From Terra Incognita to Security Technology

Terahertz applications on the verge of industrialization

Not long ago, the terahertz frequency range was considered the last remaining gap of the electromagnetic spectrum. The main reason was the difficulty of generating intense, directional terahertz radiation. During the past few years, optoelectronic approaches based on modern laser technologies have helped to bridge the "terahertz gap". This report discusses some of the scenarios in which terahertz technologies are just about to make their industrial entrance – in applications as varied as trace gas detection, process control, and the imaging of airbag safety covers.

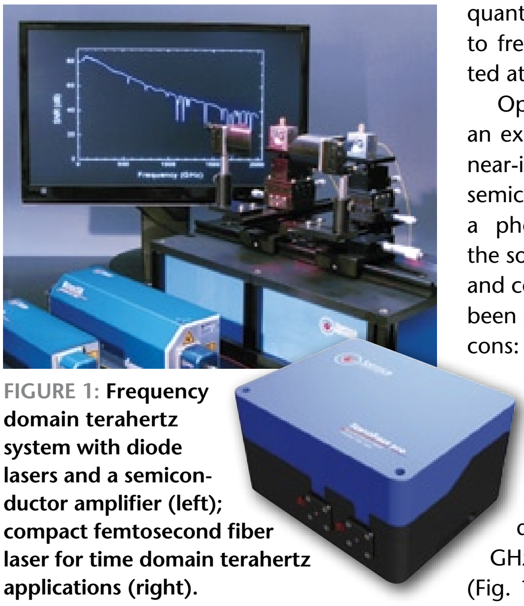

FIGURE 1: **Frequency domain terahertz system with diode lasers and a semiconductor amplifier (left); compact femtosecond fiber laser for time domain terahertz applications (right).**

The terahertz range refers to electromagnetic waves with frequencies between 0.1 THz and 10 THz, or wavelengths between 30 mm and 30 µm. Compared to visible or near-infrared light, terahertz radiation undergoes less Rayleigh scattering in amorphous materials. Compared to microwaves, on the other hand, there is less diffractive scattering. Consequently, many synthetics and textiles, but also paper and cardboard are transparent to terahertz waves. In addition, many gases and organic solids – including toxic or explosive substances – feature absorption lines at frequencies between 0.5 THz and 5 THz. The two main advantages of terahertz radiation are thus the penetration of conventionally opaque materials on one hand, and a high chemical selectivity on the other hand.

Unfortunately, the interesting frequency band of a few THz is not easily accessible. Electronic sources like Gunn or Schottky diodes with subsequent frequency multipliers, whilst providing high output (mW power levels) up to some 100 GHz, become inefficient in the submillimeter range. Moreover, these devices require elaborate production skills and can hardly, if at all, be frequency tuned. Direct optical sources, like quantum cascade lasers, are usually limited to frequencies >5 THz, even when operated at cryogenic temperatures.

Optoelectronic terahertz generation is an expression for indirect methods, where near-infrared laser light illuminates a metal-semiconductor-metal structure, generating a photocurrent that, in turn, becomes the source of a terahertz wave. Both pulsed and continuous-wave (cw) techniques have been realized, and both have their pros and cons: Time domain (pulsed) terahertz measurements offer a higher bandwidth (typically 0.1 … 4 THz) and permit very fast acquisition times – a spectrum can be obtained within milliseconds. On the other hand, the frequency resolution is limited to several GHz. A frequency domain (cw) system (Fig. 1), on the other hand, features a somewhat lower bandwidth (typ. 0.1 … 2 THz) and requires longer measurement times – recording a spectrum takes several minutes –, but offers frequency selectivity and a resolution down to single MHz.

Time domain terahertz

Pulsed terahertz radiation is generated with femtosecond lasers. The ultrashort laser pulses are focused on a semiconductor material, generating a fast current transient. This leads to the emission of electromagnetic wave packets with a broad spectrum in the terahertz range. The most established emitter technologies are photoconductive switches, based either on GaAs or InP semiconductors. Other common terahertz generation mechanisms employ optical rectification at surfaces or in nonlinear crystals, such as GaP, ZnTe or DAST. Excitation wavelengths for the different approaches range from 750 nm to 1.6 µm.

All of these wavelengths are now conveniently accessible with ultrafast fiber lasers (Fig. 1). Erbium-based femtosecond lasers take advantage of many high-quality components originally developed for telecom applications. These lasers provide superior specifications in a compact, turn-key system, without the complexity and price tag of former Ti:Sapphire lasers.

THE AUTHOR

ANSELM DENINGER

Anselm Deninger studied physics at the University of Mainz. His PhD research was focused on the application of laser-polarized ^{3}Helium to magnetic resonance imaging. He obtained his degree in 2000, then worked as visiting scientist in a pharmaceutical company in Malmö (Sweden). From 2001, Anselm Deninger has been with TOPTICA Photonics, where he became increasingly involved in terahertz research. As product manager, he is responsible for DFB lasers, non-linear optics, and terahertz technologies.

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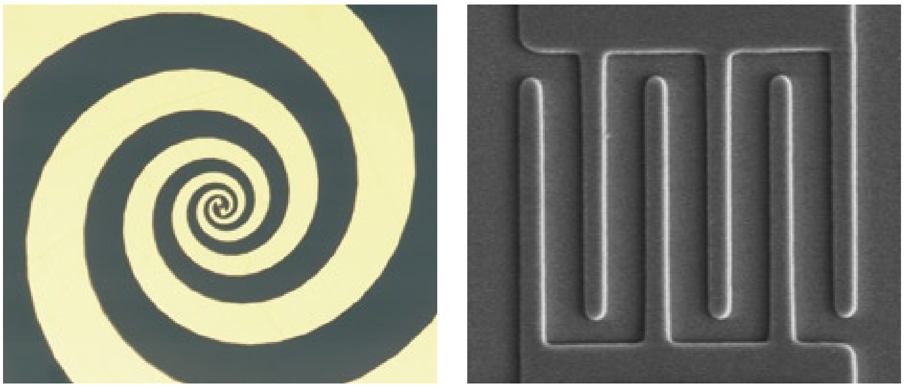

FIGURE 2: **Log-spiral antenna (left); finger photomixer (right).**
(SEM image by Th. Göbel, University of Darmstadt)

Frequency domain terahertz

Continuous-wave terahertz radiation is obtained by so-called optical heterodyning: The terahertz emitter ("photomixer", Fig. 2) is irradiated with two near-infrared lasers of adjacent wavelengths. An antenna surrounding the photomixer emits an electromagnetic wave at the terahertz difference frequency. Most photomixers employ GaAs and thus require laser wavelengths below 870 nm. More recently, InP-based emitters have been demonstrated, operating in the telecom wavelength band of 1.5 µm.

The lasers of choice for cw terahertz generation are near-infrared distributed feedback (DFB) diodes. DFB diodes comprise a frequency selective grating within the active area of the semiconductor. The grating restricts the laser emission to a single longitudinal mode; thermal tuning of the grating pitch yields very wide continuous frequency scans (>1000 GHz/diode). By selecting two diodes with an appropriate wavelength offset, one can tune the terahertz difference frequency continuously, from 0 to 2 THz. A particularly intriguing feature is the possibility to control the laser frequency with single-MHz resolution, which can be realized by a dedicated interferometer design [1].

Detection of toxic gases

Applications of terahertz spectroscopy are manifold. Many gas molecules have distinct rotational transitions at terahertz frequencies. Identifying the components of a mixture of gases by their spectral "fingerprint" requires a terahertz spectrometer with a frequency tuning range of more than a decade (e.g. 100 … 2000 GHz, Fig. 3a), yet a resolution on the MHz level.

The advantage of using terahertz frequencies, rather than working in the near-IR, is that infrared lasers generally have a limited tuning range, and thus every gas species to be measured requires an individual laser system. A single terahertz scan, by contrast, can detect and identify a large number of different species.

TOPTICA's laser technology has already been implemented in a terahertz gas spectrometer, that has been designed for highly sensitive trace gas detection in a cluttered environment. The envisaged application is the control of the air quality in public institutions, including a correct identification of potential threat chemicals against a background of e.g. cleaning agents, glues, perfumes and paint. The spectrometer has demonstrated its capabilities in a series of laboratory experiments, with gases like hydrocyanic acid, hydrochloric acid or ammonia, and has successfully passed a first field test in summer 2009. Due to its high frequency resolution, it will also contribute to the compilation of a spectral database at terahertz frequencies.

Process control in paper production lines

Industrial paper production requires monitoring of a multitude of different parameters, such as temperature, humidity, tensile strength and area density. This is necessary to guarantee the desired consistence and quality of the fast moving paper web (velocity 1000…2000 m/minute). The area density is commonly examined via beta ray absorption, using radioactive isotopes like ^{85}Krypton as emitter. The development of alternative techniques without any radiation hazards is an active area of research.

Terahertz measurements might provide the long sought-after alternative. Using a second photoconductive antenna as terahertz receiver, one obtains not only amplitude data, but the phase of the terahertz wave is measured along the way. When paper samples are placed in the terahertz beam, both the transmitted intensity and the phase vary with the accumulated thick-

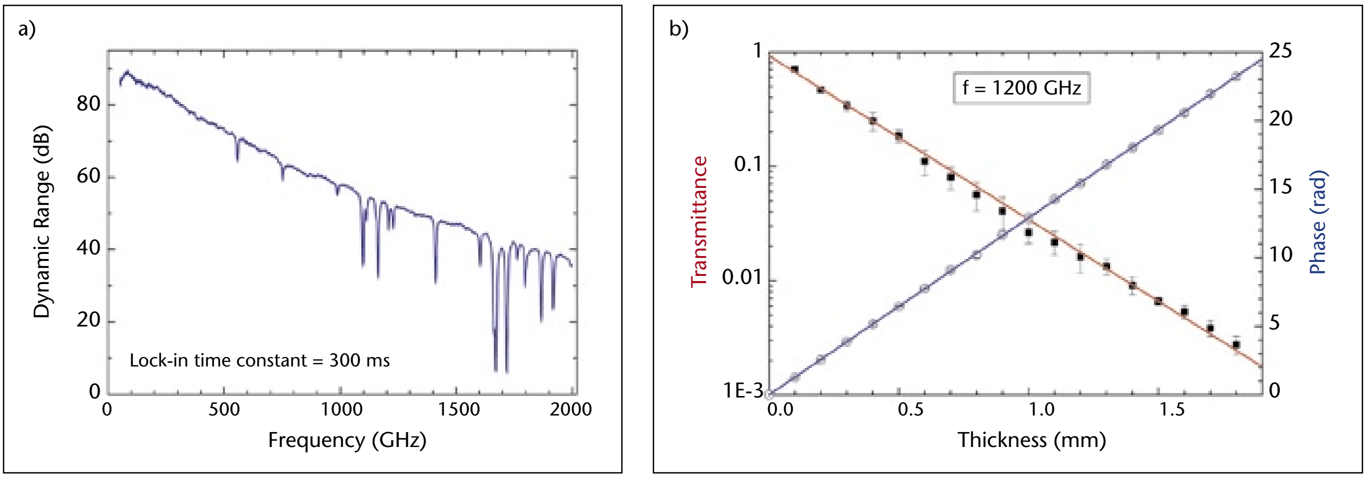

FIGURE 3: **Dynamic range of the cw terahertz spectrometer of Fig. 1. The dips are absorption lines of water vapor (left). Terahertz transmission through paper. The transmittance decreases exponentially with the accumulated sample thickness, whereas the phase of the terahertz wave follows a linear function. Each data point corresponds to a different number of sheets (right).**

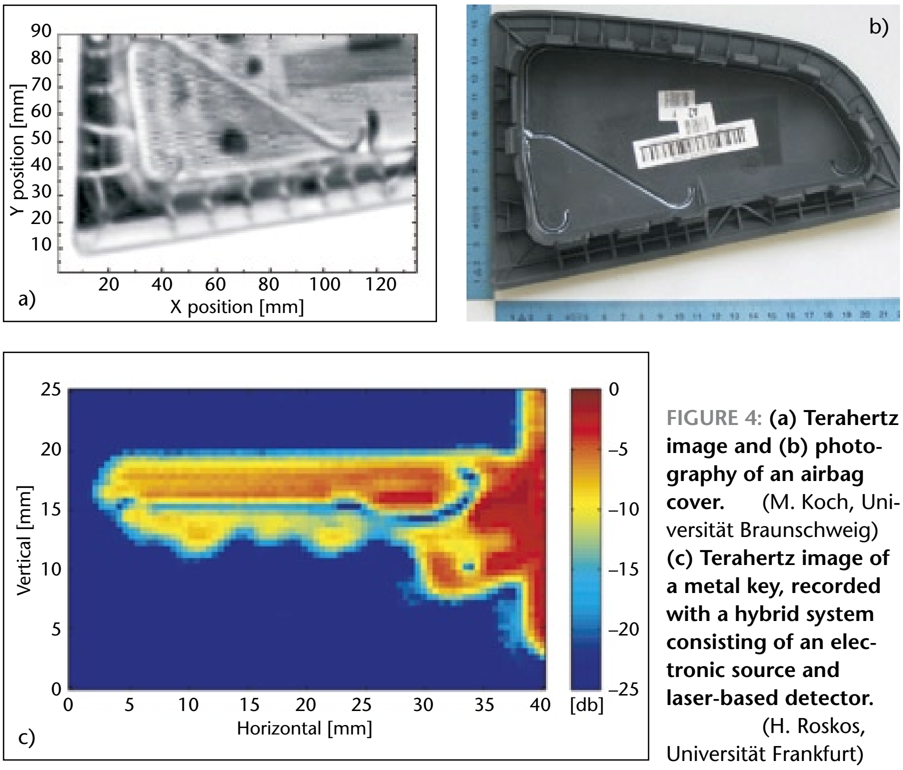

FIGURE 4: **(a) Terahertz image and (b) photography of an airbag cover.** (M. Koch, Universität Braunschweig) **(c) Terahertz image of a metal key, recorded with a hybrid system consisting of an electronic source and laser-based detector.** (H. Roskos, Universität Frankfurt)

THE COMPANY

TOPTICA Photonics

TOPTICA Photonics develops and manufactures state-of-the-art diode and fiber laser systems for scientific and industrial applications. Since 1995, TOPTICA's lasers and measurement equipment have been dedicated to the forefront of atomic physics, microscopy, printing, optical disk manufacturing, and numerous other applications. In the terahertz arena, TOPTICA is the only company worldwide that serves researchers in the two most important optoelectronic approaches – pulsed and continuous wave (cw) terahertz generation.

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ness of the paper sheets. The phase, in particular, is directly proportional to the paper thickness (Fig. 3b). Here, a high stability of the terahertz frequency is key to obtain precise phase information.

Terahertz imaging

Many plastic compounds and synthetics are transparent for terahertz light. This has been used for non-contact analysis and even imaging of hidden objects. An application with a large market potential is the inspection of the safety covers of airbags for passenger cars (Fig. 4a/b). The notch depth of the intended tear-seam line has to be thin enough to deploy the airbag in the case of a accident, yet inadvertent inflation must be avoided at all costs. Presently, this critical component can only be examined by destructive methods – in quality control routines, only individual samples are tested. Researchers at Braunschweig University have used TOPTICA lasers to demonstrate that terahertz imaging provides an alternative, non-contact measurement [2]. Using phase-sensitive detection, the notch depth can be assessed with a depth resolution in the micrometer range.

Thus far, terahertz images are usually created in a pixel-by-pixel scan, with total acquisition times ranging from tens of minutes to several hours. In the frame of a national funded research project, TOPTICA has been part of a consortium that develops a multipixel, real-time terahertz camera. The concept is based on a „hybrid" system, combining a high-power, fixed-frequency electronic source with a sensitive, laser-based detection scheme [3]. First results obtained in a laboratory setup show the potential of this approach (Fig. 4c). For a video-rate terahertz camera, a wide range of applications can be envisaged. This includes water content measurements of foodstuffs inside their air-tight packaging, investigations of the structure of pharmaceuticals, quality control inspections of semiconductors and the analysis of compound materials in industrial process control.

The usage of terahertz radiation for spectroscopy and imaging thus paves the way for a variety of exciting scenarios. Optoelectronic technologies in particular show a large potential for a compact, „real-world" assembly, and first results seem to predict a highly interesting future.

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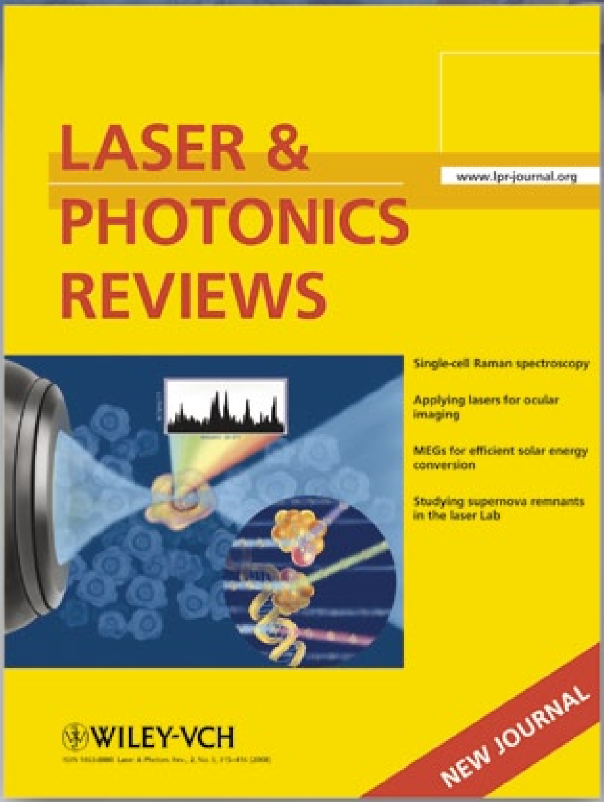

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