Bridging the terahertz gap with novel sources and sensors

Michael Johnston

Recent developments in source and sensor technology are leading to new scientific and commercial applications for terahertz radiation.

Infrared light and microwave radiation are widely used in the home: in everything from remote controls to mobile phones. However, there’s a huge swath of the electromagnetic spectrum, at frequencies between those of microwaves and infrared light, that hasn’t been fully exploited yet.

This terahertz (THz), far-infrared, or sub-millimeter radiation, at frequencies from 10GHz to 30THz, could be the next frontier for increasing the switching speed of modern electronics. THz spectroscopy may improve our understanding of systems from semiconductors and superconductors to pharmaceuticals and biomolecules.

So why is THz radiation so little used? One of the main problems is the lack of source and sensor technology. The upper switching rate of commercial electronics is still limited to high microwave frequencies, while commercial lasers have a lower-frequency limit corresponding to mid-infrared light. So there’s considerable scientific and commercial interest in developing sources and sensors that could bridge this gap.

One very successful approach to overcoming these limitations has been the development of THz time-domain spectroscopy (THz-TDS), which uses femtosecond-pulse laser technology to generate and detect pulses of THz radiation.¹ The technique, shown in Figure 1(a), enables the electric field of THz pulses to be detected as a function of time. This means that the full dielectric function of a material can be measured, which in turn means its frequency-dependent complex conductivity can be revealed. Because the technique uses pulses, it will work a little like radar to reveal spectroscopic data as a function of depth in materials. It can also be used for time-resolved spectroscopy, observing dynamic processes at sub-picosecond timescales.

The THz band is already proving extremely useful for scientific spectroscopy,² as well as in commercial applications such as medical imaging³ and security screening.⁴ We’ll be able to do more with it when the power of THz sources increases, because this will increase the signal-to-noise ratio of THz-TDS systems. Increasing the bandwidth of THz sources and sensors will also

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Figure 1. (a) In terahertz (THz) time-domain spectroscopy, a pulse is transmitted through free space and its electric field is detected in the time domain. If the pulse passes through a sample it is delayed and attenuated. The (complex) frequency spectrum is obtained by a Fourier transform of the time-domain data. (b) Simulated THz emission from an ion-implanted InP photoconductive emitter in the time (left) and frequency (right) domain.¹ The blue, green, and red normalized pulses represent emission from materials with carrier lifetimes τ of 100ps, 1ps, and 100fs, respectively. Inset: a simulated THz emitter.¹
Figure 2. A polarization-resolved THz sensor, shown at increasing magnifications from (a) to (c). In (d), three linearly polarized THz pulses (with polarization at 0°, 45° and 90° to the horizontal) are shown. These are measured using the sensor.3

open up opportunities, as will the development of polarization-sensitive technologies.

Modeling the mechanisms by which radiation is generated in semiconductor THz sources is critical to increasing the power they can radiate. Simulating charge-carrier dynamics with a semi-classical Monte Carlo model has helped explain the mechanism of THz generation from semiconductor surfaces.7 It has also helped identify the importance of screening in photoconductive switch emitters.8 Modeling has played a key role in describing why putting semiconductor sources in magnetic fields enhances the power of their THz emissions.9 Predictions from Monte Carlo simulation work9 also led to the development of a prism-based THz emitter,10 which achieved similar power increases without high magnetic fields.

Increasing the bandwidth of sources and sensors so they encompass the THz band and beyond is important for THz spectroscopy. The use of semiconductors that have been damaged by ions and grown at low temperatures is proving very successful for this. Monte Carlo modeling and experiments on ion-implanted GaAs,11 InP, and InGaAs1 devices have shown that the trapping of photo-excited carriers is crucial to improving the bandwidth of THz sources based on these materials. Figure 1(b) shows an example of simulated time- and frequency-domain data for an InP-based, photoconductive-switch THz source. A source based on an ion-damaged semiconductor will emit a wider bandwidth—that is, shorter THz pulses—at the expense of device efficiency. So we need to make careful trade-offs to increase the THz bandwidth without reducing the radiated power.

The ability to measure the full polarization state of THz pulses will increase the usefulness of THz-TDS. Vibrational circular dichroism spectroscopy, which relies on detecting the absorption of radiation with different circular polarizations, may be very useful for determining the chirality, or asymmetry, of biomolecules and pharmaceuticals. A recently developed THz sensor can measure the full polarization state of a THz pulse directly.13 Its three-electrode design (see Figure 2) enables two orthogonal components of an electric field to be measured at once. The device will soon be able to do fast measurements of birefringent and optically active materials across the THz band.

The performance of THz sources and sensors is improving rapidly, opening up new spectroscopic techniques and commercial applications for THz radiation. The key to their more widespread use will be the development of cheaper sources and sensors.

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References

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