NARROWBAND CONTINUOUSLY TUNABLE RADIATION IN THE 5 TO 10 TERAHERTZ RANGE BY INVERSE COMPTON SCATTERING*

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Abstract

5 to 10 THz has recently become the frontier of THz radiation sources development, pushed by the growing interests of spectroscopy and pump-probe material study in this frequency range. This spectrum “Gap” lies in between the several THz range covered by Electro-Optical crystal based THz generation, and the tens of THz range covered by the difference frequency generation method. The state-of-the-art EO crystal THz source using tilted pulse front technique has been able to reach ~ 100 MV/m peak field strength, large enough to be used in an inverse Compton scattering process to push these low energy photons to shorter wavelengths of the desired 5-10 THz range. The required electron beam energy is within 1~2 MeV, therefore a compact footprint of the whole system. The process would occur coherently granted the electron beam is bunched to a fraction of the radiation wavelengths (several microns). A system operating at KHz or even MHz repetition rate is possible given the low electron energy and thus low RF acceleration gradient required. This work will explore the scheme with design parameters and simulation results.

INTRODUCTION

Terahertz has been a frequency range of a plethora of molecular spectral features and dynamic characteristics, yet lack of strong sources to probe or drive the samples under study. Both transient pulses of extraordinary peak electric field strength and multi-cycle narrowband radiation of high brightness and frequency tunability are very much desired, preferably at high repetition rate for the purpose of ultrafast dynamics study. Despite of recent rapid growth on THz light sources, high-brightness tunable narrowband radiations are still rare to none on the chart, both in the low-frequency (1-5 THz) range and in the high-frequency (5-10 THz) range [1]. This type of sources are particularly interesting because of their peak power thus exceptional peak field strength to drive nonlinear effects or absorptive samples, meanwhile narrowband oscillation to exclusively excite specific vibrational or rotational modes of molecules. From the state-of-the-art terahertz source map shown in Fig. 1, the most promising source that currently covers the 5-10 THz range is the quantum cascade laser (QCL). However, it could barely reach 100 mWatt average output power level at 10 THz and needs to be operated at LH e cryogenic temperatures. Continuous-wave operation of QCL also implies low peak power.

This paper intends to propose a narrowband, continuously tunable, high peak power source in the 5-10 THz range, based on inverse Compton scattering process (ICS). Low-frequency seed light can be obtained via tabletop laser based THz generation, which is then scattered by electrons to high frequencies into the targeted 5-10 THz range. In order to enhance the electron/photon interaction, the pulse front of THz seed light can be tilted and its transverse mode modulated to a uniform profile rather than Gaussian distribution. The final radiation achieved is ultra-bright due to its small bandwidth and high peak power, and its central frequency can be continuously tuned by altering electron energy or scattering angle.

PHOTON YIELD ESTIMATION

Recent developments in high power near-Infrared laser have enabled delivery of high pulse energy THz transients from a tabletop system, based on optical rectification process in nonlinear EO crystals [2]. Groups at SLAC laser department have demonstrated generation of THz pulses of about 2 ps long and ~50 uJ energy, using a room-temperature LiNbO3 EO crystal pumped by 800 nm laser of 3 mJ pulse energy at 1 kHz repetition rate. Liquid
nitrogen cooling of the EO crystal is being experimented to potentially allow more THz pulse energy yield and higher repetition rate. After sending this THz pulse through a commercially available 1-THz bandpass filter with 10% bandwidth, about 2 uJ pulse energy can be transmitted, resulting in a multi-cycle waveform of ~10 ps long with carrier frequency at 1 THz. Assuming a one-wavelength (300 um) transverse focal spot size, peak electric field strength of 50 MV/m can be realized at its focus.

Table 1: electron and Photon Beam Parameters for the Inverse Compton Scattering Simulation

<table>
<thead>
<tr>
<th>Beam Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>4 pC</td>
<td></td>
</tr>
<tr>
<td>Bunch Length</td>
<td>20 fs</td>
<td></td>
</tr>
<tr>
<td>Normalized Emittance</td>
<td>0.3 mm²*mrad</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>0.85 MeV</td>
<td></td>
</tr>
<tr>
<td>Energy Spread</td>
<td>0.1 %</td>
<td></td>
</tr>
<tr>
<td>Laser Parameter</td>
<td>Value</td>
<td>Unit</td>
</tr>
<tr>
<td>Wavelength</td>
<td>300 um</td>
<td></td>
</tr>
<tr>
<td>Electric Field</td>
<td>200 MV/m</td>
<td></td>
</tr>
<tr>
<td>Pulse Length</td>
<td>10 ps</td>
<td></td>
</tr>
<tr>
<td>Effective Undulator Parameter $K$</td>
<td>0.023389</td>
<td>-</td>
</tr>
<tr>
<td>Effective Undulator Period</td>
<td>166.76 um</td>
<td></td>
</tr>
</tbody>
</table>

As plotted in Figure 3, simulations show a good electron bunching factor of ~0.82 during the interaction. The maximum output peak power reaches 2.3 kW.

![Figure 2: Schematics of an Inverse Compton interaction.](image)

Figure 2 illustrates an inverse Compton scattering of head-on collision between electron and photon, where electrons lose kinetic energy to boost photon energy from optical regime to X-ray. The same process can be applied at long wavelengths, and has been demonstrated at 3 mm seed wavelength [3]. Given the aforementioned 1-THz incident light, an electron beam of 0.85 MeV energy can scatter it to 10 THz. Electrons coming out of a photocathode gun would have this beam energy, thus extra linac sections are not necessary and the electron system could have a compact footprint.

The ICS process is modelled using a free electron laser code Genesis 1.3. In the electron rest frame, a magnetic undulator is viewed as an incident electromagnetic wave with a wave number $\nu k_u$. Therefore the incident laser can also be treated as an optical undulator, simply by using the effective undulator parameter for an optical laser:

$$K = \frac{eE_x}{mc^2\beta z_k},$$

where $k = \frac{2\pi}{\lambda}$ and $\lambda$ is the laser wavelength, which is related to the undulator period $\lambda_u$ by:

$$\lambda = (1 - \beta \cos \phi)\lambda_u.$$}

Here $\phi$ is the interaction angle as in Fig. 2 and $\beta = \frac{v}{c}$ is the velocity of the electron. Potential beam parameters of an X-band photocathode gun currently operating at SLAC ASTA facility are used in this simulation, and they are listed in Table 1 below together with the seed light parameters. A low charge of only 4 pC is applied in order to suppress the space charge effect at such low beam energy. Running at such low charge and low energy (thus low RF gradient), the repetition rate of the SLAC ASTA gun could be likely increased to kilohertz level. Bunch length of 20 fs (6 um) is chosen to be 1/5 of the targeted radiation wavelength at 10 THz, so that electrons radiate coherently. This bunch length can be realized by direct velocity bunching in the gun.

![Figure 3: Simulated radiation peak power at 10 THz and bunching factor along the longitudinal direction.](image)
CONCLUSION

A narrowband tunable source at 10 THz is proposed, based on inverse Compton scattering of low frequency THz photons readily available from IR tabletop laser based THz sources at SLAC. Calculation of the photon yield is done by equaling the free-space electric fields to undulation in a FEL process. Peak output power of 2.3 kW is predicted by simulation. Benefiting from the low beam energy of ~1 MeV needed in the inverse Compton scattering, the electron source could potentially be operated at 1 KHz thus utilizing every pulse of the seed THz light. With a MHz repetition rate electron source by either superconducting RF gun or dielectric laser accelerator [6], average output power of this source could reach several tens of milliWatt.

ACKNOWLEDGEMENT

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REFERENCES