High-speed measurement of terahertz waveforms using a 100 kHz Yb-doped fiber laser for terahertz imaging

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Terahertz (THz) light has been used to inspect semiconductor devices, security, biological tissues, and other applications. THz light with low photon energy allows non-destructive and non-invasive probes to be used for these inspections without influencing the molecular structure and electronic properties. THz time-domain spectroscopy (THz-TDS) has been used widely as a sensitive and accurate method to observe THz spectra. This method has already been applied to two-dimensional THz imaging [1] and time-of-flight THz tomography [2] as an inspection tool.

To realize THz imaging as a practical tool, the acquisition speed of THz imaging systems must be increased by two to three orders of magnitude, as suggested in the 2017 THz science and technology roadmap [3]. In this study, we demonstrate the high-speed measurement of THz waveforms to improve the acquisition speed of THz imaging. First, we develop a laser system to generate intense THz pulses with a repetition rate of 100 kHz. Second, we construct a system for high-speed measurement of THz waveforms with the measurement time of 10 ms.

To achieve high-speed THz waveform measurement for practical use, we develop a compact system to generate intense and short THz pulses with high-repetition rate. Intense THz pulses allow us to measure samples with high absorbance into depth. The short THz pulses allow us to measure the thickness of thin films with high resolution.

To generate intense THz pulses, optical rectification in an $LiNbO_3$ (LN) crystal pumped by near-IR light with a tilted pulse front is commonly used [4]. Calculations suggest that near-IR pump light with a pulse width of around 350 fs (transform limited: TL) is best for effective THz light generation in this method [5]. Then, we develop a Yb-doped fiber laser system to generate pump light with a repetition rate of 100 kHz, a pulse width of 320 fs, and a pulse energy of 28 μJ, as shown in Fig. 1. To avoid enhancing the amplified spontaneous emission in the fibers, we divide the amplification process into six stages.

The output light from the Yb fiber amplifier is introduced into the small-tip device (16×20 mm^2) proposed in our previous paper [6]. In the conventional method, the pump pulse front is tilted by a diffraction grating and imaged onto an LN prism to obtain an intense THz output. Our device uses a "contact grating setup" in which the diffraction grating is placed in contact with the input surface of the LN substrate, thereby downsizing the THz light source drastically. Figure 2(a) shows the THz waveform obtained from the contact-grating device pumped by a parallel beam of 4 mm in diameter and 13 μJ. The peak electric field is around 1 kV/cm. The Fourier-transformed spectrum (Fig. 2(b)) shows a peak frequency of 0.6 THz and a bandwidth of 1.5 THz.

The slow acquisition speed in THz-TDS is due to scanning the optical delay line to obtain the temporal profile of the electric field, as shown Fig. 2(a). To overcome this problem, we place a retroreflector on a speaker diaphragm vibrating at 50 Hz to scan the optical delay quickly (Fig. 3). We can measure a single waveform with a scanning time range of 15 ps (Fig. 2(a)) by a measurement time of 10 ms, which is 10^4 times shorter than the time required in the conventional method using the stepping scan. The 100 kHz laser system provides 1,000 data points during 10 ms, and therefore, the time interval between the data points is 15 fs. As described above, we realize a high-speed measurement system for THz waveforms with intense THz light. In the near future, we will realize high-speed THz imaging by using the system presented herein.

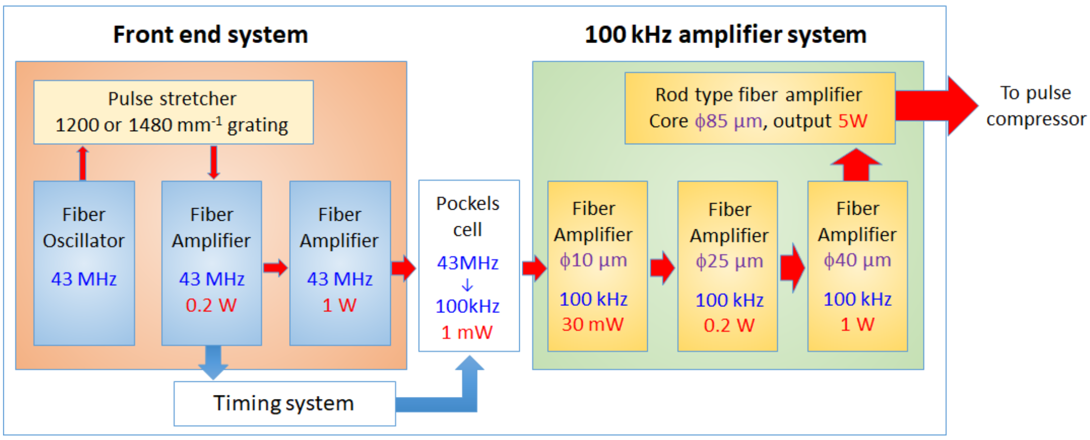

Fig. 1. Diagram of fiber laser system for THz light generation.

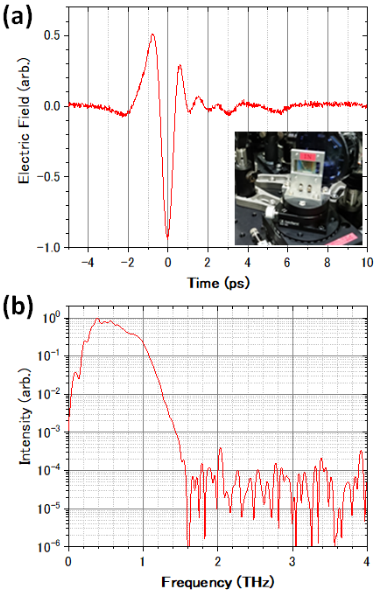

Fig. 2. (a) THz waveform and (b) Fourier-transformed spectrum obtained by our high-speed waveform measurement system. The inset shows our device used in this study.

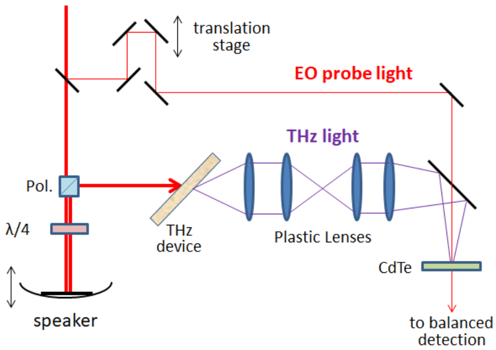

Fig. 3. Schematic of THz-TDS system with fast-scanning delay line.

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