Laser-based terahertz generation & applications

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Superior to alternative methods, optoelectronic techniques propel terahertz applications out of the lab and into the real world. One physical effect involves two laser beams at adjacent frequencies focusing on a semiconductor; another effect involves an ultrafast laser pulse separating charge carriers in a photoconductive switch. In combination with suitably structured antennas, these two effects generate electromagnetic radiation in the difficult-to-access terahertz region. Some of the principles of continuous-wave (CW) and pulsed terahertz sources are described here while exploring emerging applications.

The label "terahertz-gap" for this part of the electromagnetic spectrum is used to pinpoint the lack of suitable sources and detectors in this frequency range. Thanks to modern laser technologies, however, robust, compact and cost-efficient sources for terahertz imaging and spectroscopy are now readily available. The sources produce terahertz radiation with sufficient intensity for scientific and industrial measurement tasks, enabling many new applications, including basic research, material analysis, homeland security, and process control in biology, pharmacy and medicine.

1 Can you see what I see?

The terahertz spectrum lies between the far infrared and radio- or microwaves; this corresponds to frequencies between 100 GHz and 10 THz or wavelengths between 3 mm and 30 µm. Terahertz radiation penetrates many opaque materials, especially non-metal and non-polar materials such as textiles, paper and plastics. Compared to visible and near-infrared light, terahertz radiation scatters less due to its longer wavelength, resulting in a higher penetration depth.

Most interestingly, many substances exhibit characteristic spectral signatures in the terahertz region – so-called "fingerprints" – that allow their chemical composition identification. Many explosives and toxic agents feature characteristic absorption lines between 0.5 and 5 THz. This enables the detection of not only illicit drugs like cocaine, ecstasy and opiates, but also explosives like TNT, HMX and RDX in paper envelopes and parcels (**figure 1**). In the development and production of pharmaceuticals, terahertz spectroscopy can identify different crystalline forms (polymorphs) of the active component. Further applications include the detection of counterfeit drugs and food quality monitoring. Because terahertz radiation penetrates packaging materials made of paper or plastics, pills can be analyzed in the blister, and food can be tested through air-tight packaging.

Figure 1: Terahertz spectroscopy enables the detection of hazardous substances in envelopes and parcels

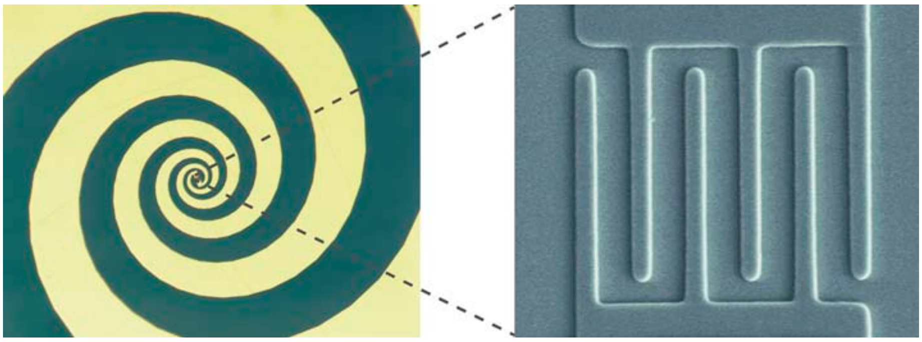

Figure 2: A photomixer with spiral antenna converts laser light into terahertz radiation

Many applications benefit from the imaging capabilities of terahertz radiation. Terahertz waves can be focused with mirrors and lenses. Scanning a sample with a terahertz beam delivers images with millimeter-range resolution. Depending on the method used, the depth resolution is even higher – by as much as two orders of magnitude. Because their photon energies range from 0.4 to 40 meV, terahertz rays do not have any ionizing effect (in contrast to gamma rays) and are considered biologically innocuous. Metals are not transparent for terahertz waves due to their high reflectivity. Organic matter is also opaque to terahertz light, as the ever-present water strongly absorbs terahertz rays.

2 Terahertz sources

The generation of terahertz radiation at spectroscopically relevant frequencies from 0.5 to 5 THz is challenging. This range cannot be directly accessed with semiconductor lasers, as no semiconductors with suitable band gaps exist. One direct optical source is the quantum-cascade-laser (QCL). A QCL generates frequencies above 1 THz but requires operating temperatures of 40 K, and therefore a He cryostat for cooling. QCLs with less complex nitrogen cooling are limited to frequencies above 2 THz. Voltage-controlled oscillators (VCOs), in conjunction with frequency multipliers, achieve frequencies up to several 100 GHz. In the terahertz regime, however,

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Figure 3: Compact two-color CW laser for terahertz generation

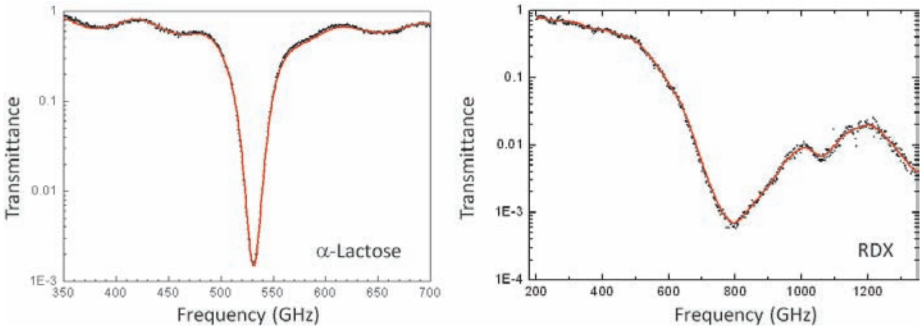

Figure 4: Absorption signatures of α-lactose monohydrate (left) and the plastic explosive RDX (right), measured with CW terahertz spectroscopy

this technique proves inefficient, technically complex, and very expensive.

Optoelectronic techniques offer an efficient and cost-effective method for terahertz generation: near-infrared laser light is focused on a special semiconductor structure (**figure 2**). The result is a photocurrent, which in turn is the source for the terahertz wave. A continuous-wave (CW) laser produces narrow-band terahertz radiation; femtosecond pulses convert into a broadband terahertz spectrum. These two techniques are explored further in the next sections.

2.1 CW terahertz techniques (frequency-domain terahertz)

Optical heterodyning of two CW lasers with adjacent wavelengths (e.g. 853 nm/855 nm or 1546 nm/1550 nm) on a dedicated antenna generates terahertz radiation at the difference frequency. The two-color laser beam is focused onto a photomixer, a metal-semiconductor-metal structure, at the center of the antenna. The laser radiation creates free charge carriers in the semiconductor, and an applied voltage accelerates them towards the metal electrodes. This gives rise to a photocurrent, which is modulated at the difference frequency of the two lasers. The antenna then translates this beat frequency into a new electromagnetic wave – the terahertz wave.

On the laser side, DFB (distributed feedback) diodes are perfect sources. They can be tuned over more than 1000 GHz and thus yield difference frequencies from 0 to 2 THz or from 1 to 3 THz. **Figure 3** shows a compact two-color CW laser that consists of two fiber-coupled DFB diodes at 1.5 µm and a polarization-maintaining fiber combiner.

CW terahertz systems offer a narrow linewidth on the order of 1 MHz, which in turn results in a high spectral resolution. This allows measurements of narrow signatures, such as trace gases at low pressure, or spectra of organic solids. **Figure 4** shows very precise absorption measurements of α-lactose and the plastic explosive RDX. Photomixers can also be used to detect CW terahertz radiation. This very efficient technique achieves signal-to-noise ratios of more than 70 dB and consequently enables fast measurements with a dwell time of only a few milliseconds per frequency point. A complete spectrum can then be acquired in less than 2 minutes. **Figure 5** shows a comparison between a conventional and a fast CW terahertz scan.

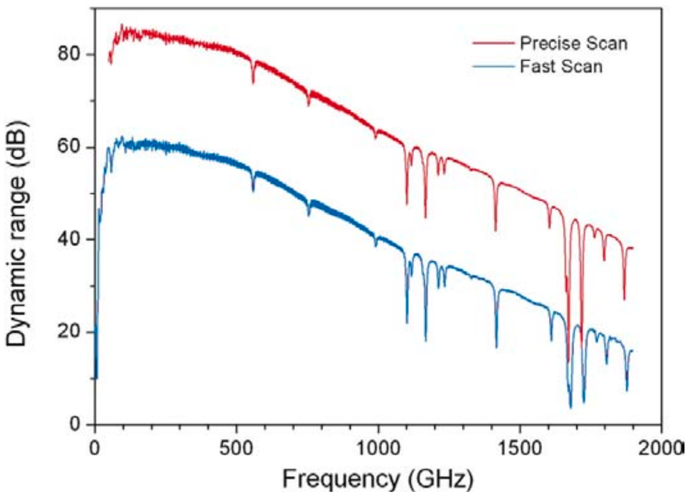

Figure 5: Comparison of two CW terahertz measurements with different integration times. The red curve was acquired with an integration time of 300 ms per frequency step, the blue curve with 3 ms/step. The measurement time is reduced from about three hours to less than two minutes

2.2 Pulsed terahertz techniques (time-domain terahertz)

Pulsed terahertz waves are generated with femtosecond lasers. When focused on a non-linear crystal or a photoconductive switch, the fs-pulse produces free charge carriers, which are accelerated by an external electrical field. This change in current induces a transient electromagnetic field.

The properties of the laser pulse determine the bandwidth of the terahertz spectrum: in the near infrared a pulse duration of 100 fs corresponds to a spectral width of 4 to 5 THz. Different emitters are available, which are suitable for laser excitation at 800 nm (GaAs antennas) or at 1550 nm (organic crystals DAST or DSTMS[1] and InGaAs/InP antennas). Erbium-doped ultrafast fiber lasers (**figure 6**) operating either at the fundamental wavelength of 1550 nm or frequency-doubled to 780 nm are a perfect match for these emitters. The lasers achieve pulse lengths of less than 100 fs and average output powers of more than 100 mW. Similar to the CW laser depicted in figure 3, these compact and robust sources even fit transportable terahertz systems.

In a typical time-domain setup, the laser

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[1] DAST (4-N, N-dimethylamino- 4'-N'-methyl-stilbazolium tosylate) or DSTMS (4-N, N-dimethylamino-4'-N'-methyl-stilbazolium 2, 4, 6- trimethylbenzenesulfonate)

Figure 6: Pulsed femtosecond fiber laser – the engine for time-domain terahertz systems

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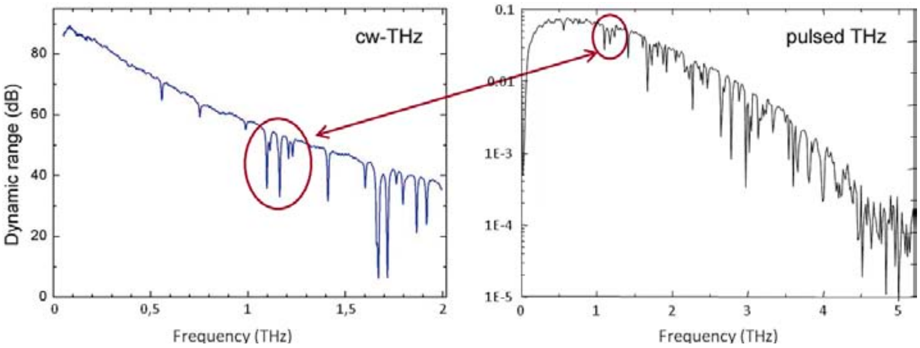

Figure 7: Comparison of frequency- and time-domain terahertz spectroscopy. The frequency-domain spectrum offers a high resolution, the time-domain measurement a higher bandwidth. The peaks are absorption lines of water vapor. Both spectra were acquired with GaAs antennas

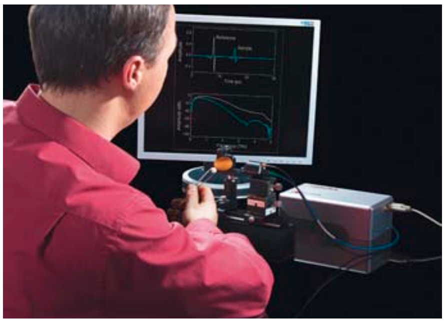

Figure 8: Experimental setup for pulsed terahertz spectroscopy with a femtosecond fiber laser and fiber-pigtailed terahertz antennas

pulse is split into two paths: one path leads to the terahertz emitter, which converts the laser light into terahertz pulses. After interacting with the sample, the terahertz light is focused onto the detector, such as a second photoconductive switch made of GaAs or InGaAs, or an electro-optical crystal. The second part of the pulse travels to the detector after passing a variable delay stage. By scanning the terahertz pulse with the narrower laser pulse, the detector measures the field amplitude of the terahertz wave[2]. A fast Fourier transform of the terahertz amplitude finally produces the spectrum of the sample. Frequencies up to 4 THz are generated with semiconductor antennas and >10 THz with organic crystal emitters, depending on the bandwidth of the laser excitation.

2.3 CW vs. pulsed terahertz – what's best?

The particular requirements of an experiment – resolution, bandwidth and measurement speed – determine whether a CW or a pulsed terahertz system is the better choice. Frequency-domain spectrometers achieve a precise frequency resolution and an excellent signal-to-noise ratio. Also, these systems do not require a delay stage, resulting in a very compact footprint. Last, but not least, DFB diode lasers remain more cost-efficient than fiber lasers.

The benefits of time-domain terahertz platforms, on the other hand, are the high bandwidth along with significantly shorter measurement times. For example, a system with a commercial fiber laser and a DAST-crystal achieves a bandwidth of up to 10 THz. The measurement time depends on the number of averaged traces, but is typically in the millisecond to second range for a complete spectrum. This compares to minutes to hours required to record the same spectrum with a CW terahertz system. **Figure 7** highlights the differences between both methods in a spectrum of water vapor. The pulsed system attains a bandwidth of 5 THz, which comes at the expense of signal-to-noise ratio and frequency resolution.

3 Applications of terahertz spectroscopy

Initial industrial applications have already implemented terahertz spectroscopy. One example is the detection of toxic gases. Many gas molecules feature distinct rotational bands, and a terahertz spectrometer can identify these gases unambiguously, even in a mixture of different gases or in a spectrally "cluttered" background. A possible scenario is the detection of hazardous gases in subway stations or public buildings. Trace amounts of industrial toxins and chemical agents must be identified rapidly and reliably, with neither false positives nor false negatives. There cannot be risks of a false alarm by exhaust fumes, cleaning agents, glues, perfume or paint.

Another promising application is the detection of toxic and acid gases in a disaster zone. Burning plastics often produce carbon monoxide, hydrochloric acid and hydrogen cyanide. Terahertz spectroscopy can identify these combustion gases as well as quantify their concentrations from a safe distance, even through black smoke, which is non-transparent for visible light [1].

Material analysis is another possible field of application. Terahertz spectroscopy can be used for process and quality control, for instance during the production of plastic compounds. Terahertz-based measurements help to determine the additive content because the polymers (polyethylene, polypropylene, or polystyrene) are almost transparent for terahertz radiation (**figure 8**). With semiconductors, terahertz spectroscopy allows determination of essential properties like charge carrier density or DC conductivity [2]. Another emerging application in the field of industrial process control assesses paper humidity in paper production lines. Here, terahertz-based techniques provide safe alternatives to the radioactive beta emitters used to date.

4 Conclusion

Thus far, the difficulties in generating intensive, directional terahertz radiation have hindered more widespread acceptance of terahertz-based techniques. New optoelectronic sources rely on compact and robust laser modules, which might finally pave the way for terahertz applications not only in science and industry but even in everyday life. These offer a huge potential for the uses of the unique properties enabled by terahertz radiation.

Literature:

[1] N. Shimizu et al., *Remote gas sensing in full-scale fire with sub-terahertz waves*, Microwave Symposium digest, IEEE MTT-S International, Baltimore (2011)
[2] A. Roggenbuck et al., *Using a fiber stretcher as a fast phase modulator in a continuous wave terahertz spectrometer*, J. Opt. Soc. Am. B 29:4 (2012) 614

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[2] The detector works in a "pump and probe" fashion: the incident THz pulse changes the properties of the material (e.g., conductivity or birefringence) and the laser pulse probes this very effect. The delay stage thus scans the THz wave packet with the optical pulse.

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