Novel THz Radiation Sources

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Abstract. We discuss three novel terahertz (THz) radiation sources which all have the potential for producing high power, tunable frequency pulses of coherent THz radiation.

Keywords: Radiation source, coherent transition radiation, Cherenkov radiation, THz radiation, frequency downconversion.

INTRODUCTION

The development of terahertz (THz) radiation sources is a very active research field driven by many applications including life sciences, material sciences, and national security. Terahertz radiation is often produced as the by-product of an experiment. For example, plasmas with densities in the $10^{16} \text{–} 10^{17}\text{ cm}^{-3}$ range have a natural plasma frequency in the THz range. Large amplitude plasma waves are therefore potential sources of powerful THz radiation. Such large amplitude plasma waves are excited for example in plasma-based accelerators. Sub-picosecond particle bunches emit THz radiation when accelerated in the field of a bending magnet [1] (coherent synchrotron radiation or CSR) or when approaching dielectric or metallic surfaces (coherent transition radiation or CTR). In this paper we briefly discuss the characteristics and prospects of two new THz coherent radiation sources: Cherenkov wakes from magnetized plasmas, and coherent transition radiation (CTR) from sub-picosecond, relativistic particle bunches. We then discuss in more detail the production of THz radiation based on the downconversion of two-frequency CO$_2$ laser pulses in GaAs crystals. Using 10 µm radiation (~0.1 eV/photon) rather than 1 µm (~1 eV/photon) naturally increases the conversion efficiency. This last THz source also has some very promising applications in advanced accelerator concepts. All of these novel sources have the potential for producing high power pulses of tunable, coherent THz radiation.

CHERENKOV RADIATION FROM MAGNETIZED PLASMAS

Very large electric fields are generated in plasma accelerators. For example fields in excess of 10 GV/m have been measured in particle-beam-driven plasma wakefield accelerators or PWFA’s [2], while fields in excess of 100 GV/m have been measured in laser-driven plasma wakefield accelerators [3]. However these accelerating fields are mainly electrostatic or longitudinal, and therefore do not couple efficiently to the vacuum electromagnetic modes. The plasma wave excited by the driver also has a zero
The energy deposited in the plasma is ultimately dissipated as heat. However, adding a static magnetic field $B_0$ perpendicular to the driver trajectory changes the dispersion relation for the plasma modes. In particular, in the case of a laser beam driver, setting $B_0$ also perpendicular to the electric field of the linearly polarized laser beam allows for the excitation of or coupling to the lower branch of the extraordinary (XO) mode of the magnetized plasma [4].

**FIGURE 1.** Dispersion diagram for the waves in a magnetized plasma. The laser or particle beam is represented by the straight line at $\omega=kv_\text{g}\cos\theta$ and couples to the lower branch of the XO mode as Cherenkov radiation. The XO mode frequency is between $\omega_\text{L}=[-\Omega_{ce}+(\Omega_{ce}^2+4\omega_{pe}^2)^{1/2}]$ and the upper hybrid frequency $\omega_h=(\omega_{pe}^2+\Omega_{ce}^2)^{1/2}$.

In the dispersion or $\omega-k$ diagram (see Fig. 1), the coupling between the laser beam and the plasma mode is given by the intersection between the beam straight line with slope $\omega/k=v_\text{Laser} = v_\text{g}$ and the plasma mode dispersion curve. The group velocity of the laser pulse with angular frequency $\omega_\text{Laser}$ in the plasma with electron density $n_e$ is given by $v_\text{g} = (1-\omega_{pe}^2/\omega_\text{Laser}^2)^{1/2}c \approx c$ for $\omega_\text{Laser}^2 >> \omega_{pe}^2$. Sideways coupling at an angle $\theta > 0$ is described by the intersection of the beam line $\omega/k=v_\text{Laser}\cos(\theta)$ and the plasma mode dispersion curve. This coupling process can be viewed as Cherenkov radiation by the laser beam (i.e., photon!) in the plasma. The dispersion curves indicate that in the forward direction ($\theta \approx 0$), the mode frequency is $f_{pe} = \omega_{pe}/2\pi$. In the magnetized plasma, the excited mode has a non-zero group velocity given by $v_\text{g} = (\Omega_{ce}/\omega_{pe})c$ where $\Omega_{ce} = eB_0/m_e$ is the electron cyclotron angular frequency. The group velocity quickly drops to zero with increasing $\theta$ and the radiation is therefore emitted predominantly in the forward direction at the plasma frequency. The XO mode has both an electrostatic (es, $E//k$) component that is trapped in the plasma, and an electromagnetic component (em, $E\perp k$) that can couple to vacuum radiation modes. The ratio between the two components is given by $E_{es}/E_{es} \approx (\Omega_{ce}/\omega_{pe})$ and the $E_{es}$ component is that obtained from laser wakefield acceleration (LWFA) theory or experiment (for $\Omega_{ce}/\omega_{pe} << 1$). The radiated intensity can be calculated as $I = (1/2)\varepsilon_0(\Omega_{ce}/\omega_{pe})^2E_{es}^2c$. The radiation pulse length $\tau_p$ is given by the smallest of the transit time of the energy along the plasma length $L_p$, $\tau_p = L_p/v_\text{g}$, and the lifetime of the plasma wave. The dispersion
diagram (Fig. 1) shows that when traversing a non-sharp plasma vacuum boundary, the Cherenkov radiation will have to cross an evanescent plasma region. This will result in a transmission coefficient that can be substantially smaller than unity for a transition region longer than the plasma skin depth $c/\omega_{pe}$. Using Cherenkov radiation from magnetized plasmas as a THz radiation source was first proposed by Yoshii et al. [5]. The analytical results are supported by detailed numerical simulations of the excitation of the magnetized plasma wakes by a single laser pulse, a train of laser pulses, as well as by particle bunches [6]. For the case of the UCLA plasma beat-wave acceleration (PBWA) experiment parameters, $n_e \approx 10^{16}$ cm$^{-3}$, an $E_{es} \approx 3$ GeV/m field inferred from acceleration results, a laser beam spot size $w_0 \approx 200$ µm, the calculated radiation power is approximately 1 MW, with a pulse length given by the plasma wave lifetime of approximately 300 ps. Note that an experiment has been performed using an LWFA scheme. However, the laser beam size necessary to drive the large amplitude plasma wave and the plasma diameter were smaller than the plasma skin depth and, as a result, the observed frequency was in the 30-200 GHz range [7], about ten times lower than that given by the plasma frequency. However, the proof-of-principle experiment showed the tunability of radiation source, as well as the relative power dependency in the applied magnetic field using a gas jet [8]. Further experiments are needed to reach the THz frequency range and the large output power.

COHERENT TRANSITION RADIATION

It is well known that relativistic charged particles or particle bunches emit broadband transition radiation (TR) when traversing the interface between vacuum and a metal [9]. In the case of a particle bunch, the transition radiation at wavelengths much shorter that the bunch length is incoherent, while at wavelengths much longer than the bunch length it is coherent and is known as coherent transition radiation or CTR. The TR from bunches shorter than 300 µm or 1 ps can therefore potentially be used as a source of coherent THz radiation. For a bunch with a Gaussian longitudinal profile with rms width $\sigma_z$, the radiation becomes coherent for $\lambda > \sigma_z$, and its energy scales as $N^2$, while the incoherent energy only scales as the number of particles in the bunch $N$.

Ultra-short (<100 fs or <30 µm fwhm), ultra-relativistic (28.5 GeV) electron bunches are now routinely produced at the Stanford Linear Accelerator Center (SLAC) [10]. These bunches have a repetition rate of up to 10 Hz, with a charge of up to 3.5 nC per bunch and can be focused to <10 µm transverse sizes. These bunches are used for the generation of ultra-short bursts of x-rays [11] and for high-gradient plasma wakefield acceleration [2]. Measuring the length of such bunches remains a challenge. One method consists in sending the CTR emitted by these bunches into an interferometer to obtain an autocorrelation trace of the bunch shape. With $\hat{E}(t)$, the electric field of the electron bunch, the energy $W(\tau)$ measured by the detector after an ideal interferometer with a time delay $\tau$ between the two arms is:

$$W(\tau) = \frac{1}{4} \int_{-\infty}^{\infty} dt (E(t) + E(t - \tau))^2$$  \hspace{1cm} (1)
FIGURE 2. a) CTR interference trace obtained from three delay scans with various steps, and b) CTR power spectra deduced from the three scans.

It consists of the sum of the energies of the two half pulses plus the interference term \( C(\tau) \):

\[
C(\tau) = \frac{1}{2} \int_{-\infty}^{\infty} dt E(t)E(t-\tau)
\]  

(2)

The bunch length is obtained from the width of \( C(\tau) \). Taking the Fourier transform of the autocorrelation trace directly yields the radiation power spectrum. Figure 2a shows an example of an autocorrelation trace, while Fig. 2b shows the corresponding power spectrum. The dips on either side of the peak of Fig. 2b are not described by (1) and indicate that the interferometer has a filtering effect on the broadband CTR signal. This filtering is attributed to the Fabry-Perot effect inside the 12.5 µm thin Mylar beam splitter, to the loss of its reflectivity at long wavelength, as well as to the loss of response of the pyro-electric detector at long wavelengths [12]. This is confirmed by the corresponding power spectrum shown in Fig. 2b. The total CTR energy can be calculated [9] and for the parameter of the SLAC bunches, the expected energy is in the 100 mJ/pulse range. An energy of \(~100\) µJ/pulse can be extracted in a 1% bandwidth at 1 THz. The energy measured in the experiment is \(> 300\) µJ/pulse, and is limited by the finite diameter (~23 mm) of the radiator foil. These numbers show that the SLAC beam can be used as a very powerful source of short pulse, broadband
coherent THz radiation. The radiation can be filtered to obtain high-energy, narrow spectrum pulses, and pump-probe experiments can easily be performed using for example multiple radiation foils.

**TERAHERTZ POWER SOURCE BASED ON DOWNCONVERSION OF A CO\(_2\) LASER**

Electromagnetic accelerators of THz-scale are of interest in advanced accelerator research for the low peak power required at a prescribed gradient, and the more favorable scaling for pulsed heating at higher gradients, e.g. the breakdown limit of a copper surface at ~1 THz is about 10 GV/m. The existing THz tube sources based on emission from bunched electrons (backward-wave tubes or carcinotrons) and harmonic multiplication of low-frequency electron tubes possess insufficient power to study accelerating structures at high fields [13, 14].

The most successful techniques for generating narrow-band, high-power THz pulses have come from frequency downconversion of 1- and 10-\(\mu\)m lasers in nonlinear crystals. According to Manley-Rowe relations the maximum power conversion efficiency for the Difference-Frequency Generation (DFG) at \(\omega_3 = \omega_1 - \omega_2\) is limited by the \(\omega_3 / \omega_1\) ratio. Therefore, for applications where kilowatt to megawatt power levels are necessary at THz frequencies, CO\(_2\)-laser-based sources have a natural advantage in the down-conversion process. Here the optical conversion efficiency of 1-3 % can be achieved. Despite their low overall efficiency, the laser pumped frequency downconverters tunable in THz range (0.3–3 THz) may become a useful tool to test different concepts for advanced particle acceleration. For instance, a 100 MW drive beam focused to a 2 cm spot should provide 100 MV/m gradient in a THz slab-symmetric dielectric structure [15]. Another application – important for the injection of a prebunched beam into a plasma accelerator – is the longitudinal modulation of the electron (ion) beam on the THz scale. Recently we proposed to seed an undulator with a THz pulse of MW power produced by the DFG in order to modulate an electron beam co-propagating with this THz beam on a PBWA frequency scale [16].

At the Neptune Laboratory at UCLA we launched an experimental program with the goal of developing high-power THz radiation sources. In this section we report the first results on the generation of noncollinear phase-matched THz difference frequency radiation by mixing two CO\(_2\) laser lines in a GaAs crystal at room temperature. The measured power at 340 \(\mu\)m (\(\omega_3 = 0.897\) THz) was ~2 MW [17]. By selecting different line pairs a step-tunable radiation in the THz range was obtained.

**Crystal Choice**

There are a number of considerations for the optimum choice of nonlinear crystals to be employed in the generation of THz radiation by difference frequency mixing of higher-frequency lasers:

1) The crystals should have a high transparency at the two input laser frequencies as well as that of at the THz frequency to be generated. The absorption losses at frequencies below the fundamental gap are essentially due to free carriers and
phonons. The free carrier absorption can be compensated by different dopings (semi-insulating semiconductors) and the phonon absorption band for the chosen crystal should lie well above the THz frequency.

2) The large nonlinearity is desirable. Since the THz frequency lies below the lattice mode frequencies, the nonlinear susceptibility has both electronic and ionic contributions [18]. The nonlinear coefficient in this case is the one obtained from the electro-optic coefficient $d^{eo}$. For semiconductor materials it results in lower nonlinearity than that for the optical range.

3) The conversion efficiency for frequency conversion of a pulsed laser is limited by the surface damage threshold, therefore the material with a high damage threshold is desirable.

Three phase matching methods to generate high-power THz radiation by CO$_2$ laser difference frequency mixing in a nonlinear crystal have been considered. They are: standard birefringent phase matching, quasi-phase matching with periodic structures, and noncollinear phase matching in isotropic material. In Table 1 we present characteristics for the most promising nonlinear materials as well as expected power generated at 340 $\mu$m (~0.9 THz) for a 1 cm long crystal at 1GW/cm$^2$ pump intensity.

<table>
<thead>
<tr>
<th>Type of Phase matching</th>
<th>Type of Crystal</th>
<th>Transmission</th>
<th>Nonlinear coefficient $d^{eo}$</th>
<th>Calculated power at 1THz in 1 cm for 1GW/cm$^2$ pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birefringent ZnGeP$_2$</td>
<td>0.7-11 $\mu$m</td>
<td>38 pm/V</td>
<td>7 MW/cm$^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>83-1000 $\mu$m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noncollinear in isotropic materials GaAs</td>
<td>1-12 $\mu$m</td>
<td>43 pm/V</td>
<td>10 MW/cm$^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100-1000 $\mu$m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QPM GaAs</td>
<td>--/--</td>
<td>43 pm/V</td>
<td>4 MW/cm$^2$</td>
<td></td>
</tr>
<tr>
<td>Structures InSb</td>
<td>8-25 $\mu$m</td>
<td>144 pm/V</td>
<td>27 MW/cm$^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200-1000 $\mu$m</td>
<td></td>
<td>L$_{coh}$340 kW/cm$^2$</td>
<td></td>
</tr>
</tbody>
</table>

Terahertz generation by difference frequency mixing is possible in birefringent materials ZnGeP$_2$, AgGaSe$_2$ and GaSe, which are transparent for both MIR 10 $\mu$m and THz radiation. Collinear phase-matched DFG have been reported in ZnGeP$_2$ [19, 20], which is the most promising material in terms of nonlinearity and the damage threshold. Our calculations have shown that up to 7 MW/cm$^2$ can be generated at 340 $\mu$m with a 1 cm long crystal at an internal intensity of 1 GW/cm$^2$. However, there are serious difficulties in growing large-aperture ZnGeP$_2$ crystals that limit power levels at 340 $\mu$m to approximately 30 MW in this crystal. Another problem is that this material requires Type II interaction for DFG. The later hinders its application for a high-power, two-wavelength CO$_2$ laser single beam system.

There are some cubic nonlinear semiconductors such as InSb, GaAs, etc., which can be used for THz DFG with CO$_2$ lasers. But these crystals, being cubic, lack birefringence. Therefore other methods for phase-matching in isotropic crystals must be considered. Even in isotropic crystals waves are propagating in phase over the coherence length ($L_{coh}$), the distance over which the relative phase changes by $\pi$. For
THz difference frequency mixing, the coherence length is quite long, for example \(L_{\text{coh}}\) is 700 \(\mu\)m in the case of GaAs. It allows the generation of THz radiation in thin InSb [21] and GaAs [22] slabs. Despite the very attractive nonlinearity of InSb, this material is not available in large sizes and very expensive. As seen in Table 1, the DFG efficiency is very low because of limited length. Quasi-phase matching is a technique for phase matching nonlinear optical interactions in which the relative phase is corrected at regular intervals using a stack of plates or periodically grown structure. This technique progressed significantly during the last decade in the mid-IR range [23] and it has a good potential for the THz region where tolerances on bonding quality are more relaxed. In the future we plan to manufacture a large-aperture quasi-phase matched (QPM) structure using 2 inch (ultimately 4 inch) commercially available GaAs wafers.

Another approach to obtain phase-matched THz DFG in isotropic nonlinear materials is noncollinear mixing of two laser beams. This is possible in any crystal that possesses anomalous dispersion between the incident \(\text{CO}_2\) laser radiation and THz difference frequency radiation. Zernike [20] and Aggarwal et al. [24] have demonstrated a noncollinear mixing of two \(\text{CO}_2\) laser beams in a liquid helium cooled semiconductor samples. The highest THz power generated by now using this method is a few kW in the 3 THz region [25].

Several reasons make GaAs the best candidate for generation of high-power 340 \(\mu\)m radiation using a noncollinear DFG scheme. It has relatively high value for the electro-optic nonlinear coefficient \(d^{eo} = 43 \text{ pm/V}\). GaAs with high resistivity > \(10^8\) \(\Omega\cdot\text{cm}\) is transparent in the THz beyond 150 \(\mu\)m at room temperature as well as in the 10 \(\mu\)m region of the \(\text{CO}_2\) laser. Up to 10 MW/cm\(^2\) can be generated according to our calculations. High-quality single crystals with a cross-section 10 \(\times\) 10 cm and length up to 10 cm are commercially available. The surface damage threshold is expected to be on a gigawatt-scale for short, 100 ps \(\text{CO}_2\) laser pulses. Below we present results of measurements obtained with a THz frequency downconverter made of GaAs.

**Noncollinear Phase-Matched THz Generation in GaAs**

The experiment has been performed at the Neptune Laboratory at UCLA with a two-wavelength, terawatt \(\text{CO}_2\) master oscillator-power amplifier system [26]. The simplified optical scheme for difference frequency mixing in GaAs is shown in Fig. 3. The two \(\text{CO}_2\) laser lines used for mixing were the 10R(16) line at 10.3 \(\mu\)m (\(\omega_1\)) and the 10P(20) line at 10.6 \(\mu\)m (\(\omega_2\)). The conservation of photon energy (\(\omega\)-matching) gives the wavelength of the difference-frequency radiation at 340 \(\mu\)m (\(\omega_3\)). To conserve momentum (\(k\)-matching) the wave vectors of the \(\text{CO}_2\) laser lines have to be noncollinear as shown in Fig. 3.

Similar to the pioneering work by Aggarwal et al. [24], we found that the phase-matching angle \(\theta\) for this pair of lines is equal 0.72° (the external phase-matching angle \(\theta_E\) is 2.38°) and the angle \(\phi\) at which the THz radiation is generated with respect to the direction of incident radiation at \(\omega_1\) is 21.64°. The angle of propagation of the THz beam inside the crystal is greater than the critical angle for total internal reflection. Therefore, as shown in Fig. 3, the output face of the GaAs crystal (in the
form of a $2 \times 4 \times 2.5$ cm rectangular parallelepiped) was cut at an angle of $\sim 10^\circ$ to decouple both the 10- and 340-µm beams. It is important to note that the refraction of the pump and THz beams in a noncollinear configuration allowed the separation of the vertically polarized, two-wavelength CO$_2$ laser beam which was split into two optical arms and combined together in the GaAs crystal. Because of the crystal geometry, only one wavelength in each arm was utilized for the DFG process of interest, and half of the THz radiation with mirror symmetric k-matching was trapped inside the crystal. Three beams ($\omega_1$, $\omega_2$ and $\omega_3$) had the same polarization parallel to the [111] axis of the GaAs crystal. The THz radiation was collected by a cone and sent onto a Golay cell for detection. For an $\sim 2.8$ m long base of both arms, we obtained an angle resolution of less than $0.01^\circ$ while scanning the phase matching angle. The latter was realized simply by adjusting both the position and angle of the movable mirror M.

![FIGURE 3. Optical arrangement for THz DFG using a two-wavelength CO$_2$ laser beam.](image)

The study of noncollinear mixing of laser lines in GaAs was divided into two parts. First, we used 200 ns pulses containing a laser power of 250 kW (intensities in the focused beam of the order of 5–6 MW/cm$^2$) to optimize phase-matching for THz generation. Having confirmed the noncollinear phase matching angle, a high-power, two-wavelength CO$_2$ laser beam with a pulse duration of 250 ps (intensities of the unfocused beam up to 1 GW/cm$^2$) was sent to the crystal.

As seen in Fig. 4, tuning of the phase-matching angle showed that the THz signal peaked at $\theta = 0.71^\circ$ ($\theta_E = 2.33^\circ$) and the full-width of the phase-matching curve $\Delta \theta$ was 0.2°. For 200 ns pulses with a peak power $P_{10.3} \approx P_{10.6} \approx 125$ kW in a focused laser beam we detected THz pulses with a peak power around 1.5 W. A narrow–band interference filter (~ 100 GHz FWHM) centered at 350 µm was used to verify the generated frequency. By selecting the different pair of laser lines – the 10P(28) +10R(24) lines – we obtained 240 µm (1.25 THz) radiation with approximately the same conversion efficiency. In general, tunability in the range 75–3000 µm may be obtained using DFG of CO$_2$ laser lines in GaAs [24]. However, according to the
spectrophotometer measurements of our samples made at Stanford University [27], increasing losses caused by absorption for wavelengths shorter than 150 \( \mu m \) will decrease the conversion efficiency, and cooling of the crystal \((T = 80^\circ K)\) may be required.

**FIGURE 4.** DFG output power at 340 \( \mu m \) (triangles) and at 240 \( \mu m \) (diamonds) measured in GaAs versus external phase matching angle between the 10.6 \( \pm \)10.3 \( \mu m \) beams and the 10.7 \( \pm \)10.2 \( \mu m \) beams, respectively. The calculated dependence of the phase matched angle upon the THz frequency.

Switching to shorter pulses may increase the frequency conversion efficiency in two ways: first, owing to the pump power increase in the experiment and second, this power can be coupled into a crystal because of the higher damage threshold for shorter pulses. For 200 ns pulses, no damage was observed with intensities \( \leq 16 \text{ MW/cm}^2 \), which is in a good agreement with a 30 MW/cm\(^2\) value of the surface damage threshold reported by Gordon et al. [23]. In a series of damage threshold measurements for 250 ps CO\(_2\) laser pulses, we observed a single shot damage of GaAs at \( \approx 0.5 \text{ J/cm}^2 \) \((\leq 2 \text{ GW/cm}^2\)). However, in the experiment for the unfocused 10-\( \mu m \) beams with a cross-section of \( 3 \times 2 \text{ cm} \), the existence of hot spots seriously limited the incident fluence especially for the multi-shot exposure. As a result, the typical pump intensity did not exceed 1 GW/cm\(^2\). Moreover, using a two-wavelength beam in each arm with a 10:1 to 20:1 ratio between the 10.6 and 10.3 \( \mu m \) lines in combination with a beam splitter efficiency of \( \approx 0.7 \) caused the useful pump power to be around 250 MW/cm\(^2\). As shown in Fig. 3, a phase-matched THz beam produced by another part of the pump with the symmetric k-matching was trapped inside the crystal. The detector placed after a 0.5-m long Cu waveguide and teflon filters measured an energy of approximately 250 \( \mu J \); taking into account the measured attenuation of the THz transport system, up to 0.5 mJ energy was generated [17]. The achieved peak power corresponds to the \( \approx 10^{-3} \) external conversion efficiency and represents an improvement by a factor of 500 of the peak power obtained previously by DFG in nonlinear crystals.
Future Development Toward a 10-100 MW Power Source

In Fig. 5, we summarize the data on THz power obtained for both pulse durations. Clearly, switching from 200 ns to 250 ps CO$_2$ laser pulses resulted in a significant increase of THz power from 2 W to 2 MW. This is mainly due to the increased damage threshold of GaAs for the subnanosecond pulses. A further increase in the THz power is expected from pumping the crystal by one wavelength beam in each arm and/or from switching to even shorter, 50 ps CO$_2$ laser pulses for which the damage threshold is expected to increase. The power level of THz radiation generated by a noncollinear phase-matching scheme may be scalable to the 100 MW level by increasing the crystal aperture. A typical beam diameter of the Neptune two-wavelength CO$_2$ laser system is 12 cm. This beam, in combination with commercially available large-aperture GaAs crystals (4 inch diameter), opens the possibility of creating a very high-power source of coherent radiation tunable in the range of 0.1–3 THz (projected power shown in Fig. 5).

![Projected power, 50 ps, L= 1 cm](image)

**FIGURE 5.** Measured output power density at 340 µm versus pump intensity for 200-ns long (triangle) and 250-ps long CO$_2$ laser pulses. The star marks the calculated power for the THz FEL amplifier.

We also plan to amplify a relatively low-power, 1 kW THz pulse generated by a nonlinear crystal in a seeded THz FEL pumped with the Neptune S-band photoinjector. This will result in a high-pulse repetition frequency (1–5 Hz) source tunable in the 1–3 THz range. According to 3-D simulations, a 2 m long FEL driven by a 10 ps (FWHM) electron beam with a peak current of ~60 A will amplify a THz pulse to an ~10 MW peak power level in a single-pass configuration.
SUMMARY

The novel THz radiation sources described in this paper have the potential to produce frequency tunable, high power, short pulses. While frequency down-conversion is a well known non-linear optical process, the use of a CO$_2$ laser and an isotropic crystal allow for broadband tuning and high power generation as demonstrated in the experiment. CO$_2$ lasers can also be operated at high repetition rates (100 Hz to multi-kHz) also opening the possibility for high average power THz sources.

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