Using high-power THz radiation imaging systems for implementation of classical optical techniques in the terahertz range

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Abstract: A complex of imaging techniques to measure high-power THz radiation is developed and successfully used for implementation of classical optical schemes, such as speckle metrology, classical holography, Talbot self-imaging, generation of non-diffracting vortex beams, *etc.*

OCIS codes: (040.2235) Far infrared or terahertz, (140.2600) Free-electron lasers (FELs), (110.2970) Image detection systems, (110.6795) Terahertz imaging, (090.2890) Holographic optical elements, (260.6970) Total internal reflection, (140.3300) Laser beam shaping, (240.6680) Surface plasmons, (070.6760), Talbot and self-imaging effects.

1. Introduction

In this paper I summarize terahertz imaging findings of 10 years following the commissioning of the first stage of the Novosibirsk free electron laser (NovoFEL) in 2004.

So far, terahertz imaging systems have been used mainly in measurements based on the time domain technique. This technique has both advantages (direct measurement of electromagnetic field amplitude and phase; availability of spectroscopic measurements) and shortcomings. Namely, (1) in accordance with the uncertainty relation, the radiation, which is a series of very short pulses, spans a wide spectral range, whereas many classical experiments require monochromatic radiation; (2) to obtain a single image one needs to record a series of signals with discrete changes in the delay time of the reference signal, which makes real-time imaging impossible; (3) the intensity of broadband light sources is very small, which prevents using low-sensitivity image recorders.

In recent years there appeared sources of monochromatic terahertz radiation, e.g. quantum cascade lasers, of gradually improving quality, increasing radiation intensity and expanding frequency spectrum tunability. We can anticipate that in the near future the monochromatic sources will occupy a significant niche in the terahertz optics, and many of the classical optical techniques, which are now routine in the visible region, will appear in the THz range. Since the materials and detectors used in the visible and NIR spectral ranges cannot be applied to the THz imaging, it is necessary to develop new instrumentation or properly modify and adapt the existing techniques.

2. Terahertz source and imaging devices

The Novosibirsk free electron laser (NovoFEL) [1] emits monochromatic radiation, the wavelength of which can be tuned in the range of 90-240 microns, as a continuous stream of 100 ps pulses with a repetition rate of 5.6 MHz. The maximum average power of the radiation is as high as hundreds of watts. In our experiments, the characteristic radiation power arriving at the workstation was typically several tens of watts. Four imaging devices were applied to the terahertz imaging (Fig. 1). Three of them record terahertz images via the radiation thermal effect, whereas the fourth one senses terahertz radiation directly.

For the first time we developed a thermal sensitive interferometer (TSI) [2] for recording power density distribution of laser radiation via observation of the interference pattern produced by two coherent visible-light plane waves reflected from two facets of a glass plate. To measure the distribution one needs to expose the plate to the radiation under study and perform real-time few-second recording of the interference pattern. It should be noted that the TSI has two remarkable features. First, the spectral sensitivity of the TSI spans the regions where the glass plate is non-transparent to the radiation under study, including THz, IR and UV regions. Second, the TSI is an absolute power density meter: no calibration is necessary, because the well-known thermal-optical glass characteristics enable easy calculation of energy per area unit corresponding to one interference fringe, which is equal to 5.1 J/cm^2 for the BK7 glass. The novel TSI configuration is shown in Fig. 2, a. We have developed a new method for practical solution to the unwrapping problem, and now the software enables immediate display of the results.

Thermal sensitive phosphor screens (TSPS), which were initially developed by Macken Instruments for detection of intense 10 μm radiation, have large 75×75 mm^2 sensitive areas, which is beneficial for recording of THz holograms. However, their low sensitivity in the THz range requires high-intensity scene illumination. The inset in Fig. 2, b shows quenching of phosphor plate #8 vs. temperature of the plate; the plate was subjected to luminescence excitation with a mercury lamp. The response is practically linear up to 50% quenching.

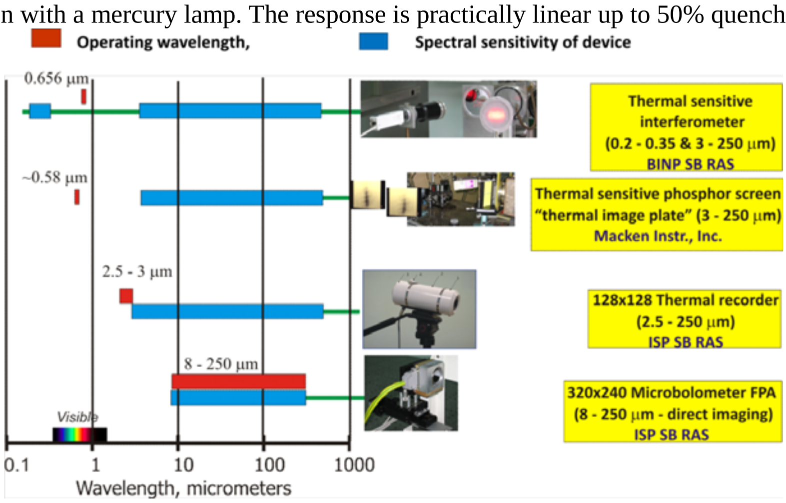

Fig. 1. Terahertz imaging devices, operating wavelengths, and sensitivity ranges

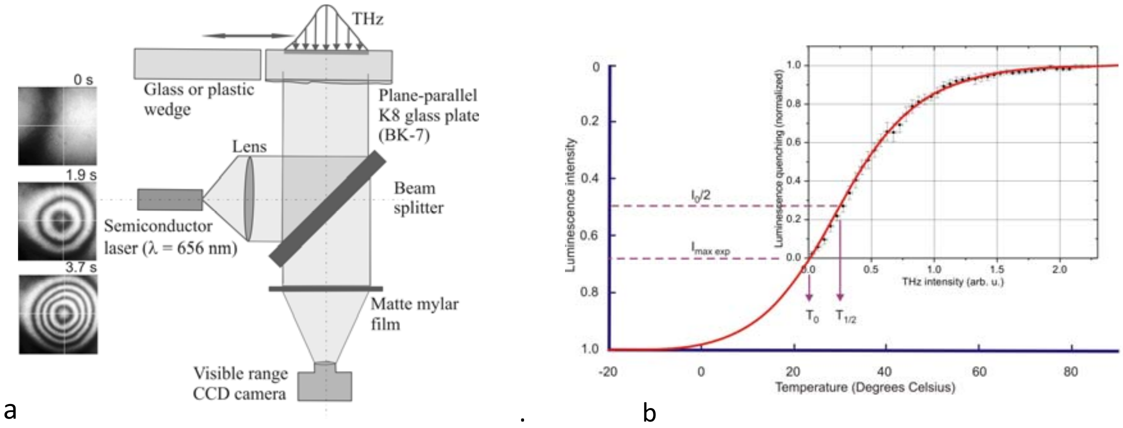

Fig. 2. (a) New configuration of the thermal sensitive Fizeau interferometer for absolute measurement of radiation power density distribution and example of interference patterns induced by NovoFEL beam; (b) Response of thermal image plate #8 to heating with 130 μm THz radiation

We also examined a thermal recorder for detection of THz beam "fingerprints". It showed itself a rather sensitive device, although the intense background radiation in the environment near a wavelength of 3 μm and thermal conductivity in the screens restrict its application capability.

The most sensitive device for real-time THz imaging is a 320 × 240 microbolometer array (MBA) [3], which was designed and fabricated at the Novosibirsk Institute of Semiconductor Physics. The pixel size (51 × 51 μm) less than THz wavelength enables recording radiation with a wavelength-limited spatial resolution. We discovered that, in contrast to the mid-IR region, in the THz region the MBA appeared to be a polarization sensitive device, and in case of unidirectional radiation the image quality may suffer from artifacts, which originate is the Fabri-Perot interference inside the device. Another shortcoming of the device in some applications is the small physical size of the array

3. Classical optics experiments realized using the imaging devices

The imaging devices were used in many experiments, five of which we will describe in brief in this section.

The first application of the MBA for THz imaging turned out to be the first demonstration of the speckle structure of coherent THz radiation scattered by rough surfaces [4], which earlier was detected only in the time domain. Examination of the speckle statistics data showed that they obey the classical theory. The feasibility of terahertz speckle metrology was also demonstrated.

We were the first to demonstrate the Talbot effect in the THz range. The self-imaging of a 2D lattice with the thickness of 2/3 wavelength was observed even when the size of the lattice holes was less than the wavelength. The results will be published elsewhere.

Study of surface plasmon polaritons (SPPs) is one of the popular areas in the terahertz science. Using imaging with the MBA, we investigated diffraction of SPPs on the edge of Au-ZnS-air interface and developed a new technique for SPP study in the THz range [5]. In recent experiments we observed “jumps” of SPPs over 100-mm gaps between samples, which is beneficial for designing all-optical planar integrated circuits.

For the first time, classical holograms in the THz range were recorded using the thermal recorder and the TSPS [6]. Later on, holographic systems with MBA were realized and applied to recording and reconstruction of images. Using the holographic technique enables solving the problem of image reconstruction in planes inclined with respect to the optical axis, which is important, in particular, in an imaging attenuated total reflection spectrometer.

At the end of 2014, we first formed and investigated the characteristics of Bessel diffraction-free beams with orbital angular momentum (vortex beams) in the THz range (Fig. 1). The MBA application was critically important for imaging of beam cross-sections (Fig. 3, b) and interference patterns (Fig. 3, d), which clearly demonstrated the beam twist, its direction and values of the topological charge. Using vortex beams for launching SPPs gave unexpected results, which were detected with the MBA and will be published elsewhere.

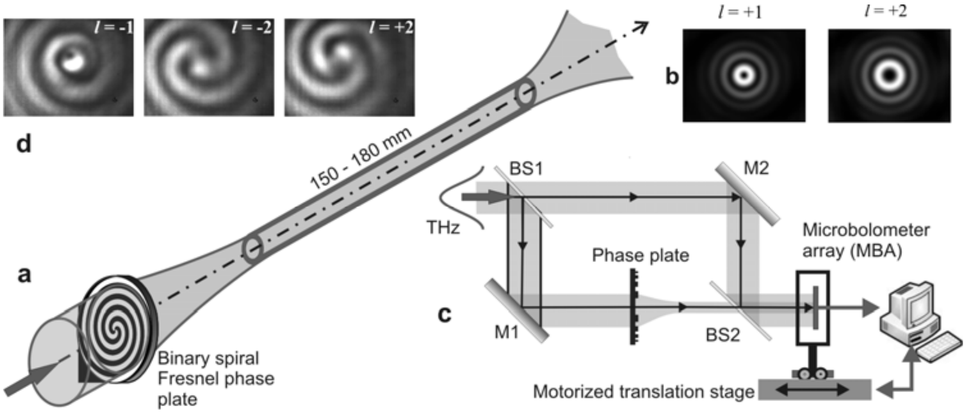

Fig. 3. (a) Vortex beam generation; (b) Images of vortex beams with the topological charges $l=+1$ and $l=+2$; Schematic (c) and patterns (d) of interference of the vortex beams and the NovoFEL Gaussian beam.

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