

Optical Engineering

SPIEDigitalLibrary.org/oe

Terahertz Physics and Applications

Mehdi Anwar
Joseph S. Melinger
Ekmel Ozbay
Masayoshi Tonouchi



Terahertz Physics and Applications

Mehdi Anwar

University of Connecticut
Department of Electrical and Computer Engineering
Storrs, Connecticut 06269-2157
E-mail: anwara@engr.uconn.edu

Joseph S. Melinger

Naval Research Laboratory
Electronics Science and Technology Division, Code 6812
Washington, DC 20375
E-mail: joseph.melinger@nrl.navy.mil

Ekmele Ozbay

Bilkent University
Department of Electrical and Electronics Engineering
Bilkent, Ankara 06800 Turkey
E-mail: ozbay@bilkent.edu.tr

Masayoshi Tonouchi

Osaka University
Institute of Laser Engineering
2-6 Yamada-Oka, Suita-city
Osaka 565-0871, Japan
E-mail: tonouchi@ile.osaka-u.ac.jp

Radiation in the terahertz range, loosely defined as 0.1 to 10 terahertz (THz), spans the relatively undeveloped gap between electronics at the low end of the spectrum, and optics at the high-frequency end. Initially, THz radiation was used exclusively by astrophysicists for applications such as the detection of antimatter. However, this extremely expansive and spectrally unique portion of the electromagnetic spectrum was of interest for such applications as space-based communications, upper atmospheric sensing and communications, and potentially for short-range terrestrial communications and nonintrusive package screening. More recently, radiation in the THz range has been identified as ideal for an extremely wide range of applications from security to medical systems. Moreover, the realization of THz transistors and the use of negative index materials, and more recently its use in counterfeit integrated circuit detection, may revolutionize THz technology. In this special section, we present a collection of selective papers that represents to a certain extent the recent advances in THz and related technologies.

The first paper entitled "Identification of concealed materials, including explosives, by terahertz reflection spectroscopy," by N. Palka uses THz spectroscopy to identify concealed materials. THz fingerprints of materials covered with semitransparent layers such as a sheet of polyethylene or paper are detected in the range of about 0.5 to 1.8 THz. The method takes into account the only part of the signal reflected from the covered sample and analyzes its Fourier transformed spectra.

S. Yamauchi, S. Hatakeyama, and Y. Imai, in their paper entitled "Nondestructive evaluation of crystallized-particle size in lactose-powder by terahertz time-domain spectroscopy," use THz to evaluate crystallized lactose particles smaller

than 30 μm . The THz absorption feature is dependent on the crystallized particle size. The integrated absorption intensity ratio was able to determine the average particle size.

K. A. Salek et al., in their paper "Laser terahertz emission microscopy studies of a polysilicon solar cell under the illumination of continuous laser light," explore THz emission properties of a polysilicon solar cell excited by femtosecond laser pulses. The laser terahertz emission microscopy images also permitted the visualization of the crystalline grain structure, dynamics of photocarriers, and the local electric field distribution in the solar cell.

In the paper entitled "Evaluation of human hairs with terahertz wave," K. Serita et al. discuss the use of a scanning laser THz imaging system to detect features in a single human hair. By detecting the transmitted THz wave pulses that are locally generated at the irradiation spots of the excitation laser, the THz transmission image and spectrum are obtained with an imaging time of 47 s for 512×512 pixels and maximum resolution of $\sim 27 \mu\text{m}$.

T. Otsuji et al., in their paper entitled "Emission and detection of terahertz radiation using two-dimensional plasmons in semiconductor nanoheterostructures for nondestructive evaluations," review the nondestructive evaluation of semiconductor nanoheterostructures using two-dimensional plasmons. Excellent THz emission and detection performances are experimentally demonstrated by using InAlAs/InGaAs/InP and/or InGaP/InGaAs/GaAs heterostructure material systems.

In the paper entitled "Asymmetric split-ring resonators: a way toward high-quality metamaterials," S. Engelbrecht et al. discuss the use of millimeter-wave spectroscopy to study the electromagnetic response of asymmetric split-ring resonators made from superconducting niobium. A small asymmetry

allowed the excitation of an otherwise dark mode with only a weak coupling to electromagnetic field. Reduced ohmic losses in the superconductor led to high-quality factors (150) of split-ring resonators.

The paper entitled "Aeronautics composite material inspection with a terahertz time-domain spectroscopy system," authored by F. Ospald et al., describes pulsed broadband terahertz radiation for the inspection of composite materials. Defects such as foreign material inserts, delaminations, and moisture contamination can be visualized. If a defect is not too deep in the sample, its location can be correctly identified from the delay between partial reflections at the surface and the defect itself.

H. Ito et al., in the paper entitled "Broadband photonic terahertz-wave emitter integrating uni-traveling-carrier photodiode and self-complementary planar antenna," introduce two types of terahertz-wave emitters, fabricated using self-complementary planar antennas (a log-periodic antenna or a bowtie antenna) and InP/InGaAs uni-traveling-carrier photodiodes. The module with a bowtie antenna had more stable polarization characteristics, better linearity of the output powers, and was capable to be operated even under zero bias conditions.

In the paper "Characterization of low-loss waveguides and devices for terahertz radiation," B. M. Azizur Rahman et al. provide a theoretical framework for the determination of modal loss and dispersion in various types of practical dielectric and metal-coated waveguides. Design optimization of quantum cascade lasers, multimode interference coupler-based power splitters, and narrow-band filters are presented by using a full-vectorial H-field finite element method.

The final paper in the special section is authored by E. Cristofani et al., entitled "Nondestructive testing potential evaluation of a terahertz frequency-modulated continuous-wave imager for composite materials inspection," which reports the use of the sub-THz frequency band as an option for nondestructive testing of nonmetal aeronautics materials. An automated two-dimensional scanner carrying three sensors partially covering the 70- to 320-GHz band is operated, using two complementary measurement approaches: conventional focused imaging and synthetic aperture (SA). Conventional focused imagery offers finer spatial resolutions, but imagery is depth-limited due to the beam waist effect,

whereas SA measurements allow imaging of thicker samples with depth-independent but coarser spatial resolutions.

Mehdi Anwar is a full professor of Electrical and Computer Engineering at the University of Connecticut. He served as the Associate Dean for Research & Graduate Education of the School of Engineering and as the founding director of the Department of Homeland Security Center of Excellence. At present, his research focuses on ZnO/ZnMgO nanowire-based solar blind ultraviolet detectors and memristors and counterfeit electronics detection using THz spectroscopy. He serves as the Editor-in-Chief of *Circuits & Systems*, as an Editor of *IEEE JEDS*, and as conference chair of SPIE's Terahertz Physics, Devices and Systems conference. He is an SPIE Fellow.

Joseph S. Melinger received a BA from Grinnell College, Grinnell, Iowa, in 1980 and a PhD from Cornell University, Ithaca, New York, in 1989. From 1989 to 1992 he did postgraduate research at Princeton University and the Naval Research Laboratory. In 1993 he joined the staff at the Naval Research Laboratory (NRL). At NRL he has made contributions to understanding the photophysics of organic-based materials and supramolecular systems, in the application of pulse laser methods to simulate cosmic ray effects in semiconductor circuits, and, more recently, in the application of terahertz technology to the measurement of terahertz vibrational spectra of organic materials and detection of vapors.

Ekmel Ozbay received his PhD degree from Stanford University in electrical engineering in 1992. He worked as a postdoctoral research associate at Stanford University, and he later worked as a scientist at the Department of Energy Ames National Laboratory in Iowa State University. He joined Bilkent University (Ankara, Turkey) in 1995, where he is currently a full professor in the Department of Electrical and Electronics Engineering and the Department of Physics. His current research topics involve nanophotonics, nanometamaterials, nanoelectronics, nanoplasmonics, nanodevices, photonic crystals, GaN/AlGaIn MOCVD growth, fabrication and characterization of GaN-based devices, and high-speed optoelectronics.

Masayoshi Tonouchi received his BS, MS, and DrE degrees from Osaka University, Japan, in 1983, 1985, and 1988, respectively. Currently he is a professor at the Institute of Laser Engineering, Osaka University, and a concurrent professor of Nanjin University. His current research interests include ultrafast optical and terahertz science of strongly correlated electron systems and 2-D atomic layer materials, and development and applications of terahertz systems such as the laser terahertz emission microscope. He is a member of the Optical Society of America, the Japan Society of Applied Physics, the Physical Society of Japan, and the Institute of Electronics, Information and Communication Engineers.