Enhancement of contrast and spatial resolution in confocal coherent terahertz imaging system.

N.N. Zinovev[a], A.V. Andrianov[a], A.J. Gallant[2], J.M. Chamberlain[b]
[a]A.F. Ioffe Physical Technical Institute, 194021 St. Petersburg, Russia.
[b] *Department of Physics, Durham University,* Durham DH1 3LE, UK

Abstract— **The effect of enhancement of image contrast and spatial resolution without the loss of the spectral composition of the radiation under investigation has been experimentally demonstrated for a terahertz far-field imaging system. The result has been obtained by using a confocal aperture placed in the intermediate-focus region of the optical system. The result is a fundamental advance towards the achievement of subwavelength resolution and the contrast of microscopy systems in the terahertz spectral range.**

I. Introduction And Background

THE resolution of a far-field terahertz (THz) imaging system is primarily determined by the beam width at the focus. This is diffraction limited and is related to the mean terahertz wavelength averaged over the irradiating spectrum $\bar{\lambda}_{THz}$, where $\bar{\lambda}_{THz}$ ~1 mm in a typical THz setup [1]. Achieving sub-wavelength resolution in far-field optics, significant enhancement of imaging contrast and optical slicing can be obtained with the use of spatial filtering [2]. The earliest and simplest realization of these approaches is known as the confocal microscopy [3] and applied to fluorescence imaging in a plethora of biological applications [4], but, so far there has been no attempt to apply confocal principle of microscopy to coherent THz imaging. In this work, we introduce confocal filtering technique to terahertz imaging. It demonstrates significant improvement of the image contrast and resolution overcoming the diffraction limit. This is necessary for a true three-dimensional (3D) optical slicing to be achieved with terahertz far-field optics.

II. Experimental details

For the experimental examination of the effect of confocal filtering on terahertz imaging, we used a typical coherent terahertz time domain spectroscopy system (Fig. 1) modified with the addition of a confocal attachment containing adjustable pinhole filter and focusing condensers (parabolic mirrors). Terahertz radiation (with central wavelength λ_{THz}~1 mm) was generated with a LT-GaAs based photoconductive antenna, excited by 25 fs pulses of a Ti:sapphire laser (λ=800) nm and average incident power held below 50 mW, and focused on the subject. The secondary radiation (scattered and transmitted) emanating from the subject, was collected and focused into the conjugated focal plane to the subject's one where we placed the pinhole filter of 1.2 mm in a diameter. The THz radiation transmitted through the pinhole filter was further focused onto a ZnTe electro-optic THz detector. It is important to add that the pinhole did not change the spectrum

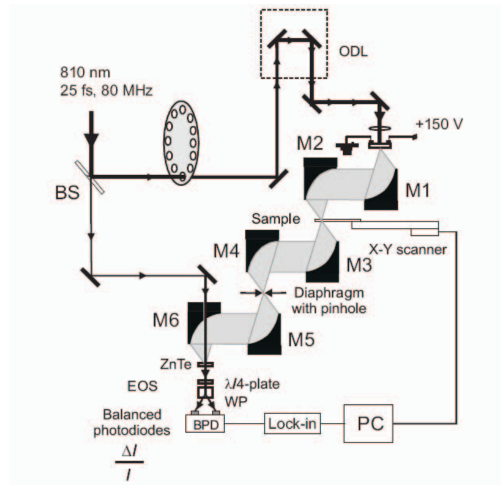

Fig. 1. The scheme of confocal coherent terahertz far-field imaging system.

of the THz radiation arriving to the detector. The subject, a phantom structure (Fig. 2), was formed from stacks of Si plates. Each plate (p-type Si, resistivity 20 Ωcm, 0.6mm thick,

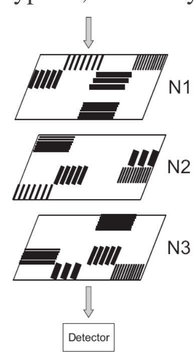

Fig. 2. The layout of phantom structure used in the experiments.

24 by 24mm in area) included grating patterns defined in a thin (80nm) layer of evaporated Cr. The gratings had spatial frequencies of up to 4 lines/mm and allowed the image resolution of the system to be determined. The separations between Si plates were adjusted to a range of required values with variable spacers. The phantom structure was placed at the center of focal caustic of the intermediate focal plane of the imaging system. With such alignment we imaged the test phantom using two-dimensional raster scanning of the subject, with reference to the fixed coordinate frame in the objective focal plane. The terahertz signal forming raster image was sampled at the delay time, corresponding to the first positive half-wave maximum of terahertz electric field waveform. The images were obtained with scanning steps 50 or 100 μm.

III. RESULTS

A comparison of terahertz images of the subject in the generic and confocal configurations, shows that the insertion of the confocal aperture yields a considerable enhancement of the contrast and resolution of the subject details. The spatial frequencies of the grating arrays, not resolved in the generic configuration, become perfectly resolved in the confocal scheme of terahertz imaging system. Fig. 3b depicts the line scans of the terahertz electric field, extracted from the image along the horizontal solid lines, as shown in Fig. 3a. The line scans in Fig. 3b provide the quantitative proofs of the enhancement of both spatial resolution and image contrast achieved with the confocal configuration. It indicates that the ratio of terahertz electric field amplitude minima and maxima in the case of the optical confocal configuration is on average 0.76 for x between x=3 mm and x=7 mm, which corresponds to the array of metallic strips in plate $N2$ with the width and spacing 250 μm (Fig. 1b) corresponding to the spatial frequency 4 lines/mm. It is seen that in the case of the generically configured optical system (Fig. 2b, curve 2), the same ratio is measured within 0.9–1. Thus, with applied confocal filter the structure with the spatial frequency 4 lines/mm becomes well resolved, according to the Rayleigh criterion [5].

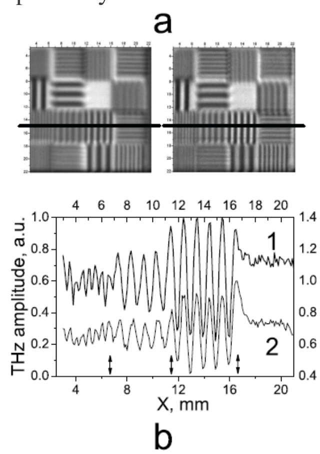

Fig. 3. Demonstration of the enhancement of lateral resolving power: a) terahertz image of the test phantom with widely open confocal pinhole (left) and with the confocal pinhole of the diameter of 1.2 mm (right); b) terahertz field line scans along the black lines of the images (a), curve 1 corresponds to the right hand side of (a) and curve 2 corresponds to the left of (a). The arrows in (b) designate the boarders of grating arrays.

In order to demonstrate the axial selectivity of confocal terahertz imaging, we performed imaging of two grating arrays with identical major spatial frequencies, *N2* placed in the focal plane and *N3* set in the position with small offset $\Delta z \sim \lambda_{THz}$ along the optical axis. This was achieved by moving the phantom through the focal plane of the objective. Fig. 4 demonstrates strong effect on axial object selectivity. In point of fact, the ratio of minimum to maximum of terahertz electric field strength, becomes approximately 0.65 for the phantom *N2* being in the focal plane as is concluded from Fig. 4b, curve 1. The same parameter takes approximately the value of 0.9 for the phantom $N3$ positioned with the offset Δz as follows from Fig. 4b, curve 2. The experimental data of Fig. 4 indicate that the application of confocal configuration introduces a pronounced improvement of the axial resolution and contrast. If the image contrast is defined as the ratio $\nu = (U_{max} - U_{min})/(U_{max}+U_{min})$, then the confocal image contrast enhancement in z-direction achieves the increment of 2.5 measured on the phantom array with high spatial frequencies $\geq 1/\lambda_{THz}$. The experimental studies are supported by the theoretical analysis, paving the way toward achieving further increase in sub-wavelength resolution and optical slicing, using far-field terahertz imaging layout enhanced by purpose-designed filtering technique.

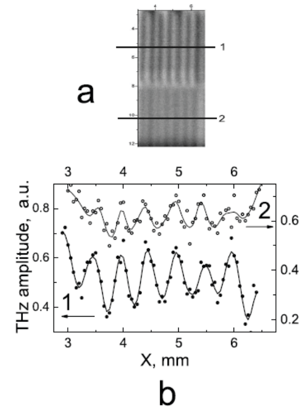

Fig. 4. Demonstration of the enhancement of axial resolving power in the confocal configuration: a) the upper part of terahertz image is produced by the grating of $N2$ (top) placed in the focal plane and the lower part is generated by the identical grating of $N3$ offset from the focal plane by $\Delta z \sim \lambda_{THz}$; b) the line scans of terahertz field along the solid lines 1 and 2, respectively. Solid curves result from smoothing of experimental points.

To summarize, the enhancement of image contrast and spatial resolution breaking through the diffraction limit, due to the application of confocal optical scheme, has been demonstrated. With the 1.2mm pinhole in place we can attain a spatial resolution of order of 250 μm at the mean wavelength of the THz radiation λ_{THz}~1 mm. That is the sub-wavelength spatial resolution of λ/4 was achieved with the far-field THz imaging system. The achievement of depth resolution in the images of the subject with using the confocal configuration of the THz imaging system has also been demonstrated.

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