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Light: Science & Applications (2017) 6, e17063; doi:10.1038/lsa.2017.63
Official journal of the CIOMP 2047-7538/17
www.nature.com/lsa

NEWS AND VIEWS

Novel efficient THz undulator using a laser-driven wire

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Light: Science & Applications (2017) **6,** e17063; doi:10.1038/lsa.2017.63; published online 19 May 2017

Terahertz (THz $=10^{12}$ cycles per second, or *T*-ray) radiation sources are indispensable for modern materials science, chemical and biomedical imaging and sensing, as well as for a broad range of applications in diagnostic systems and advanced telecommunications[1,2]. The electromagnetic spectrum of the THz radiation is loosely characterized by the frequency range of 0.1 − 10 THz, or wavelengths between 30 μm and 3 mm. In particular, a low photon energy of 4.2 meV or 48 K at 1 THz, which is less than the thermal energy at room temperature, allows precise measurements with a simplified setup and very high signal-to-noise ratio in time-domain pulsed THz spectroscopy[2]. Since the spectral region is located on the boundary between electronics and photonics, the diversity of the THz sources relies on either frequency up-conversion of electronic sources, such as solid-state photo-switches and radio-frequency (RF) electron-beam accelerators[3], or frequency down-conversion of optical sources, such as optical rectification[2,3] in nonlinear optical processes and laser-gas interaction induced by two-color lasers[3]. Both technologies, however, exploit ultrashort pulse lasers as a driver. In a recent publication, Tian *et al.*[4] at Shanghai Institute of Optics and Fine Mechanics (SIOM) and Nankai University developed a new THz radiation source using a laser-driven wire that generates a femtosecond electron bunch and helical undulator fields to emit THz synchrotron radiation with high efficiency.

Relativistic electron beams render ubiquitous sources of broadband THz radiation through various physical mechanisms; for instance, synchrotron radiation in bending magnetic fields and undulator fields, transition radiation, Cherenkov radiation, diffraction radiation and Smith-Purcell radiation. When the dimensions of an electron bunch are smaller than the THz wavelength, spontaneous emission of the THz radiation from individual electrons builds up in a coherent manner. This produces so-called coherent or super-radiant radiation, implying that all electrons inside the bunch radiate electromagnetic fields in the same phase, which interfere constructively, and the intensity increases with the square of the number of electrons.

Coherent transition radiation (CTR), characterized by a broadband spectrum and high-energy single-cycle pulse, is generated by the interaction of ultra-relativistic electron bunches accelerated from an RF linear accelerator with a metal foil. Such THz sources have been operated parasitically at fourth-generation X-ray light sources. For example, relativistic electron bunches with energy of 14 GeV, charge of 350 pC and duration of 50 fs (15 μm, bunch length) generate CTR with ~200 μJ per pulse at 2.5 THz through a 10-μm-thick Be foil at the Linac Coherent Light Source (LCLS)[5].

Meanwhile, relativistic electron beams with relativistic factor γ ($=E_e/mc^2$ with electron energy E_e and rest energy $mc^2=511$ keV) delivered from RF accelerators can generate synchrotron radiation, the wavelength of which is Doppler-shifted by a factor $\sim 1/2\gamma^2$ in the passage through an alternating magnetic field B_u of the undulator with period λ_u. Under the resonance condition that radiation emitted in one undulator period overtakes the electron and interferes constructively with radiation emitted in the next undulator period, that is, the radiation wavelength $\lambda_r=\lambda_u(1+K^2/2)/2\gamma^2$ with the parameter $K=eB_u\lambda_u/2\pi mc^2 \approx 0.934 B_u[\mathrm{T}]\lambda_u[\mathrm{cm}]$, the radiation at the end of the undulator periods N_u has a spectral bandwidth $\Delta\omega/\omega=1/N_u$. In a low-gain free electron laser (FEL), where the undulator is installed inside an optical cavity, the radiation via the spontaneous emission process from the electron beam is stored and amplified throughout the stimulated emission process inside the cavity, which is analogous to a conventional laser. As a consequence of the interaction between electrons and radiation, the electron beam undergoes the energy modulation, resulting in spatial modulation (microbunching) at the radiation wavelength. This FEL process transforms incoherent emissions from individual electrons with initially random phases into their coherent emissions with the same phase. As developed in modern X-ray FELs, a high-gain mechanism exploiting high-peak current electron beams, referred to as a self-amplified spontaneous emission FEL, enables saturation to be reached in a single pass through the undulator. After compression to microscopic length scales in an RF accelerator, ultrashort electron bunches are injected into a long undulator, and the spontaneous emission in the first periods of the undulator is amplified through the energy modulation and microbunching processes. For example, a nine-pole electromagnetic undulator installed at the FEL in Hamburg (FLASH) generated pulse energy of up to 100 μJ at 1 THz with a spectral bandwidth of 10% from 500 MeV electron bunches with 0.6 nC charge[3,6].

While relativistic electron beam-driven THz sources, such as CTR and the THz undulator, are capable of generating high-energy THz pulses with > 100 μJ only at large-scale accelerator facilities, laser-driven THz sources, such as semiconductor photoswitches and nonlinear optical crystals, are suited to small-scale ubiquitous applications requiring limited pulse energies of the order of 1 μJ, which is

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Received 15 March 2017; revised 1 April 2017; accepted 6 April 2017

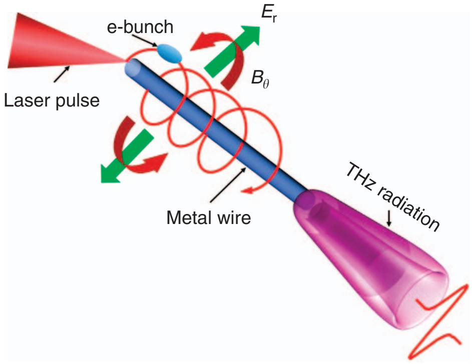

Figure 1 A schematic view of the laser-driven-wire-guided undulator (LWGU) developed at SIOM. A femtosecond laser pulse irradiating a metal wire emits an energetic electron bunch. Concurrently, a highly positive transient current excites an outward-pointing radial electric field (E_r) and azimuthal magnetic field (B_θ) along the wire. The laser-generated fast electrons undergo helical betatron motion due to strong Lorentz forces and emit amplified THz radiation.

restricted due to dielectric breakdown. The new THz emitter, named laser-driven-wire-guided undulator (LWGU), developed at SIOM, combines capabilities of high-energy pulse generation pertaining to the undulator scheme and an extremely simplified miniature device comprising a millimeter-scale metal wire that functions as an energetic electron-beam source, helical undulator, waveguide and antenna of THz radiation. In the LWGU experiment, an electron bunch having a typical energy of 100 keV and charge of at least 300 pC was created on the surface of a metal wire with 50–90 μm diameter while being irradiated by a 30-fs, 3-mJ laser operated at a repetition rate of 1 kHz. Concurrently, an intense transient current induced in the wire excited an outward-pointing radial electric field of the order of ~0.3 GV m^{-1} and an azimuthal magnetic field ~10 T in a decay time of ~2 ps, owing to a positive-charge pulse propagating along the wire nearly at the speed of light. The laser-generated fast electrons undergo helical betatron motion due to strong Lorentz forces along the wire and emit synchrotron radiation (Figure 1). The THz radiation was characterized with a single-shot pump probe technique using the electro-optic sampling method to measure a temporal THz pulse waveform and Fourier-transformed spectrum. The spectral measurements show a tuneable peak frequency from 0.12 to 0.35 THz with the bandwidth 0.09 − 0.17 THz when varying the wire diameter from 90 to 50 μm. The angular-distribution measurement shows a typical THz emission concentrated within a narrow cone between 10° and 30°, while the THz wave has mainly a radial polarization similar to the direction of the induced electric field. The total energy of THz emission was ~28 μJ in the 0.1–0.3 THz band for a 10-cm long wire with a 50-μm diameter driven by a 3-mJ laser pulse, which means a conversion efficiency of ~1%. It is noted that the energy-conversion efficiency of the LWGU is much higher than those of large-scale accelerator-based THz sources, such as 0.004% for CTR at LCLS and 0.03% for THz FEL at FLASH. The overall performance of the LWGU has confirmed the dominant properties of FELs, namely, frequency-tunability, narrow bandwidth, indication of gain saturation depending on the undulator length and 1%-level energy-conversion efficiency.

The new femtosecond laser-driven THz radiation source, LWGU, may bring many beneficial properties in power, efficiency and stability as well as in operational and structural simplicity to currently prevailing THz devices for a wide range of applications. To understand the underlying physics of THz emission by the LWGU and further improve the performance of the THz source, it will be necessary to implement *ab initio* analysis of the physical processes for THz radiation, for instance, laser-solid interactions, free electron generation, transient current generation, self-excitation of electromagnetic fields, and THz wave generation and guiding, in addition to phenomenological modeling. Such comprehensive investigations on the THz radiation sources may evoke not only technical innovations but also new insights into modern plasmonics research on surface plasmon-polaritons.

CONFLICT OF INTEREST

The author declares no conflict of interest.

1 Ferguson B, Zhang XC. Materials for terahertz science and technology. *Nat Mater* 2002; **1**: 26–33.
2 Ulbricht R, Hendry E, Shan J, Heinz TF, Bonn M. Carrier dynamics in semiconductors studied with time-resolved terahertz spectroscopy. *Rev Mod Phys* 2011; **83**: 543–586.
3 Stojanovic N, Drescher M. Accelerator- and laser-based sources of high-field terahertz pulses. *J Phys B At Mol Opt Phys* 2013; **46**: 192001.
4 Tian Y, Liu JS, Bai YF, Zhou SY, Sun HY *et al.* Femtosecond-laser-driven wire-guided helical undulator for intense terahertz radiation. *Nat Photon* 2017; **11**: 242–246.
5 Wu ZR, Fisher AS, Goodfellow J, Fuchs M, Daranciang D *et al.* Intense terahertz pulses from SLAC electron beams using coherent transition radiation. *Rev Sci Instrum* 2013; **84**: 022701.
6 Gensch M, Bittner L, Chesnov A, Delsim-Hashemi H, Drescher M *et al.* New infrared undulator beamline at FLASH. *Infrared Phys Technol* 2008; **51**: 423–425.

doi:10.1038/lsa.2017.63