Terahertz imaging with optical resolution by femtosecond laser filament in air

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Abstract: We introduce a superresolution resolution THz imaging technique which uses the THz radiation generated by a femtosecond laser filament in air as the probe, based on the fact that the femtosecond laser filament forms a waveguide for the THz wave in air. The diameter of the THz beam, which propagates inside the filament, varies from 20 μm to 50 μm, which is significantly smaller than the wavelength of the THz wave. Using this highly spatially confined THz beam as the probe, THz imaging with resolution as high as 20 μm (~λ/38 at 0.4 THz) is promising.
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Resolution enhancement of terahertz (THz) imaging is one of central concerns in the THz science and technology research. Because of the used long wavelength ($\lambda_{1\text{ THz}}$ = 300 μm), THz imaging's resolution is generally in the scale of millimetre. This constitutes a major obstacle for the application of THz imaging in bio-medical diagnosis and semiconductor device inspection [1-3]. Here, we report on a novel sub-wavelength THz imaging method via the femtosecond laser filament in air, which refers to the plasma channel created by a femtosecond laser pulse [4].

Fig. 1 schematically shows the experimental setup. A two-color (1 kHz, 50 fs, 1 mJ/pulse, 800 nm + 400 nm) laser filament was created at the focus of the lens (f = 30 cm). The generated THz pulse was detected by a standard electric-optic sampling (EOS) setup [5]. Sub-wavelength resolution THz imaging was carried out by inserting a Printed-Circuit-Board plate with multiple through-holes in the middle of the filament. Just in front of the PCB plate, a ceramic plate was placed, in touch with the PCB plate. The ceramic plate terminates the filament and excludes the laser damage of the PCB plate. The THz power transmission of the ceramic plate is about 50%. On the other hand, the PCB plate has poor transmission of THz wave. Mainly the THz energy passing through the holes could be detected by EOS setup. The THz image of the holes on the PCB plate was taken by moving the two plates together in the x-y plane (z axis is defined as the laser propagation direction). The step sizes were 100 μm and 100 μm along x and y axes, respectively. Note that full THz temporal waveforms have been recorded for each position.

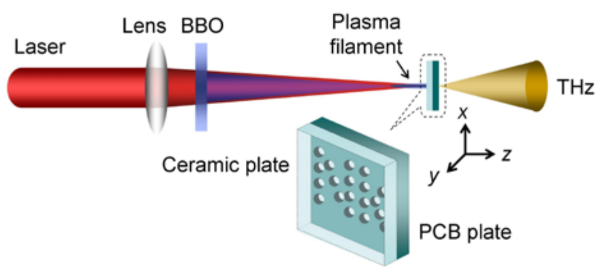

Fig. 1. Experimental setup.

Fig. 2a illustrates the image of the multiple holes under optical microscope (resolution: 5 μm). The diameter of each hole is about 600 μm. The holes form two characters of "NK", abbreviation for NanKai. The corresponding scanning THz image is displayed in Fig. 2b. Comparing Fig. 2a and 2b, no significant blurring effect could be noticed. Reminding ourselves that the peak wavelength of the THz pulse generated in our experiment is about 750 μm, which is even larger than the size of the holes on the PCB plate. However, Fig. 2 indicates that the minimum resolvable structure by THz imaging is less than 100 μm. For example, according to the optical image (Fig. 2a),

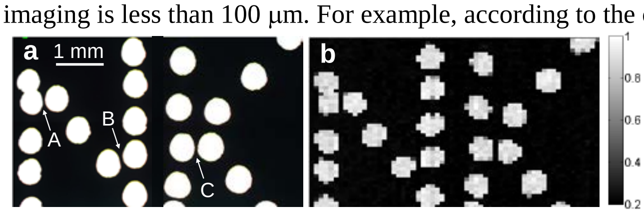

Fig. 2. Comparing optical microscope image (a) and THz image (b).

three hole pitches pointed by arrow A, B and C have characterized widths of about 60 μm, 80 μm and 75 μm, respectively. And they can be clearly resolved by the THz imaging (Fig. 2b). Hence, the resolution of the obtained THz image by our method is much smaller than the THz pulse wavelength.

The knife-edge method [6] was applied to measure the THz beam diameter at different positions *z*, which determines the THz imaging resolution in our experiment. Note that $z = 0$ corresponds to the starting position where significant THz signal was able to be detected. The obtained THz beam diameters *d* as a function of *z* is depicted in Fig. 3. What Fig. 3 impresses us most is that the THz pulse energy is spatially constrained inside a space which is much smaller than the wavelength. The jump of the curve in Fig. 3 taking place between $z = 5$ mm and $z = 6$ mm gives a hint that the THz wave is in fact strongly guided from $z = 0$ mm to $z = 5$ mm. Coincidentally, this region superposes with the zone where significant plasma, i.e. a filament, was produced during the filamentation (see Fig. 3a). We have reason to believe that a THz waveguide is created inside the filament. It is this waveguide that strongly confines the THz energy into a region with only a few ten microns in diameter. And this phenomenon makes a novel sub-wavelength THz imaging technique feasible as we have demonstrated. In order to confirm that creation of a THz waveguide by the filamentation, we have also calculated the THz wave eigenmodes by the full-vector finite-element method (FEM) with the commercial software COMSOL Multiphysics. The THz doublet degenerated modes (diameters < 100 μm) localized in the filament area are found in our simulation (not shown).

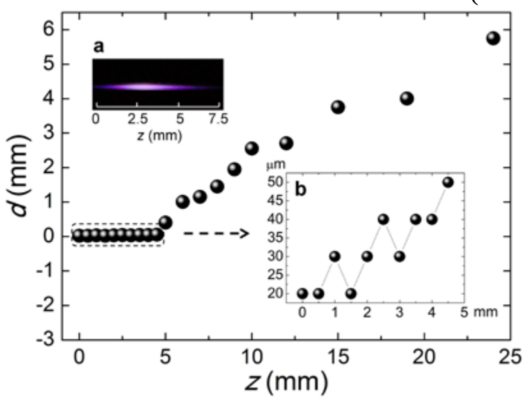

Fig. 3. THz beam diameter *d* as a function of *z*.

Furthermore, by using some other detection techniques, broader detection bandwidth could be achieved as compared with our TDS system [7-10]. Thus, though the proof-of-principle of the sub-wavelength imaging method is reported in the present work for the low frequencies, the investigation about its application at high frequency range has been planned for future systemic study in terms of various experimental parameters, including pump laser energy [11], pulse duration [12], laser polarization [13], laser wavelength [14], gas species [7], gas pressure [15] and detection technique [9-11,16,17], etc.

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