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TERAHERTZ RADIATION: LAST DECADE PUBLICATIONS

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Terahertz radiation: last decade publications

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Abstract

This article briefly reviews recent publications on generation, detection and applications of the free-space terahertz radiation corresponding to a wavelength range between 3 and 300 μm. A bibliography list contents more than 300 papers published in 1990–2002.

Терагерцовое излучение: публикации последнего десятилетия

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Аннотация

Дан краткий обзор выполненных за последние годы работ в области генерации, регистрации и применения излучения в терагерцовом диапазоне частот, соответствующем длинам волн 3–300 мкм. Библиографический список содержит более 300 работ, опубликованных в 1990–2002 г.

Introduction

A high-power infrared free-electron laser (FEL) for the Siberian Center of Photochemical Research is now under construction in Novosibirsk [83,85]. A 100-MeV 8-turns accelerator-recuperator intended to drive the FEL. The full-scale machine is to generate intense coherent radiation in a wide infrared spectral range. The first stage of the machine, that is anticipated to be put into operation within a year, will be driven a reduced (one-turn) 14 MeV accelerator-recuperator, and correspondingly, the FEL will generate radiation in the submillimeter spectral range.

In this article[1] we present a collection of papers, those content directly or non-directly may appear to be interesting for the FEL team and for FEL users. This collection is not a bibliography in the strict sense of the word, — a selection method was rather taste of the authors, than some regular principles. For convenience of a reader the papers in the bibliography list are sorted by the matter and the sections are supplied with brief comments.

Terahertz radiation, generators and detectors

Terahertz radiation occupies a very large portion of the electromagnetic spectrum between infrared and millimeter waves. In this paper we assume the *terahertz range* to be a spectral range from 3 μm to 0.3 mm. This corresponds (Fig. 1) to the range of 1—100 THz in the frequency scale or 30—1000 cm^{-1} in the wavenumber scale[2]. This range is of great importance due to many physical and chemical processes occure in this region, but high intensity of the thermal background radiation (see Fig. 2) and a lack of robust sources and sensitive detectors restricted for many years both explorations and applications in the MIR and FIR ranges. For a long time the submillimeter radiation can be obtained only from the weak blackbody radiators and a few gas lasers.

The situation had changed in the end of 1980th, when advances in the coherent generation and detection of short-pulses of THz radiation initiated an extraordinary development of basic and applied studies. Investigation of new terahertz sources and detectors, semiconductor physics, non-linear optical effects, terahertz imaging, terahertz spectroscopy,

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[2]By standard definition the near-infrared (NIR) is the region from 0.8 μm to 3 μm, the medium infrared (MIR) — from 3 μm to 20 μm, and far-infrared (FIR) — from 20 μm to 1 mm.

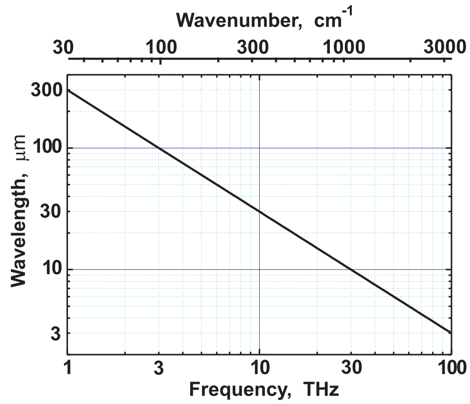

Fig. 1. Wavelength of THz radiation vs. frequency and wavenumber $(1/\lambda)$

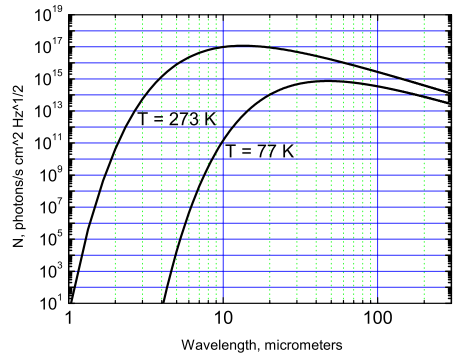

Fig. 2. Spectral density of thermal photon flow vs. wavelength λ for two background temperatures

biological and medical applications, atmosphere and space studies is an incomplete list of research fields.

Two new kinds of terahertz sourses have induced this growing interest to the long-wavelength radiation. First kind is THz generators driven by a short-pulse (mostly femtosecond) lasers. There are two main variants of such sources: a technique using photoconducting structures and a technique using electro-optics materials. Schematic of the former one is shown in Fig. 3.

Second kind of the terahertz sources is free-electron lasers (Fig. 4). There already exist many lasers operating in the THz spectral range. In comparison with the laser-driven sources FELs can generate a very intense and practically monochromatic radiation. This opens new exciting opportunities for studies and applications. Appearance in the currant years several lasers with average power of several kW must initiate the applications that require high energy input. As an example one can mention industrial isotope separation and, probably, material processing.

Spectroscopy, atmosphere, space

Terahertz radiation, obviously, must strongly interacts with the oscillators those have the eigenfrequencies resonant to the radiation frequency. It can be vibrational and rotational molecular transitions, free carriers in semiconductors and so forth. Thus, the THz radiation may be a natural probe of such objects, and it is really often used for molecule identification. For example, in astrophysics it plays an important role in study of interstellar clouds,

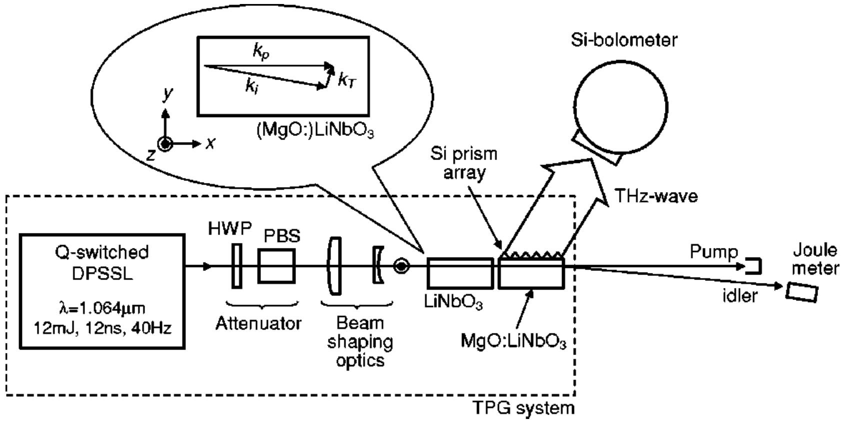

Fig. 3. Experimental setup for the THz-wave parametric generator using a diode-pumped solid-state laser [16]

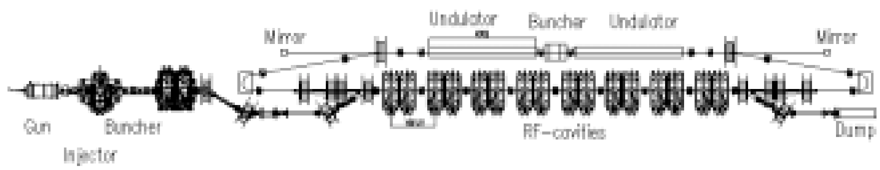

Fig. 4. Schematic of the Novosibirsk far-infrared FEL [85]

circumstellar shells, comets and other astronomical objects.

For practical purpose it is helpful to mention that the radiation penetrates non-polar substances such as fats, cardbord, cloth and plastic and is strongly attenuated by polar moleculas. A subject of special interest is transmission of the THz radiation through the atmosphere. It was carefully investigated for a wide spectral range (Fig. 5). One can observe in the plot strong absorption in the THz region that is attributed to the water vapor in the atmosphere. Consequently, free FIR radiation cannot be used for signal transmission and energy transfer in the Earth atmosphere. However, in a very dry condition transparency of the atmosphere for the THz radiation may drastically increase, as it was observed on a mountain of 4000 m height, Hawaii (Fig. 6). One can easy estimate that similar humidity may appears to be on the ground level at a temperature of -40 C. Strong sub-millimeter absorption of water is suggested to apply for monitoring material humidity in commercial purposes.

FELs can be used as intense sources for the conventional spectroscopy with Fourier transform or grating spectrometers. They, probably, can be also used in a manner similar to a time-domain spectroscopy (TDS,— Fig. 7) or a frequency-domain spectroscopy (FDS) those are recently invented with the laser-driven wide-band THz sources. A fast spec-

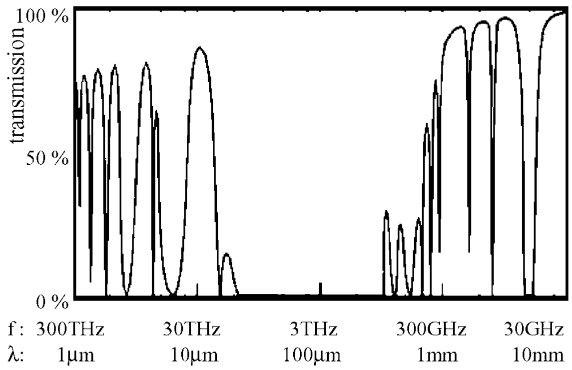

Fig. 5. Atmospherical transmission against wavelength (λ) and frequency (f) [51]

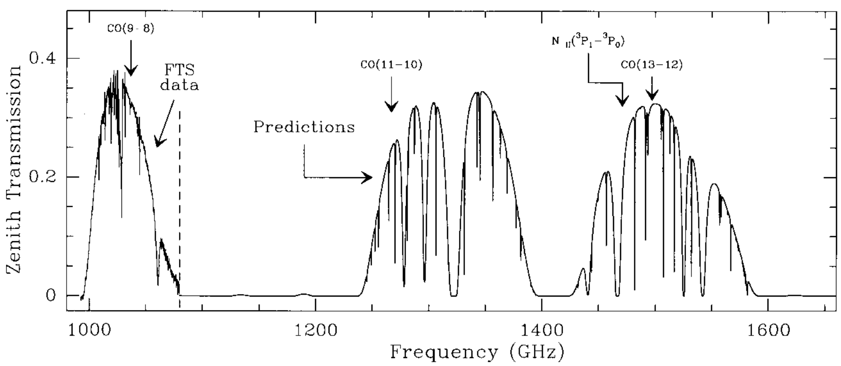

Fig. 6. Observed transmission and predictions of 1.10–1.65 THz zenith opacity for the atmospheric conditions on Mauna Kea on April 1st 1998 [220]

troscopy in the far-infrared is practically interesting, because one can study the dynamics of chemical reactions, which are very important in understanding how chemical and biological systems operate and interact.

New sources and new methods initiated a tremendous upgrowth of THz detector development. One can mention, for example, antennae and electro-optic sampling, high-electron-mobility-transistor and heterojunction bipolar transistors, new effective bolometers. Combination of sources and detectors enabled creation of reliable TDS instrumentations for performing complex reflectance and transmittance measurements of dielectrics, metals, and superconductors in the THz frequency range. Terahertz spectroscopy has capability of obtaining the amplitude and phase from a single measurement. Because of the time-resolved feature TDS it can be used to investigate the interaction evolution between FIR light and matter. One of the most exciting achievements in the THz instrumentation is the construction of an atomic streak camera to measure the temporal profile of mid- to far-infrared pulses

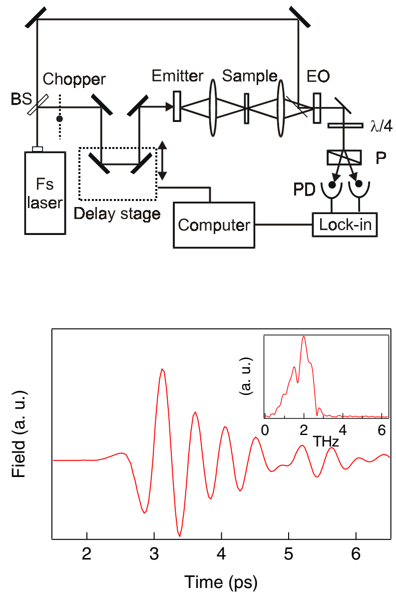

Fig. 7. Schematic illustration of the experimental setup for THz spectroscopy and a typical time-domain THz waveform and its spectrum obtained from time-domain spectroscopy [171]

using ionization of Rydberg atoms by IR photons.

Imaging, biology, medicine

Imaging in the THz range is nowaday one of the popular fields of activity. There are many papers with the description of different variants imaging systems. Terahertz imaging was used to map the carrier density through the Hall effect and the conductivity of superconducting YBCO thin films. The time-domain imaging technique has been explored extensively to study of alteration of human tissues. One of the examples of such applications is shown in Fig. 8. The TDS technique can operate in a transmission or reflection tomography mode that opens great possibilities. For such applications it is very important that the THz radiation is *non-ionizing radiation* and can be used in medicine for *in-vivo* examinations.

The imaging TDS techniques are restricted for now by a relatively low power of radiation. This requires scanning images or parallel processing with some array detectors. Application of FELs to imaging may also give a new impulse to this application.

Reflection THz spectroscopy has been used to observe the accumulation of cholesterol ester in atheromatous plagues of aorta. The spectra give information about the chemical

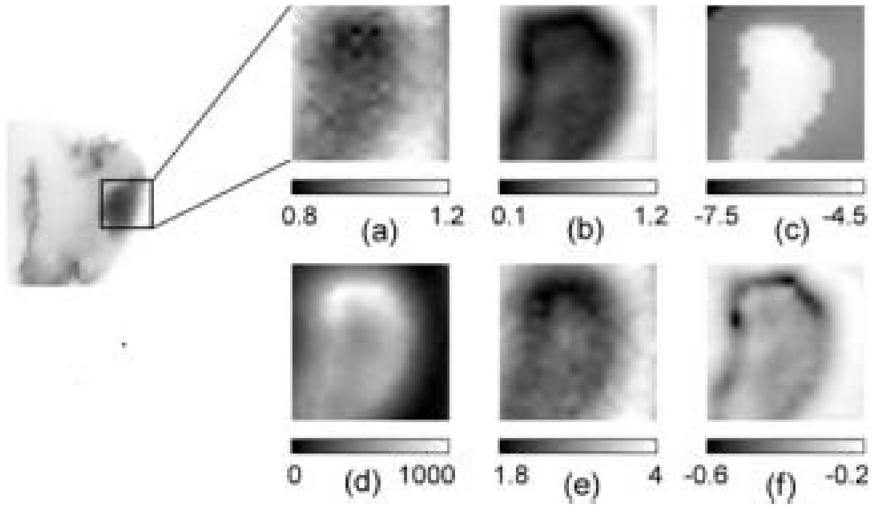

Fig. 8. Parametric images of the wax embedded melanoma sample (shown in the photograph on the left)which was prepared in the normal histo-pathological procedure. Images are: (a) transmittance at 0.5 THz, (b) transmittance at 2 THz, (c) phase angle at 1 THz (from Fourier transform), (d) $\alpha(\nu)/(n(\nu)-1)$, (e) dispersion at 1 THz, (f)dual frequency image (transmittance at 1 THz relative to 1.5 THz). The images have been interpolated to reduce pixelation effects [201]

composition of atheromatous plagues togather with the degree of eventual lesions. FEL has been used for study of vibration relaxation rates of myoglobin using high peak power picosecond duration IR pulses capable of driving the system into the nonlinear response region. Much additional experimental work is required in order to understand the interaction between THz radiation and biological moleculas and tissue. Probably, in such interaction bulk motion of the molecules (polarization and conduction) is more important than microscopic absorption of radiation due to transitions between molecular energy levels. Much information in this field, including the behaviour of DNA and genetic diagnostics, one can find in the original and review papers listed in the bibliography.

Other applications

There is a number of exciting developments in THz science and technology which may in future contribute to a greater understanding of material physics and chemistry, biology and medicine, as well as to many practical applications of the terahertz radiation. Among possible applications one can mention material characterization, study of carrier concentration and mobility of the silicon wafers, analysis of painting, drying technologies, isotope separation, development of a Rydberg-atom register for a quantum computer using a shaped terahertz pulses, and so forth.

Conclusion

In this brief review we could not, obviously, describe in detail so wide field as the terahertz radiation and the applications. We believe, however, that the collection of papers listed below will be helpful for researchers and practicians working with the THz radiation.

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