A HIGH-GAIN, TRANSFORM-LIMITED FAR-INFRARED FREE-ELECTRON LASER AMPLIFIER SEEDED BY A THZ SINGLE-FREQUENCY DIFFERENCE FREQUENCY GENERATOR

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Abstract

Narrow-line coherent radiations are important for applications requiring high spectral resolution. A free-electron-laser oscillator is usually complicated in alignment and hard to produce transform-limited linewidth without an intracavity dispersive optical element. An SASE free-electron laser, however, produces broad-band laser-like output in a single electron transit. In this paper, we discuss a high-gain, narrow-line far-infrared free-electron laser amplifier seeded by a THz single-frequency difference frequency generator. The wavelength-tunable THz seed laser is realized by using nonlinear frequency mixing in Nd:YAG-laser-pumped periodically-poled lithium niobate. The high-gain free-electron laser amplifier employs a 2-5 MeV microwave gun and a single-pass solenoid-derived stagger wiggler for producing transform-limited wavelength-tunable THz radiations between 100-300 micron wavelengths.

INTRODUCTION

In a self-amplified spontaneous emission (SASE) free-electron laser (FEL), laser-like radiation is built up from relativistic spontaneous radiation in one electron transit. This technique is particularly important in the THz and x-ray spectra where effective reflecting mirrors are not available. Because the output of an SASE FEL is essentially an amplified spontaneous noise in the FEL bandwidth, the spectral and temporal structures of a SASE FEL are fairly spiky. With the advancement in THz nonlinear frequency mixing, seeding a high-gain FEL amplifier with a weak narrow-line THz signal has become a viable technique to generate high-power THz coherent radiation.

An ultra-compact, low-cost THz FEL driven by a 1-1/2 cell RF thermionic gun was first built at Stanford University during 1990 and 1994 [1]. Since then, the RF thermionic gun was further improved for lower emittance and higher current. In the high-gain mode, the FEL signal grows exponentially along the wiggler length. To drive an FEL into the high-gain or SASE mode, a complex, expensive, and yet high-quality photocathode electron gun [2] is usually indispensable. Although a thermionic RF gun has high thermal emittance, at the THz wavelengths, the requirement on electron beam quality, including energy spread and emittance, is relatively less stringent for FEL operation. With an optimized system design, our study in this paper shows that a simple thermionic RF gun is capable of providing an amplification gain comparable to an SASE FEL to an injected-seeded high-gain THz FEL amplifier. In the following, we discuss a high-gain, narrow-line far-infrared FEL amplifier seeded by a THz single-frequency difference frequency generator (DFG) built from Nd:YAG-laser-pumped periodically poled lithium niobate (PPLN). The injection-seeded high-gain FEL amplifier is capable of producing > 100 kW peak power with a transform-limited linewidth at THz.

SINGLE FREQUENCY THZ DIFFERENCE FREQUENCY GENERATOR

In a THz nonlinear frequency-mixing process involving the second-order susceptibility, one pump photon produces two low-frequency output photons, the signal and idler, through an optical parametric process. The three photons must satisfy the energy and momentum conservation rules, $\omega_T + \omega_i = \omega_p$ and $\vec{k}_p = \vec{k}_T + \vec{k}_i$, where $\omega_{p,T,i}$ are the angular frequencies and $k_{p,T,i}$ are the wave numbers of the pump, THz signal, and idler photons, respectively. When the energy and momentum are conserved in the THz optical parametric process, the signal laser enjoys exponential growth in the high gain regime. Specifically the signal power has the form $P_s(z) = P_s(0)\exp(\Gamma z)/4$, where $P_s(z)$ is the signal power at position *z*, and the exponential gain coefficient Γ is proportional to the effective nonlinear coefficient of the material d_{eff} and the square root of the pump power P_p, $\Gamma \propto d_{eff}\sqrt{P_p}$. The effective nonlinear coefficient depends on materials and laser polarizations. Like an SASE FEL, the THz radiation can be amplified to an appreciable value from the vacuum noise, if there is enough parametric gain. The THz parametric generation (TPG) is based on stimulated scattering of polaritons in lithium niobate. The parametric gain of $LiNbO_3$ TPG mostly results from cooperative coupling between electronic and ionic nonlinearity [3]. $LiNbO_3$, a polar crystal, has a transverse optical phonon mode that is Raman-active and infrared absorptive. Only the wave polarized along the crystal axis of the $LiNbO_3$ crystal can excite this mode. In such a material, the effective nonlinear coefficient d_{eff} becomes a linear sum of the electronic nonlinear coefficient d_E and an ionic nonlinear coefficient d_Q [4]. For THz laser generation from $LiNbO_3$, it has been observed that, although $d_E = d_{33} = 27$ pm/V, the ionic nonlinearity accounts for ~80% d_{eff} in $LiNbO_3$. This means that, despite that the THz-wave radiation is strongly absorbed in $LiNbO_3$, coherent TPG from the crystal is still fairly efficient by using a sufficiently strong pump power. Unfortunately, the material dispersion of lithium niobate only permits a non-collinear phase-matching configuration which severely limits the gain length in THz nonlinear frequency mixing [5]. Recently, periodically poled lithium niobate (PPLN) has attracted many attentions [6]. Nonlinear frequency conversion in PPLN permits collinear wave mixing with the highest possible nonlinear coefficient and the longest possible interaction length. Therefore, the TPG efficiency in a PPLN crystal can be considerably higher than that in non-collinear TPG. With the so-called quasi-phase-matching (QPM) technique in PPLN, the phase matching condition becomes

$$k_p = \pm k_T + k_i + \frac{2\pi}{\Lambda_{PPLN}}, \tag{1}$$

where Λ_{PPLN} is the ferroelectric domain period of the PPLN crystal. The $\pm k_T$ denotes the forward and backward propagations of the THz wave relative to the pump and idler waves. Given the mixing wavelengths, one can simply determine Λ_{PPLN} from the material dispersion of $LiNbO_3$ in the THz spectrum. Figure 1 shows the PPLN grating period versus the THz wavelength for 1064-nm pumped PPLN forward and backward TPGs. The PPLN grating can be fabricated by using standard semiconductor micro-fabrication techniques.

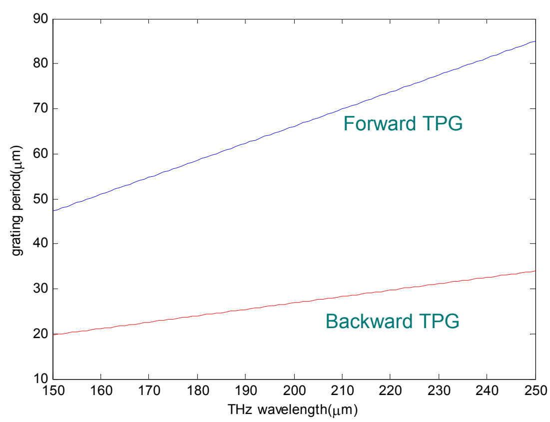

Figure 1: The PPLN grating period versus the THz wavelength for 1064-nm pumped PPLN forward and backward TPGs.

Recently, we have measured 150~300 μm wavelengths from 1064-nm pumped PPLN forward and backward TPG systems with unprecedented parametric efficiency. Usually TPG produces an output with a broad linewidth. To achieve transform-limited linewidth, two single-frequency lasers can be employed to perform difference frequency generation in lithium niobate and produce single-frequency THz radiations [7]. Coupled to the high-efficiency PPLN THz-generation technique developed in our laboratory, the THz DFG is to become an ideal seeding source for the proposed narrow-line, high-power THz free-electron laser amplifier.

HIGH-GAIN THZ FEL AMPLIFIER

Figure 2 depicts the layout of the proposed high-gain THz FEL amplifier. The RF system operates at the standard SLAC S-band frequency, 2.856 GHz. The thermionic gun produces 2~5 MeV electrons for the high-gain FEL amplifier. The electron beam line with a 90-deg bending angle is convenient for characterizing the energy spectrum and emittance of the electron beam. The THz seeding signal can be easily injected into the wiggler magnet from the second bending magnet. The lens-like symbols are magnetic quadruples for collimating the electron beam.

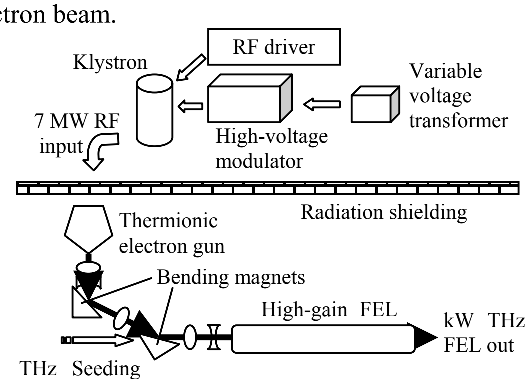

Figure 2: Equipment layout of the proposed high-gain THz FEL amplifier.

The microwave electron gun to be used in this design is similar to the 1-1/2 S-band thermionic gun installed at the Stanford Synchrotron Radiation Laboratory and the SUNSHINE facility on the Stanford campus [8]. This electron gun produces 2-5 MeV electrons with > 10-A peak current and < 1% energy spread in each 10 ps micropulse. The measured normalized emittance was about 10 mm-mrad. The technical details of this thermionic gun used in conjunction with a far infrared FEL were studied extensively in the past [9]. Since the invention of this RF gun in the late 1980s, the design of this RF gun has been greatly improved in reducing the emittance and enhancing the emission current. We anticipate a higher peak current, lower emittance, and much longer lifetime from this improved electron gun. In our following design, we still use the old-gun parameters to obtain a worst case estimate, while varying other FEL parameters to reach the FEL high-gain regime.

The FEL radiation wavelength is governed by the FEL synchronism condition,

$$\lambda = \lambda_w \frac{1 + K_w^2/2}{2\gamma^2}, \tag{2}$$

where λ is the FEL radiation wavelength, γ is the Lorentz factor, and $K_w = 0.093 \times B_w \times \lambda_w$ is the FEL parameter with B_w being the peak wiggler field in kgauss and λ_w being the wiggler wavelength in cm. For a peak wiggler field of 7 kgauss, a wiggler period of λ_w = 1 cm, and a 3-MeV electron beam, the FEL radiation has a wavelength of about 120 μm or a frequency of 2.5 THz.

In the high-gain regime, the seeding signal grows along the FEL-amplifier length z according to the exponential gain expression,

$$G = \frac{P(z)}{P_{in}} = \frac{1}{9}\exp(2z/L_g), \qquad (3)$$

where P_{in} is the injection seeded THz power and L_g is the field gain length. To have high gain, it is preferred to have a smaller L_g. According to the 1-D SASE theory [10], the FEL gain length is given by

$$L_g = \lambda_w / 2\sqrt{3}\pi\rho, \qquad (4)$$

where $\rho = (1/\gamma)(K_w\omega_p / 4\sqrt{2}ck_w)^{2/3}$ is the fundamental FEL parameter with $k_w = 2\pi/\lambda_w$, ω_p being the plasma frequency of the beam, and c being the velocity of light in vacuum. The 1-D model, Eqs. (3-4), is valid when the electron emittance < $\lambda/4\pi$, energy spread < ρ, and the electron pulse length is longer than the slippage distance. For THz SASE FEL producing wavelengths of a few hundred microns, a thermionic RF electron is sufficient to meet the requirements on emittance and energy spread. For an FEL amplifier, the slippage problem is minimized by seeding a signal pulse width much longer than the electron pulse length. In our case, the seeding THz has a pulse width of ~ns and the electron pulse length is ~10 ps.

From Eq. (4), the larger the FEL parameter, the smaller the field gain length, and the larger the amplification gain. After incorporating the electron parameters, one has the approximate expression for the FEL parameter

$$\rho \approx \frac{0.88}{\gamma}\frac{B_w\lambda_w^{4/3}I^{1/3}}{\varepsilon_n^{1/3}}, \qquad (5)$$

where ε_n is the normalized emittance. From this expression, it is possible to adjust the beam parameters to obtain a larger FEL parameter and thus a higher FEL gain. Assuming B_w = 7 kgauss, λ_w = 1 cm, and $\varepsilon_n = 2\times10^{-5}$ m-rad, we plot in Fig. 3 the power gain G versus the wiggler length for several peak currents. It is seen from the plot that, as long as the peak current is larger 5 A, the FEL power amplification gain can exceed the SASE FEL saturation gain, 10^8, in a meter-long FEL wiggler. The maximum output power is limited by the intrinsic FEL efficiency, $1/2N_w$, where N_w is the number of the wiggler periods. For a 1-m long wiggler and λ_w = 1 cm, the ideal limit of the saturation output power of the THz wave is about 150 kW.

In summary, we are conducting an experimental effort on a high-power far-infrared FEL amplifier seeded by a THz single-frequency optical parametric generator. We have produced mW-level THz waves from 1064-nm pumped PPLN TPG between 150~300μm wavelengths with an optical efficiency exceeding 10^{-6}. Transform-limited seed THz is being generated from a DFG process in the same experiment. With our design parameters, we predict a transform-limited THz radiation of ~150 kW from this FEL amplifier.

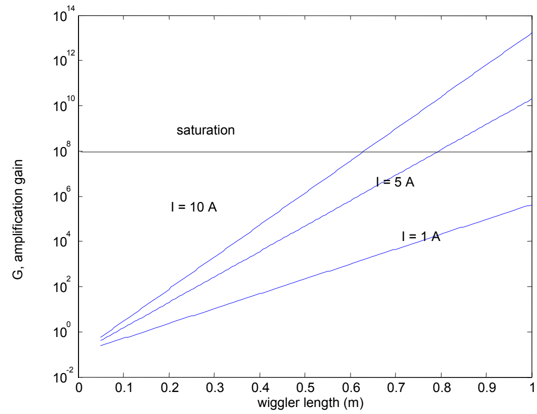

Figure 3: The FEL amplification gain versus FEL wiggler for the peak currents I = 1, 5, and 10 A.

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