High-resolution terahertz tomography using 17-fs ultrashort-pulse fiber laser

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***Abstract*—We describe the generation and detection of coherent broadband terahertz waves using ultrashort-pulse fiber laser, and its application to terahertz tomography. A pulse compression technique using nonlinear and dispersion effects of optical fibers leads to the development of high-peak-power 17-fs ultrashort- pulse fiber laser. With the optical rectification in an organic crystal, 4-dimethylamino-N-methyl-4-stilbazolium tosylate (DAST), ultra-broad terahertz pulses are successfully generated. The spectrum ranges widely from 0.1 to 25 THz. By applying these broadband THz pulses to THz tomography, the thickness of 5-μm thin Teflon film is measured correctly.**

I. Introduction And Background

Terahertz (THz) tomography using ultrashort THz pulses is useful for measurement of tablet coatings or films of paint, and the high-resolution- and practical-system is required[1-3]. THz tomography reported so far use a Ti:Sapphire laser as a pump light source. If a fiber laser is used instead of the Ti:Sapphire laser, the stable, compact, and robust system is realized. However, the longer pulse width and the weaker peak power of the fiber laser than those of the Ti:Sapphire laser prevent from developing high-resolution THz tomography.

Generally, to realize the high-resolution THz tomography, the generation and detection of broadband THz waves are required. So far, several techniques for broadband THz radiation have been demonstrated using Ti:Sapphire laser[4-6]. In this experiment, to obtain the broadband THz pulses using the fiber laser, we generate high-peak-power sub-20-fs ultrashort- pulses by controlling nonlinear and dispersion effects caused in optical fibers strictly. By use of this laser as a pump light source, the high-resolution THz tomography based on the fiber laser is demonstrated.

II. Experiment

We compressed and amplified optical pulses from a passively-mode-locked erbium-doped fiber laser using optical fibers. The fiber laser oscillator produced 300-fs optical pulses at 1.55 μm with the repetition frequency of 48 MHz. To control the nonlinear and dispersion effects caused in the optical fibers, four kinds of optical fibers were used. They were standard single-mode fiber (SMF), small- and positive-dispersion erbium-doped fiber (EDF), large mode-area photonic-crystal fiber (PCF), and fiber with a high nonlinearity (HNLF). First, the optical pulses were amplified and compressed using SMF, EDF, and PCF. The peculiar dispersion characteristics of the EDF and low nonlinearity of the PCF led to the generation of almost pedestal-free 55-fs pulses with the average power of 280 mW. Next, the pulses were compressed further by higher-order soliton compression caused in the HNLF.

The pulse width and average power of compressed pulses were 17 fs and 200 mW, respectively. The temporal and spectral waveforms of these pulses are shown in Fig.1. In the temporal waveform, the pedestal components are suppressed well. The spectrum ranges widely from 1.3 to 1.8 μm. The peak power attained up to beyond 150 kW. To our knowledge, this is the first demonstration of high-peak-power sub-20-fs ultrashort pulses using the all-fiber system.

The experimental setup for THz tomography using the fiber laser is shown in Fig.2. The 17-fs pulses from the fiber laser were divided into two beams using a 50:50 beam splitter. One of divided beams was input to the periodically-poled lithium niobate (PPLN) to generate 780-nm pulses, which were used for the THz-wave detection. The THz wave was radiated in a 4-dimethylamino-N-methyl-4-stilbazolium tosylate (DAST) crystal by focusing the 17-fs pulses on it[7]. The DAST crystal has a large electro-optic coefficient and a long coherence length around 1.55 μm. Therefore, broadband radiation of THz waves was expected. The generated THz pulses were focused on a sample using pairs of parabolic mirrors. Then, the THz waves reflected from each layer of the sample were detected using a

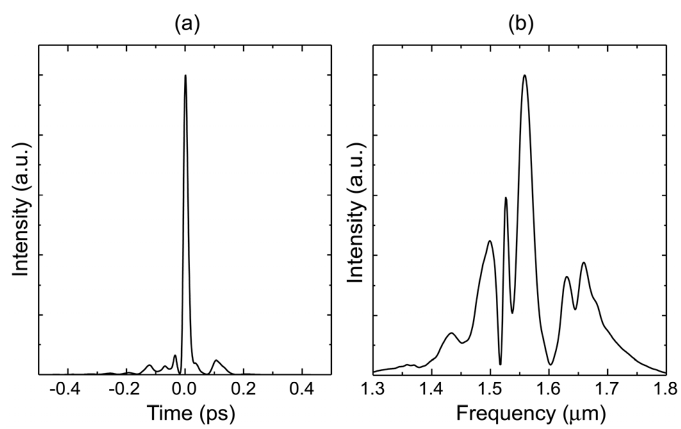

Fig.1 (a) Temporal and (b) spectral waveforms of compressed pulses

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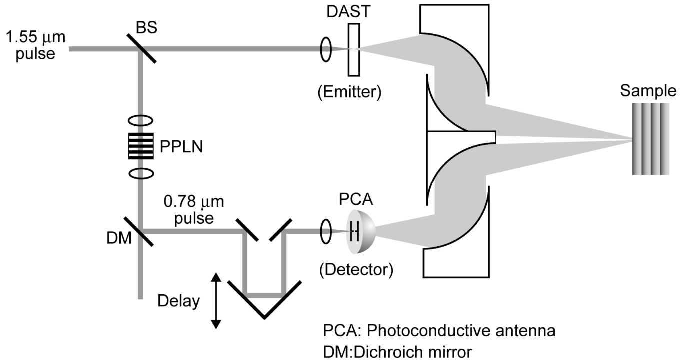

Fig.2 Experimental setup for terahertz tomography.

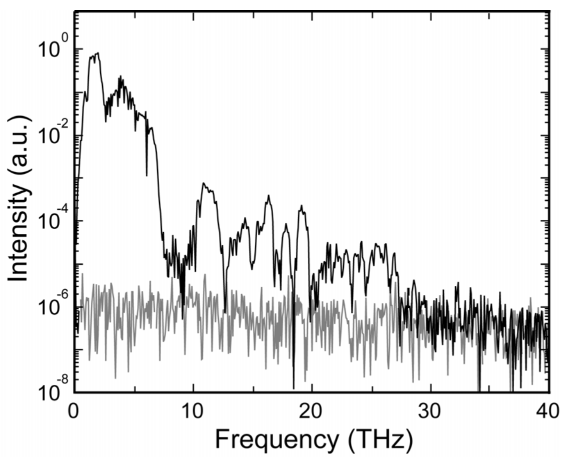

Fig.3 Spectrum of detected terahertz pulses.
The noise level of the system is shown in gray curve.

LT-GaAs photoconductive antenna with a 5-μm electrodes gap operated by SHG of the laser. The delay stage provided the time delay between the THz pulses and the frequency-double pulses. The obtained signal was amplified by a pre-amplifier with a gain of 70 dB and was detected using a lock-in amplifier referenced to the chopper frequency of 1 kHz.

Figure 3 shows the frequency spectrum of detected THz pulses when an aluminum-coated mirror was used as a sample. This data was obtained when the experimental setup shown in Fig. 2 was purged with dry nitrogen gas to reduce the effect of water vapor absorption. The spectrum was broadened widely from 0.1 to 27 THz. This frequency bandwidth is, to our knowledge, wider than any other ones obtained using fiber-laser-based system reported in the past. The maximum SNR was about 60 dB at 1.8 THz. Since the LT-GaAs substrate has the strong absorption, there is the spectral dip around 8 THz. The spectral oscillation observed at the frequency range above 12 THz is considered to be caused by the phase mismatching between the pump laser source and the generated THz waves.

To extract the boundaries of each layer of the sample clearly, the detected temporal waveforms were signal processed using deconvolution technique. In this signal processing, the temporal waveform reflected from the aluminum-coated mirror was used as a reference signal.

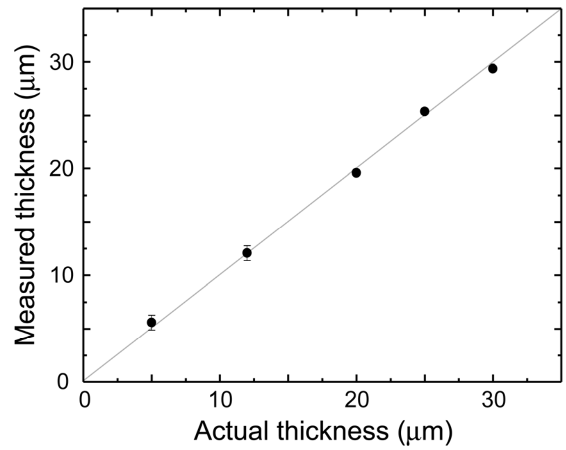

Fig.4 Measured thickness of Teflon films
as a function of actual one.

Then, to evaluate the axial resolution of our system, the thickness of Teflon films was measured. The experimental result is shown in Fig. 4. The horizontal and vertical axes show the actual and measured thickness, respectively. Here, a micrometer was used to measure the actual thickness. The film thickness of 5 μm, 12 μm, 20 μm, 25 μm, and 30 μm were measured correctly. Therefore, our system has high axial resolution enough to measure 5-μm thin layer.

III. Conclusion

We present the high-resolution terahertz tomography using ultrashort pulse fiber laser. By combining several kinds of optical fibers to control the nonlinear and dispersion effects, 17-fs pulses with the peak power of beyond 150 kW were generated. The terahertz wave generation using these pulses and a DAST crystal led to the terahertz waves broadened widely from 0.1 to 27 THz. With a simple signal processing using deconvolution, the thicknesses of 5-30μm Teflon films were measured correctly.

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