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ScienceDirect
C. R. Physique 9 (2008) 127–129
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Recent developments in terahertz optoelectronics/Développements récents en optoélectronique térahertz

Foreword

It could appear astonishing that the far infrared part[1] of the electromagnetic spectrum is nowadays so largely studied worldwide, in academic laboratories as well as in private companies. As a testimony of such huge amount of activity, Google has referenced 44 000 entries for the word ‘terahertz’ in the last 12 month period! This is even more surprising in that the far infrared has been investigated for more than one century, since the pioneering works of Jagadis Bose [1] at the turn of the 19th century, promptly followed by several other researchers. Among them, as early as 1923, Nichols [2] made the link between optics and electronics as he used both techniques to produce and study far infrared waves. Moreover, outstanding results have been achieved since the 1950s, for example, in molecular spectroscopy using the remarkable technique of Fourier transform spectroscopy [3].

The explanation of this current interest in THz science is manifold.

First, time-domain optoelectronic techniques [4] that appeared late in the 1980s have made experiments simpler and faster, and thus they spread into many non-specialized laboratories. They have permitted, on a first stage at the academic level, many different studies in several scientific domains like spectroscopy, solid state physics, chemistry and more recently biophysics and telecommunications, amongst others. Based on the results achieved, developments towards industrial and mass-market applications have been proposed, stimulating applied and technological research. Simply speaking, these applications are mostly based on spectroscopy and imagery. The interaction of THz waves with matter involves mostly low-energy molecular levels, like rotational levels, which results in a unique spectroscopic signature for several compounds. Therefore, THz spectroscopy may serve to detect molecules and substances that could not be properly detected using other spectroscopic techniques. Beside low-energy level excitation, absorption of THz by matter is mostly due to free carriers and polar molecules. Thus many materials, opaque in the visible and infrared ranges, are transparent for THz waves, while moist materials absorb THz light, and metals reflect it perfectly. Therefore, THz imaging could supply information that is not obtainable by other techniques (X-rays, visible light or IR).

The second explanation could be found in the frequency characteristics of the far infrared waves. Indeed, the frequencies of these waves spread typically from 100 GHz up to 10–20 THz. At the lower end, these frequencies constitute the values that high-speed electronics and high bit-rate telecommunications try to reach. Consequently, high-frequency electronic devices and techniques are among the possible ways to deal with THz waves under the 1 THz limit. In the case of waves propagating in free space, the 100 GHz range could be seen as an extrapolation of present radar frequencies, and thus radar and, more generally, microwave techniques are used with benefit in the THz domain. On the other hand, at the upper limit of the THz range, waves exhibit wavelengths of some tens of microns, reaching and overlapping the infrared domain of the electromagnetic spectrum. This is the field of optics and more generally of physics, whose concepts and techniques are used to generate and manipulate high frequency THz signals. Thus the THz domain lies in between optics and electronics, benefiting from both concepts and technological know-how. This importance of the central position of the THz range, positioned in between electronics and optics, may also be understood by examining electrical currents involved in the related phenomena. In the optical domain, most phenomena arise from the contribution of the displacement current, i.e. the polarization of matter through the

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[1] When involving modern opto-electronic or/and electronic techniques, the far infrared range is called the terahertz domain, which typically spreads from 100 GHz ($\lambda = 3$ mm) to 10 THz ($\lambda = 30$ μm).

doi:10.1016/j.crhy.2008.02.005

generation of induced dipoles at the atomic or molecular scale. In electronics and microwaves, the conduction current is the main vehicle for the electrical signals. In the THz range, both contribute.

Finally, the last possible explanation of the present interest in THz waves is found in the time domain. An electromagnetic pulse should exhibit a duration of the order of one picosecond for its frequency spectrum spreading up to the THz range. The picosecond scale is of prime importance in both basic and applied sciences. This is typically the duration of a chemical reaction and this is also the upper value towards which digital electronic circuits and telecommunication systems tend. This picosecond duration is likely generated when photoconductive devices or non-linear crystals are excited by mode-locked lasers that deliver customarily very stable trains of femtosecond light pulses. As a matter of fact, THz opto-electronics was boosted when such femtosecond lasers became technically reliable and commercially available at the beginning of the 1990s. In addition, time-domain studies benefit from specific techniques, derived from radar electronics and time-resolved optics, like the sampling technique that allows one to record the temporal shape of the THz pulse with an unequaled precision. Numerical Fourier transforms give both the amplitude and phase of the THz signal, in a much simpler manner than in the optical domain, opening new fields of investigation.

So today, what is the situation and state-of-the-art concerning THz research? In laboratories, THz phenomena have been widely and exhaustively studied in many topics such as solid state physics (phonons, free carrier dynamics, observation of vortices in superconductors ...), spectroscopy (rotational spectra of gaseous molecules, of flames, detection of pollutant compounds, dipolar interactions in liquids ...), electromagnetism (waveguides, near field effect, observation of the Gouy shift, super-transmission, surface plasmons ...) and so on. One can say that, in laboratories, THz waves are nowadays used as a basic tool of investigation in physics, chemistry, biology, ... But there is still a lack of sources and detectors that are efficient, reliable, and easy to use. This is a major obstacle for a large diffusion of THz techniques from laboratories towards industry, for mass-market and customer applications. Therefore many groups are working towards the production of smart THz sources and detectors. Today in 2008, no solution appears to overtake others. Concerning sources, Quantum Cascade Lasers (QCL) are promising, but their characteristics must improve, especially their temperature of operation and their frequency tunability. Other devices, like plasma-oscillation transistors, micro-klystron, optical mixers, ... may lead to attractive results. In detection, two types of devices emerge, namely micro-bolometers and plasma electronic devices. Both could be manufactured to form matrix detection arrays that are requisite for imaging and video applications. Micro-bolometers are expected to run at room temperature. Plasma devices are based on the excitation, by the incoming THz beam, of a plasma oscillation of a confined electron gas within the detector. Single THz photon detection [5] has already been demonstrated using THz plasma oscillation in a quantum dot deposited over a single electron transistor, but at a temperature lower than 200 mK. Other detection schemes are also studied, for example superconducting hot electron bolometers that are widely used in millimeter-wave astronomy.

This special issue presents some relevant and up-to-date works performed by several laboratories in Europe, United States, Russia and Japan, which gives an overview of modern THz research. The theme of this issue is voluntary restricted to opto-electronic studies, to maintain the journal size to a reasonable limit and to offer the reader a coherent content. V. Malevich and colleagues describe THz wave generation at the surface of ultrafast semiconductors. The phenomena are explained by the photo-Dember effect and by electric field induced optical rectification. J. Mangeney and P. Crozat summarize recent works on ultrafast ion-implanted semiconductors, which can be excited at the telecom wavelength $\lambda = 1.5$ μm. J.-F. Lampin et al. address the measurement of THz signals using electro-absorption (Franz–Keldish effect) in semiconductors, with application to the characterization of high frequency integrated circuits, while A. Adams et al. treat the detection of THz near-field features using electro-optic (Pockels effect) sampling, with amazing results on the time-evolution of diffracted light fields near metal structures. H. Murakami and M. Tonouchi use THz emission in electronic circuits to map electrical fields over the circuits and detect possible electrical failures by optical means (a technique they call laser terahertz emission microscope). The next part of the issue is devoted to devices and systems. D. Lippens describes the design and characterization of meta-materials that show a negative refractive index in the THz domain. P. Kuzel and F. Kadlec present THz filters whose frequency response can be tuned by different means (illumination, applied voltage, ...). J.A. Deibel and colleagues shows how Sommerfeld THz waves propagate nicely along metallic wires while Nazarov et al. are concerned with surface plasmon propagation properties and about their excitation using diffraction gratings. Finally, the last papers in this issue concern two important and promising applications of THz science, in environment and security. Federici et al. address the detection of illicit materials, like drugs or explosives, carried illegally. F. Hindle et al. describe gas phase pollutant detection using continuous-wave terahertz beam generated by photomixing.

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Jean-Louis Coutaz
IMEP-LAHC Laboratory,
University of Savoie,
73376 Le Bourget du Lac,
France,
E-mail address: coutaz@univ-savoie.fr