PROOF OF PRINCIPLE: THE SINGLE BEAM PHOTONIC FREE-ELECTRON LASER

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Abstract

The photonic free-electron laser (pFEL) aims to realize a compact microwave source with the potential of generating Watt-level TeraHertz radiation. In a pFEL several coupled electron beams stream through a photonic crystal (PhC) leading to the emission of fully coherent Cerenkov radiation. Hence, the pFEL's output power can be scaled by the number of coupled electron beams, allowing Watt-level output at THz frequencies with a compact device. As a first step toward a multi-beam pFEL we investigate a single beam pFEL that can operate both on the forward and backward wave interaction. In this paper we present the design of the device and the experimental characterization of its PhC.

INTRODUCTION

Various, compact, well-developed, high power microwave sources exist to date, however, their output power seriously reduce when the operating frequency is increased. Therefore, the so-called THz range, spanning from about 100 GHz to a few THz, is still lacking compact, robust and powerful sources [1]. The availability of such a source would enable numerous scientific and industrial applications [2] as THz radiation penetrates dielectric materials, like ceramics, paper, wood or clothes, which are opaque for IR or visible light. Additionally, sharp and molecular-specific resonances exist in this frequency range, which can be used for highly material-specific imaging. Examples are control of chemical reactions, quality control in manufacturing, chemical selective security-surveillance, and imaging of goods, mail or people.

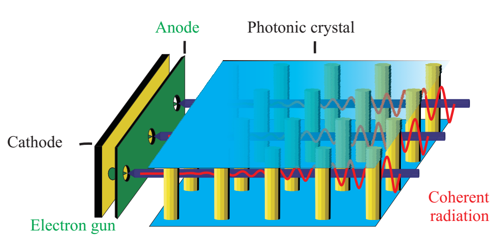

Figure 1: Schematic overview of a pFEL, Not shown: solenoid for electron beam guiding.

Recently, we presented the concept of a photonic free-electron laser (pFEL) to realize a compact microwave source, which has the potential to emit Watt-level output power at THz frequencies [3]. In a pFEL, see Fig. 1, several low energy electron beams ($< 30\,\mathrm{keV}$) stream through a photonic crystal (PhC). Inside the PhC each electron beam emits Cerenkov radiation. The radiation of all beams becomes phase-locked due to the transverse scattering of the PhC. This allows a unique power scaling of the pFEL by increasing its transverse size and number of electron beams. Furthermore, it allows to keep the total beam current driving the device constant, even if the lattice constant of the PhC is decreased to operate the device at THz frequencies. Finally, low energy electron sources are compact. These two aspects indicate the potential of the pFEL to provide a compact, Watt-level THz source in the future.

The use of a PhC in a free-electron laser (FEL) to influence the dispersion of an electromagnetic wave was investigated before [4, 5, 6, 7]. However, so far very little experimental work has been done on the Cerenkov emission of low energy electrons ($< 30\,\mathrm{keV}$) using a PhC to both bunch the electrons and to slow down the co-propagating radiation field [5].

As a first step toward a multi-beam device, we first investigate the interaction between electrons and radiation field in a single beam pFEL (spFEL). Since the PhC introduces a periodicity in the wave dispersion, this type of device allows, a priori, the electrons to interact with both forward and backward waves. The spFEL will be designed to study both types of interactions with the same device. In the remaining part of this paper we will first present a brief overview of the spFEL, then present the PhC that allows us to investigate both types of interaction and finally experimentally validate the PhC's dispersion.

SINGLE BEAM PHOTONIC FREE ELECTRON LASER

As electron source for the spFEL we have selected a standard, nominal 14 kV, thermionic electron gun used in traveling wave tubes [8]. The gun has a perveance of $1.18\mu\mathrm{AV}^{-3/2}$. The advantages of such a gun are: it is a proven design, it is compact and its high perveance should allow easy detection of both spontaneous and stimulated emission. The disadvantage of such a high perveance is the magnetic field required to guide the electron beam through the PhC. The magnetic field is provided by a solenoid (see Fig. 2), which has a hollow core of $45\,\mathrm{mm}$ to place the PhC. Inside the solenoid the magnetic field limits the electron beam diameter to $2.5\,\mathrm{mm}$. An iron shield is placed around the solenoid to (i) reduce the magnetic field in the

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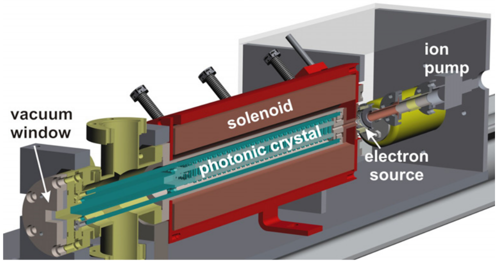

Figure 2: 3 dimensional drawing of the spFEL setup.

cathode region of the electron gun, (ii) to make the magnetic field more homogeneous inside the solenoid and (iii) to reduce the magnetic field quickly behind the PhC interaction region. Due to the latter the electron beam quickly diverges behind the solenoid and can be collected in the walls of the output waveguide. Furthermore, the output waveguide transports the emitted Cerenkov radiation to a vacuum window, behind which the diagnostic setup will be placed.

The electron beam diameter places a lower limit on the channel dimensions in the PhC ($> 2.5\,\mathrm{mm}$) to minimize electron beam interception. The development of such a PhC will be summarized in the next section.

PHOTONIC CRYSTAL DESIGN

The magnetic field present in the spFEL is used only to guide the electron beam. The device relies on the PhC to slow down the phase velocity of the electromagnetic wave so that it becomes resonant with the co-propagating electrons. This can be achieved by almost any PhC, however the pFEL relies also on the electromagnetic wave to bunch the electrons. It is therefore crucial that the PhC possesses TM-like modes ($E_z \neq 0$). In addition, the PhC design should minimize beam interception by providing a channel for electron beam propagation which is at least $2.5\,\mathrm{mm}$ in diameter. Finally, it would also be desirable that the analysis of the produced output can be done unambiguously. This can be achieved by separating the different PhC eigenmodes in frequency.

The unit cell of the PhC is shown in Fig. 3. It is an improved design of the PhC used by Jerby [5]. The design is described in [9] and we summarize its main properties here by discussing the unit cell and the calculated dispersion of the first two TM-like modes. First, the PhC will allow efficient electron beam transmission. By omitting the center post in the PhC's unit cell (Fig. 3) a channel of $4\,\mathrm{mm} \times 8\,\mathrm{mm}$ is available for electron beam propagation. This is more than one and a half times larger than the electron beam diameter inside the solenoid.

Second, the PhC provides TM-like modes to study coherent Cerenkov emission. Figure 4 shows the dispersion of the lowest two PhC TM-like modes together with the electron beam dispersion at maximum and minimum electron energy (7 keV and 15 keV). The electrons are resonant

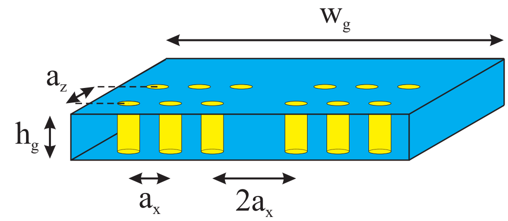

Figure 3: Unit cell of the PHC for the single beam pFEL, consisting of a rectangular waveguide and metal posts of radius $r = 0.75\,\mathrm{mm}$, $a_x = 2.7\,\mathrm{mm}$, $a_z = 3\,\mathrm{mm}$, $w_g = 18.9\,\mathrm{mm}$, $h_g = 8\,\mathrm{mm}$.

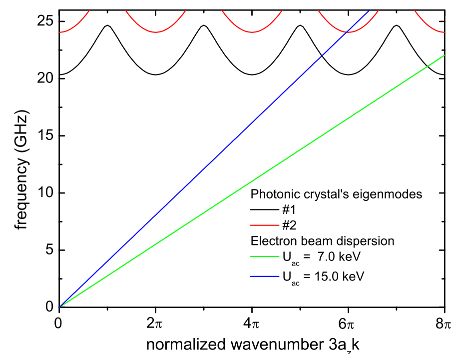

Figure 4: Dispersion of the first two TM-like modes of the PhC and electron beam dispersion for beam energies of $U_a = 7\,\mathrm{keV}$ and $U_a = 15\,\mathrm{keV}$.

to the third spatial harmonic or the fourth spatial harmonic and the emission of the spFEL is expected to appear between 20 to 24 GHz for the fundamental transverse TM-like mode. By tuning the electrons energy, different interactions can be investigated: backward wave interaction, forward wave interaction, interaction close to cut-off and far away from cut-off.

Third and finally, the PhC allows unambiguously studying the emitted output because the TM-like modes are well-separated from each other. This is achieved by using a more complex unit cell, a so-called double periodic unit cell, where every third row of posts is completely omitted.

In conclusion, this PhC design will allows us to study the various interactions between PhC modes and low energy electrons using the high perveance electron source of the last section.

EXPERIMENTAL VERIFICATION OF PHC DESIGN

For the experimental verification of the design, we make use of the scaling law for PhC [10] and build a scaled version of the unit cell shown in Fig. 4. If the PhC and radiation wavelength are both scaled by the same factor, the wave velocity and pattern remain unchanged. A scaling

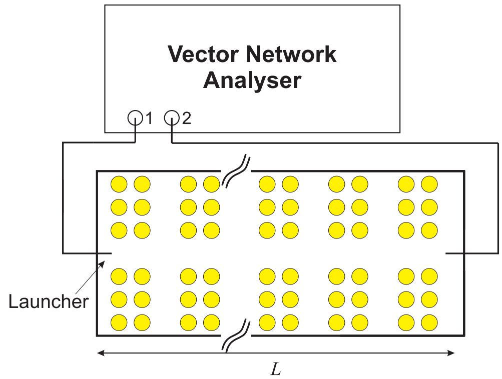

Figure 5: Experimental setup to verify the dispersion of the PhC: A Vector Network Analyzer excites by a launcher a cavity of 15 unit cells of the PhC, a similar launcher at the end acts as a receiver.

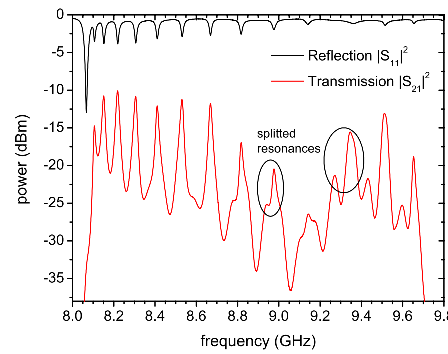

Figure 6: Measured transmission and reflection spectrum from the setup shown in Fig.5.

factor of 2.5 shifts the cut-off of the fundamental TM-like mode to around 8 GHz. This and allowed us to use an existing microwave source (0 - 20 GHz). Over the course of the measurements, the PhC was assembled and disassembled a few times. This inevitably leads to small variations in the position of the posts ($< 1\,\%$) and some information can be obtained on the influence of the accuracy of the PhC on its dispersion properties.

The PhC allows emission of Cerenkov radiation due to the low phase velocity of its modes. Therefore, the PhC's phase velocity $v_{ph} = \omega/k$ is the most important feature of the PhC for our work. The phase velocity is validated by measuring the dispersion, i.e. measuring the wave vector k against the frequency ω.

The dispersion can be measured by using a technique described by Guo [11]. This technique requires building up a weakly coupled cavity of several of the PhC unit cells and determining its resonances. The resonances only appear at certain frequencies corresponding to the longitudinal eigenfrequencies of the cavity. For a weakly coupled cavity, these resonances are expected at the following normalized wave numbers $(3a_z k)$ [9, 11]:

$$0 \leq \frac{n}{m}\pi \leq \pi \tag{1}$$

where m is the number of PhC periods and n an integer.

The measurement setup is shown in Fig. 5. The microwave power of a Vector Network Analyzer is coupled to the TM-like modes of the cavity by a short Hertzian launcher, which is aligned along the z-axis. The cavity consists of 15 PhC unit cells and at its end a similar launcher is used as a receiver to extract a small part of the radiation inside the cavity.

The measured reflection spectrum and transmission spectrum is shown in Fig. 6. As expected several resonances are detected, but the resonances at $3a_z k = 0$ and $3a_z k = \pi$ are missing. The small coupling length of the launcher prohibits exciting them. However, a short launcher also prevents to alter the other cavity resonances significantly. In the transmission spectrum also the resonance $\frac{1}{15}\pi$ is not measured, due to high losses close to cut-off. However, this resonance is clearly visible in the reflection spectrum.

By comparing various transmission and reflection spectra after the PhC was disassembled and again assembled, we observed that the shape of some resonances may change and sometimes a doubly peaked resonance is observed (a kind of splitting of the resonance). Examples are the marked resonances in the transmission spectrum at 9.3 or $8.8\,\mathrm{GHz}$ in Fig. 6. Qualitatively, we could numerically reproduce these effects by introducing a small asymmetry in the PhC. We therefore conclude that this resonance splitting results from breaking the perfect periodicity of the PhC. Still, if the main maxima are assigned with a normalized wave number using the technique of Guo, we get the points shown in Fig. 7. A comparison of these points with the numerical calculated curve shows a very good agreement between them. The frequency of these points does also hardly change between several assemblings. The standard deviation of the point's frequency is less than 8 MHz. Thus, the dispersion and thereby the phase velocity, of the lowest order TM-like mode is validated. The breaking of the perfect periodicity (at least for positioning accuracy of the order of $1\,\%$ or less) does not affect the dispersion much; it seems only to change the local field pattern slightly.

To verify this we plan to measure the local field by introducing a small metal sphere in the cavity. This induces a shift in the resonance frequency depending on the local field strength at the position of the sphere. This method will allows us to map the local field strength, and hopefully small deviations in the field strength induced by breaking of the perfect periodicity of the structure.

In conclusion we have shown good agreement between the measured and calculated dispersion of the lowest order TM-like mode for the PhC considered.

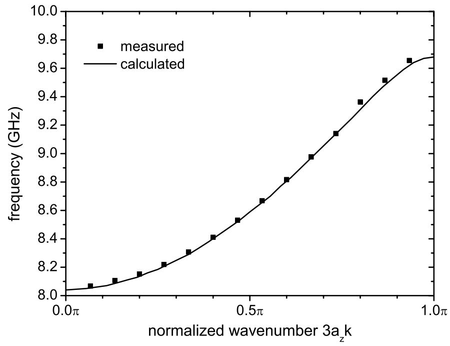

Figure 7: Comparison between measured and calculated dispersion of the lowest TM-like PhC mode.

CONCLUSION

The pFEL is investigated to provide a compact microwave source, which could be scaled to also emit Watt-level THz radiation. As a first step toward such a pFEL we presented the design for a spFEL. Due to its PhC design the spFEL will allow to investigate several different operation regimes, like forward and backward wave interaction. The PhC design was validated by measuring its dispersion, which agreed very well with the design calculations.

ACKNOWLEDGEMENT

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