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DIELECTRIC WAVEGUIDE BASED THz RADIATOR STUDY FOR SwissFEL*

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Abstract

THz pulses have many unique properties in terms of radiation matter interaction. In particular, their non-ionizing excitation of phonons in matter makes them a preferred pump for pump-probe studies at free-electron laser facilities. Among many THz generation techniques, the one based on dielectric lined waveguide and electron beam is emerging as a compact and powerful means for the THz generation. We will investigate the feasibility of this technique to produce narrowband pulses of 1-20 THz with above 100 µJ per pulse for SwissFEL. As a first step, we focus on the proof of principle experiments. This paper overviews the project with a focus on the numerical study of the dielectric lined waveguide, in terms of mode structure, energy, pulse length etc, which are essential parameters for the pump-probe experiments. These waveguides will be fabricated and tested in the near future at SwissFEL.

INTRODUCTION

THz radiations, which lie between approximately 1 and 20 THz, have multiple properties in terms of radiation matter interaction due to the unique spectroscopic signatures for a wide range of phenomena. In particular, their non-ionizing excitation of phonons in matter, which is important to understand the physiochemical as well as biological processes of condensed matter [1]. The dynamics of the excited states can be probed by the high brightness, ultrashort X-ray pulses available at free electron laser facilities [2].

Due to the appealing characteristics and the great potential applications of the THz radiation, there are ever-increasing efforts in generating THz [3], including but not limited to the methods based on the solid state oscillators, the quantum cascaded laser, the laser pumped solid state devices and accelerators etc. In this paper, we report on a THz radiator study based on a relativistic electron beam and a dielectric lined waveguide (DLW) [4]. Many experiments have been performed in the field in order to show the validity of this means of high power generation but they are normally limited to a few tens or hundreds GHz due to the quality and the length of the electron beam. We aim to demonstrate the generation of narrowband pulses in the range of 1-20 THz, which will require a rather small vacuum aperture for the electron beam to traverse. If demonstrated successfully, this narrowband THz source can be a strong candidate for the pump-probe setup aforementioned. Especially, the high power of these THz pulses would open new possibilities of experiments for the photon beamline users at SwissFEL (Swiss Free Electron Laser) [5].

SwissFEL is a less than one kilometer long free electron laser facility based on normal conducting RF technique as schematically shown in Fig. 1. It is able to generate ultrashort and ultra-bright soft and hard X-ray pulses simultaneously in the two undulator lines Athos and Aramis, respectively [5]. These are driven by the electron bunches from an RF injector followed by S and C-band RF accelerating structures.

To demonstrate the plausibility of the THz generation based on this method, the proof of principle beam test of the DLW will be carried out in the ACHIP vacuum chamber [6] in the switchyard of the Athos beamline. If this DLW based THz source can provide above 100 µJ per pulse, less than 10% bandwidth in the frequency range of 1-20 THz, we then plan to investigate further to propose a possible design implementation of such a DLW based device for the THz generation. By exploiting the electron bunches after the Aramis undulator right before the electron beam dump as indicated in Fig. 1 , the THz could be generated together with a DLW device without too much complication. This is essentially due to the insensitivity to the energy spread of the otherwise still bright blow-up electron beam. The THz could be transported to the ATHOS station before the soft X-ray pulse to form a pump-probe experiment setup.

THE DLW BASED THZ RADIATOR

An electromagnetic field is excited when a relativistic electron bunch traverses a DLW. The electromagnetic fields can be decomposed in multipole expansion into orthogonal modes. Among these modes, the monopole transverse magnetic modes, showing azimuthal symmetry, are of particular interest due to the strong coupling between the electron beam and its longitudinal field. By tailoring the geometry size of the DLW, radiation in the THz can be obtained. The mode can be guided out of the DLW and is the principal source of the THz radiation.

A sample DLW is shown in Fig. 2 and it consists of a vacuum channel ($0 < r < a$) for the electron bunch passage, and a dielectric layer ($a < r < b$), characterized by the relative permitivity ε_r, for slowing down the phase velocity of the mode to match it with the velocity of the electron bunch. The outer side of the DLW is coated with metallic material to enclose the radiation and to form a set of discrete electromagnetic modes. The total length L of the DLW governs the bandwidth and power of the THz pulses. In

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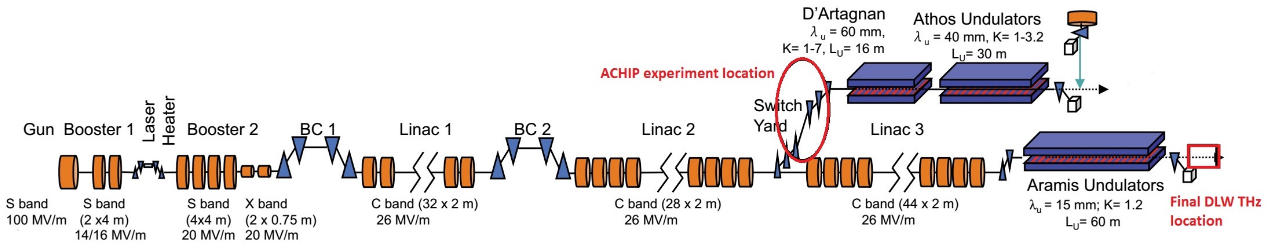

Figure 1: Layout of SwissFEL.

this paper, we only consider the DLW with a circular cross section due to its robustness and simplicity.

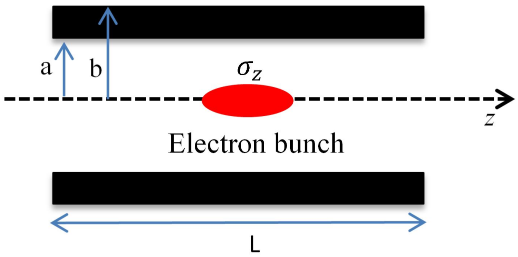

Figure 2: Schematic of a DLW structure with its inner and outer radius a and b respectively.

The mode frequencies and the field distributions can be solved analytically as shown in [7] and [8]. These are functions of a, b and ε_r. The longitudinal field component of $\mathrm{TM}_{0\mathrm{n}}$ is shown in Fig. 3. In the vacuum passage the field strength is almost constant, which indicates that the interaction between electron bunch and the field is independent of the bunch transverse position. The oscillatory behavior of the field is only in the dielectric layer.

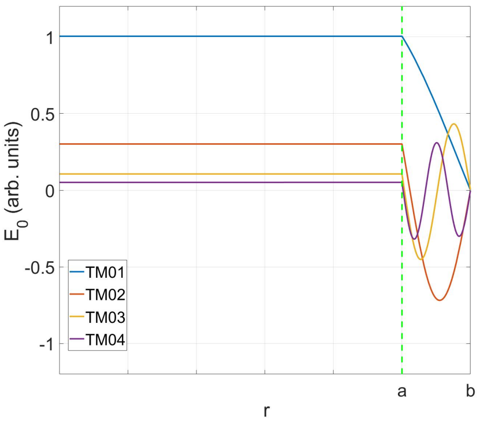

Figure 3: Transverse profile of the longitudinal field strength of the TM mode.

Figure 4 shows the mode frequencies for a parametric scan of a and b, with $\varepsilon_r = 3.8$. To get the TM_{01} above 1 THz, a and b should be approximately in the range of one hundred micrometers.

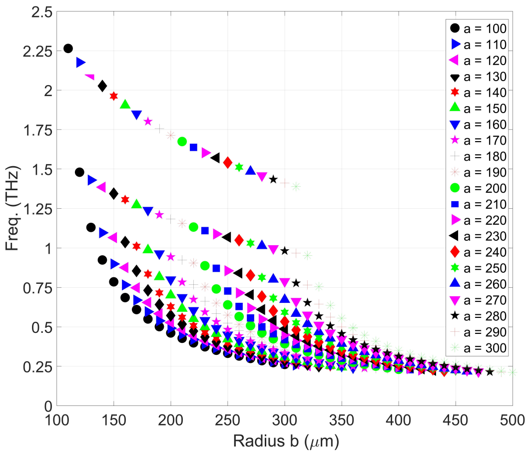

Figure 4: TM_{01} mode frequency versus radius b at different a.

Our design aims to cover the frequency range between 1-3 THz with the fundamental mode TM_{01}, and the remaining 3-20 THz with its harmonics. The pulse length, group velocity, energy per pulse can be obtained as described in [8]. A case study with $a = 100\,\mu\mathrm{m}$, $b = 120\,\mu\mathrm{m}$, and $\varepsilon_r = 3.8$ is summarized in Table 1. The following estimates the associated parameters for a point charge of 1 pC traveling through a 1 cm long DLW.

Table 1: THz Pulse Parameter Estimation for a Point Charge of 1 pC

$\mathrm{TM}_{0\mathrm{n}}$ n	Freq. (THz)	Vg (c)	E (μJ)	$\mathrm{T}_{\mathrm{pulse}}$ (ps)	E0 (MV/m)	BW (%)
1	1.48	0.53	0.0113	30	2.26	2.2
2	5.06	0.75	0.0034	11	0.68	1.8
3	9.29	0.78	0.0012	9.6	0.24	1.1
4	13.66	0.78	0.0006	9.2	0.11	0.8
5	18.09	0.79	0.0003	9.2	0.07	0.6

The energy per pulse scales with the charge q, DLW inner radius a and length L as $E \propto q^2 \times L/a^2$. One will obtain approximately 100 μJ with 100 pC charge for the DLW parameters in the case study. Increasing the length L or decreasing the inner radius a can increase pulse energy. At the same time, this also increases the head-tail kick to the bunch and imposes severe beam transmission issue if the bunch is not well centered. However, this is mitigated in our case by using external focusing magnets as we discuss the experiment setup in the next section. One can observe from the table that the relative bandwidth due to the finite length of the DLW is well below 10% requested as a user pump, however there are other processes which degrade the bandwidth in any real experimental setup. This will be reported in another paper.

After the generation of THz pulse, it can be guided out of the DLW structure with an opening end, which is essentially converting the waveguide mode into a Gaussian Hermite mode of the free space propagation [11]. Due to the impedance mismatch, part of the THz will be reflected back to the DLW. The power transmission versus the inner and outer radius ratio is calculated by the electromagnetic field solver HFSS [10] and is shown in Fig. 5 for $\varepsilon_r = 3.8$.

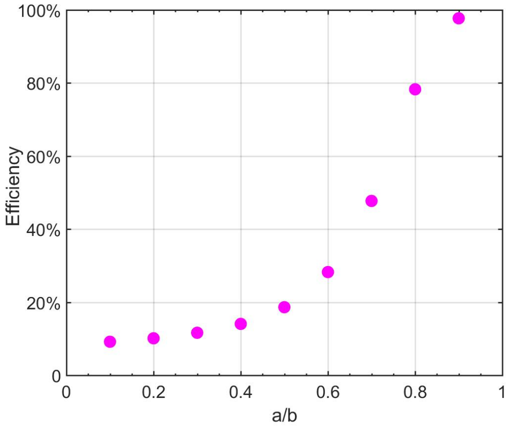

Figure 5: Radiation extraction efficiency with a vertical cut end.

It can be concluded that higher transmission can be obtained with relatively thinner dielectric layer. The opening can form certain angle with respect to the beam axis as described in [11] and the angle can also affect the radiation efficiency. The optimal angle will be studied in the future. This method has the advantage of separating the exiting electron bunch from the radiation and therefore it reduces the background radiation.

The fundamental mode frequencies can be varied by changing the parameter a (though there is complicated nonlinear dependence on other parameters as well). For example, if b is fixed at 120 µm, 90 um in a gives 1.1 THz as fundamental mode and 3.5 THz as its second harmonic mode. On the other hand, 110 µm in a gives 2.2 THz, while the second harmonic is 9.5 THz. A parametric scan of dielectric thickness $(b-a)$ and ε_r at fixed inner radius $a = 100$ µm is show in Fig. 6. To get the mode above 1 THz at $\varepsilon_r = 3.8$, the dielectric thickness should be less than 35 µm. One can choose relatively small ε_r to relieve the requirements on the thickness. Though dielectric material can provide continuous ε_r up to hundred, the multiphysics effects such as vacuum compatibility, heat conduction, mechanical rigidity should be taken into account.

So far, we have considered the eigenmode of the DLW and the excitation with a single point charge. In reality not all modes supported by a DLW can be excited due to the finite length of the electron bunch. For example, to excite 1 THz, an electron bunch which is approximately 1 ps long will be required for the coherent excitation. Thanks to the ultrashort electron bunches (~ 25 fs) available at SwissFEL, the frequency range of 3-20 THz can be covered via harmonic excitation.

One disadvantage with the circular cross section DLW is that the mode in the different set of frequencies will require a different DLW, which might be inconvenient for some experiments involving frequency scan. If the requested pulse frequency falls out of the mode family of a certain structure, then a different DLW is requested, which could be also easily loaded into the experimental environment. As an alternative, a variable gap may be introduced into the DLW as an additional degree of freedom for frequency control. However, this is reserved for future research and is beyond the scope of the current paper.

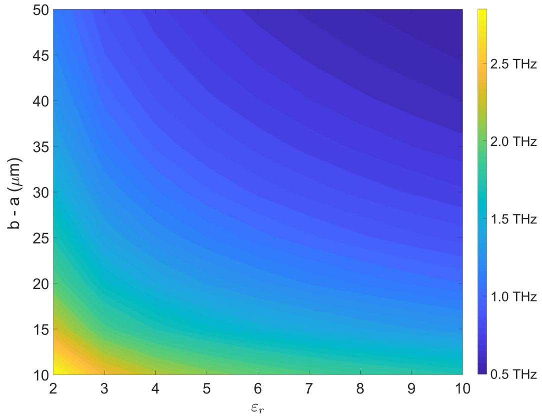

Figure 6: TM_{01} frequency versus ε_r with different thickness $b-a$.

EXPERIMENTS AT SWISSFEL

To test the numerical model, we have several DLW with different sizes (a, b and L) available in the lab. These DLWs are normally with 10% nominal tolerance in their radii. They will be tested in the switchyard of the ATHOS beamline in the ACHIP chamber [6] as depicted in Fig. 1. A schematic of the experimental setup is shown in Fig. 7. The beam optics study in [12] shows the promise of the electron transmission as outlined for the dielectric laser acceleration structure for the ACHIP experiment. In that numerical study, the electron beam could be focused strongly down to sub µm size with a quadrupole triplet made of permanent magnet before the DLW location in the chamber and another quadrupole triplet was designed to rematch the beam optics to the following beam line. Though the study in [12] was for 1 pC charge, 100 pC would only bring the transverse size approximately twice larger if one assumes that the emittance scales roughly with the charge Q as $Q^{1/3}$ when generated in the RF gun and optimized for the minimal emittance. This is not an issue for the present hundred µm aperture of the DLW.

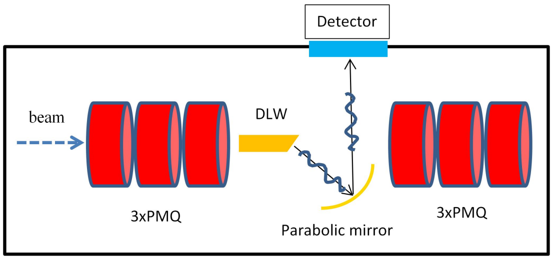

Figure 7: Experimental setup for THz generation and detection.

Subject to the success of the proof of principle experiment in the ACHIP chamber, the final THz setup could be located at the end of the ARAMIS beamline. We could then transport the generated THz to the photon end station in combination with the soft X-ray pulses from ATHOS for pump-probe experiments. The THz pulse due to its high power and peak field can certainly serve as an independent THz source as well. Although the DLW can be used for the experiments if the mode frequencies matches with what requested by users, a different tunable structure might be needed in case a continuous scanning of the spectrum is desired. We therefore will also investigate other tunable dielectric structures after the first demonstration experiment.

CONCLUSION & OUTLOOK

We presented the numerical study of the DLW based THz radiator. It can provide high power, narrowband pulses with certain tunability operating in the range of 1-20 THz. The DLWs will be characterized both in the lab and at SwissFEL.

The transmission, attenuation and heat load will need to be quantified for the DLW in 1-20 THz. We also ignored the nonlinear effect of the dielectric material, which should be investigated in the future. To achieve continuous tunability of the mode frequency, a more advanced dielectric structure with a tunable gap will have to be investigated in the future.

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