Noncontact Terahertz Paintmeter for Real-Time Two-Dimensional Cross-Section Imaging of Paint Film Thickness

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Abstract. Non-contact, remote monitoring of thickness and drying progress of a paint film is required in fields of non-destructive testing and evaluation. For rapid image acquisition of 2D cross-section in paint film, we propose a terahertz (THz) paintmeter based on real-time 2D THz tomography, which is achieved by a combination of electro-optical time-to-space conversion and line focusing of a THz beam on a sample. To evaluate a potential of the proposed method, we demonstrate the real-time monitoring of the paint thickness distribution in a moving paint sample and the drying progress in a wet paint film. The THz paintmeter can be a powerful tool for quality control of the paint film on the inspection during painting process of car bodies or parts on a moving stage.

1. Introduction

Terahertz (THz) tomography [1, 2] has recently attracted attention as a possible substitute for “invasive” X-rays and “contact” ultrasonic waves in the fields of nondestructive testing and biomedical diagnostics because it can serve as a "non-invasive” and “non-contact” probe. THz tomography is realized by the time-of-flight measurement of THz pulse echoes when a THz electromagnetic pulse is incident upon a sample in a reflection geometry. This technique can be used in various applications to reveal the cross-section of internal structures, such as floppy disk [1], skin burning [2], and car painting [3]. However, since conventional THz tomography is based on a point-to-point measurement, it is necessary to perform 2D mechanical scanning of the time delay and sample position to construct a 2D tomographic image of the sample. The resultant high time consumption of this method limits applications of conventional THz tomography to stationary objects. If THz tomography can be extended to moving objects, such as industrial products on a moving stage or the human body, the fields that THz tomography can be applied to will be greatly increased. For this, real-time image acquisition is essential.

In this paper, we propose real-time 2D THz tomography of moving objects by the combined use of non-collinear 2D-FSEOS and line focusing of the THz beam onto a sample coupled with a CCD camera [4]. After describing the experimental setup of the proposed method, we present a THz tomographic movie of a moving paint film.

2. Experimental setup

Figure 1 shows an experimental setup of the real-time 2D THz tomography. A femtosecond Ti:Sapphire regenerative amplifier (pulse energy = 1 mJ, pulse duration = 100 fs, central wavelength = 800 nm, repetition rate = 1 kHz) is used to generate and detect the THz pulse. An intense THz pulse is generated via optical rectification of amplified femtosecond pulse light (300-μJ pulse energy) in a 4-mm-thick <110> ZnTe crystal (not shown). To obtain a 1D transverse image along the X-axis of the sample, the THz beam is first line-focused on the sample using a cylindrical THz lens with the focal line parallel to the X-axis of the sample, resulting in an area of 14-mm height by 1-mm width being illuminated. Next, the line of the THz beam reflected from the sample is imaged by an imaging THz lens onto a 1-mm-thick <110> ZnTe crystal for THz detection. A probe beam of 5-mm diameter (1-μJ pulse energy) is incident on the ZnTe non-collinearly with the THz beam at a certain crossed angle. This results in the formation of a 2D spatiotemporal THz image on the probe beam at the exit window of the ZnTe, in which the temporal profile of the THz pulse and the 1D transverse distribution along the X-axis develop in the horizontal and vertical directions in the ZnTe. EO sampling is then performed at the near zero optical transmission point using two crossed polarizers (not shown). Finally, the 2D spatiotemporal THz image is imaged via an imaging lens onto a 12-bit thermoelectric-cooled CCD camera (640×480 pixels, cooled to -15 °C, 10 frame/sec) as the 2D spatial distribution of the probe beam in real time. The resulting 2D spatiotemporal THz image provides an X-Z cross-sectional image of the sample, namely real-time 2D THz tomography.

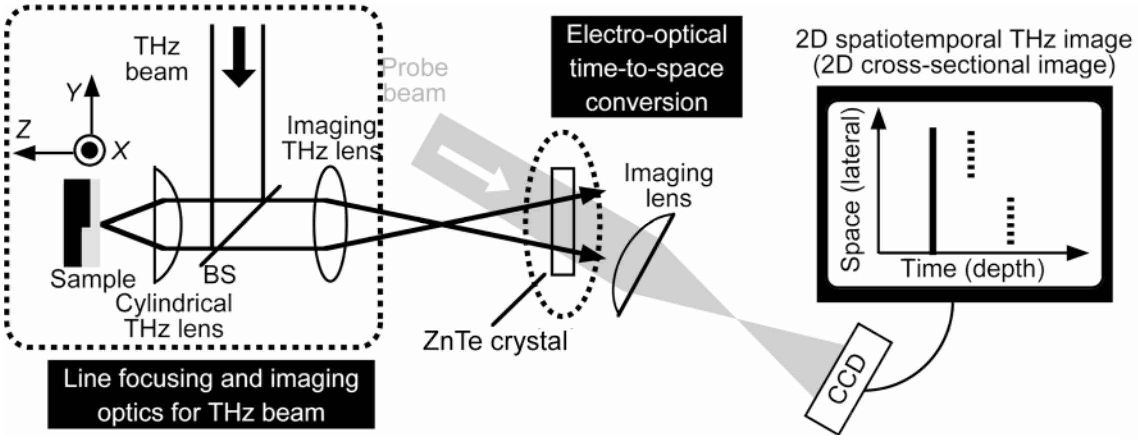

Fig. 1. Experimental setup of real-time 2D THz tomography. CCD: charge-coupled-device camera; BS: beam splitter.

3. Results

Figure 2(a) shows a 2D spatiotemporal THz image of a plane Al mirror surface for an exposure time of 70 ms (image size = 9 ps × 5 mm). The image was obtained by subtracting the CCD image measured in the absence of the THz electric field (background image) from the EO modulated image. The white and black areas in the image indicate positive and negative THz electric field, respectively. The time scale was calibrated from a known time delay produced by a conventional optical delay stage. The unit increment in the time axis was 14.1 fs/pixel, resulting from the time window of 9 ps and the horizontal width of 640 pixels. The transverse resolution along the X direction was determined to be 3.1 mm using a knife-edge test. The THz pulse echo reflected from the sample appears as a signal line around 4.1 ps [the white line in Fig. 2(a)]. This straight-line profile results from the uniform distribution of the mirror surface without internal structures. Figure 2(b) shows the temporal waveform of the THz electric field extracted from a line profile of the 2D spatiotemporal THz image [line (A) in Fig. 2(a)]. As shown, a pulsed THz electric field with 0.5-ps pulse duration was obtained with a signal-to-noise ratio of 80. Figure 2(c) shows an amplitude spectrum of the THz radiation obtained by Fourier transform of the temporal waveform in Fig. 2(b). The peak frequency and bandwidth of the spectrum are 0.55 THz and 1.04 THz, respectively.

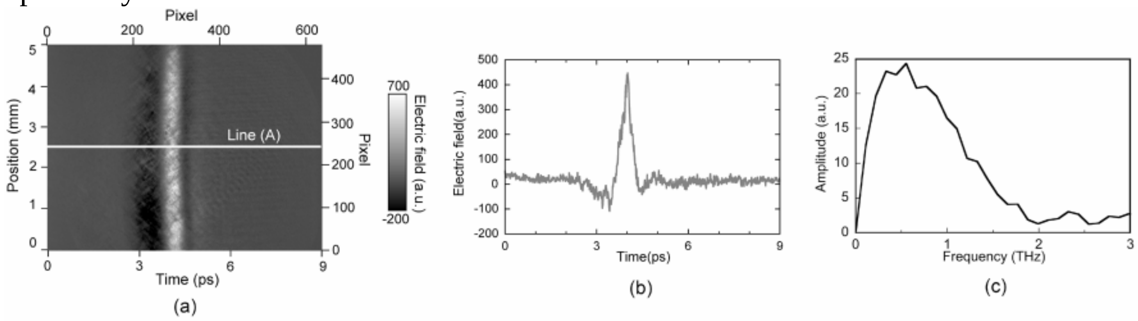

Fig. 2. 2D spatiotemporal THz image of a plane Al mirror surface (image size = 9 ps × 5 mm). (a) CCD image for an exposure time of 70 ms. (b) Temporal waveform of the THz electric field extracted from a line profile of the 2D spatiotemporal THz image and (c) corresponding spectrum of THz amplitude.

To confirm the performance of the proposed method, we have demonstrated real-time 2D THz tomography of a moving paint film. The sample used in the experiment was a half-paint film, in which a dry white alkyd painting is layered on half the area of an Al substrate. The paint thickness around the centre of the painting area was 175 μm, determined beforehand with a contact-type thickness meter. Because the THz beam is line-focused on the sample (see Fig. 1), the sample was continuously moved along the direction of the focus line by a translation stage (moving speed = 5 mm/s). Figure 3 shows snapshots of 2D THz tomographic movie of the moving half-paint film at a frame rate of 10 frame/s, which corresponds to a 2D spatiotemporal THz image with a size of 6 ps by 5 mm. In the unpainted area, one THz echo line from the surface of the Al substrate appears at around 2.8 ps [Fig. 3(a)]. In the painted area, two THz echo lines from the paint surface (2.3 ps) and the paint-substrate interface (4.5 ps) are clearly separated [Fig. 3(c)]. Here, the upper horizontal coordinate is scaled by the paint thickness using the group refractive index of the paint (2.14) and the time delay. The paint thickness in position range of 1 ~ 4 mm was determined to be 162 ± 21 μm [(mean) ± (standard

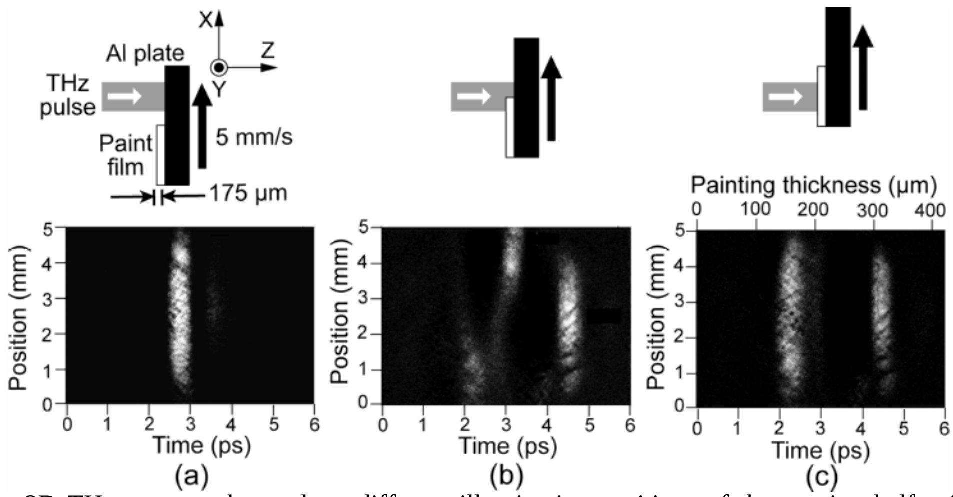

Fig. 3. 2D THz tomography at three different illuminating positions of the moving half-paint film (image size = 6 ps × 5 mm). (a) Unpainted area, (b) boundary between unpainted and painted areas, and (c) painted area.

deviation)] by the time separation between the two THz echoes, which is consistent with that measured by the contact-type thickness meter (175 μm). At the boundary between the unpainted and painted areas, a mixture of one and two echoes is observed [Fig. 3(b)]. To the best of our knowledge, this is the first experiment that achieves 2D THz tomography of a moving object.

4. Conclusions

We have proposed real-time 2D THz tomography based on the combined use of electro-optical time-to-space conversion and line focusing of the THz beam on a sample. We have demonstrated real-time monitoring of paint thickness in a moving paint sample as examples of its application in a THz paintmeter. This method will be useful in monitoring and/or controlling products on belt conveyors in factories, baggage carousels at airport, and similar applications.

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