency is scaled from microwave to teraHertz frequencies. Here we propose to obtain a successful scaling with what may be called a photonic free-electron laser (pFEL). In our approach, a photonic structure serves for phase matching the radiation field to a set of co-propagating electron beams. The photonic structure additionally provides transverse coupling between the individual electron beams, such that phase locking through the interaction with the radiation field leads to the generation of transversely coherent radiation. This phase locking mechanism allows power scaling by extending the number of parallel beams propagating through the structure. We expect to be able to produce Watt-level output at THz frequencies from a handheld device and will present the basic ideas behind this concept.

INTRODUCTION

TeraHertz (THz) radiation spans the range from about 100 GHz to 10 THz, with wavelengths between 3 mm and 30 μm. These waves penetrate most dielectric materials, such as plastics, glass, paper, wood or clothes, while sharp, molecular-specific resonance can be used for highly material-specific imaging. Thus, tuneable THz radiation with Watt-level power from a compact device would enable numerous applications in science, industry and society [1]. Examples are control of chemical reactions, quality control in manufacturing, security-surveillance, and imaging of goods, mail or people. However, the central problem for industry to apply existing THz sources is that there is no THz source available which can deliver a tuneable multi-Watt average output in a small and robust format. As an illustration, the most powerful THz sources today are free-electron lasers (FELs) driven by RF accelerators [2, 3, 4], however, even the most compact RF-accelerator based FEL has still a large size compared to, e.g., a traveling wave tube (TWT) and are far more costly. On the other hand THz sources based on fs laser systems offer high-quality radiation and allow for advanced detection techniques [1]. However, the average output power is rather poor, typically only in the pW to μW-range, which is many orders of magnitude lower than desired. Other techniques to produce THz radiation include, amongst others, optically pumped gas lasers [9], optical rectification [5], quantum cascade lasers [7], direct multiplication [6] and backward wave oscillators [8]. Again the average output is for almost all of these sources limited to around a mW or less at THz frequencies. The much higher output produced by optically pumped gas laser is only produced at a finite number of discrete laser lines. For an electron beam based THz radiation to be of the size of a TWT one needs to limit the electron beam energy to a few tens of keV at most. The scaling properties of undulator based FELs do not allow these devices to generate THz radiation at these electron beam energies. On the other hand, Smith-Purcell [10] and Cerenkov free-electron lasers [11] may be able to operate at THz frequency at these beam energies. The Cerenkov FEL, as a slow wave device, has the disadvantage that the characteristic length scales with the wavelength and hence the output power will drop as the frequency of the device is increased. This disadvantage my be circumvented by using a photonic structure to couple the electrons to the radiation field. The photonic free-electron laser (pFEL), also labeled volume free-electron laser [12], can be considered as a three-dimensional extension of the Smith-Purcell FEL. In the following sections we discuss the principle of operation, the advantages of the pFEL and present a design for operation at THz frequency.

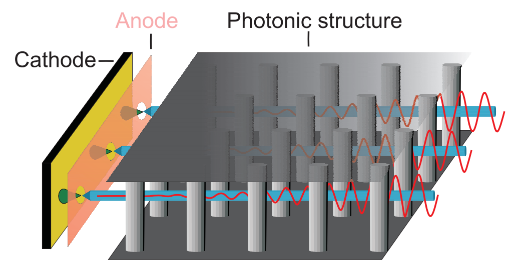

Figure 1: Schematic overview of a photonic free-electron laser

THE PHOTONIC FEL

In a photonic FEL low-energy electrons are streaming through a photonic structure such that it acts as a medium amplifying THz waves. The schematic setup of the pFEL is shown in Fig. 1. For pumping, a set of low-energy electron beams is generated by an electron source, that either consists of a masked thermionic cathode or an appropriate array of field emitters, and the electrons are accelerated with an adjustable voltage of a few tens of keV. The beam

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path of the electrons is enclosed by a solenoid (not shown) for space-charge balanced flow. The electron beams are directed through hollow (empty space) channels in a photonic crystal that are a natural part of the structure. Using a photonic crystal serves four essential tasks for a proper working of the pFEL. First, the photonic structure can be chosen to support traveling electromagnetic (EM) waves for which the electric field is partly directed along the electron velocity (say the z-direction). Thereby the electrons can be decelerated, and EM waves can be amplified, as in any FEL. Second, the crystal structure can be chosen to strongly reduce the velocity of EM waves around selected frequencies, down to the relatively low velocity of the electrons (about c/5). This is clearly feasible because, in fact, much stronger slowing has already been realized, e.g., down to c/1000 for near-IR photonic crystals [13]. The wavelength at which slowing occurs is in the order of the spatial period of the photonic crystal. As an example, a period of 0.3 mm slows waves at about 1 THz frequency. This means that the pFEL belongs to the class of slow wave devices, similar as the Cerenkov FEL, traveling wave tube and backward wave oscillator. Third, distributed feedback (DFB) in the photonic crystal (by Bragg reflection, as also in other DFB lasers) increases the effective amplification length to well beyond that of the physical length of the crystal [14]. This leads to a low lasing threshold, as is know from other types of DFB lasers. Fourth and last, the transverse periodic structuring of the photonic crystal, phases-locks the field output from adjacent gain channels which leads to a spatially coherent, high-quality output beam. Increasing the number of gain channels that work in parallel (i.e, increasing the transverse width of the laser) makes the pFEL scalable in output power. It is this last characteristic that gives the photonic free-electron laser its biggest advantage and allows to compensate for the reduction in output power per gain channel when the device is scaled to operate at higher frequencies. This is due to the interesting property that electromagnetism in (periodic) dielectrics has no fundamental length scale [15]. This means that a wave profile found for a certain structure at frequency ω is the same as found for the same structure that is reduced in size by a factor s in every direction and for a frequency $s \cdot \omega$. In particular, if the pFEL operates at a frequency ω for a structure with a lattice constant a and electron beam energy E_b, then the pFEL operates at a frequency $s \cdot \omega$ for the same structure with lattice constant a/s while using the same beam energy E_b. Of course, the reduction in size means that the channel through which the electron beam has to propagate reduces in size as well. One thus has to reduce the electron beam diameter by the same factor s. This will lower the gain and output per gain channel, however, as mentioned above, this can be compensated by increasing the number of gain channels in parallel.

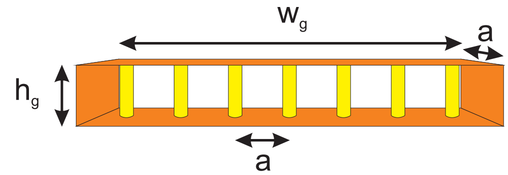

Figure 2: Schematic view of a unit cell of the rectangular waveguide filled with a period array of metal posts.

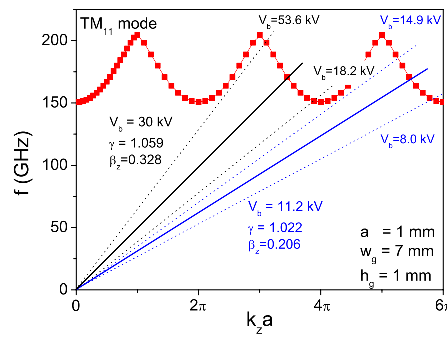

Figure 3: Dispersion of the lowest order TM mode and of electrons with different beam voltages V_b.

PHOTONIC STRUCTURE

To illustrate that THz waves can be generated by a compact pFEL we have first calculated the dispersion properties of an appropriate photonic structure. As stated in the previous section, the EM waves of interest should have a nonzero electric field component in the propagation direction of the electrons, here taken to be the z-direction. One structure that provides such waves is an rectangular waveguide, with dimensions w_g by h_g, that is oversized in one dimension ($w_g >> h_g$) and that contains a periodic array of metal posts with lattice constant a. A unit cell of such a waveguide is shown in fig. 2. We have used the Concerto EM modeler [16] to calculate the dispersion properties of the unit cell displayed in fig. 2 using $a = 1$ mm, $w_g = 7$ mm and $h_g = 1$ mm. The posts have a radius of $r_p = 0.125$ mm. The result for the lowest order TM_{11} mode (with non-zero E_z) is shown in fig. 3 and shows that the mode frequency is in between 150 and 200 GHz for these parameters. The field distribution of E_z in the transverse plane through the center of the posts of the unit cell is shown in fig. 4 for $k_z a = 2\pi$, where k_z is the longitudinal wavenumber of the mode in the waveguide. The envelope of E_z follows that of the fundamental TM_{11} mode of an empty waveguide and E_z is of course zero in the regions of the posts. Fig. 4 shows that E_z is maximum in the middle between the posts where the electron beam will be moving, and thus shows one of the advantages of using metallic post over dielectric ones. One other advantage of using metallic posts is that these are not susceptible to charging which may distort and even disrupt electron beam propagation through the structure.

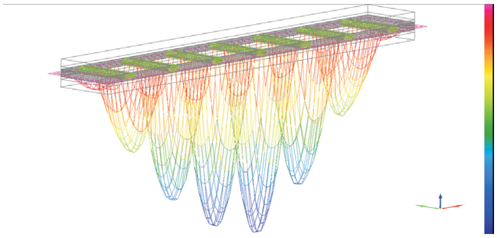

Figure 4: E_z field component in the transverse plane through the center of the posts ($k_z a = 2\pi$).

ELECTRON BEAM CONSIDERATIONS

As in any other electron-beam based radiation source, the TM_{11} mode is amplified whenever the electron velocity is at or just above the phase velocity of this mode. Fig. 3 therefore also shows the dispersion for the electron beam for two beam voltages, 30 kV and 11.2 kV. At the higher voltage, the electron beam will interact with the second spatial harmonic and at the lower voltage the interaction takes place with the third spatial harmonic. Note, that at these beam voltages the phase velocity of the TM_{11} mode is opposite to the group velocity, so that the interaction is of the backward-wave type. In order to tune over the frequency range of 150 to 200 GHz, the electron beam voltage should be varied from 18 to 54 kV and from 8 to 15 kV for interaction with the second respectively third spatial harmonic. This shows that the photonic FEL is capable of generating microwave to THz frequencies using a low energy electron beam. Note that an undulator based FEL requires a beam energy of at least 350 keV to produce 175 GHz radiation assuming an undulator period $\lambda_u = 1$ cm.

Each gain channel in the structure of fig. 2 has a dimension of h_g by $a - 2r_p$ (height by width), which is 1 mm by 0.75 mm in the case considered. We will therefore consider a set of multiple electron beams each having a cross section of πr_b^2, where $r_b = 0.25$ mm is the electron beam radius. Using a conservative estimate for the current density of 10 A/cm^2, this means that each electron beam carries a current of about 20 mA. The total current transmitted through the structure then becomes 0.12 A for 6 beams in parallel. A model for the pFEL is still under development, however the small signal gain of a single gain channel can be estimated using a Cerenkov FEL gain code [17] for the same electron beam parameters and configured to show gain for the same frequency. As the Cerenkov gain code does not contain distributed feedback and since in a Cerenkov FEL the E_z field is minimum at the center of the electron beam whereas it is maximum for the pFEL, the gain will be underestimated by the Cerenkov gain code. A small signal gain in excess of 100 % is found for an interaction length of only 10 cm. The loss of an empty waveguide made of copper is calculated to be about 1 Neper/m at a frequency of 175 GHz, so the single pass loss is approximately 18 %. The pFEL can therefore be pumped above threshold.

CONCLUSION

The photonic FEL uses a set of electron beams propagating through a photonic structure to coherently amplify electromagnetic waves. The output power of such a device can be scaled be varying the number of electron beams (i.e., by varying the transverse size of the structure). Through this mechanism the pFEL has the ability to overcome the disadvantage of slow-wave devices like the traveling wave tube and backward wave oscillator that drop in output power if scaled to higher frequencies. We have shown an example of a structure that supports TM-modes required for operation. The operating frequency is expected to be in the 150 to 200 GHz range, which is already well into the THz range. Using field emitter arrays, the size of the channels in the photonic structure can be scaled down to the tens of micron range, which is at least a factor of 10 smaller than what we considered here. Hence operation at well above 1 THz is anticipated, though this would require a large amount of gain channels (electron beams), which are naturally provided by field-emitter arrays. The low electron beam energy of only ten to a few tens of keV, and short interaction length results in a compact source, roughly the size of a TWT or even a handheld device. Therefore the pFEL is a promising source for millimeter and THz waves.

ACKNOWLEDGEMENT

This research is supported by the Dutch Technology Foundation STW, applied science division of NWO and the Technology Program of the Ministry of Economic Affairs.

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