BROADLY TUNABLE THZ FEL AMPLIFIER*

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Abstract

In this paper we present a broadly tunable high-power THz FEL amplifier driven by a photoinjector with a seed source tunable between 0.7-2.0 THz. A fully synchronized THz seed pulse is provided by an optical parametric amplifier pumped by the very driver laser of the electron injector. The FEL amplification gain is almost 3000 at 2 THz for nominal input beam parameters.

INTRODUCTION

In the THz region, high power radiation sources are scarce. A free electron laser is known to be high-power and tunable over a wide spectral range. In the past, FEL oscillators were often built generate high-repetition-rate [1,2] or quasi-CW [3] THz radiation. With rapid advancement on high-brightness photoinjectors, single-pass FELs are playing a crucial role in generating high-peak-power laser radiation through self-amplified spontaneous emission (SASE) [4]. Unfortunately a low-energy beam is susceptible to the space charge effects and makes a SASE THz FEL more difficult to realize. In addition, it is well known that the noisy spectral and temporal output of a SASE FEL is suitable for applications requiring high spectral and temporal purity. Recently, kW-level tunable THz radiation sources are becoming available from optical technologies. A possible path to realizing a MW-level tunable narrow-line THz source is to seed an FEL amplifier with a fully tunable optical THz source. This idea was studied in the past with a limited wavelength-tunability from a CO_2-laser pumped THz different frequency generator (DFG) using GaAs as its gain material [5]. In this paper, we present a design for a high-power tunable THz FEL seeded by an all-solid-state THz parametric amplifier (TPA) broadly tunable between 0.7 and 2 THz.

SYSTEM LAYOUT

Figure 1 shows the design concept of the proposed FEL amplifier to generate fully tunable, narrow-line, high-power THz radiation. The proposed THz FEL system comprises two major components, the FEL amplifier and the THz seed. The FEL beamline consists of a high-brightness photoinjector and an undulator. The THz seed is a tunable TPA using a lithium niobate ($LiNbO_3$, LN) crystal as its gain material. One unique design that greatly simplifies the operation of the system is to use the driver laser of the photoinjector to pump the TPA and generate a fully synchronized seed THz pulse for the FEL. First, a Nd:YVO_4 mode-locked laser at 1064 nm is sent into a Nd:YAG regenerative amplifier to gain tens of mJ pulse energy. The laser pulse is then divided into two parts; the first part is frequency-quadrupled to ultraviolet to drive the photoinjector and the other is sent to pump the TPA to generate a THz seed pulse to the undulator. As will be shown below, this TPA is capable of generating a kW THz pulse with tunability between 0.7 and 2.0 THz.

Figure 2 shows the hardware arrangement of the proposed single-pass THz FEL amplifier, including a photoinjector, a solenoid, and an undulator. The total length of the setup is about 3.5 m. The accelerator is a 2.856-GHz BNL/SLAC/UCLA type photoinjector [6], generating a 3-5 MeV electron beam with 0.5-nC charge. A solenoid magnet following the gun compensates the emittance growth of electron bunch and focuses the electron beam to the undulator. Installed between the solenoid and the undulator is an input mirror for the THz seed. To keep the whole system compact, the mirror has an aperture to transmit the electrons.

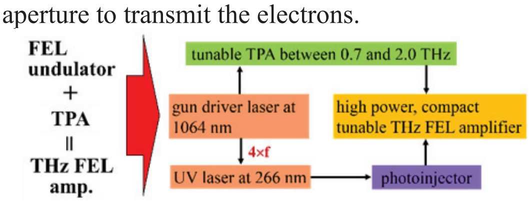

Figure 1: The design concept of the proposed high-power tunable THz FEL amplifier.

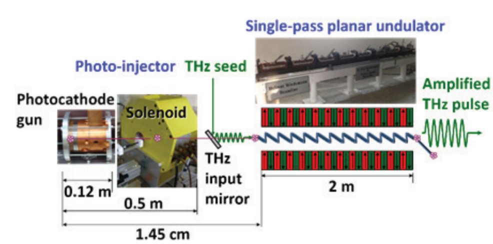

Figure 2: The hardware arrangement of the proposed THz FEL amplifier (planar undulator).

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THZ PARAMETRIC AMPLIFIER

Among various optical THz technologies, nonlinear frequency mixing is known to offer an effective means to gemerate coherent THz-wave radiations at room temperature. One notable example is the THz optical parametric generation from LN. This nonlinear optical material is relatively stable, low-cost, and high-gain. In the nonlinear wavelength conversion process, birefringence phase matching in LN requires the THz wave to propagate away from the nearly co-directional optical pump and signal beams at about a 65° angle. In the past we have demonstrated efficient, narrow-line THz-wave generation from optical parametric oscillations in LN waveguides [7, 8]. Recently, using the same material, Minamide *et. al* further demonstrated kW THz radiation from a sub-ns TPA [9]. The proposed THz FEL amplifier, driven by a ps electron bunch, is to radiate a ps THz pulse. We therefore propose a TPA pumped by the ps driver laser of the photoinjector to seed the FEL amplifier with a fully synchronized THz pulse. Figure 3 depicts the schematic of our kW TPA seed source, wherein a pulse laser at 1064 nm pumps an LN crystal to amplify a weak signal tunable around 1070 nm and generate a tunable THz idler wave through difference frequency generation. The driver laser of the injector is an amplified mode-locked Nd:YVO_4 laser producing 10-mJ, 12-ps pulses at 1064 nm with a 10-Hz repetition rate. Approximately 1-mJ pulse energy is split from the gun driver laser to pump the TPA. The pumping intensity in an LN crystal can reach a few GW/cm^2 with a millimetre pump laser radius. Figure 4 shows the calculated parametric gain of LN over a frequency range between 0.5 and 2.5 THz based on a pump intensity of 1 GW/cm^2 [10]. For a parametric gain coefficient of 12 cm^{-1}, it is sufficient to generate 1 kW THz radiation from a 1-W seeded TPA with a LN crystal length of 1 cm. The 1-W signal seed to the TPA can be obtained by amplifying an external-cavity tunable diode laser (ECDL) at ~1070 nm in a Yb fiber laser amplifier. An ECDL laser usually has a MHz line width. Pumped by a transform-limited Nd laser at 1064 nm and seeded by a MHz line-width signal, the TPA is expected to generate a transform-limited THz seed pulse for the FEL amplifier.

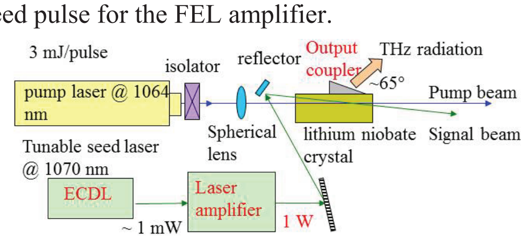

Figure 3: Configuration of a proposed TPA to seed the FEL undulator. The pump laser, derived from the gun driver laser, is focused into an LN gain crystal to amplify a laser signal tunable around 1070 nm and generate a tunable THz radiation.

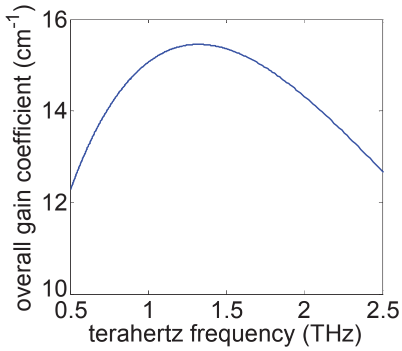

Figure 4: Calculated gain coefficient for the proposed TPA with 1 GW/cm^2 pumping intensity at 1064 nm. Such gain is sufficient to generate 1 kW power at THz from 1-cm long LN TPA with 1-W seed power at about 1070 nm.

THZ FEL AMPLIFIER

We simulated the acceleration and propagation of the electrons by using the simulation code ASTRA. By varying the peak acceleration gradient of the photoinjector from 72 to 120 MV/m, the electron output energy varies from γ = 6.41 to 10.76, respectively. Assuming an undulator period of 18 mm and undulator parameter of 0.98, the radiation frequency is in the range of 0.7 to 2 THz. The solenoid after the gun provides a peak magnetic field adjustable between 1.4-2.1 kG to compensate emittance growth at different beam energies. From our stimulation study, the optimized beam parameters at the undulator entrance are: electron bunch length = 10 ps, transverse beam width = 0.5 mm, normalized emittance = 3.5π mm-mrad.

The electrons form microbunches when interacting with the seed THz field in the undulator. Therefore bunching factor in the undulator is an important indication for the FEL amplification gain. Figure 5 shows the bunching factors of the electrons obtained from time-dependent GENESIS simulations with 1 kW seed power at 0.7, 1.4, and 2.0 THz in the 2-m long undulator. The corresponding beam energies are γ = 6.41, 9.06 and 10.76 for the 0.7, 1.4, and 2.0 THz radiations, respectively. Since a higher energy beam suffers less from the space charge effects, the bunching factor of the 2-THz case is evidently higher than the others. As will be seen below, this higher bunching factor helps the FEL power to build up at 2 THz.

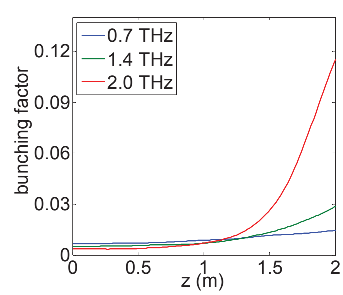

Figure 5: Variation of the bunching factors in the undulator with 1 kW seed power at 0.7, 1.4, and 2.0 THz. (Results obtained from simulation in GENESIS).

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Figure 6 shows the FEL power versus undulator length, obtained from our GENESIS simulation. The FEL output power varies between 0.013 – 2.74 MW for the frequency range between 0.7 - 2.0 THz. The amplification gain at 2.0 THz is almost 3000.

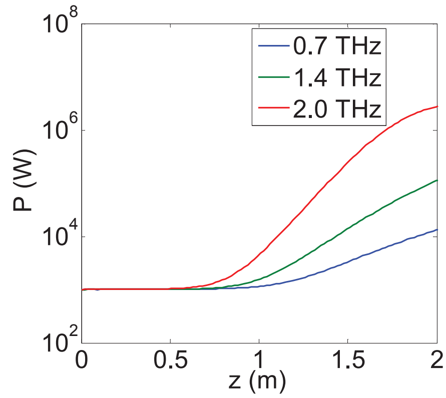

Figure 6: Radiation power vs. undulator length at 0.7, 1.4, and 2.0 THz with 1 kW seeding power.

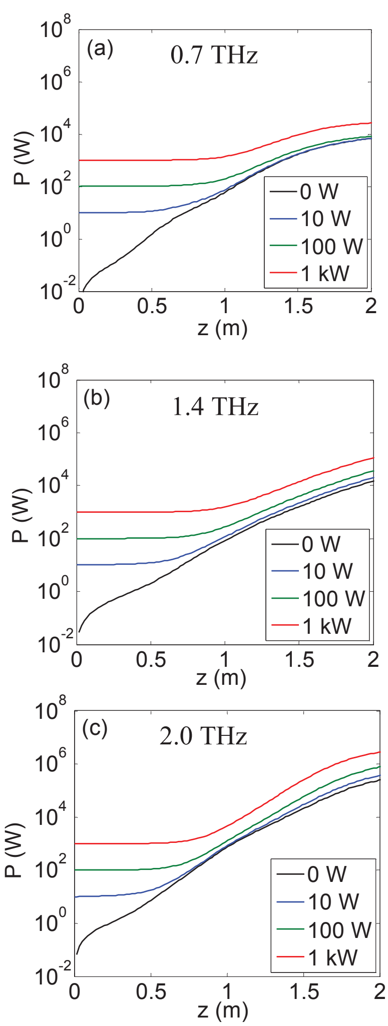

Figure 7: Build-up of FEL powers at (a) 0.7, (b) 1.4, and (c) 2.0 THz with different seeding powers to the undulator. A higher seeding power helps to quickly build up the FEL output.

In Fig. 7, we compare the radiation powers of the FEL amplifiers at (a) 0.7, (b) 1.4, and (c) 2.0 THz with different seed powers. The 0-W case is equivalent to a SASE FEL, which is known to give a noisy output. It is seen from the figures that a high seed power helps to quickly build up the FEL power, in addition to ensuring the spatial and temporal coherence of the output.

CONCLUSION

We have presented a compact, high-power FEL amplifier broadly tunable between 0.7 and 2.0 THz. The FEL amplifier consists of a 3-5 MeV photoinjector, an enmittance compensating coil, a 2-m long undulator, and a kW tunable seed source at THz frequencies. A unique feature of this FEL amplifier is to convert part of the gun driver laser pulse to a fully synchronized THz pulse to seed the FEL amplifier, permitting generating of amplified coherent tunable radiation at the output with a power range between 13 kW and 3 MW.

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