Imaging techniques for a high-power THz free electron laser

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Abstract

Imaging in the terahertz spectral range is a subject of special interest for many applications. In this paper we describe two methods for the THz imaging with a high power free electron laser. First method based on the transformation of THz radiation to near-infrared radiation and visualization with a thermograph. The second method based on the record of the visible light phase shift that appears due to heating of an optically transparent, but opaque in terahertz, medium. The experiments had performed on 100 W continuous Novosibirsk terahertz free electron laser.

1. Introduction

Imaging in the terahertz spectral range is a subject of special interest for many applications such as medicine, biology, industry, custom control and so on. Recently developed methods for terahertz imaging are based on the employment of the wideband or narrowband low-power THz sources. Due to a low power of these sources the visualization of images requires the employment of rather sophisticated detectors, and, in most cases, recording of an image requires a plenty of time.

Recently commissioned Novosibirsk terahertz free electron laser [1] generates coherent radiation in the spectral range from 110 to 180 μm. The output radiation with the average power of about 100 W is now available for users at the first workstation. The radiation follows as a continuous sequence of 100-ps pulses. The pulse repetition rate can be changed from 2.8 to 5.6 MHz. Such average power is much higher than the power of the existing terahertz sources including other terahertz free electron lasers.

Such a feature of the laser enables using for the visualization of laser radiation methods, which, probably, sometime are used for the intense visible and NIR radiation, but were never previously employed in the terahertz range. In this paper we briefly describe two methods which we employed for terahertz radiation visualization in a wide variety of the experiments at the first workstation. These experiments are in progress and we describe here mainly principles of the techniques. Anticipated results will be presented in detail at the conference.

2. Visualization with a FIR-NIR converter (FNC)

The FNC technique employs growing of a thin-film screen (further referred as "thermoconverter") temperature exposed by terahertz radiation (Fig. 1). Two-dimensional field of temperature at the screen surface is recorded with a thermograph SVIT [2], which have a 128x128 InAs focal plain array (FPA) sensitive to radiation within the spectral range of 2.6–3.1 μm. Thermograph sensitivity at the room temperature is 0.03 °C at the frame frequency up to 30–40 Hz. In our case the frame frequency (~ 10 Hz) was restricted mainly due to limited rate of heat dissipation. Since the absorbed power of 10^{-2} W/mm^2 is quite enough to increase screen temperature by 0.1 °C, while FEL power is 100 W, the FNC technique approved itself to be very adequate for experiments with our FEL.

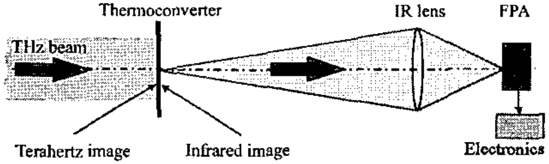

Fig. 1: Two-dimensional visualization of a THz image with thermoconvertor.

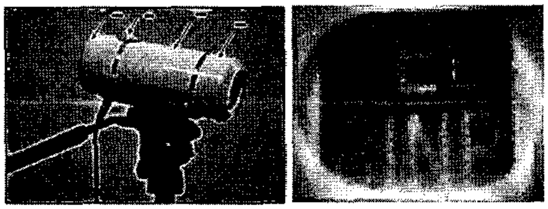

Fig. 2: Thermograph SVIT and a snapshot of the THz image recorded after a metal mask with 2-mm holes drilled with a step of 5 mm, placed across the beam of the Novosibirsk free electron laser ($\lambda = 120$ μm) at the first user workstation (13 meters from the laser output mirror).

3. Visualization with the thermo-optical detector

The other technique used for the visualization of terahertz images is the Thermo-Optical Detector (TOD). The technique employs the change of the optical length of a medium, which is transparent for probe visible light but is opaque for terahertz radiation, when a terahertz radiation pulse is absorbed at the medium surface. The change of the optical length within expose time τ is

$$\Delta S \equiv \frac{\partial S}{\partial t}\tau = \Delta\left(\int_L n(z,T(t))\,dz\right), \qquad (1)$$

where z is the coordinate across the medium slab and T is a local temperature. The difference occurs because of both the thermal expansion and the change of the refraction index for the heated portion of the medium. Corresponding phase shift with the accuracy to the members of second order infinitesimal can be written as

$$\Delta\varphi\left(x,y\right) = \frac{\psi}{\lambda}\cdot Q(x,y)\,, \qquad (2)$$

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where $Q(x, y)$ is an areal distribution of the specific energy density absorbed in the medium and λ is a wavelength of the probe (visible) radiation. The value

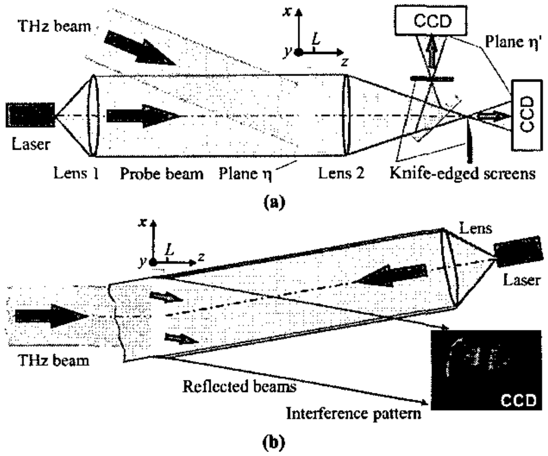

Fig. 3: Visualization of a THz image (a) with the two-dimensional Toepler method (TOD-T) and (b) with the interference technique (TOD-I).

$$\psi[\mathrm{m}^3/\mathrm{J}] = 2\pi(\beta + \alpha n) / \rho c_p \qquad (3)$$

(where $\beta = dn/dT$ and α is the coefficient of thermal expansion) is a constant for each optical material. Recording the phase shift, one easy finds the energy density distribution.

We have considered two variants of this technique. The first one (Fig. 3, a) is a variant of the Toepler scheme with addition of a beamsplitter that enables recording, using two edge-knife screens, both components of two-dimensional gradient $\nabla_{x,y}\varphi(x,y)$. Absolute value of the gradient is proportional to the change of probe light intensity at the image plane η'. The phase shift distribution $\Delta\varphi\left(x,y\right) = [\varphi(\tau) - \varphi(0)]$ is calculated from the difference between local phases obtained by two-dimensional integration of the intensity through the images recorded before and after terahertz image expose.

Other variant of this scheme employs two plane waves reflected from two surfaces of a slab (Fig. 3, b) with small wedging. Apparently, the origin of the interference pattern at the output CCD has the same nature, as for the Toepler scheme, but Eq. 3 must be doubled because of double passing through the slab probe light, reflected from the back surface, and one needs take into account the dip angle of the probe radiation.

Primary signal of the Toepler technique (TOD-T method) is two scalar fields of probe light intensity, which are proportional to two components of $\nabla_{x,y}\varphi(x,y)$. Primary signal of the interference technique (TOD-I method) is the interference fringes. Fringe shift at each point is proportional directly to the energy density, deposited into the slab. Proportionality factor $k = 2\psi$ is about 4 J/fringle·cm^2 for light glasses and decreases to 0.44 J/fringle·cm^2 for PMMA [3]. Thus, the last scheme enables direct measurement of the energy density distribution. Apparently, all problems intrinsic to the problem of interferogram processing have to be solved to create a system working in real time.

A primary terahertz image recorded with the TOD-I technique is shown in Fig. 4. As a target we used a thick slab of the light glass. Shift of the fringes in this experiment could not be resolved within time less than one second because of relatively low power density. Top-bench experiments with 25 ns, 0.3 J pulse of KrF laser as a source of energy showed that initial interference pattern resumes its original shape in about one second after the pulse. Cooling of the target by a gas flow should lead to further improvement of time resolution. Sensitivity of the technique can be increased ten times if to use as the target a PMMA wedge of optical quality.

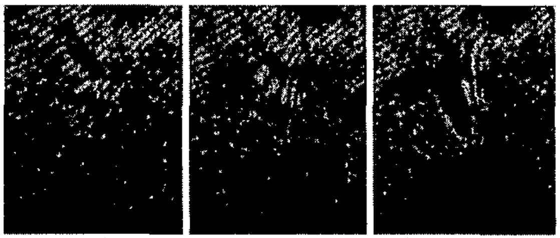

Fig. 4: Three interferograms recorded with the TOD-I technique using a glass target placed across the terahertz beam of the free electron laser at intervals of one minute.

4. Conclusion

Experimental verification of the techniques based on the visualization of thermal effect of terahertz radiation showed that they may be used for both qualitative and quantitative measurements. Visualization with FIR-NIR converter is a very simple and sensitive method. It well maps the temperature distribution (and qualitatively energy distribution) and can be routinely used for monitoring of intense terahertz beams. However, a problem of the retrieve of the energy distribution requires careful consideration for each material target.

Thermo-optical Toepler method also requires the reconstruction of primary data (phase gradient), but calibration of the result is very obvious, and it is easy to do in real time. The interference method displays visually less clear picture, but paradoxically reflects, in fact, directly the energy distribution of a terahertz beam. Practical application of this method requires development of software for digital reconstruction of the energy field from the interference pattern in real time.

5. Acknowledgements

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