Breakthroughs in Terahertz Science and Technology in 2009

Daniel Mittleman

(Invited Paper)

Rice University, Houston, TX 77005 USA

DOI: 10.1109/JPHOT.2010.2045490

Manuscript received February 1, 2010. Current version published April 23, 2010. Corresponding author: D. Mittleman (e-mail: daniel@rice.edu).

Abstract: Terahertz science and technology continues to advance at a rapid pace. This article reviews a few of the most exciting advances from 2009, including reports in high-field THz science, imaging, and plasmonics.

Index Terms: Terahertz, sub-millimeter, far infrared.

In 2009, the field of terahertz science and technology continued to grow very rapidly. The number of peer-reviewed journal articles topped 1000, and attendance at related conferences (such as the IRMMW-THz conference series and the Optical Terahertz Science and Technology topical meeting) continues to grow. The field is highly interdisciplinary, since terahertz techniques are valuable for everything from spectroscopy to sensing. Rapid progress in source, detector, and systems technologies are matched by equally dramatic advances in materials research, photonic components, the development of new applications areas, and so on. Here, we discuss just a few of many important studies whose results were reported in 2009.

One important current research area in terahertz photonics is the quest to reach high intensity. Time-domain spectroscopy has become a standard tool for the generation and detection of single-cycle terahertz pulses, but in most cases, the pulse energy is quite low. As a result, schemes for exploiting the high temporal resolution have been mostly limited to using the terahertz as a probe, rather than as the pump pulse that can initiate a nonlinear interaction. Within the last few years, researchers have demonstrated tabletop methods for producing terahertz pulses with microjoules of energy per pulse or with peak electric fields in the 100-MV/cm range. This, in turn, has enabled new experimental capabilities in the study of terahertz-induced nonlinear optics.

In 2009, several groups reported measurements which rely on these new capabilities. Most notably, Nelson and his coworkers at the Massachusetts Institute of Technology have published the results of several terahertz-pump, terahertz-probe measurements, illustrating the new types of spectroscopic information that can be obtained. For example, in a conventional optical pump-probe measurement on a semiconductor, interband transitions give rise to a population of both electrons and holes. A time-delayed probe pulse interacts with both of these hot carrier distributions, and therefore, disentangling the dynamics of the two can be challenging. In contrast, a terahertz pump (using an n-doped sample, for example) creates only nonequilibrium electrons and not holes. The relaxation dynamics, which are measured with a time-delayed terahertz probe pulse, are therefore unambiguous [1].

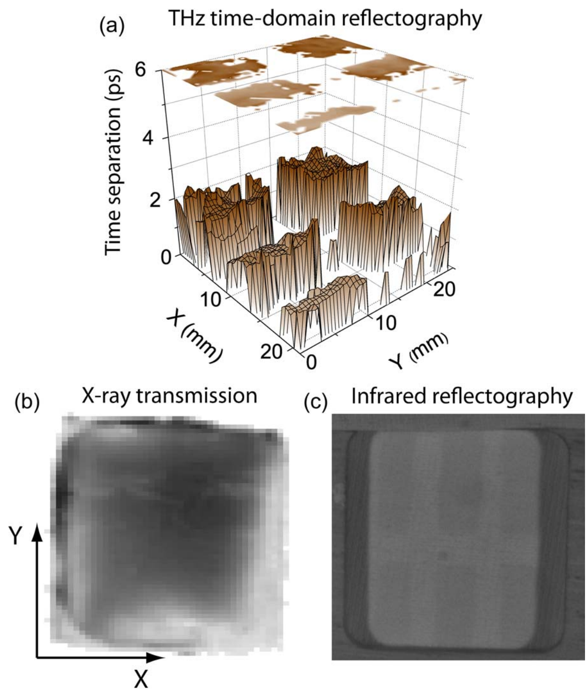

Fig. 1.

The design and construction of novel terahertz resonators continues to be a hot topic. This effort is motivated by sensing applications, in which a small shift in the resonant frequency can be correlated with the presence of a sensing target. Unlike in the optical regime, where compact high-Q resonators (e.g., $Q \sim 10^4$ or higher) are fairly routine, the state of the art in integrated terahertz resonant devices is less well developed. 2009 saw some significant progress in waveguide-integrated resonators, notably from groups at Oklahoma State University (using Bragg resonances) [2] and Rice University (using groove cavities) [3]. Perhaps the most impressive result came from the University of California at Santa Barbara, where a photonic crystal cavity was demonstrated with a Q of about 1000 [4].

Another research area making rapid progress in 2009 is terahertz plasmonics. The terahertz range lies between the range of microwaves, where surface waves at metal surfaces have been well known for over a century, and the regime of plasmonics, where the surface response of metals is strongly influenced by resonant plasmon interactions. In the terahertz range, it is natural to extend and merge these two related concepts. Using ideas from the optical plasmonics community (such as the concept of metamaterials) or from the microwave photonics community (such as waveguides based on surface waves), researchers have made important steps in the development of components and techniques for terahertz science and technology.

The field of terahertz metamaterials provides some excellent examples. Taylor and her coworkers at Los Alamos National Laboratory, along with collaborators at Sandia National Laboratory, Boston College, and Boston University, demonstrated a metamaterial-based phase modulator for terahertz radiation. Although the response is resonant, as dictated by the nature of a typical split-ring-resonator-based planar metamaterial, the modulation is broadband, since the metamaterial affects both the amplitude and the phase of the terahertz signal over a broad spectral range [5]. The Los Alamos and Sandia groups also collaborated with researchers at Rice University to demonstrate the first high-speed spatial control of a terahertz wave front using a metamaterial-based modulator [6]. This spatial light modulator could have important uses in many future terahertz applications. For example, it could replace the need for a multipixel focal plane array in a real-time terahertz imaging system.

Speaking of terahertz imaging, this area also saw several important advances, both in techniques and devices for image formation and in expanding the range of applications. A collaboration between groups at the University of Wuppertal and the Johann Wolfgang Goethe-University Frankfurt demonstrated a focal plane array fabricated in 0.25-μm CMOS [7]. This device, operating at room temperature, exhibits impressive sensitivity for radiation at 0.65 THz and has a clear route for scaling to a large number of pixels. This low-cost solution could eliminate one of the key barriers to the widespread implementation of terahertz imaging. The goal of subwavelength resolution continues to attract a great deal of attention. Impressive results have been described by a group at Aachen University. In this paper, a surface wave propagating on a tapered wire waveguide was compressed to a region that is much smaller than the wavelength. A target, which is held in the near field of the tapered tip, was then imaged with resolution in the few micrometer range [8]. Meanwhile, the list of possible applications of terahertz imaging continues to grow. One exciting area with enormous potential is that of art conservation, which saw several important feasibility studies in 2009 [9], [10]. Fig. 1 illustrates the unique types of information that can be obtained. This and other imaging applications continue to be one of the key motivating factors in the growth of the field.

References

[1] M. C. Hoffmann, J. Hebling, H. Y. Hwang, K.-L. Yeh, and K. A. Nelson, "THz-pump/THz-probe spectroscopy of semiconductors at high field strengths," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 26, no. 9, pp. A29–A34, 2009.

[2] S. S. Harsha, N. Laman, and D. Grischkowsky, "High-Q terahertz Bragg resonances within a metal parallel plate waveguide," *Appl. Phys. Lett.*, vol. 94, no. 9, p. 091118, Mar. 2009.

[3] R. Mendis, V. Astley, J. Liu, and D. M. Mittleman, "Terahertz microfluidic sensor based on a parallel-plate waveguide resonant cavity," *Appl. Phys. Lett.*, vol. 95, no. 17, p. 171 113, Oct. 2009.

[4] M. S. Sherwin and C. M. Yee, "High-Q terahertz microcavities in silicon photonic crystal slabs," *Appl. Phys. Lett.*, vol. 94, no. 15, p. 154 104, Apr. 2009.

[5] H.-T. Chen, W. J. Padilla, M. J. Cich, A. K. Azad, R. D. Averitt, and A. J. Taylor, "A metamaterial solid-state terahertz phase modulator," *Nat. Photon.*, vol. 3, no. 3, pp. 148–151, Mar. 2009.

[6] W. L. Chan, H.-T. Chen, A. J. Taylor, I. Brener, M. J. Cich, and D. M. Mittleman, "A spatial light modulator for terahertz beams," *Appl. Phys. Lett.*, vol. 94, no. 21, p. 213 511, May 2009.

[7] E. Öjefors, U. R. Pfeiffer, A. Lisauskas, and H. G. Roskos, "A 0.65 THz focal-plane array in a quarter-micron CMOS process technology," *IEEE J. Solid-State Circuits*, vol. 44, no. 7, pp. 1968–1976, Jul. 2009.

[8] M. Awad, M. Nagel, and H. Kurz, "Tapered Sommerfeld wire terahertz near-field imaging," *Appl. Phys. Lett.*, vol. 94, no. 5, p. 051107, Feb. 2009.

[9] K. Fukunaga, I. Hosako, I. N. Duling, and M. Picollo, "Terahertz imaging systems: A non-invasive technique for the analysis of paintings," *Proc. SPIE*, vol. 7391, pp. 739 10D-1–739 10D-9, Jul. 2009.

[10] A. L. Adam, P. C. M. Planken, S. Meloni, and J. Dik, "Terahertz imaging of hidden paint layers on canvas," *Opt. Express*, vol. 17, no. 5, pp. 3407–3416, Mar. 2009.