A COMPACT, WAVELENGTH TUNABLE MW-THz FEL AMPLIFIER

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Abstract

In this paper, we study the amplification of a tunable THz seed laser in an FEL amplifier driven by an rf photoinjector. The THz seed laser is an optical parametric amplifier pumped by an external-cavity tunable diode laser. By varying the beam energy and undulator parameter, the radiation frequency of the THz FEL amplifier can be tunable in a broad spectral range between 1.5 and 3.0 THz. Our simulation results show that the radiation power of the THz FEL amplifier can achieve few MW with a 10-W seed power.

INTRODUCTION

For optic-based light sources, THz waves can be generated by difference frequency generation (DFG) in a nonlinear optical material [1], optical rectification (OR) using an ultra-fast laser in a nonlinear optic material [2], photoconductive switching with a laser gated current in a photoconductive material [3], quantum cascade laser (QCL) [4], laser plasma interaction [5] and so on. However, the peak-power can be achieved by most of optic-based THz sources are usually under MW-level.

On the other hand, broadly tunable THz waves can be generated by some accelerator-based light sources, such as synchrotron radiation, backward-wave oscillation (BWO), and free-electron laser (FEL). Thus, the THz radiation from a SASE FEL is difficult to reach saturation. In addition, the noisy spectral and temporal profiles of a SASE FEL are unsuitable for applications requiring high spectral and temporal purity. To overcome the problems in SASE FELs and shorten the undulator, several schemes have been proposed, such as superradiant THz FELs [6], and FEL amplifiers with THz seeds [7].

Since kW-level tunable THz sources are available from optical technologies, there is a good possibility of realizing a MW-level tunable narrow-band THz source by seeding an FEL amplifier with a tunable optic-based THz laser. As an example, a group in the Neptune Laboratory at UCLA designed an FEL amplifier driven by 5-14 MeV electron beams, with a kW THz seed generated by frequency mixing two beamlines of a CO_2 laser into a GaAs nonlinear crystal [7]. In this paper, we present a design of a MW THz FEL amplifier with a considerably broad tunability between 1.5 and 3 THz driven by a low energy electron beam and seeded by an all-solid-state THz parametric amplifier (TPA).

THz PARAMETRIC AMPLIFIER

Here, we employ an external-cavity tunable diode laser (ECDL), which typically has a spectral bandwidth of few MHz, to achieve TPA near the transform-limit. Figure 1 shows the experimental setup of the TPA system. A microchip 1064-nm Nd:YAG laser produces 550-ps pulses with a repetition rate of 10 Hz is used as the pump laser in the TPA system. The gain medium of the quasi continuous wave (QCW) amplifier is a diode-pumped Nd:YAG. The amplified 1064-nm wave can reach 6 mJ in a double-pass configuration. The pump intensity in an LN crystal can reach few GW/cm^2 with a millimeter pump laser radius. Figure 2 shows the measured pump intensity of our ECDL at different wavelengths, and calculated parametric gain of LN within a spectral range between 0.3 and 3 THz based on a pump intensity of 1 GW/cm^2. The horizontal axis in Fig. 2 represents the converted wavelength of the output THz radiation corresponding to the signal wavelength. In addition, those peaks show the experimental spectra from the wavelength-tunable ECDL. For a parametric gain coefficient of 12 cm^{-1}, it is sufficient to generate 1 kW THz radiation from a 500-mW pumped TPA with a 4.5-cm long LN crystal.

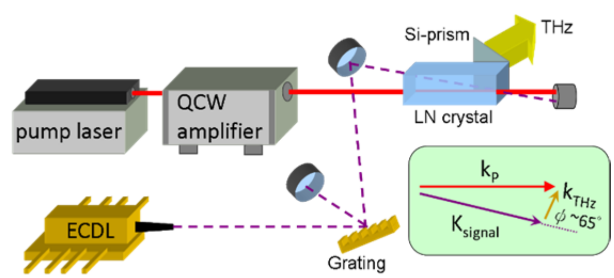

Figure 1: Configuration of the proposed TPA to seed the FEL amplifier.

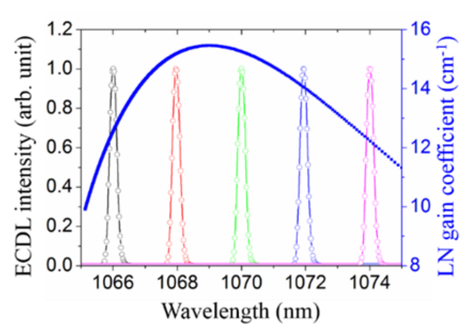

Figure 2: Calculated gain coefficient for the proposed TPA.

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SYSTEM LAYOUT

The proposed THz FEL amplifier system is composed of an rf photoinjector, a solenoid magnet, a tunable THz seed, and a variable-gap undulator. The hardware arrangement of the proposed single-pass THz FEL amplifier is shown in Fig. 3. The THz seed laser is a spectral-tunable TPA using a LN crystal as its gain material. The total length of the setup is within 3.5 m. The electron source is a 2.856-GHz BNL/SLAC/UCLA type rf photoinjector [8] driven by a 266 nm UV laser, generating a MeV electron beam with 0.5-nC charge. The solenoid magnet following the photoinjector compensates the emittance growth of the electron bunch and focuses the electron beam into the variable-gap undulator. Between the solenoid and undulator, there is an input mirror for reflecting the THz seed with an aperture at the center for transmitting the electrons. The FEL radiation wavelength λ_r depends not only on the undulator parameter, but also on the energy of the electron beam, as expressed as [7, 9]

$$\lambda_r(z) = \lambda_u \frac{1+a_u(z)^2}{2\gamma(z)^2}, \quad (1)$$

where z is the longitudinal position in the undulator, λ_u, $a_u(z)$ and $\gamma(z)$ are the undulator period, undulator parameter and Lorentz factor of the electron beam, respectively. Eq. (1) is known as the resonant condition. By varying the beam energy or the undulator parameter, the radiation wavelength of the FEL amplifier can be adjusted. The beam energy can be conveniently adjusted by varying the acceleration gradient of the photoinjector, and the undulator parameter $a_u(z)$ is also tunable in a variable-gap undulator.

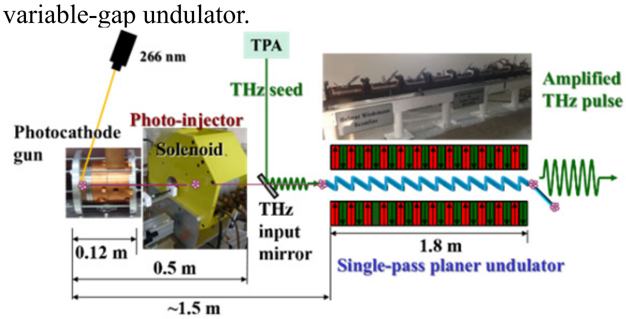

Figure 3: The hardware arrangement of the proposed THz FEL amplifier.

The acceleration and propagation of the electron beam from the cathode of the photoinjector to the entrance of the undulator is simulated by using the particle tracking code ASTRA. Table 1 lists the relevant parameters used in our simulation. By varying the peak acceleration gradient of the photoinjector from 94 to 116 MV/m, the electron output energy varies from 4.29 to 5.37 MeV (γ = 9.40 to 11.51). Such an energy-tunable beam is suitable for driving a spectrally tunable THz FEL amplifier.

In our design, a 1.8-m long planar undulator with a fixed period $\lambda_u = 18$ mm and a tunable undulator parameter $a_u(z)$ is used as the radiator in our FEL amplifier. To compensate the energy loss, the undulator parameter $a_u(z)$ is linearly tapered along the z-direction. In order to fully cover a broad spectral range between 1.5 and 3.0 THz, we set the initial undulator parameter $a_u(0)$ to be 0.98 and 0.69 for the spectral ranges $1.5 \le f_r \le 2.25$ and $2.25 < f_r \le 3.0$ THz, respectively, where f_r represents the radiation frequency. Note that, the peak solenoid field is adjusted between 0.176 and 0.206 Tesla for slowly focusing electron beams into the undulator. Since the focal point (or the waist position) of the electron beams with different energies are slightly different, the position of the undulator should be adjusted correspondingly. Table 1 lists the beam parameters at the undulator entrance obtained from our ASTRA[10] simulation. The interaction between electron bunch and seed source will lead to the growth of FEL, a significant field interaction is building on the seed pulse fully covering with the electron bunch in the beginning of FEL process. Figure 4 shows that the injections of the electron beam and seed laser are both of 12-ps duration to synchronize in the undulator, and use the beam parameters in Table 1 to simulate the FEL amplification in the undulator by the 3D time-dependent simulation code GENESIS[11].

Table 1: Parameters of the THz FEL Amplifier

Parameters of the photoinjector, solenoid and undulator	
Accel. gradient in the photoinjector (MV/m)	94 ~ 116
Solenoid field (Tesla)	0.176 ~ 0.206
Position of the undulator entrance (m)	1.46 ~ 1.70
Total length of the undulator (m)	1.8
Period length of the undulator (cm)	1.8
Period number	100
Initial undulator parameter a_u (0)	0.98 (1.5~2.25 THz), 0.69 (2.25~3.0 THz)
Beam parameters at the undulator entrance	
Beam charge (pC)	500
Beam energy (MeV)	4.29 ~ 5.37
Bunch length (rms) (ps)	3.3
Energy spread (%)	0.97 ~ 1.4
Peak current (A)	52 ~ 54
Normalized emittance (πmm-mrad.)	2.9~3.1
Beam radius (rms) (μm)	340 ~ 370
Slippage length (cm)	1~2

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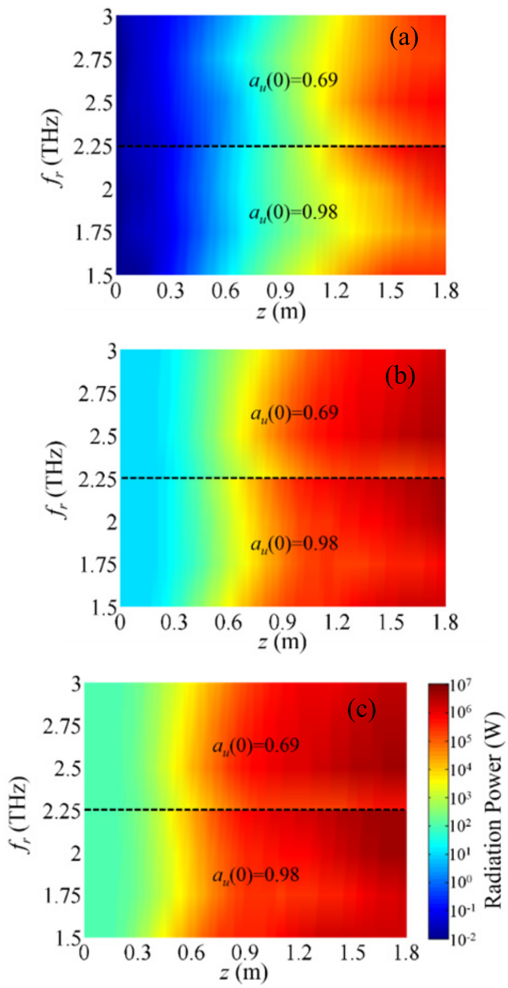

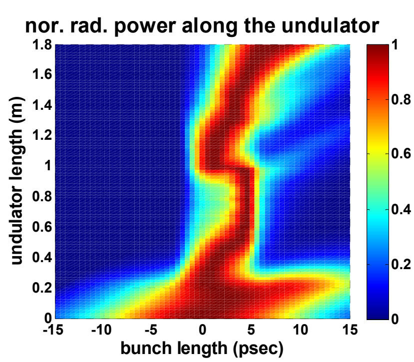

Figure 4: The length of injection beam and seed laser are synchronized in the undulator entrance .

THz FEL AMPLIFIER

With a high-brightness electron source, a high power THz seed and a tapered undulator, it is possible to establish a THz FEL amplifier and generate broadly tunable MW THz radiation. Figure 5 (a-c) show our GENESIS simulation results of the THz FEL radiation growth between 1.5 and 3.0 THz with 0, 10 and 100 W seeds in a 1.8-m long variable-gap undulator. Note that, the initial undulator parameter $a_u(0)$ is set to be 0.98 and 0.69 for $1.5 \leq f_r \leq 2.25$ and $2.25 < f_r \leq 3.0$ THz, respectively. Since we used different undulator parameters for the two parts of the full coverage in our simulations, the radiation growths in Fig. 5 (a-c) are discontinuous around f_r = 2.25 THz. The 0-W case in Fig. 5 (a) is equivalent to a SASE FEL, the start-up from weak noises results in a noisy output spectrum and poor temporal coherence. As shown in Fig. 5 (b, c), the propagation distance of an electron beam in the undulator to achieve the FEL saturation regime can be shorten by increasing the seed power. Form Fig. 5 (b, c), we can see that the radiation peak power of the electron beams can achieve few MW at the undulator exit with 10 and 100 W seed powers.

Figure 5: Radiation power v.s undulator length with (a) 0, (b) 10 and (c) 100 W seed powers. Note that, the initial undulator parameter $a_u(0)$ for $1.5 \leq f_r \leq 2.25$ and $2.25 < f_r \leq 3.0$ THz are set to be 0.98 and 0.69 in the simulations, respectively.

CONCLUSION

We present the scheme of TPA for generating broadly tunable THz seed pulses, and a compact design of a broadly tunable MW THz THz FEL amplifier. Among a variety of optic-based THz sources, TPA is a relatively compact, stable, low-cost and highly efficient nonlinear wavelength conversion scheme for generating high power THz waves. According to our experimental results and analysis, the peak power of the THz radiation generated from 500 mW pumped TPA is possible to achieve 1 kW with a wide spectral range.

To further increase the power of THz radiations, we propose to seed a THz FEL amplifier by the TPA seed laser. The THz FEL amplifier is composed of an rf photoinjector, a solenoid magnet and a 1.8-m long variable-gap undulator, and the length of the whole system is within 3.5 m. With an energy modulation imprinted by the seed laser, the electron beam rapidly microbunched at the wavelength of the seed laser within a short undulator distance. We employ a linear undulator tapering in our design to convert more energy from the electron beam into the radiation at the resonant frequency. Our simulation results show that the radiation power of the THz FEL amplifier can achieve MW-level within a 1.8-m long undulator with a 10-W THz seed, and the radiation frequency of the THz FEL amplifier is broadly tunable between 1.5 and 3.0 THz.

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