HIGH-GAIN SEEDED FEL AMPLIFIER TUNABLE IN THE TERAHERTZ RANGE

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Abstract

The lack of a high-power, relatively low-cost and compact terahertz (THz) source in the range 0.3-3x10^{12} Hz is the major obstacle in progressing on biomedical and material studies at these wavelengths. A high-gain, single pass seeded FEL technique allows to obtain high power THz pulses of a high spectral brightness. We describe an ongoing project at the Neptune laboratory where a ~ 1kW seed pulse generated by difference frequency mixing of CO_2 laser lines in a GaAs nonlinear crystal is injected into a waveguide FEL amplifier. The FEL is driven by a 5 ps (r.m.s) long electron pulse with a peak current up to 100A provided by a regular S-band photoinjector. According to 3-D, time dependent simulations, up to ~ 10 MW THz power can be generated using a 2 meter long planar undulator. By mixing different pairs of CO_2 laser lines and matching resonant energy of the electron beam, tunability in the 100-400 μm range is expected. A tunable Fabry-Perot interferometer will be used to select a high-power 5ps THz pulse. This pulse is synchronized both with 1μm (photoinjector driver) and 10 μm lasers allowing time resolved pump-probe measurements.

INTRODUCTION

Free-electron lasers (FELs) are well established as a versatile source of high-power tunable laser radiation in wavelength ranges where other laser sources are scarce [1]. In particular, the THz range of the spectrum can be conveniently covered by FELs because of the rather modest requirements on the electron beam parameters. Two FEL configurations can be used for generating high-power THz pulses: an FEL oscillator and a single-pass FEL amplifier. A multi-pass FEL oscillator is driven by a few microsecond long electron beam of relatively low peak current that makes the task of obtaining high THz peak power difficult. A single-pass FEL amplifier based on self-amplified spontaneous emission (SASE) is capable to produce a MW power THz pulse in a multi-meter long undulator. However, picosecond synchronization of the radiation pulse with an external laser source important for pump-probe experiments is hindered. A seeded single-pass FEL amplifier can significantly shorten the undulator length, but this technique in the THz range is not studied yet due to the lack of a proper THz seed source.

Here we describe an ongoing project at UCLA on a seeded high-gain FEL amplifier tunable in the 0.5-3 THz range [2]. A THz seed source is based on the difference frequency mixing of CO_2 laser lines in GaAs. Seeding will allow to obtain a 1-10 MW power level in a compact 2-m long undulator driven by a 10 MeV, 10 ps (FWHM) electron pulse from a regular S-band photoinjector.

HIGH-GAIN SEEDED THZ FEL AMPLIFIER AT NEPTUNE

A high-gain seeded THz FEL amplifier at the Neptune Laboratory at UCLA consists of four main subsystems: an RF photoinjector, a THz seed source, a waveguide FEL undulator and THz diagnostics.

The S-band photoinjector at the Neptune Laboratory can provide a relativistic 10 ps long electron pulse with a peak current up to 100A. The electron beam is sent through a hole in a mirror to propagate collinearly with a THz seed pulse inside the undulator.

The THz seed pulse is generated by mixing two lines of a CO_2 laser via difference frequency generation (DFG) in a nonlinear crystal GaAs. A 20MW, high pulse-repetition-rate, dual-beam CO_2 laser operating at two independently tunable wavelengths is under development. When two CO_2 laser lines are mixed into GaAs for DFG, the step-tunable THz seed radiation is generated in the range 0.3-3 THz.

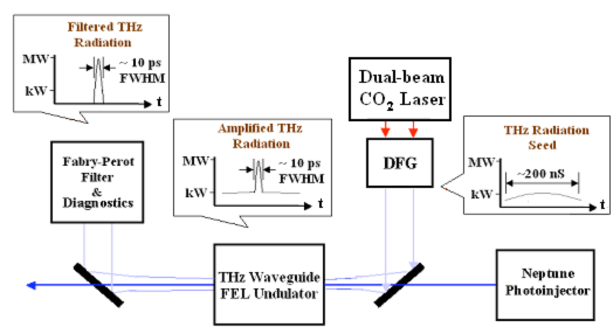

Figure 1. Schematic of the high-gain seeded THz FEL amplifier experiment at the Neptune Lab, UCLA.

This kW power THz seed radiation is focused into a waveguide within a planar THz undulator and is amplified to 10 MW level in the FEL.

After the undulator, 200ns long, 1kW seed pulse is filtered out by a scanning Fabry-Perot interferometer. To characterize the 10ps long, MW level amplified THz pulse, an electro-optic sampling technique in combination with a fast steak camera has been considered.

WAVEGUIDE FEL AMPLIFIER

It is known that power increase in a high-gain, seeded FEL is directly related to the energy modulating process of the electrons occurring along the undulator.

If an electron experiences a full cycle of changing of electric field while wiggling one period in the undulator, the energy modulation is maximized and the resonant condition is:

$$\lambda = \frac{\lambda_w}{2 \cdot \gamma^2} \cdot \left(1 + \frac{K^2}{2}\right) \tag{1}$$

where $K=eB_w/mc^2k_w$ is the dimensionless undulator parameter, λ is the radiation wavelength, γ the electron energy, λ_w the undulator wavelength, k_w the undulator wave number and B_w the undulator magnetic field.

As seen in Eq. 1, in any given undulator, tunability can be obtained by tuning energy γ of electron beam to match the prospective resonant wavelengths. Results of 1-D optimization of undulator parameters are shown in Fig. 2. Considering the THz wavelength range and the Neptune photoinjector operating range, we choose the resonant condition (solid curve in Fig. 2) such that $\gamma=26$ and 15 corresponds to $\lambda=100\mu$m and 300μm, respectively. As seen in Fig. 2, to maximize the FEL interaction, λ_w and B_w are chosen along the solid cure for the largest possible K (dashed lines). However, the Halbach criterium (shown in Fig. 2 by dotted lines) limits the choices because of the physical restriction in building magnets with small periods. Due to the large divergence angle of the THz radiation, guiding is necessary for a meter or longer undulator. After the optimization, the waveguide ID is chosen to be 5mm and a planar undulator with λ_w=2.7cm, and B_w=1.14 T (K=2.85) is used for following simulations. Note that the fundamental mode size of THz radiation inside the waveguide is around 1.5 mm. It covers the whole wiggling motion amplitude (<700μm) plus the electron beam size ($\sigma_{r.m.s}$ < 220μm.).

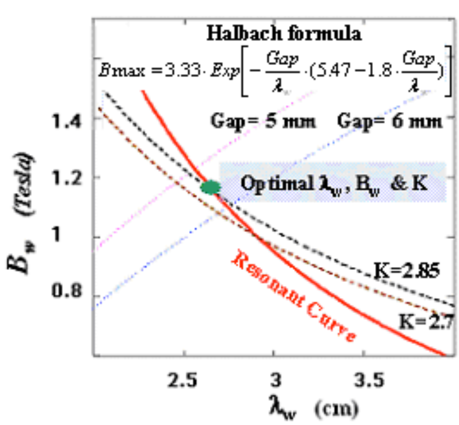

Figure 2: Optimization of undulator parameters for THz waveguide FEL.

A 3-D, time-dependent code GENESIS, which includes the space charge effect, is used for modeling the seeded waveguide FEL amplification process. The results are shown in Fig. 3.

In Fig. 3(a), it is shown that with a seed power 1kW, a 10ps long electron pulse with a modest peak current 40A provides MW level of THz power in an approximately 2 m long amplifier. As seen in Fig. 3(b), a higher seed power doesn't affect the gain or the saturation power level but makes the saturation happen earlier.

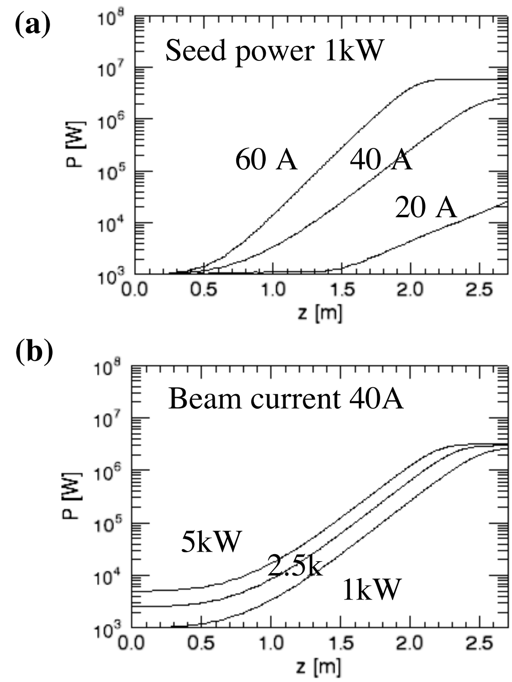

Figure 3: Calculated THz power vs. the undulator length with various (a) beam current and (b) seed power (λ_w~2.7cm, B_w~1.14 T, γ~19.5, and λ~200μm).

The spectral tunability of the optimized undulator is shown in Fig. 4. The tunability in our case is limited by the energy of the electron beam obtained from the photoinjector and LINAC. Simulations were run to model three fixed wavelengths 100, 200, and 300 μm. However, full coverage of the spectral range of 0.5-3 THz is expected. Even with the step tunable CO2 laser based seed source (steps of the order of 30-40GHz), the 10 ps THz pulse with a transform-limited bandwidth of ~100GHz will fill the whole mentioned spectral window.

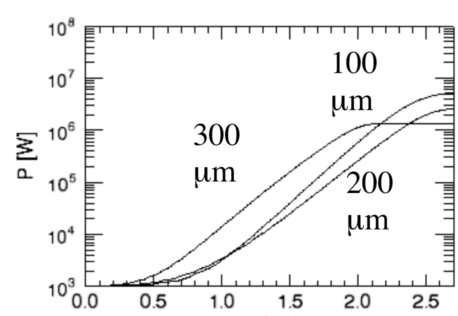

Figure 4: Calculated THz power as a function of the undulator length for different wavelengths (λ_w~2.7cm, B_w~1.14 T, γ~19.5, and λ~200μm).

Note that in Fig. 4, the gain difference between various wavelengths is mainly due to the slippage effect between the electron beam and the amplified THz radiation. When number of periods of the THz wave contained in the electron bunch is smaller than number of wiggling periods, the newborn radiation eventually overtakes the whole electron beam because of the slippage. This effect is stronger when operating at a longer wavelength and limits the overall gain of the FEL amplification.

We summarize parameters of the proposed tunable waveguide high-gain seeded THz FEL amplifier at the Neptune laboratory in Table 1.

Table 1: Parameters of the Neptune seeded waveguide THz FEL amplifier

E-beam parameters		Undulator parameters	
Energy	5-14 MeV	Period	2.7cm
Bunch length	~10ps FWHM	Strength	1.14 T
Current	20-60 A	Gap	5.5 mm
Beam size	100-250 μm	K	2.85
Transverse emittance	5-15 mm-mrad	Waveguide ID	5mm
		Length	2 m
THz radiation parameters			
Wavelength	100-300 μm		
Seed power	~ 1kW (~200ns)		
Pulse repetition rate	1Hz		
Amplified THz power	**< 10 MW**		
Amplified THz pulse length	**~ 10 ps FWHM**		

THZ SEED SOURCE

Recently, we demonstrated the THz generation via nonlinear frequency mixing of CO_2 laser lines in GaAs [3]. A two-wavelength laser beam was split and sent onto a GaAs crystal cut for noncollinear phase matching. Low power measurements achieved ~1W at 340 μm using 200 ns CO_2 pump pulses with wavelengths 10.3 μm and 10.6 μm. We also demonstrated tunability of difference frequency radiation by mixing two different CO_2 laser lines. For high power multi-GW pump pulses, we produced ~2 MW of 340 μm radiation using 200ps pulses. As shown in the experiments, THz beams can be easily guided by a metallic waveguide for more than few meters without any noticeable loss. All these measurements give us confidence in building a kW-power THz seed source for waveguide FEL.

We are presently developing a 1 Hz, 1 kW THz spectrometer via DFG for FEL seeding by using a dual-beam CO_2 laser. This dual-beam CO_2 laser utilizes one spark gap to trigger two parallel CO_2 discharging sections. There is no jitter between two optical pulses. To synchronize two optical beams, the gas mixture in the long wavelength (10.6μm) section is adjusted to compensate the gain difference between two lines. Preliminary measurements showed that the output energy of 2 J for a 200 ns long pulse was obtained in each arm. According to calculations using a plane wave approximation, this 20 MW pulses should be sufficient to generate the required 1 kW THz seed pulses.

In the experiment the two vertically polarized CO_2 laser beams are combined on a GaAs crystal according to a non-collinear phase-matching configuration. The optical scheme is shown in Fig. 5, which is very similar to the setup in the ref [4].

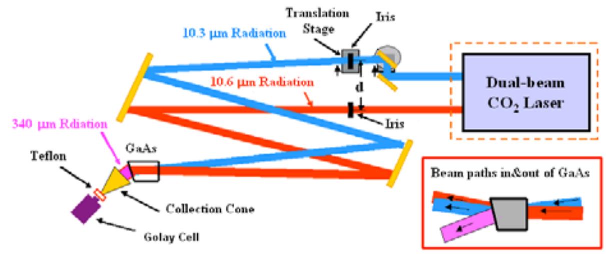

Figure 5. Optical scheme for THz seed generation.

The 10.6 arm is aligned at a normal incidence to the crystal face. The beam angle of the short waveguide arm (e.g. 10.3 μm) is adjustable in order to scan the phase matching angle. Because of a very long base of both arms, an angle resolution of less than 0.01° can be achieved when varying the distance between two irises. A 2x4x2.5cm GaAs crystal is cut in such a way that the newborn radiation is separated from the pump lasers due to refraction in the crystal to air interface (see the insert in Fig. 5). A slab of Teflon is also used to absorb any residual 10 μm radiation. Golay cell is used to measure the power of a long THz pulse.

THZ FILTERING AND DIAGNOSTICS

For many applications, a short, 10ps THz pulse with a high contrast is needed. Therefore, it is preferable to separate the amplified THz pulse from the original seed THz pulse. Considering the tunability of the FEL amplifier, we propose to use a scanning Fabry–Perot interferometer as a filter [4].

A Fabry-Perot interferometer (FPI) can be used to measure the radiation wavelength based on the constructive or destructive composition of radiations due to multiple reflections between two surfaces when adjusting the distance *d* between them. A metal wire grid polarizer with a reflectivity R > 99.9% at 1 THz is commercially available and can be used as a reflector to build a high finesse FPI. When the separation between two metal wire grids is ~ 5 mm, the bandwidth of the filter (~10 MHz) is larger than the transform-limited bandwidth of a 200ns pulse (~ 5 MHz). Therefore, it is possible to have a high transmission of the long seed pulse by finely adjusting *d*. However, the filling time of this Fabry-Perot cavity is on the ~10 ns scale such that the 10 ps amplified pulse will not interfere and be directly reflected by the first surface. With a multiple-path configuration, one could improve the contrast of the 10ps THz pulse up to 10^7.

Electro-optic sampling (EOS) is a common technique to diagnose and characterize a high power THz radiation. When the linearly polarized THz radiation passing through a nonlinear crystal, such as ZnTe, it introduces birefringence in the crystal. If a linearly polarized probe pulse is sent collinearly with this THz radiation in the crystal, the temporal information of the THz pulse can be deduced by analyzing the polarization change of the probe beam. Many groups have used EOS to resolve the temporal profile of a ~100fs THz pulse by measuring transmission while varying delay distances between pump and probe beams [5,6].

The pulse length of our undulator radiation is on 10 ps time scale. Therefore, it is possible to have a single shot EOS measurement by using a fast streak camera. The proposed visualization scheme using a red laser diode based on EOS is shown in Fig. 6. The filtered 10ps, 10MW THz pulse is focused onto a ZnTe crystal and combined with a linearly polarized 20ns long red pulse from a laser diode. By streaking the red pulse after the analyzer, the temporal profile of the THz pulse could be extracted.

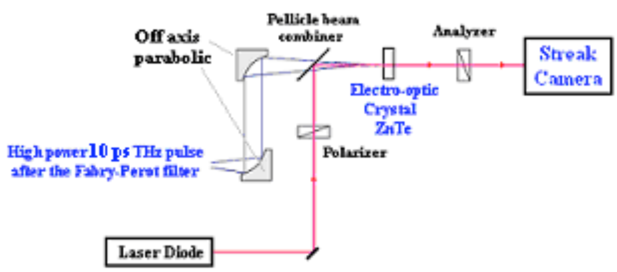

Figure 6. Dignostics of a 10ps, 10MW THz pulse by using electro-optic sampling with a streak camera.

STATUS AND FUTURE PLANS

In this paper, we describe a high-gain seeded waveguide FEL amplifier tunable in the range of 0.5-3 THz planned to build in the Neptune Laboratory at UCLA. Simulations have shown that a 10ps long THz pulse with a peak power 10 MW can be obtained in a 2-m long, uniform planar FEL undulator driven by the Neptune photoinjector At present, our efforts are concentrated on increasing the charge of the electron beam from 0.3 to 1.0 nC. The 1Hz THz spectrometer based on difference frequency mixing of two CO_2 laser lines for FEL seeding is being built and characterized.

Both Fabry-Perot interferometer and electro-optic sampling diagnostics for the THz radiation are in construction.

Further experimental results will be report in the future.

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