IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access
Invited Paper

Breakthroughs in Photonics 2013: Terahertz Wave Photonics

Volume 6, Number 2, April 2014

Hiromasa Ito

DOI: 10.1109/JPHOT.2014.2309648
1943-0655 © 2014 IEEE

Breakthroughs in Photonics 2013: Terahertz Wave Photonics

Hiromasa Ito

(Invited Paper)

Terahertz-wave Research Group, RIKEN, Sendai 980-0845, Japan

DOI: 10.1109/JPHOT.2014.2309648

Manuscript received February 10, 2014; accepted February 25, 2014. Date of publication March 4, 2014; date of current version April 30, 2014. Corresponding author: H. Ito (e-mail: h-ito@riken.jp).

Abstract: This paper presents an overview of recent developments in terahertz science and technology. Important advances have occurred in higher power terahertz sources and in other devices. They are described along with some notable applications.

Index Terms: Terahertz, THz, quantum cascade laser, resonant tunneling diode, parametric down-conversion, THz comb, THz STM.

Terahertz (THz) wave science and technology are attracting considerable interest because of their variety of potential applications in fields such as physics, chemistry, bio-science, agriculture, and engineering. Recent technical innovations, especially powerful and reliable terahertz source development, constitute a key to exposing new opportunities for THz waves. The THz sources are classifiable into two major categories: electronic and optical. THz photoconductive antennas and THz QCLs, as well as parametric THz sources, are the most common THz photonic sources. They have spurred the development of sources of many types, each with their respective benefits.

This review describes some of the most notable advances for THz photonics that took place in 2013. Particularly, the latest results related to high-power THz wave generation are reviewed both for time-domain broadband sources and monochromatic sources. Advances in some notable applications are also explained.

1. Short Pulse THz Wave Sources

Laser-driven THz photoconductive antennas (THz-PCAs) are among the most promising broadband-coherent THz wave sources for developing compact, portable, low-power-consuming, rugged, and low-cost systems for various THz applications. The salient benefit of photoconductive THz emitters compared to the THz sources based on nonlinear optical effects is that their optical-to-THz conversion efficiency is not restricted by the Manley–Rowe limit. This is true because each absorbed photon can generate one electron–hole pair, which can emit several THz photons upon reaching the THz antenna.

Low-temperature-grown GaAs, because of its subpicosecond carrier lifetime, high-electric breakdown field, and high carrier mobility, have been widely used as ultrafast photoconductors operating in the 800 nm wavelength range. At 1550 nm and 1030 nm wavelengths, where high power, tunable, narrow linewidth and compact lasers are commercially available, short-carrier lifetime substrates are prepared by growing InGaAs at low temperature using ion irradiation and other means. Another approach is plasmonic photoconductors. The plasmonic contact electrodes offer nanoscale carrier transport path lengths for most photocarriers, increasing the number of collected photocarriers in a sub-picosecond time-scale, and enhancing the optical-to-THz conversion efficiency of photoconductive THz emitters as well as the detection sensitivity of photoconductive THz detectors. Actually, 50-times-higher THz power has been reported from a plasmonic emitter, and 30-times-higher THz detection sensitivity has been achieved from a plasmonic photoconductive detector compared to those of similar photoconductive devices with non-plasmonic contact electrodes [1]. More than three-order-of-magnitude enhancement was reported in the signal-to-noise ratio of time-domain and frequency-domain THz spectroscopy and imaging system. Great benefits of this device include obviation of the need to use short-carrier lifetime substrates which are a major source of quantum efficiency degradation in conventional photoconductors. Moreover, they open the door to future longer-wavelength applications.

2. Down-Conversion THz Wave Sources

Optical down-conversion to THz frequencies based on nonlinear optical effects has been used extensively for generating high-power THz waves. Recently, the generation of extremely intense THz pulses has been achieved via the non-resonant optical rectification using lithium niobate [$LiNbO_3$: LN] crystals. Although the highest reported output pulse energy is sub-milliJoule and although the highest reported electric field exceeds 1 MV/cm, photon conversion efficiencies are still low because of the material absorption and the Manley–Rowe limit. It was proposed theoretically that optical rectification in LN can be improved significantly by optimizing the Fourier-limited pump pulse duration and cooling LN to cryogenic temperatures to reduce its THz absorption. The highest conversion efficiency of 3.8% was demonstrated by cryogenic cooling of congruent LN and using a close-to-optimal pump pulse duration [2]. This is more than an order of magnitude higher than previously reported. More detailed studies for optimum conditions for pulse duration and temperature have also been reported [3].

Intense monochromatic THz-wave generation and highly sensitive detection were obtained by wavelength conversion with nonlinear optical susceptibility $\chi^{(2)}$ of LN crystals operated at room temperature. Maximum peak output of about 50 kW corresponding the electric field of 0.5 MV/cm was demonstrated with an injection-seeded THz-wave parametric generator (transform limited spectral width of a few tens of gigahertz) pumped by post-amplified emission from a microchip Nd: YAG laser [4]. Using the sub-nanosecond (approx. 100 ps) pulse duration of the laser proposed herein provides effective mitigation of stimulated Brillouin scattering in LN, producing higher gain for wavelength conversion between a near-infrared (near-IR) pump and THz waves. Monochromatic THz wave radiation was obtained in the continuous tuning range of 0.7–2.9 THz. Furthermore, sensitive THz-wave detection was demonstrated based on up-conversion from THz waves to near-IR light. Highly sensitive detection with minimum energy of about 80 aJ/pulse (0.8 μW at peak) and a large dynamic range of more than 100 dB were demonstrated. The means for optimizing the pump pulse duration and cooling LN [5] is a similar approach to that described above [1], [2].

3. THz Electronic Semiconductor Sources

Nearly 1 W output THz quantum cascade lasers (QCLs) were demonstrated from two groups. Compact coherent THz sources able to emit adequately high power are always desired. A possible means to increase the laser power is the use of more semiconductor layers. For increasing the active volume of THz QCL with semi-insulating surface plasmon waveguides, stacking two symmetric active regions on top of each other was accomplished via a direct wafer bonding technique. For this operation, a specific design of the QCL structure was required by which electrons can pass in both bias directions. The device emitted 470 mW optical power from one facet (940 mW two-facet output power) at 3.9 THz and 5 K, and exhibited a maximum operating temperature of 122 K [6]. Another nearly 1 W THz QCL was a standard single plasmon waveguide structure using wet etching. An active cascaded layer was consisted of 200 periods based on four quantum wells embedded between 40-nm-thick top and 400-nm-thick bottom contacts. The maximum collected peak power from both facets was about 875 mW around 4.8 THz [7].

Conventional edge-emitting ridge-waveguide THz QCLs suffer from multiple-mode operation and an extremely wide beam divergence. Moreover, the strong mode confinement in the laser cavity engenders a large impedance mismatch between the modes inside and outside the cavity, resulting in low output power. To overcome these shortcomings, several approaches have been demonstrated such as MEMS-based DFB devices [8], and second-order DFB to couple the optical power vertically [9]. Newly achieved single-mode surface emitting THz QCLs were designed to use concentric-circular gratings (CCGs). They exhibited single-mode operation over the full range of injection currents where lasing is observed, with a high side-mode-suppression-ratio of about 30 dB. This device showed a similar threshold current to that of a ridge laser of comparable area, but with a three-fold increase in output power with evenly distributed emission pattern across the top surface [10].

Semiconductor-based room-temperature-operation THz wave sources are strongly desired. This goal can be realized via nonlinear mixing of two mid-infrared wavelengths inside a single QCL. A monolithic nonlinear mixer converts the mid-infrared signals into Thz radiation using the process of difference frequency generation (DFG) with a Cherenkov phase-matching scheme. By stacking two QCL emitters in a single laser, and by applying the epilayer-down mounting, room-temperature, single-mode emission was obtained at 3.51 THz with output power up to 215 μW and side mode suppression ratio of 30 dB [11]. A wide spectral range tuning capability (1.70–5.25 THz) has been demonstrated using an external grating cavity feedback system for dual-period DFB grating mid-IR QCL device. At 3.6 THz, maximum power and conversion efficiency of 40 μW and 0.3 mW/W^2, respectively, were reported [12].

Additional improvements that might be implemented in the future for both THz-QCLs and THz-DFG-QCLs include optimizing the quantum design of the active regions to achieve higher efficiency and higher non-linearity.

Resonant tunneling diodes (RTDs) are another good candidate for use as a compact battery-operated THz source operated at room temperature. The direct oscillation frequency increases year by year. It has been recorded up to around 1.4 THz [13]. At higher output power, RTDs have been reported via array configuration [14]. Preliminary demonstrations for application to imaging and wireless data transmission have also been demonstrated.

4. Metrology

To control the emission frequency of THz QCLs precisely, researchers have used the repetition rate of a mode-locked laser to realize ultrastable phase-coherent links between the THz domain and the radiofrequency range. This technique, originally developed for metrological purposes, opens a direct link with femtosecond lasers, which operate in a completely different region of the electromagnetic spectrum.

Optical frequency combs are innovative tools for broadband spectroscopy because a series of comb modes can serve as frequency markers that are traceable to a microwave frequency standard. Recently, using a combination of a THz comb with dual-comb spectroscopy, broadband THz spectroscopy traceable to a microwave frequency standard has been achieved [15]. Furthermore, the frequency gaps between THz comb modes were interleaved using swept dual THz combs.

The THz comb further expands the scope of its application. In the field of frequency metrology, a low-noise microwave signal was synthesized from a CW-THz source using a photocarrier THz comb in a photoconductive antenna as a frequency linker between THz and microwave regions, serving as a THz frequency divider that is potentially useful for future high-speed wireless networks [16]. However, in the field of laser stabilization, a CW THz-QCL, phase-locking to THz comb, was applied for a tunable THz synthesizer for precise THz spectroscopy, although its tuning range was limited to a frequency range of 1 GHz [17].

The THz and sub-THz frequency are the longest wavelength ranges for which optical methods are useful to measure the power of electromagnetic radiation. Traceable radiometry offers the possibility of tracing back the THz power responsivity scale to the more accurate responsivity scale in the visible spectral range, thereby significantly reducing the uncertainty of detector calibrations in the THz range [18].

5. Microscope

Important advances have been made in THz near-field imaging using scanning probe tips. Coupling free-space THz pulsed to an STM tip (THz-STM) offers new possibilities for modulating tip bias, which can avoid limitations induced by capacitive coupling, microstrip bandwidth, and thermal expansion. This provides simultaneous subpicosecond time resolution and nanometer imaging resolution under ambient laboratory conditions, and can directly image ultrafast carrier capture into a single InAs nanodot. The THz-STM accessed an ultrafast tunneling regime that opens the door to subpicosecond scanning probe microscopy of materials with atomic resolution [19].

A THz chemical microscope (TCM) has been proposed to map chemical and electric potential shifts because of chemical reactions [20]. Since the spatial resolution of this type of laser-emission THz technique is not limited by the wavelength of the THz radiation, but by the wavelength of the femtosecond laser applied to generate the THz radiation, higher spatial resolutions can be achieved than those produced using conventional THz imaging systems. The TCM can detect chemical reactions of diverse types, such as protein bindings, diffusions of the ion in the membrane, and catalytic reactions of metal. Only a size comparable to the laser spot size is necessary to detect a single type of material, which implies that materials of many types are detectable using single scanning of the femtosecond laser on one sensing chip. Consequently, TCM can be a useful ‘combinatorial sensing’ tool for medical diagnosis and for materials research.

6. Biological THz Wave Radiation Studies

Recent technological breakthroughs in THz radiation and instrumentation blaze a new trail for biological studies.

Irradiation of lab-grown tissue by intense picosecond THz pulses caused significant induction of phosphorylation of histone (H2AX), which is the major basic nuclear protein in human skin tissue [21]. This result affords collateral evidence of DNA damage. The inherent sign was also observed that a THz-pulse might increase the production of proteins that help to fight tumors or cancers. These findings suggest that intense THz pulses should be studied for future therapeutic applications. A method used to determine the complex dielectric constant of single-layered biological cells was proposed using a highly stable pulsed THz attenuated total reflection spectroscopy system [22]. This method might suggest ways to understand intercellular water dynamics on an ultra-short timescale and to estimate the existence of weakly hydrated water molecules inside a cell.

Research in THz wave science and technology has experienced considerable levels of activity and a broad variety of new applications in 2013. Researchers from all over the world contribute on a daily basis to its continuing progress. Although all important contributions of the last year could not be reviewed in this short article, these explanations are intended to stimulate further research in this highly interdisciplinary field, contributing to the successful development of THz wave photonics.

References

[1] C. W. Berry, H. Wang, M. R. Hashemi, M. Unlu, and M. Jarrahi, “Significant performance enhancement in photoconductive terahertz optoelectronics by incorporating plasmonic contact electrodes,” *Nature Commun.*, vol. 4, p. 1622, Mar. 2013.

[2] S.-W. Huang, E. Granados, W. R. Huang, K.-H. Hong, L. E. Zapata, and F. X. Kärtner, “High conversion efficiency, high energy terahertz pulses by optical rectification in cryogenically cooled lithium niobate,” *Opt. Lett.*, vol. 38, no. 5, pp. 796–798, Mar. 2013.

[3] C. Vicario, B. Monoszlai, Cs. Lombosi, A. Mareczko, A. Courjaud, J. A. Fulop, and C. P. Hauri, “Pump pulse width and temperature effects in lithium niobate for efficient THz generation,” *Opt. Lett.*, vol. 38, no. 24, pp. 5373–5376, Dec. 2013.

[4] H. Minamide, S. Hayashi, K. Nawata, T. Taira, J. Shikata, and K. Kawase, “Kilowatt-peak Terahertz-wave generation and sub-femtojoule Terahertz-wave pulse detection based on nonlinear optical wavelength-conversion at room temperature,” *J. Infrared, Millimeter, Terahertz Waves*, vol. 35, no. 1, pp. 25–37, Jan. 2014.

[5] J. Shikata, M. Sato, T. Taniuchi, H. Ito, and K. Kawase, “Enhancement of terahertz-wave output from LiNbO3 optical parametric oscillators by cryogenic cooling,” *Opt. Lett.*, vol. 24, no. 4, pp. 202–204, Feb. 1999.

[6] M. Brandstetter, C. Deutch, M. Krall, H. Detz, D. C. MacFarland, T. Zederbauer, A. M. Andrews, W. Schrenk, G. Strasser, and K. Unterrainer, "High power terahertz quantum cascade lasers with symmetric wafer bonded active regions," *Appl. Phys. Letters.*, vol. 103, no. 17, pp. 171113-1–171113-5, Oct. 2013.

[7] D. Turcinkova, K. Otani, G. Scalari, M. Beck, and J. Faist, "High power terahertz quantum cascade laser at 63 μm," in *Proc. IRMMW-THz*, 2013, pp. 1–3.

[8] Q. Qin, J. L. Reno, and Q. Hu, "MEMS-based tunable terahertz wire-laser over 330 GHz," *Opt. Lett.*, vol. 36, no. 5, pp. 692–694, Mar. 2011.

[9] J. A. Fan, M. A. Belkin, F. Capasso, S. Khanna, M. Lachab, A. G. Davies, and E. H. Linfield, "Surface emitting terahertz quantum cascade laser with a double-metal waveguide," *Opt. Exp.*, vol. 14, no. 24, pp. 11 672–11 680, Nov. 2006.

[10] G. Liang, H. Liang, Y. Zhang, S. P. Khanna, L. Li, A. G. Davies, E. Linfield, D. F. Lim, C. S. Tan, S. F. Yu, H. C. Liu, and Q. J. Wang, "Single-mode surface-emitting concentric-circular-grating terahertz quantum cascade lasers," *Appl. Phys. Lett.*, vol. 102, no. 3, pp. 031119-1–031119-4, Jan. 2013.

[11] Q. Y. Lu, N. Bandyopadhyay, S. Slivken, Y. Bai, and M. Razeghi, "Room temperature terahertz quantum cascade laser sources with 215 μW output power through epilayer-down mounting," *Appl. Phys. Lett.*, vol. 103, no. 1, pp. 011101-1–011101-4, Jul. 2013.

[12] K. Vijayraghavan, Y. Jiang, M. Jang, A. Jiang, K. Choutagunta, A. Vizbaras, F. Demmerle, G. Boehm, M. C. Amann, and M. A. Belkin, "Broadly tunable terahertz generation in mid-infrared quantum cascade lasers," *Nature Commun.*, vol. 4, p. 2121, Jun. 2013.

[13] Y. Koyama, R. Sekiguchi, and T. Ouchi, "Oscillations up to 1.40 THz from resonant-tunneling-diode-based oscillators with integrated patch antennas," *Appl. Phys. Exp.*, vol. 6, no. 6, pp. 064102-1–064102-3, Jun. 2013.

[14] S. Suzuki, M. Shiraishi, H. Shibayama, and M. Asada, "High-power operation of terahertz oscillators with resonant tunneling diodes using impedance-matched antennas and array configuration," *IEEE J. Sel. Topics Quantum Electron.*, vol. 19, no. 1, p. 8 500 108, Jan./Feb. 2013.

[15] Y.-D. Hsieh, Y. Iyonaga, Y. Sakaguchi, S. Yokoyama, H. Inaba, K. Minoshima, F. Hindle, Y. Takahashi, M. Yoshimura, Y. Mori, T. Araki, and T. Yasui, "Terahertz comb spectroscopy traceable to microwave frequency standard," *IEEE Trans. Terahertz Sci. Technol.*, vol. 3, no. 3, pp. 322–330, May 2013.

[16] S. Nagano, H. Ito, M. Kumagai, M. Kajita, and Y. Hanado, "Microwave synthesis from a continuous-wave terahertz oscillator using a photocarrier terahertz frequency comb," *Opt. Lett.*, vol. 38, no. 12, pp. 2137–2139, Jun. 2013.

[17] L. Consolino, S. Bartalini, A. Taschin, P. Bartolini, P. Cancio, M. De Pas, H. E. Beere, D. A. Ritchie, M. S. Vitiello, R. Torre, and P. De Natale, "THz spectroscopy with an absolute frequency scale by a QCL phase-locked to a THz frequency comb," in *Proc. 38th Int. Conf. Infrared, Millimeter, Terahertz Waves*, 2013, pp. 1–2.

[18] Steiger, M. Kehrt, C. Monte, and R. Muller, "Traceable terahertz power measurement from 1 THz to 5 THz," *Opt. Exp.*, vol. 21, no. 12, pp. 14 466–14 473, Jun. 2013.

[19] T. L. Cocker, V. Jelic, M. Gupta, S. J. Molesky, J. A. J. Burgess, G. De Los Reyes, L. V. Titova, Y. Y. Tsui, M. R. Freeman, and F. A. Hegmann, "An ultrafast terahertz scanning tunnelling microscope," *Nat. Photon.*, vol. 7, no. 8, pp. 620–625, Aug. 2013.

[20] T. Kiwa, A. Tenma, S. Takahashi, K. Sakai, and K. Tsukada, "Label free immune assay using terahertz chemical microscope," *Sens. Actuators B, Chem.*, vol. 187, pp. 8–11, Oct. 2013.

[21] L. V. Titova, A. K. Ayesheshim, A. Golubov, D. Fogen, R. Rodriguez-Juarez, F. A. Hegmann, and O. Kovalchuk, "Intense THz pulses cause H2AX phosphorylation and activate DNA damage response in human skin tissue," *Biomed. Opt. Exp.*, vol. 4, no. 4, pp. 559–568, Mar. 2013.

[22] K. Shiraga, Y. Ogawa, T. Suzuki, N. Kondo, A. Irisawa, and M. Imamura, "Determination of the complex dielectric constant of an epithelial cell monolayer in the terahertz region," *Appl. Phys. Lett.*, vol. 102, no. 5, pp. 053702-1–053702-4, Feb. 2013.