Near-IR lasers may close the terahertz gap

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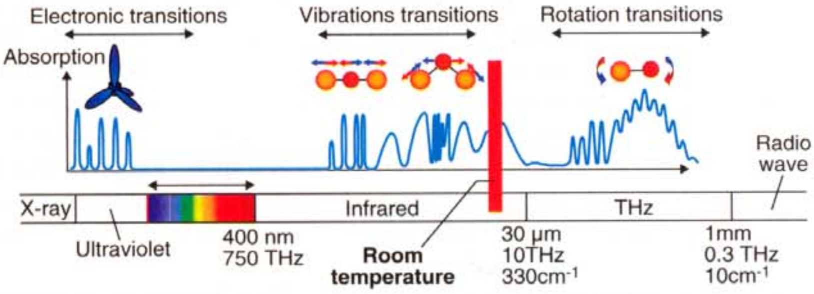

FIGURE 1. In the electromagnetic spectrum, terahertz radiation sits between the far-IR and radio waves. It is absorbed by molecular rotation transitions, whereas x-ray and UV radiation couples to electronic transitions, and IR radiation to molecular vibration bands.

In seafarers' maps of Renaissance times, the term *terra incognita* was used to denote unknown land—areas beyond the known frontiers that were yet to be documented. In modern science, the terahertz region represents the last frontier of the electromagnetic spectrum. Even though the potential of terahertz technologies is unquestioned, their industrial exploitation is just beginning. Recent progress in the generation of terahertz radiation has opened up new fields of activity, the most promising being imaging, sensing, and communication. Two laser-based approaches to producing these wavelengths might help to finally close the "terahertz gap."

Two laser-based approaches to terahertz generation—one using near-IR distributed-feedback diodes and the other using femtosecond lasers—may open up the terahertz region to more widespread use in imaging, spectroscopy, and communications.

Terahertz applications

The "terahertz range" refers to frequencies between 0.3 and 10 THz—or wavelengths from 1 mm to 30 μm (see Fig. 1). Electromagnetic radiation at these frequencies has some unique properties. Terahertz waves pass through a variety of amorphous substances that are normally considered opaque, such as clothing, paper, or plastics. The underlying principle is scattering: terahertz waves are not scattered as much as those at visible and near-infrared (IR) wavelengths, and reduced scattering means increased penetration depth. However, terahertz radiation is strongly absorbed by water molecules—and liquid water turns out to be a more dominant absorber than water vapor, so a single green plant leaf blocks a terahertz beam.

Within the last few years, several academic and industrial research groups have produced spectacular terahertz images, such as a ceramic knife blade hidden behind denim, high-resolution three-dimensional renderings of coins, and safety covers of air bags (see Fig. 2).[1, 2, 3] Unfortunately, a terahertz image is usually created in a "pixel-by-pixel" scan, with total acquisition times of at

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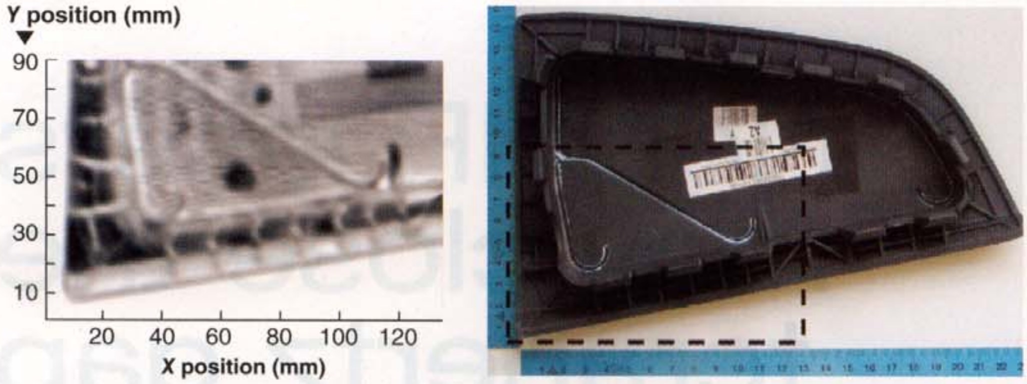


FIGURE 2. A terahertz image (left) is compared to a photograph (right) of an air-bag safety cover. Terahertz imaging helps determine the notch depth of the intended tear-seam line. (*Courtesy of R. Wilk and M. Koch, University of Braunschweig, Germany*)[3]

least several tens of minutes. Research in Germany and elsewhere is thus aimed at the development of a multipixel, real-time terahertz camera.[4] One potential approach is a "hybrid" concept whereby a powerful electronic source is used to illuminate the object and is combined with a phase-sensitive detection scheme for three-dimensional imaging.

Another attractive scenario is to unite the advantages of imaging and spectral sensitivity characteristic of terahertz radiation. Many chemical compounds have distinct absorption lines at frequencies between 0.5 and 5 THz. Potentially, explosives or illicit drugs could not only be localized within a parcel or an envelope, but also identified unambiguously because of their spectral "fingerprint." Other areas that would benefit from an imaging terahertz spectrometer include quality control of pharmaceuticals and the analysis of foodstuffs inside air-tight packages.

The communications sector represents another potential terahertz market. Faster data transfer rates require higher carrier frequencies. Admittedly, technical challenges have to be met—there are, for instance, no suitable terahertz transmission lines—but free-space communication channels (satellite communication, or "hot spots" for wireless download of high-data videos) at frequencies of 100 GHz and above can already be envisaged.

Terahertz generation

Widespread use of terahertz technologies has been hampered by the difficulties involved in generating intense, directional terahertz beams. Terahertz frequencies correspond to thermal energies equivalent to temperatures of between 3 and 100 K, which has two important consequences. First, room-temperature objects and living beings do, to some extent, emit terahertz radiation, a property that has been used for passive terahertz imaging (albeit with elaborate detectors). Second, far-IR quantum-cascade (QC) laser diodes, which could potentially emit terahertz waves directly, have to counter the thermal population of the upper lasing level. Hence, QC lasers are commonly operated at cryogenic temperatures, and are limited to frequencies above 2 THz (room-temperature QC lasers are available, but have much higher emission frequencies of 35 to 70 THz.)

On the low-frequency end of the terahertz spectrum, electronic devices (Schottky or Gunn diodes with frequency multiplier chains) provide very attractive power levels (100 to 1000 mW at 100 GHz), but their output decreases by five to six orders of magnitude per decade of frequency. Moreover, these devices can hardly, if at all, be frequency-tuned.

As it turns out, the frequency band between 0.5 and 5 THz is the domain of laser-based techniques. Optoelectronic approaches make use of femtosecond lasers or tunable diode lasers emitting in the near-IR, and photomixers, photoconductive switches, or nonlinear crystals that convert the laser output into terahertz waves—either broadband or spectrally resolved, depending on the method used.

Continuous-wave terahertz

Tunable continuous-wave (CW) terahertz emission is obtained by so-called "photomixing." The output beams of two lasers with adjacent wavelengths are superimposed on a dedicated antenna, usually a metal spiral embedded in low-temperature-grown gallium arsenide (see Fig. 3). At the heart of the antenna lies the photomixer, an interleaved finger structure, onto which the two-color laser beam is focused. When illuminated, free-charge carriers are generated in the semiconductor, creating an oscillating photocurrent at the metal electrodes. The antenna then converts the photocurrent into a new electromagnetic wave at the terahertz difference frequency of the lasers.

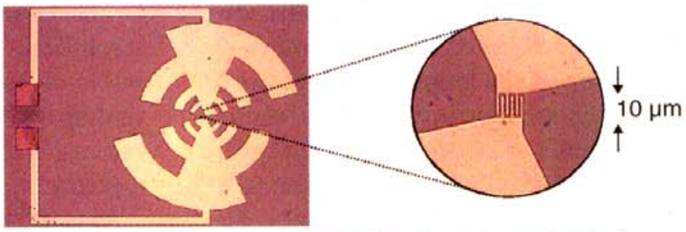


FIGURE 3. The finger structure (inset) of a metal spiral antenna embedded in low-temperature-grown gallium arsenide photomixes two laser beams to produce CW terahertz radiation. *(Courtesy of Th. Göbel and C. Sydlo, University of Darmstadt, Germany.)*

For a variety of reasons, the ideal laser sources for CW terahertz generation are near-IR distributed feedback (DFB) diodes. These lasers emit at wavelengths between 850 and 860 nm with high output power, narrow linewidth (due to their intrinsic grating structure), and a wide mode-hop-free tuning range of more than 1000 GHz. By selecting two diodes with appropriate wavelength offset, the terahertz difference frequency can be tuned continuously from, for instance, 0 to 2 THz, or from 1 to 3 THz.

State-of-the-art "two-color" diode lasers use fiber-optic components for beam combination and delivery (see Fig. 4). Polarization-maintaining 2 × 2 fiber couplers enable a robust, "hands-off" setup, and automatically secure the necessary beam overlap on the photomixer. The optical output power of these systems is about 60 mW per two-color fiber output, which translates into 50 to 1000 nW of terahertz power, depending on the photomixer design and the actual difference frequency—the efficiency of photomixers decreases with the fourth power of the terahertz frequency. For spectroscopic applications, this power level is usually sufficient, especially as signal-to-noise ratios of more than 35 dB have been achieved for the photo current.

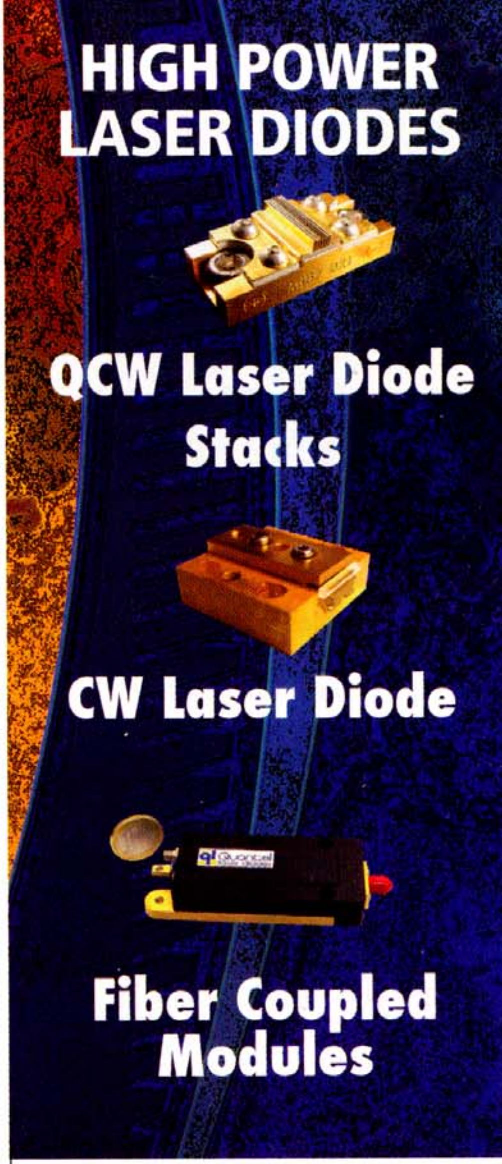
An intriguing feature of DFB diodes is the possibility of controlling the laser frequency with megahertz or even submegahertz precision. We have used electronic feedback from a low-finesse, temperature-stabilized Fabry-Perot etalon to regulate the wavelength of the DFB lasers and were able to generate highly linear scans of the terahertz difference frequency while, at the same time, maintaining a terahertz linewidth of only 1.2 MHz on time scales as long as 80 ms. The accurate, computerized adjustment of the terahertz frequency paves the way for new applications in high-resolution terahertz spectroscopy such as the quantitative assessment of hazardous gases and biological agents.

Pulsed teraherz

Ultrafast broadband terahertz radiation is generated with femtosecond lasers. Here, too, the laser output is focused on a semiconductor antenna and free charge carriers are produced that are subsequently accelerated by external or internal electric fields. This transient current induces a spectrally broad electromagnetic field. A 100 fs laser pulse in the near-IR, for instance, translates into a terahertz pulse of 4 to 5 THz spectral width. Different antenna designs function at wavelengths of about 800 nm, or in the telecom range around 1550 nm, respectively.

On the laser side, one favorable option is femtosecond fiber lasers. Erbium-doped glass fibers form the basis of compact and reliable modelocked lasers. They emit spectrally broad pulses at 1550 nm, with more than 250 mW average power. Second-harmonic generation can convert the fundamental radiation into 775 nm pulses. Their pulse width of 150 fs and average power of more than 100 mW are compatible with available gallium arsenide antennas.

A pulsed terahertz experiment is, in a way, similar to conventional pump-probe setups. The terahertz beam interrogates the properties of a sample ("pump"), and is superimposed on a detector together with pulses of a second ultrafast beam ("probe"). Varying the time delay of the beams relative to one



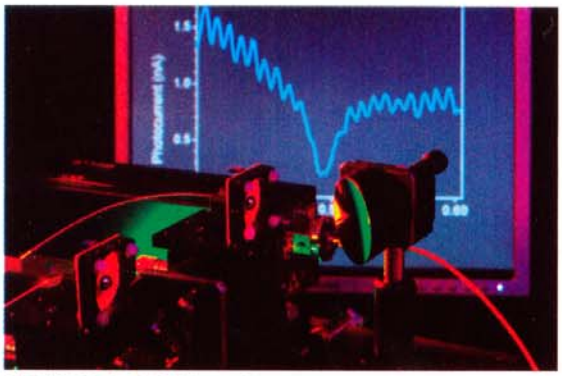


FIGURE 4. A CW terahertz setup uses two distributed-feedback diode lasers and fiber-optic components for beam combination and delivery.

another enables the electric field of the terahertz wave to be reconstructed, and a Fourier transform finally yields the desired spectral information. Traditionally, the output beam of the femtosecond laser was divided by a beamsplitter, and one of the beams was transferred to a bulky mechanical delay line that often was susceptible to acoustic noise and complicated optical alignment.

A newly developed method, dubbed ECOPS (Electrically Controlled OPtical Sampling), is based on two ultrafast lasers that are phase stabilized to each other. A slight modulation of the length of one of the fiber oscillators via a piezo-element serves to sweep the "probe" pulse through the terahertz pulse in a precisely controlled manner. Mechanical delay lines are unnecessary because the terahertz setup is all electronic. In a first installation at Dan Mittleman's lab at Rice University, we were able to demonstrate less than 100 fs timing jitter at scan frequencies of several hundred hertz and a typical pulse delay of 50 ps.

Flexibility with optoelectronic techniques

The choice of pulsed or CW terahertz emission is determined by the needs of the particular experiment. Pulsed terahertz emission provides broadband spectral data within the shortest times. In addition, by detecting the "echoes" of the pulses—in a manner similar to lidar or radar—depth information of the sample is obtained. Alternatively, CW terahertz provides increased frequency resolution. This method thus lends itself to measurements of narrow spectral signatures. The lasers used are also less expensive than currently available femtosecond sources.

As is often the case, terahertz imaging, spectroscopy, and communications are cutting-edge technologies with great potential for which common expectations currently outweigh the technological feasibility. Optoelectronic techniques such as those based on DFB diode lasers and femtosecond fiber lasers offer novel approaches that are currently being evaluated in academia and industry, and may lead to further commercial opportunities. ☐

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