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 LHe 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.
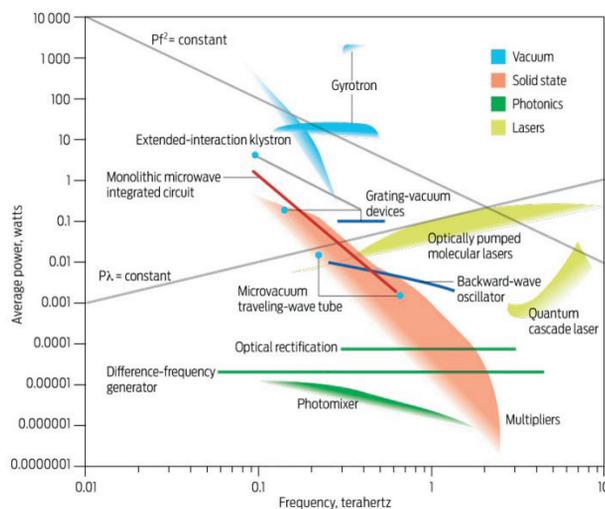
Figure 1: A radiation sources map in the 0.01 to 10 THz range. The power-frequency slope of Pf^2= constant is expected for RF based devices to develop into higher THz frequencies, whereas the power-wavelength line of $P\lambda$= constant is expected for commercial laser based sources. Courtesy of Carter M. Armstrong, IEEE SPECTRUM, Aug. 17, 2012, illustrated by George Retseck.

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 $LiNbO_3$ 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.
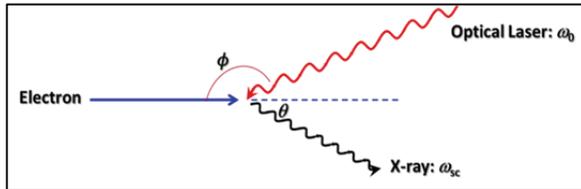
Figure 2: Schematics of an Inverse Compton interaction.

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 γk_u. Therefore the incident laser can also be treated as an optical undulator, simply by using the effective undulator parameter for an optical laser:

$$K = \frac{eE_x}{m_e c^2 \beta_z k} \; ,$$

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

$$\lambda = (1 - \beta_z \cos\phi)\lambda_u \; .$$

Here ϕ 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.

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

Beam Parameter	Value	Unit
Charge	4	pC
Bunch Length	20	fs
Normalized Emittance	0.3	mm*mrad
Energy	0.85	MeV
Energy Spread	0.1	%
Laser Parameter	Value	Unit
Wavelength	300	um
Electric Field	200	MV/m
Pulse Length	10	ps
Effective Undulator Parameter K	0.023389	-
Effective Undulator Period	166.76	um

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.
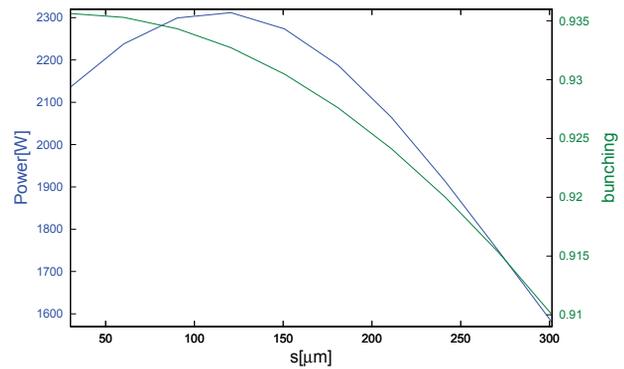
Figure 3: Simulated radiation peak power at 10 THz and bunching factor along the longitudinal direction.

EXPERIMENT SETUP

Free-space radiation based undulation relies on strong transverse focusing of the incident light while maintaining a uniform longitudinal profile over 10-20 FEL gain lengths to reach high gain lasing. Short Rayleigh range resulted from the tight focusing prevents such longitudinal profile from being achieved in a stationary setup. For example, a 1 THz light focused down to 300 um waist size would have a Rayleigh range of 236 micron beyond which the light quickly diverges. A pulse front tilted light with field maxima co-propagating with the electron bunch could provide that gain length.

Figure 4 depicts the optical layout of the THz –ICS scheme using a tilted pulse front. A NIR laser at 800 nm is split into two beams. One beam gets passed through an EO crystal e.g. ZnTe or $LiNbO_3$ to generate a THz transient, through a THz bandpass filter to get a THz frequency comb of 1 THz carrier frequency, then hit a THz grating to get its pulse front tilted [4], and then illuminate on a silicon wafer which acts as a THz spatial light modulator (SLM). This THz SLM is essential in order to obtain a uniform longitudinal intensity profile electrons can experience later on, to ensure the FEL exponential growth. Principle behind this THz SLM is based on a recent work [5] on photo carrier excitation

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based THz light encoder. As Fig. 3 shows, the other NIR beam is expanded in its transverse size, shine into a SLM for 800 nm so that encoded, and then further diverged onto the silicon wafer where the THz photons income simultaneously. The encoded 800 nm intensity gets transferred to the Si wafer local reflectivity pattern, as high intensity regions would carry enough 800 nm photons to excite local photo carriers to reach high surface reflectivity. The Si wafer is then transferred to an encoded THz mirror. The incident THz light is therefore spatially modulated, achieving a flattop profile with extra wavefront tilting to the desired ~45° with respect to the relativistic electron bunch. Then after a 2*f* relay imaging lens pair, the THz pulse traverses the electron path with its electron field polarized along the y direction, and synchronous FEL interaction occurs.
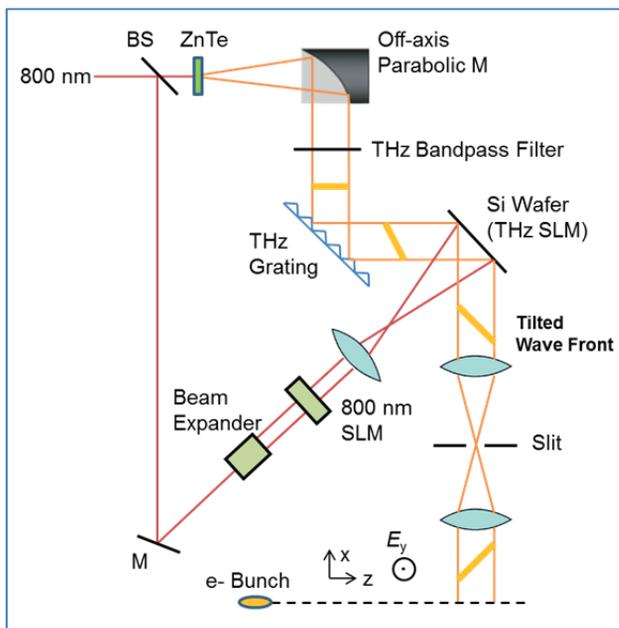
Figure 4: Optical schematic of a high-gain THz-ICS source. Relative optical paths are not to scale. NIR beam: dark red lines; THz beam: orange lines; THz wavefront: light yellow ribbons.

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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