Proceedings of 2008 International Symposium on Electrical Insulating Materials, September 7-11, 2008, Yokkaichi, Mie, Japan



# Terahertz imaging for water content measurement

H. Zhang*, K. Mitobe and N.Yoshimura
Department of Electric and Electronic Engineering Faculty of Engineering and Resource Science, Akita University,
1-1, Tegata Gakuencho, Akita City 010-8502, Japan
* E-mail: hozeliz@hotmail.com

**Abstract:** We proposed a quantitative method to calculate water content of the thin materials by terahertz (THz) imaging. First, we constructed a THz imaging system by using a Tunnel injection Transit Time (TUNNETT) THz wave generator with automatic scanning control. Images of the plant leaves under different conditions were taken with the THz imaging system. We have introduced an algorithm with the attenuation law of Lambert-Beer to calculate the water contents from the THz imaging. To verify the accuracy of this method, we also took images of a piece of filter paper with different content of water. Comparing the calculated result with the measured value by the electronic balance showed that our method has a good possibility to measure the water content of the relative thin materials with non-contact and non-invasive method from the THz imaging.

## INTRODUCTION

The terahertz wave regions lie between the infrared and the microwave. It has been a well unexplored gap in the electromagnetic spectrum for a long time due to difficulties in generation and detection of the wave. In recent years as THz wave generators and detectors have become not only available but also affordable and easier to use, THz technology has attracted a great deal of interest in many important applications and technologies.[1-8] It has the unique properties: the ability to penetrate different types of materials, such as, plastic and cloth; non-invasive nature.

It is extremely important to know the water state of the plant in cultivating and managing. And recently, a specific fruit color, tannin, flavor, etc. are drawn out by intentionally adjusting the moisture of the plant for a certain fruit.[9-11] Plant cells cease to function normally when they are more or less saturated with water. At moderate levels of water stress, they cease to expand, whereas, when exposed to severe stress, the cell division process may be halted. In fact, plant water status and water transport dynamics of higher plants are interesting problems that can be perfectly addressed with terahertz spectroscopy. When a detached leaf dries out, its relative water content reduces at an exponential rate and its thickness changes. This drying process can be conveniently monitored by performing transmission experiments using THz waves.[12] In the THz region, since the absorption to water is large and the influence of the dispersion to biological tissue is low for the wave length is long, it can obtain transmitted images such as plant leaf with non-destruction, inform the circumstances of the moisture. It can be used for continuous estimate of water content and capacity in plant leaves.

Analysis of spectroscopic measurements of leaf water content at terahertz frequencies using linear transforms was reported in other paper.[10] Again absorption coefficient in terahertz range of water was measured by using the wedge-cell technique.[3] They provided a unified framework theoretically, but they did not confirm their methods with practical measurements. In their analysis, series THz spectrum is necessary and thus concrete calculation of water content was yet not reported. Here, in the condition of individual THz wave, we have applied the attenuation law of Lambert-Beer to analyze the relation of the water content weight and the THz transmitted intensity integrating the infinitesimal parts of the sample's structure to calculate the water content of objects from THz imaging. Thus we have succeeded to estimate the distribution of the water status of a plant leaf, and qualitative evaluating of plant leaf water content. By using the THz wave, we think it is an effective technique for diagnosing the moisture state such as the cultivation plants. We can judge the time and the amount adequately if a simple technique for diagnosing the moisture stress level of the plant can be developed. In the other hand, the plants need certain nutrients for proper growth. The lack of these nutrients will cause some disease to the plant, such as leaf chlorosis, yellowing and necrosis. Air pollution, herbicide etc. can cause some injury to the plant. And, then the distribution of water content will be changed. So it can be used to detect the disease by THz imaging, because the distribution of water content is noticeably different in a leaf with disease.

## TERAHERTZ IMAGING SYSTEM:

The experimental setup is shown in Fig.1. It is constructed with a THz wave generator, imaging optical system, the detector, the lock-in amplifier and a personal computer. For the THz imaging system, there are some important factors: a powerful and compact THz generator and a high sensitivity and low noise THz detector.

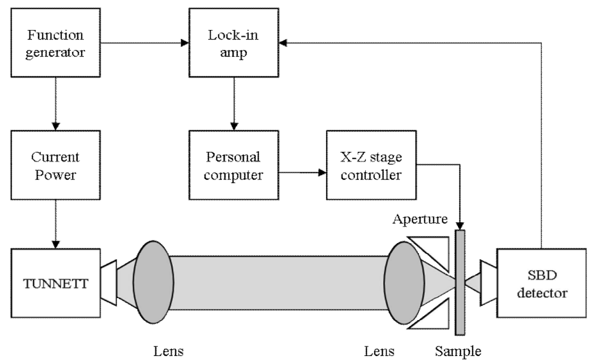


Fig. 1. Experimental setup for THz imaging.

Using a TUNNETT oscillator which uses the tunnel effect for the THz wave illuminant, the TUNNETT diode[13-15] which oscillates by letting flow electric current the THz wave is discharged to the free space by the horn antenna.

A pair of polyethylene lens is used to collimate and focus the generated THz beam. After condensing the wave with the polyethylene lens (focal length 30 mm), it is irradiated to the sample through the aperture (opening diameter 1.0 mm). The THz wave which transmitted to the sample was detected by the detector SBD (the Schottky barrier diode) which is possible to operate at room temperature. The signal is read by a lock-in amplifier from the detector at 4 kHz rate and is feed into a computer. The frequency is 0.189THz (λ: about 1.58 mm).

The sample is placed in the middle of the aperture and the detector. Two crossed motorized translation stage are used to move the object in the x-z plane perpendicular to the beam. At each x-z position, the transmitted intensity is recorded. The time used for imaging depends on the time constant of the lock-in amplifier, the number of the spatial points, and the number of sampling points. The time constant and time constant rate is 3 and 5 ms respectively.

**EXPERIMENTAL METHOD:**

We also confirmed the change of the image of the plant leaf under different conditions of water content and the filter paper (0.15mm). In order to estimate the water distribution in the plant leaf and the filter paper, 4 images were taken at room temperature at the frequency of 0.189THz. The sample can be penetrated by THz wave for the THz imaging system. We selected a spinach leaf for its low thickness and smaller water content. Since the THz imaging system uses scanning method and need longer time in one operation, in order to avoid the vaporization of the leaf and the filter paper (Fig.2), we pasted samples in the middle of two layers of wrap (thickness 0.013 mm) and locked by a holder. In this experiment we used a scanning THz imaging device using TUNNET diode in transmission method. The scanning area was 42×30 mm for the spinach leaf and 24×24 mm to the filter paper and it moved in 0.2 mm steps, which corresponded to 211×151=31860 and

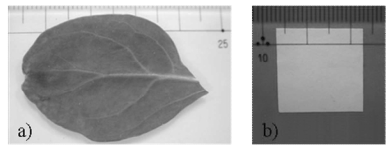


Fig. 2. The visible optical image of the spinach (a) and the filter paper (b).

121×121=14641 pixels respectively. We calculated the water content of the sample from the transmission data of the THz wave under different conditions and measured weight by an electronic balance AB204-S (Mettler-Toledo GmbH, Laboratory & Weighing Technologies).

As the detected signal data is in voltage value, for imaging of sample and calculating water distribution and content, the output voltage data detected by using the THz imaging system was processed with the MatLab software. For the imaging of sample, we assumed that the maximum value of detected voltage is equal to 100% THz wave density. Then we regarded the quotient of other data with the maximum value as

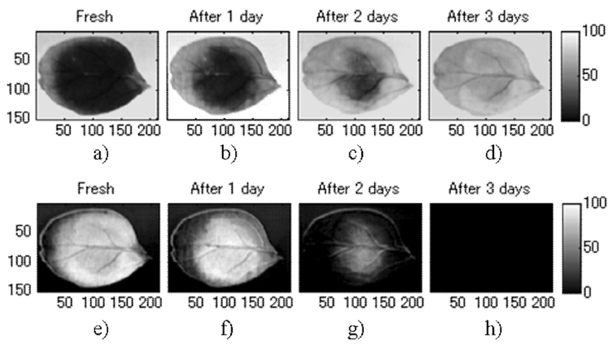


Fig. 3. THz images of a spinach leaf in different times: (a) fresh spinach THz image, natural dried after (b) 1 day, (c) 2days, (d) 3days image. The bar shows THz transmission density. The number in the x,y axis is the munber of pixel, each pixel is 0.2 mm. The processed THz images: (e)~(h). Reversed the acquired data, removed the absorption portion of the plant leaf itself and became into comprehensible images. The bar shows the water content percentage of the leaf.

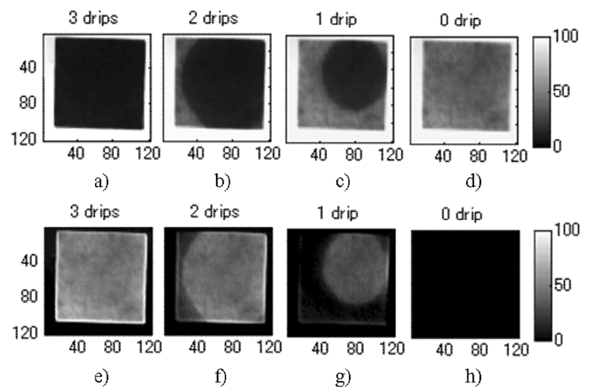


Fig. 4. THz images of a filter paper in different water content: (a), 3 drips (b) 2drips, (c) 1 drip water, and (d)no water THz image. The bar shows THz transmission density. The number in the x,y axis is the munber of pixel, each pixel is 0.2 mm. The processed THz images of the filter paper: (e)~(h). Reversed the acquired data, removed the absorption portion of the cotton itself and became into comprehensible images. The bar shows the water content percentage of the filter paper.

the relative density shown in Fig.3 (a ~ d) and Fig.4 (a ~ d). The black and the white region showed THz wave transmission is 0% and 100% respectively. For the imaging of water content and distribution, as it is the contrary relation of the transmission and water content, we reversed the acquired data into comprehensible images. First, we had picked out the maximum and minimum values of voltage data, new data were reformed by the difference of each data from the sum of the maximum and minimum data in percentage showing in Fig.3 (e ~ h) and Fig.4 (e ~ h). The white and the black region showed water content is 0% and 100% respectively.

## RESULTS AND DISCUSSION:

The THz images of the spinach leaf which were processed by MatLab software are shown in Fig.3 (e ~ h). Because of the absorption of THz wave to water is stronger than the leaf tissue, and the water in the veins for fresh leaf is more than other part, the leaf outline and the veins are seen clearly in the Fig.3 (a) from the THz imaging. The white regions of the images reflected the larger absorption of THz wave where as, the black region reflects the lower absorption of THz. The leaf was kept at room temperature and THz images were taken up to 4 days. The images were processed as described in section experimental method and shown in Fig.3 (a) ~ (d). From the figures, we find that the black range reduced by degrees. It means that the water content of the leaf decreased little by little. After 3 days, the THz image of the leaf shows a little sign of water content in it. However, we considered this image as the spinach leaf without water (Fig.3 (d)).

The THz images of the filter paper are shown in Fig.4 (a) ~ (d). At first, the THz images were taken with no water, then with 1 drip, 2drips and 3drips of water into the filter paper (the weight of one drip's water is 0.008g). From the figures, we find that the black range increased by degrees with increasing the water.

It is assumed that the thin sample which can be transmitted by the THz wave is made of gathering of smaller cube. The attenuation law of Lambert-Beer can apply to it,

$$I(v)_i = I_0(v)_i\, exp(\quad k(v)c_i l_i) \qquad (1)$$

where $I_0(v)_i$ and $I(v)_i$ are the power of THz wave strength of incident before and after, respectively, $k(v)$ is the absorption coefficient of the sample, $c_i$ is the water content concentration, and $l_i$ is thickness of the minute cube in the sample.

The scanning step of the THz imaging system is $s_i \times s_i$. If we consider the smaller cube's length is $s_i$, and then the smaller cube's volume is $s_i \times s_i \times l_i$. From eq. (1) the water content weight of one of the minute cube in the sample is

$$M_i = \frac{s_i^{\,2}}{k(v)} ln \frac{I_0(v)_i}{I(v)_i} \qquad (2)$$

then the equation of water content weight of the gathering of minute cube becomes to,

$$M = \Sigma M_i = \Sigma \frac{s_i^{\,2}}{k(v)} ln \frac{I_0(v)_i}{I(v)_i} \qquad (3)$$

From eq.(3) we can find that the water content measured with THz wave is only related with the power of THz wave transmission of before ($I_0\ (v)_i$) and after ($I(v)_i$), the scanning step ($s_i$) of the THz imaging system and the absorption coefficient ($k(v)$) in the typical frequency. We can calculate the water content in the plant leaf if we know these parameters. Certainly, the volume of a leaf reduces when the leaf gets dry. It is clear from eq.(3) that the calculation method is dependant only on the area of the object. The volume reduction due to the dry process is very small and hence negligible for this calculation. For example, the length of the leaf decreased 1 mm during the experimental period (reduced 49 mm from 50 mm). So, from our calculation, the scanning step ($s_i$=0.2mm) reduction become to 0.4% (1/250). And the smaller cube area reduction is only 0.16%. So, after considering the volume reduction of the leaf, the water content reduced only 0.16% from the results of our calculation method. If the scanning step is smaller, the reduction is lower. From the result we find that the influence with volume reduction is very low to measurement water content. In our method we are assuming very small cubes of volume for the calculation. It can be assumed that even for larger volume reduction of leaf has a very little affect on the minute cubes. So, our method can also be applicable for big leaf as well as large volume.

The THz imaging contains the information of the absorption by the plant leaf and the water in it. In order to calculate the water content of the plant leaf, we must remove the absorption amount of the leaf. We assumed that the water content became zero in the leaf after four days. Because the itself absorption is same in the condition of different water content, so the pure water content is the difference of the THz imaging from the third day's image with the other day's images. After removing the absorption portion of the plant leaf, the distribution of the water content in the plant leaf is shown in Fig.3 (e) ~ (h). Using formula (3), we calculated the water content in the spinach leaf with the different conditions, the water content is corresponding 0.0205, 0.0116, 0.0039 and 0 g respectively. Again we measured the weight of the leaf with an electric balance each time before starting THz imaging.

To evaluate the accuracy of this calculation method, we compared the measured value and calculated value of water content in the plant leaf. The results can be found in Fig.5 (a). We can see that the measured values by the electronic balance and the calculated values of water contents were quite similar. The two values' deviation for fresh leaf is only 1.47%. It shows that we can analysis the water state of the plant in cultivating and managing by the THz imaging.

As the same processing method, after removing the

absorption portion of the filter paper, the distribution of the water content in the filter paper is shown in Fig. 4 (e) ~ (h). We also confirmed the relation of measured value and calculated value of water content of the filter paper shown in Fig. 5(b). It also proves the validity of our method.

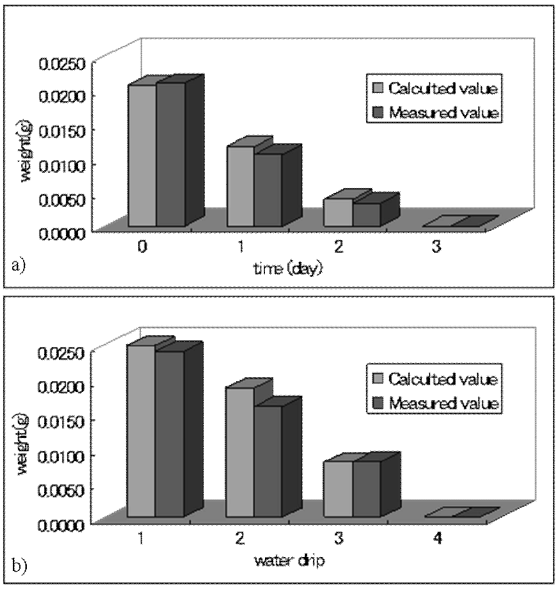


Fig. 5. The calculated and measured weight of water in the spinach leaf (a) and the filter paper (b).

## CONCLUSION

THz imaging is a new technique in bioscience, agriculture, astronomy etc. There are a lot of possibilities in this technology. In this experiment, we proposed a quantitative method to evaluate water content of the plant leaf by the THz imaging. We used the system to examine the water content of the spinach leaf and the filter paper, and studied the relationship of the water content and transmitted imaging of the THz wave. From THz imaging, water change and water distribution in the plant leaf can be verified. We also calculated the weight of water in leaf. In addition, from comparing the calculated result and measured value demonstrated that the THz imaging has a good possibility to measure the water content of plant leaf. Thus the water content and distribution can simply be measured by this new technique with non-contact and non-invasion.

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