Biomedical applications of a real-time terahertz color scanner

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Abstract: A real-time THz color scanner has the potential to further expand the application scope of THz spectral imaging based on its rapid image acquisition rate. We demonstrated three possible applications of a THz color scanner in the biomedical field: imaging of pharmaceutical tablets, human teeth, and human hair. The first application showed the scanner's potential in total inspection for rapid quality control of pharmaceutical tablets moving on a conveyor belt. The second application demonstrated that the scanner can be used to identify a potential indicator for crystallinity of dental tissue. In the third application, the scanner was successfully used to visualize the drying process of wet hairs. These demonstrations indicated the high potential of the THz color scanner for practical applications in the biomedical field.

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1. Introduction

Color scanners are in widespread daily use. They can be considered a type of spectral imaging apparatus using visible light. Unfortunately, since visible light is strongly scattered and/or absorbed in opaque objects, visible-light color scanners can probe only in the vicinity of the object surface. Therefore, their utility has been limited to scanning documents and photographs. However, if color scanner technology could be developed so that their scanning wavelengths could be extended to regions of the spectrum having high penetration in opaque objects, it would become possible to visualize the internal structure of opaque objects. Although X-ray scanners (radiography) have been widely used in nondestructive inspection and biological imaging, the hazardous ionizing effects of X-rays limit their utility. Also, too high penetrative power of X-rays often makes it difficult to create good image contrast in low-density materials. Furthermore, this imaging modality only produces monochrome images of the test object. One promising electromagnetic wave that can be used for deeply penetrative color scanning is terahertz (THz) radiation. Features of THz radiation include its moderate penetration in dry, non-polar materials, insensitivity to scattering, and low photon energy. Furthermore, THz waves effectively provide color images of the test object in the THz range in contrast to the monochrome images provided by conventional X-ray scanners. Since many materials exhibit unique THz spectral fingerprints that can be used for material characterization [1], one could understand *where* and *what* is the test object on the basis of its THz color images. Such material characterization and imaging of opaque objects have received interest as a new tool for screening of illicit drugs [2] and explosives [3], detection of cancerous tissue [4], quality evaluation of pharmaceutical tablets [5], and art conservation [6]. However, since usual THz time-domain spectroscopic (THz-TDS) imaging is based on point-to-point measurement, it is necessary to perform several mechanical scans while measuring the time delay and sample position to construct a THz color image of the sample. As a result, the method has so far only been applied to stationary objects. If THz-TDS imaging can be extended to moving objects, such as industrial products on a conveyor belt, the number of applications of THz-TDS imaging would be greatly increased. To achieve this, real-time image acquisition is essential.

Rapid image acquisition can be achieved if, instead of a mechanical stage, we use an alternative technique for measuring the time delay and sample position. One effective method to realize a stage-free configuration is a combination of single-shot measurement of the temporal waveform and its one-dimensional (1D) transverse imaging, which enables real-time two-dimensional (2D) spatiotemporal (ST) imaging. Recently, real-time 2D-ST imaging in the THz region [7] has been achieved by a combination of non-collinear electro-optical time-to-

space conversion [8] and line focusing of a THz beam, which has been effectively applied to THz tomography [7] and THz-TDS imaging [9]. The latter system functions as a color scanner in the THz spectral region with real-time line-scanning, namely, a real-time THz color scanner, and has been successfully used to image an object that is moved unidirectionally at a constant speed of 10 mm/s by a translation stage. To the best of our knowledge, this is the first time that THz-TDS imaging of a moving object has been achieved. When pixel rate is defined as the ratio of the total number of pixels to acquisition time, the achieved imaging rate ($\gamma = 23,200$ pixel/s) is four orders of magnitude higher than that ($\gamma = 0.063$ pixel/s) of a conventional point-scanning THz-TDS imaging system equipped with a stepping-motor-driven time-delay stage. However, evaluation of its potential for practical applications is still lacking. In this article, we demonstrate possible applications of such a real-time THz color scanner in the biomedical field.

2. Experimental setup

Let us consider the operating principle in a usual visible-light color scanner, which acquires three-dimensional information composed of two spatial dimensions and one color (wavelength or optical frequency) dimension. A color charge-coupled device (CCD) line sensor camera is used to capture a color line image or a 1D spectral image, composed of one spatial dimension and one color dimension, in real time. To construct a 2D color image, consecutive color line images are acquired while scanning the line sensor across the object with a translation stage, and the individual line images are then pieced together.

If a THz color scanner is constructed based on this principle, the key technique is real-time THz-TDS line imaging. We have achieved this with 2D-ST THz imaging based on a combination of non-collinear electro-optical time-to-space conversion [8] and line focusing of a THz beam [7]. The experimental setup is shown in Fig. 1. Because the setup is described in detail elsewhere [9], only a brief description of it is given here. A femtosecond Ti:sapphire regenerative amplifier (pulse energy = 550 μ J, pulse duration = 150 fs, central wavelength = 800 nm, repetition rate = 1 kHz) was employed to generate and detect THz pulses (not shown in Fig. 1). An intense THz pulse was generated via optical rectification of the pump light in a 1 mm-thick, 25 mm-square <110> ZnTe crystal (ZnTe1). The THz pulse passing through the sample and the probe light were non-collinearly incident on another 1 mm-thick, 25 mm-square <110> ZnTe crystal (ZnTe2) for 2D free-space electro-optical sampling (2D-FSEOS). This resulted in non-collinear 2D-FSEOS for the time-to-space conversion of the pulsed THz electric field [8]. The electric field of the pulsed THz temporal waveform induces a spatial birefringence distribution in ZnTe2. Since the birefringence changes the polarization state of the probe beam, the spatial distribution of the polarization state reflects the temporal waveform of the pulsed THz electric field. The spatial polarization distribution of the probe beam was converted into a spatial intensity distribution using two crossed polarizers (P and A). The resulting spatial intensity distribution was imaged onto a high-speed complementary metal-oxide semiconductor (CMOS) camera (sensor area = 4.6 mm $\times$ 4.6 mm, resolution = 232 $\times$ 232 pixels, frame rate = 1000 frames per second (fps), digital output = 12 bit) with a lens (L2). As a result, the temporal waveform of the pulsed THz electric field was expanded along the horizontal dimension of the CMOS camera. On the other hand, the vertical dimension of the CMOS camera was used for 1D transverse imaging of the sample. To this end, the THz beam was line-focused onto the sample with a THz cylindrical lens (CL1, $f = 50$ mm), resulting in a line of illumination along the vertical direction of the sample. The THz line image of the sample was imaged onto ZnTe2 by a combination of a THz plano-convex lens (L1, $f = 100$ mm) and a THz cylindrical lens (CL2, $f = 100$ mm). In this way, a 2D-ST THz image was acquired at a frame rate of 500 Hz by the CMOS camera working in the dynamic subtraction mode [10], in which the temporal profile of the THz pulse and the THz line image was expanded along the horizontal and vertical dimensions, respectively. A THz-TDS line image of the sample along the THz focal line was obtained by a fast Fourier transform (FFT) of the time dimension in the 2D-ST THz image. Finally, consecutive THz-TDS line images were acquired while the sample was continuously moved across the THz

focal line using a translation stage, and the individual line images were then pieced together to construct a 2D THz-TDS image. We adjusted the image acquisition rate and the sample moving speed in order to capture the THz-TDS line images at intervals of 100 μm .

Fig. 1. Experimental setup. ZnTe1 and ZnTe2: zinc telluride crystals; CL1 and CL2: THz cylindrical lenses; L1: THz plano-convex lens; P: polarizer; A: analyzer; L2: plano-convex lens.

3. Results

3.1 Basic performance

Figure 2(a) shows a THz spectral line image of power in the absence of a sample (image acquisition rate = 10 line/s), in which the frequency profile and the line image of the pulsed THz radiation are expanded along the horizontal and vertical dimensions, respectively. The frequency scale was calibrated using a metal hole array as a band-pass filter in the THz region [9]. The frequency resolution was 25.5 GHz because the temporal window of the 2D-ST THz image obtained by the present system was 39.2 ps (not shown). From the image in Fig. 2(a), the length of the THz focal line on the sample was 15 mm, whereas the width of the focal line depended on the frequency, as discussed in the previous paper [9]. The uneven profile of the THz power along the vertical direction was caused by the Gaussian spatial distribution of the THz power across the beam cross-section. On the other hand, the horizontally scratched pattern observed on the image was mainly due to uneven detection sensitivity of ZnTe2 and/or scattering of the probe light, caused by defects and impurities in ZnTe2. The red line in Fig. 2(b) shows the logarithmic-scale spectrum of the THz power extracted along line x in Fig. 2(a). Several absorption lines caused by atmospheric water vapor were clearly observed as dips in the signal spectrum (see arrows). For comparison, a power spectrum measured in the absence of the THz beam (noise spectrum) is shown as the blue line in Fig. 2(b). The decrease in the noise spectrum around 1 THz is mainly due to the uneven spatial distributions of inherent birefringence in ZnTe2 and/or the probe beam intensity. When dynamic range (DR) is defined as the ratio of the power spectrum in the presence of the THz beam to that in the absence of the THz beam [11], the frequency dependence of DR in the present system is shown as the red line in Fig. 2(c). On the other hand, the frequency dependence of the signal-to-noise ratio (SNR), defined as the ratio of the mean to standard deviation in ten repeated measurements of the THz power spectrum, is shown as the red line in Fig. 2(d). For comparison, frequency profiles of DR and SNR when the image acquisition rate was set to 1 line/s are shown as the blue lines in Figs. 2(c) and 2(d). We consider that the sharp spike at

0.75 THz in the blue line of SNR was caused by air disturbance in the beam path of the THz pulse because the frequency of the sharp peak coincides with the absorption line of water vapor at 0.75 THz. These results indicate that rapid spectral imaging can be performed within a spectral range of 2 THz with a combination of single-shot measurement [8] and dynamic subtraction detection [10].

Fig. 2. Spectral characteristics in the absence of a sample. (a) THz spectral line images of power and (b) power spectrum along line x (image acquisition rate = 10 line/s). Frequency dependence of (c) dynamic range and (d) signal-to-noise ratio.

3.2 Pharmaceutical tablets

Quality control of pharmaceutical tablets is one promising application of THz spectral imaging because many medicines show sharp spectral fingerprints in the THz region resulting from their crystal structures [1,2,5]. Also, changes in their crystallinity, such as crystal polymorphism, are sensitively reflected in the THz spectral fingerprints [1]. Furthermore, THz spectral imaging enables even screening of hidden samples [2]. These characteristics are significant advantages compared with traditional spectroscopic analysis, such as infrared spectroscopy. However, the scope of this application does not include total inspection in a manufacturing process because the imaging rate in conventional point-scanning THz-TDS imaging systems is quite low. Here, we demonstrate the potential of our real-time THz color scanner for rapid nondestructive classification of pharmaceutical tablets moving on a translation stage.

We prepared three different sugar tablets (D-glucose, D-maltose, and lactose powders mixed with polyethylene powder) and one reference tablet (polyethylene powder) with identical shapes (diameter = 10 mm and thickness = 1 mm), as shown in Fig. 3(a). Table 1 shows the chemical compositions of the tablets. Before performing THz spectral imaging of the tablet samples with the THz color scanner, we measured their THz absorption spectra using a commercial THz-TDS system (Otsuka Electronics Co., Ltd., TR-1000). Figure 3(b) shows a comparison of the absorption spectra of the three sugar tablets. Each absorption spectrum was calculated from THz power spectra of the sugar tablet and the reference tablet.

The three sugar tablets exhibited characteristic spectral fingerprints of THz absorption. The frequencies of the THz spectral fingerprints for each tablet are also summarized in Table 1. Thus, it should be possible to classify these pharmaceutical tablets based on their THz spectral fingerprints even though they have a similar appearance.

Fig. 3. (a) Photograph of tablet samples and sample holder concealed in a paper envelope. (b) Absorption spectra of D-glucose, D-maltose, and lactose tablets.

Table 1. Chemical composition of four tablet samples and their THz spectral fingerprints

Tablet sample	Chemical composition				THz spectral fingerprint (THz)
	Polyethylene	D-glucose	D-maltose	Lactose	
D-glucose	75	25	0	0	1.44
D-maltose	75	0	25	0	1.10, 1.61
Lactose	50	0	0	50	0.525, 1.37
Reference	75	0	0	0	-

To measure these four tablet samples with the THz color scanner, we set them in a sample holder made of a polyethylene plate, as shown in Fig. 3(a). The tablet samples placed in the sample holder were concealed in a paper envelope to simulate an application for screening of a hidden object [2]. Spectral images of THz power for all four tablets were acquired within 60 s at an image acquisition rate of 10 line/s while the tablets were moved at a rate of 1 mm/s using a translation stage. The resulting scanned areas of the samples were 20 mm in height by 60 mm in width, which corresponds to an image with 232 pixels by 600 pixels. A pixel rate of 2,320 pixel/s was achieved in this demonstration. Spectral images of THz power transmittance were constructed by calculating the ratio of the THz power images with and without the sample at each THz frequency. Although we acquired 116 consecutive spectral images of THz transmittance of the sample with a frequency resolution of 25.5 GHz ranging from 0 to 2.98 THz, Fig. 4 shows THz power transmittance images of the samples at four different frequencies appearing in the THz spectral fingerprints shown in Table 1: 0.511 THz for the lactose, 1.073 THz for the D-maltose, 1.405 THz for the D-glucose and lactose, and 1.609 THz for the D-maltose. Also, consecutive spectral images of THz power transmittance are shown as a movie in Media 1. The blue color in these images corresponds to a low transmittance and therefore to a high absorption. Low-transmittance images appeared at 0.511 and 1.405 THz for the first tablet, at 1.073 and 1.609 THz for the second tablet, and at 1.405 THz for the fourth tablet, respectively. The third tablet did not indicate low-transmittance images at any frequencies. From these results, we can determine that the first, second, third, and fourth samples are the lactose, D-maltose, reference, and D-glucose tablets, respectively. The reason why the images at the higher frequencies were less clear is that the absorbance of the sugar samples increased as the frequency increased [see Fig. 3(b)]. Another reason is the insufficient DR of the THz power at the higher frequencies, as shown in Fig. 2(c). On the other hand, spectral images at specific frequencies in Fig. 4 and Media 1 indicated the

transmittance over 1 in the background area around the sample. We consider that the reason for too high transmittance is that scattering of THz wave enhanced at edges of the sample and/or sample holder disturbs these images.

Fig. 4. THz spectral images of transmittance in four tablet samples (Media 1). The scanned areas of the samples were 20 mm in height by 60 mm in width (image acquisition time = 60 sec). Each image consists of 232 by 600 pixels.

3.3 Human tooth

An interesting application of THz spectral imaging is in functional imaging of biological tissues. However, strong THz absorption caused by liquid water [12] has often been a limitation in biological THz imaging. For example, since the high water content in soft tissues has prevented the measurement of fresh specimens, fixed [13] or frozen [14] specimens are often measured. On the other hand, hard tissues, such as bone, tooth, and hair, have relatively low water content, making it easier to apply THz imaging to these materials. Also, their crystal structure may be reflected in characteristic spectral fingerprints in the THz region because THz spectral fingerprints are common to many crystalline materials [see Fig. 3(b)]. However, to the best of our knowledge, THz spectral imaging of hard tissues has not been demonstrated yet, although there is a report on cross-sectional imaging of a human tooth

based on THz tomography [15]. Therefore, we performed THz spectral imaging of a human tooth with the real-time THz color scanner.

We used a human tooth as a sample to investigate the potential of the THz color scanner for biological imaging of hard tissues. We sliced a human molar (extracted from a subject in their forties) with a tooth cutter in its longitudinal direction (thickness = 0.5 mm). To remove the influence of THz absorption caused by water, the sliced tooth specimen was dried for 2 hours with a heater (setting temperature = 60 °C) before starting the measurement. A photograph of the sliced tooth specimen is shown in Fig. 5(a). Figure 5(b) shows typical spectral images of THz power transmittance at eight different frequencies (image size = 20 mm in height by 20 mm in width, number of pixels = 232×200 , image acquisition time = 200 s, image acquisition rate = 1 line/s, pixel rate = 232 pixel/s). Also, consecutive spectral images of THz power transmittance are shown as a movie in [Media 2](#). The characteristic distribution of the THz power transmittance was observable, depending on the sample position. Furthermore, the spatial distribution of the transmittance changed with respect to the THz frequency. The outer portion of the specimen absorbed the THz waves more strongly than the inner portion at the lower THz frequency [see upper row in Fig. 5(b)], whereas there were no large differences in the THz transmittance between the inner and outer portions at the higher THz frequency [see lower row in Fig. 5(b)].

Fig. 5. (a) Photograph of a sliced tooth sample. (b) THz spectral images of transmittance in the tooth sample ([Media 2](#)). The scanned areas of the samples were 20 mm in height by 20 mm in width (image acquisition time = 200 s). Each image consists of 232 by 200 pixels.

To investigate the difference in THz power transmittance with respect to the tissue components, from [Media 2](#), we extracted THz transmittance spectra of power at six different

sample positions shown in Fig. 5(a). Figure 6 shows a comparison of the THz power transmittance spectra. The enamel portions [positions (A) and (B)] showed a relatively similar spectral shape, having the transmittance peak at 0.25 THz (see red arrow), whereas the dentin portions [positions (C)-(F)] showed varying spectral shape depending on the position. The primary dentin portions [positions (C) and (D)] showed a transmittance peak at 0.55 THz (see blue arrow), whereas the secondary dentin portion [position (E)] had a transmittance peak at 0.2 THz (see green arrow). Furthermore, the boundary region between the primary dentin and secondary dentin [position (F)] showed a mixture of their spectra, having two transmittance peaks at 0.2 and 0.55 THz (see blue and green arrows).

Fig. 6. Comparison of THz transmittance spectra among six different positions in the tooth sample.

Here, we consider the structure of the dental tissue. The tooth is mainly composed of hydroxyapatite (HAP), which contains Ca^{2+} cations and forms a three-dimensional crystal structure. This structure is distributed among two different layers, the outer layer (enamel) and the inner layer (dentin). By weight, the HAP content in the enamel is as high as 96%, making it the hardest and most mineralized tissue in the body, and it plays an important role as a protective layer to cover the dentin. Conversely, the dentin contains collagen (20% content) and water (10% content) in addition to HAP (70% content). It is a harder tissue than bone but softer than enamel. Furthermore, dentin is categorized into primary and secondary dentins. Primary dentin is the outermost layer of dentin and borders the enamel, and its formation is

completed before the tooth has erupted. Conversely, secondary dentin is a layer of dentin produced after the formation of the tooth root is completed, and is formed by a biological response to stimulation from occlusion. This dentin grows much more slowly than primary dentin. The growth of this dentin causes the decrease in the size of the pulp chamber with age, as shown in position (E) in Fig. 5(a).

Next, based on the above knowledge, let us discuss the reason for the difference in the THz transmittance spectra between the enamel and dentin portions. The difference in chemical composition between the enamel and dentin is the collagen content. THz absorption of collagen monotonically increases with increasing frequency [16]. However, it is difficult to find such a tendency from a comparison of the THz transmittance spectra in Fig. 6. Conversely, from the viewpoint of crystal structure, the enamel has a crystal structure composed of enamel rods, which are tightly packed masses of HAP crystals in an organized pattern, whereas the dentin consists of dentinal tubules, which contain fluid and cellular structures. Due to the structural difference, the degree of crystallization in the dentin is lower than that in the enamel. The transmittance peak at 0.25 THz in positions (A) and (B) may reflect the characteristic crystal structure of enamel rods in the enamel.

We next consider the reason for the difference in the THz transmittance spectra between the primary and secondary dentin portions from the viewpoint of the crystal structure because there is little difference in chemical composition between them. The primary dentin has a maturely organized structure and a regular pattern of dentinal tubules, which radiate outward through the dentin from the pulp to the exterior cementum or enamel border. On the other hand, the secondary dentin has an immaturely organized structure and an irregular pattern of dentinal tubules because the growth is still in progress. One possible reason for the spectral features in Fig. 6 is that the physical structures in the sample, such as crystal structure in the tooth, cause scattering at specific frequencies [17]. We consider that size effects of the crystal structure depending on the structural maturity of the dentinal tubules contributes to the difference in the THz transmittance peak between the primary and secondary dentins. Further examination of different types of teeth is necessary in order to verify that the observed spectral features are genuine. Work is in progress to investigate the changes of these spectral features when the crystal structure is chemically or physically modified.

3.4 Human hair

Water content in hair plays an important role in determining its cosmetic, mechanical, and electrical properties, such as suppleness, luster, feeling, tensile strength, and amount of static electricity. Hair usually absorbs atmospheric water vapor depending on the humidity, and the typical water content is 10-15% in a standard room environment and 30-35% immediately after shampooing. Since damaged hair loses the ability to hold water, decreasing the water content, the water content is an important indicator of the degree of damage of hair. There is a considerable need for non-contact measurement of hair water content in the field of hair cosmetics. Reflective near-infrared spectroscopy has been employed for this purpose due to the strong absorption of infrared light, but both absorption and scattering of the incident light contribute the observed signal [18]. A potential electromagnetic wave for the measurement of hair water content is THz radiation because of the strong absorption caused by liquid water [12] and insensitivity to scattering. However, measurement of water content in hair using THz radiation has not been reported yet, although there are a few reports on sensitive measurement of water content in plant leaf [19], dry food [20], and paper [21]. Therefore, we attempted to demonstrate THz spectral imaging of human hair with the real-time THz color scanner.

We prepared two kinds of human hair bundles (approximate diameter = a few hundred μm): one was a bundle of wet hairs after sufficiently moistening them with water and quickly wiping off excess moisture with a towel, and the other was a bundle of dry hairs. We compared the changes in the THz spectral images of the two kinds of hair bundles when they were left in air for 90 minutes, because only the drying process of the wet hair is accelerated by evaporation of the water. Since the transmittance peak of the hair bundle appeared at 0.26 THz (result not shown), we chose this frequency for observation. Figure 7 and [Media 3](#) show

the temporal evolution of the THz power transmittance image at 0.26 THz with respect to elapsed time (image size = 20 mm in height by 20 mm in width, number of pixels = 232 × 200, image acquisition time = 200 s, image acquisition rate = 1 line/s, pixel rate = 232 pixel/s), in which the left vertical-line image (see blue arrow) and the right one (see red arrow) respectively indicate bundles of wet hairs and dry ones. In the case of the bundle of wet hair, the THz power transmittance increased over time, and its temporal variation stopped after 40 minutes, indicating completion of the drying process. In contrast, the bundle of dry hairs showed no significant change in the THz power transmittance, implying that the water vapor in the atmosphere hardly influences the water content in the dry hair. In this way, the real-time THz color scanner will be a powerful tool for monitoring dynamic changes and visualizing the spatial distribution of the water content, which are technically difficult in conventional point-scanning THz-TDS imaging systems due to the slow image acquisition time.

Fig. 7. Temporal change of THz transmittance image in two bundles of wet (blue arrow) and dry (red arrow) hairs at 0.26 THz (Media 3). The scanned areas of the samples were 20 mm in height by 20 mm in width (image acquisition time = 200 s). Each image consists of 232 by 200 pixels.

Next, we estimated the water content in the bundle of wet hairs during the drying process. The estimated area is the center portion of the wet hair bundle, which is enclosed with the white dotted line in the THz transmittance image at 0 min in Fig. 7 (size = 13 mm height by 1 mm width). The red line in Fig. 8 shows the temporal change in the mean THz transmittance of this area with respect to elapsed time, which was extracted from Fig. 7. The THz transmittance changed from 0.51 to 0.71 during the first 40 minutes, after which it hardly changed, implying completion of the drying process. We here assumed that the water mainly contributes to THz absorption in the wet hair bundle because the fully dry hair is a non-polar material which the THz wave penetrates well. Under this assumption, the THz transmittance (T) and percentage of water content (d) in the bundle are given by

$$T(\nu) = \exp \left[-\alpha(\nu) L_{\text{sample}} \frac{d}{100} \right], \quad (1)$$

$$d = -\frac{100}{\alpha(\nu) L_{\text{sample}}} \ln [T(\nu)], \quad (2)$$

where $\alpha(\nu)$ is the absorption coefficient of liquid water, and L_{sample} is the effective thickness of the sample. Assuming that $\alpha(\nu)$ is 130 cm⁻¹ at 0.26 THz [12] and L_{sample} is 0.2 mm, we estimated the water content from Eqs. (1) and (2) as the blue line in Fig. 8, indicating that the water content decreased from 25% to 13% during the drying process. Since the detection limit of the water content (d_{limit}) is limited by the relation between power level of THz radiation

after passing through a sample and fluctuation of THz power in repeated measurements, namely, SNR , d_{limit} is given by

$$d_{lim}(v) = -\frac{100}{\alpha(v)L_{sample}} \ln \left[1 - \frac{1}{SNR(v)} \right]. \quad (3)$$

Since SNR at the image acquisition rate of 1 line/s was 31 at 0.26 THz [see Fig. 2(d)], d_{limit} in this demonstration was 1.3% based on Eq. (3). In this way, our THz color scanner can be used for sensitive measurement of the water content in human hairs.

Fig. 8. Temporal change of THz power transmittance at 0.26 THz and estimated water content in a bundle of wet hairs.

4. Conclusions

We demonstrated three possible applications of a real-time THz color scanner in the biomedical field.

In the first application, imaging of pharmaceutical tablets, 116 consecutive THz-TDS images of four tablets with an image size of 20 mm in height by 60 mm in width (232 pixels by 600 pixels) were acquired within only 60 s and were used for material characterization of unknown tablets based on their THz spectral fingerprints. Although the sample speed of 1 mm/s in this application is much fast than that available in conventional point-scanning THz-TDS imaging systems, further speed-up will be required to expand the application scope of the THz color scanner more widely to manufacturing processes. For example, the maximum moving speed of a conveyor belt can reach 1,000 mm/s. If the sample speed is increased to 10 mm/s while keeping the same image acquisition rate (= 10 line/s), the number of horizontal pixels in the spectral image is reduced to 10%, namely 60 pixels, although the DR and SNR are maintained at the same level. When the sample moving at a speed of 1,000 mm/s is measured at the maximum image acquisition rate in the present system (= 500 line/s), THz-TDS line-images can be captured at intervals of 2 mm. To achieve this application at the maximum image acquisition rate, DR and SNR have to be further enhanced by highly efficient generation of THz pulse, discussed later.

In the second application, imaging of a sliced human tooth, the THz transmittance images significantly changed depending on the sample position and THz frequency. We consider that such local and spectral dependence of the THz transmittance is mainly related to the crystal structure of the dental tissues. Therefore, the THz color scanner provides a potential indicator of the crystallinity of mineralized hard tissues and is expected to become a powerful tool to clarify the growth mechanism of the initial stages of caries or osteoporosis.

In the third application, sensitive measurement of the water content of human hair was performed by exploiting the strong THz absorption caused by liquid water. The drying

process of wet hairs was clearly visualized by the temporal evolution of the THz transmittance image. The THz color scanner is also promising in the field of hair cosmetics.

While these demonstrations showed the high potential of the THz color scanner for practical applications in the biomedical field, they revealed technical problems that need to be solved. The THz transmittance images obtained at higher frequencies were less clear than those obtained at lower frequencies. One reason for this is the insufficient DR at higher frequencies, as shown in Fig. 2(c). Also, although many THz spectral fingerprints are located within the 3 THz band [1–5], the presented system cannot fully cover them. Furthermore, when the THz color scanner is applied to faster moving objects or more absorbent materials, higher DR will be required. On the other hand, the SNR should be further improved to make quantitative analysis more precise. Recently, highly efficient generation of THz pulses has been proposed based on Cherenkov radiation with tilted pulse-front excitation [22] and laser induced plasma in air [23]. Work is in progress to increase DR, SNR, and/or the spectral bandwidth in a real-time THz color scanner using these methods.

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