Quantitative evaluation of fiber structure by using coherent terahertz wave

著者	Chao Tang, Tadao Tanabe, Shintaro Yudate, Yutaka Oyama
journal or publication title	Composites Part B: Engineering
volume	159
page range	1-3
year	2018-08-31
URL	http://hdl.handle.net/10097/00128830

doi: 10.1016/j.compositesb.2018.08.135

Composites Part B xxx (2018) xxx-xxx

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com

Quantitative evaluation of fiber structure by using coherent terahertz wave

Chao Tang*, Tadao Tanabe, Shitaro Yudate, Yutaka Oyama

Department of Materials Science, Graduate School of Engineering, Tohoku University, Aramaki-Aza Aoba 6-6-11-1021, Sendai, 980-8579, Japan

ARTICLE INFO

ABSTRACT

The structures of fiber, including the distance between fibers and the arrangement direction of fibers, were quantitatively investigated using coherent terahertz (THz) wave. Composite fibers with periodically arranged 57% silk and 43% nylon are measured, then the specific absorption spectra due to intermolecular vibration and interference effect are observed in terahertz frequency region. It is shown that, not only the period and direction of woven but also the type of material could be specified by the THz spectroscopy. This study enlightens a novel method for fiber nondestructive inspection beyond microscopy imaging, which has potential to be applied in quality control, infrastructure disaster prevention.

1. Introduction

Woven fabrics are ubiquitous in our daily life. The silks and cottons can be seen in clothes, papers, and fiber composite materials like fiber reinforced plastic (FRP) are widely applied in conveyance (cars, jet airplanes, etc.) [1], and infrastructures (transportation facilities, transmission facilities, etc.) [2]. To control the quality of daily necessities and ensure the infrastructures safety, it is significant to contrive an effective non-destructive method to confirm the health condition of woven fiber structure.

The properties of fabric depend on the material of fiber and how the fiber knitted with each other. To determine the type of material and structure of fiber, X-ray diffraction (XRD), Fourier transform infrared spectrometer (FTIR), nuclear magnetic resonance spectroscopy (NMR) [3,4] have been applied. To measure how the fibers knitted with each other, optical microcopy has been mainly used. Also, it is reported that there are some commercially available apparatus called imaging fiber analyzer (IFA) [5], which can analyze the images of texture by algorithm. However, all of these characterization methods have their disadvantages. For instance, the high energy X-ray used in XRD may destroy the polymer molecular in fiber and let them degrade, and this is harmful for human tissue. Besides, usual NIR-FTIR is hard to determine the intermolecular interaction in fiber. Moreover, for IFA, a photograph of texture is necessary and the analysis is only possible when the fiber is located in an orderly arrangement in a long distance.

The terahertz (THz) wave is the electromagnetic wave whose frequency is from 0.1 to 10 THz. This frequency band is located between radio waves and light. Due to the combination of the characteristics of the radio waves and light waves, the terahertz wave is transparent to non-polar materials like polymers. Unlike X-rays, terahertz radiation is not ionizing radiation, so its low photon energy usually does not damage sample nor human tissues. Specific terahertz radiation spectra can provide new information for chemistry and biochemistry [6]. Different from other THz wave source, terahertz generated by nonlinear optical process is coherent monochromatic beam with strong power at room temperature. By using that, terahertz tomography has been demonstrated to be able to measure and obtain images of opaque samples in the visible and near-infrared regions of the spectrum [7]. Therefore, the application of THz wave is expected in many fields, especially in the industrial manufacturing. In previous published research [8], how the absorption coefficient of polymer arranged in certain direction changes as a function of the angle between the polarization direction of THz wave and the polymer deformation direction has been explored. The result shows the coherent THz is sensitive to the periodically arranged structure of deformed high density polyethylene. We can quantitatively evaluate of fiber structure by using linearly polarized coherent terahertz wave.

In this study, we demonstrate a novel method to quantitatively evaluate the fiber structures by using linearly polarized coherent terahertz (THz) wave. The terahertz wave has wavelength of micrometer and millimeter order, which corresponds to the period of woven fabric, so it is possible to investigate the fiber structure by using THz.

* Corresponding author.
Email address: tang.chao.s5@dc.tohoku.ac.jp (C. Tang)

https://doi.org/10.1016/j.compositesb.2018.08.135
Received 21 June 2018; Accepted 29 August 2018
Available online xxx

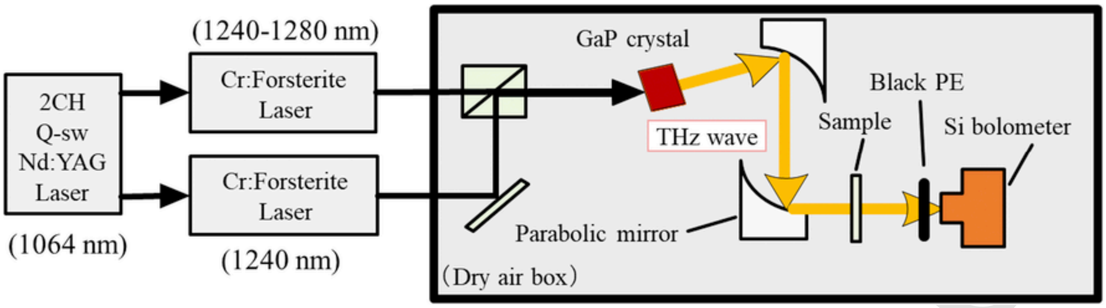

Fig. 1. Optic system of Terahertz generation and detection.

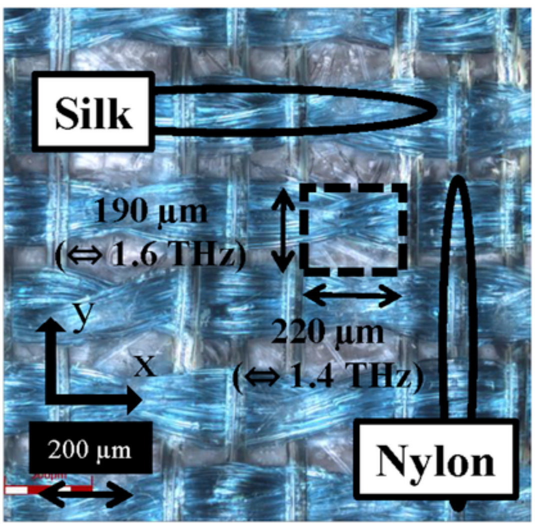

Fig. 2. Morphologies of samples: a, periodically arranged component fiber (row: silk (53%) column: nylon (47%)), b, randomly woven silk fiber. c, randomly woven nylon fiber.

2. Experiments

Composite fiber with periodically arranged silk (57%) and nylon (47%) is selected as the samples of this study. The morphologies of samples are measured by a scanning probe microscope (SPM-9700HT, SHIMADZU Co. Ltd.). Besides the characterization of microscopy, the coherent THz spectra were measured by a nonlinear optical process THz system, in which the terahertz wave was generated by difference frequency generation (DFG) process implemented with GaP crystal [9] as shown in Fig. 1. In this system, a Cr:Forsterite laser fixed wavelength of 1240 nm is used as the signal beam for DFG, The pump beam wavelength was turned in the range from 1240 nm to 1280 nm with the wavelength selection by prism. Both of them are generated by a two channel Q-switched Nd:YAG laser with wavelength of 1064 nm. The pump beam and signal beam were incident into GaP crystal, then the monochromatic THz wave with range from 0.5 THz to 5 THz are generated via DFG. Generated THz beam was collected by parabolic mirror then penetrate the samples. There is a silicon bolometer behind the sample to detect the transmit THz wave. Between the sample and detector, a black polyethylene film is located, which is transparent to THz but absorbs visible and infrared light. To prevent the disturbance of water vapor in the air, the system was placed in a box with flowing dry air.

3. Results and discussions

The microscopy images of periodically arranged composite fiber (53% silk and 47% nylon) is shown in Fig. 2. The blue parts are the silk

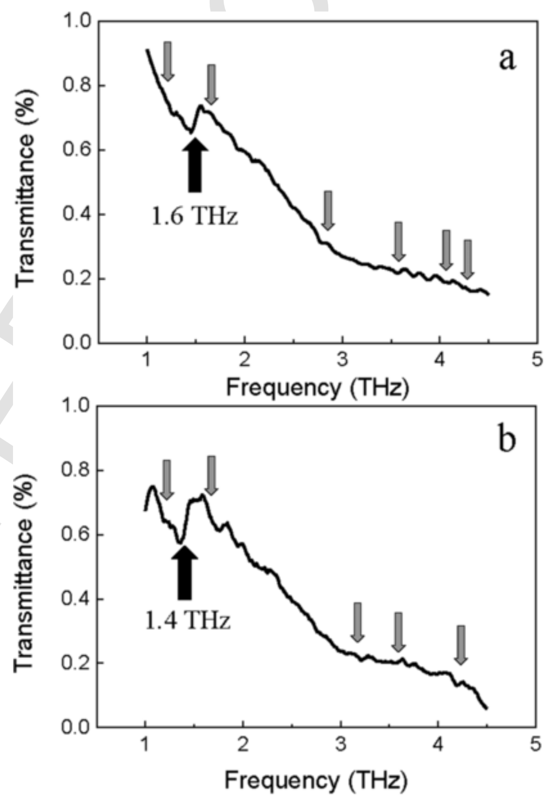

Fig. 3. THz transmittance spectra of samples: a, b, the spectra of component fiber using THz with polarization direction parallel to silk row and nylon column respectively, c, the THz spectrum of randomly woven silk fiber, d, the THz spectrum of randomly woven nylon fiber.

components, and nylon fibers arrange perpendicular to the silk. The periods of rows and columns are 220 µm and 190 µm for silk and nylon fibers respectively. These distances are similar to the wavelengths of electromagnetic wave with frequencies of 1.4 THz and 1.6 THz. The transmittance spectra of samples with range from 1 THz to 4.5 THz are shown in Fig. 3 and the absorption peaks due to intermolecular interaction are marked with grey downward arrow. The transmittance spectra of composite fiber using THz wave with polarization direction parallel to x direction (direction of silk fiber rows) and y direction (direction of nylon columns) are shown in Fig. 3a and b. When the polarization of THz wave is parallel to the direction of silk fiber row, the absorption peaks appears at about 1.6 THz (marked with black upward arrow). When the polarization of THz wave is parallel to the direction of nylon fiber columns, an absorption peak appears at 1.4 THz. At arbitrary location the monochromatic electromagnetic wave with frequency of f can be represented as $E = A exp\ (ikx/f)$ where x is the position and A is the amplitude. Considering parallel beams incident into a periodical structure with period of d and there is a detector behind sample, the intensity detected (E_d) can be described with Fraunhofer diffraction theorem [10].

$$E_d = \sum_{n=0}^{N} \int_{nd+a}^{nd-a} A e^{ikx/f} dx$$
$$= 2Aae^{\frac{i2\pi(N-1)}{\lambda} dsin\theta} \frac{\sin\left(\frac{\pi asin\theta}{\lambda}\right) \sin\left(\frac{\pi dNsin\theta}{\lambda}\right)}{\frac{\pi asin\theta}{\lambda} \sin\left(\frac{\pi dsin\theta}{\lambda}\right)}$$

where d is the period of repeated unit, N is the number of repeated unit, a is the length of hollow part in a single unit, θ is the direction angle between incident beam and detector and λ is the wavelength. This equation shows its maximum when $d = \lambda$, which means when the period of repeat unit is equivalent to the wavelength of irradiated beam, detected intensity will be enhanced by diffraction effects. So, the change of transmittance marked by black arrow can be explained as the contribution of interference of terahertz wave with periodical fiber structure. That means, by the results of coherent THz spectra of composite fibers, we can derive that, firstly, there are fibers periodically arrange along one direction with distance of 190 μm, and there are fibers periodically arrange along the perpendicular direction to first arrangement with distance of 220 μm, besides, the composite fibers sample contains silk and nylon fiber.

In our THz systems, frequency resolution was well below 30 GHz in the case of wavelength selection by prism in Cr:forsterite laser. Thus it is expected when periodicity of fiber structure is damaged and distributed within a few 10 microns, our sharp THz monochromatic light can evaluate the disturbance of periodicity and broken area of giber structures. In addition, we have already developed sharper THz light source with a few GHz band width by grating wavelength selection laser [11], and only a few MHz band width THz source by semiconductor laser excitation [12]. When these very narrow band width THz light sources are applied for the damage evaluation of fiber structures, very precise evaluation can be achieved well below a few microns.

4. Conclusion

In conclusion, the structure of woven fibers is investigated by coherent THz wave successfully. From the THz spectra, not only the arrange direction, periods of fiber, but also the type of material can be known. This research has confirmed coherent THz wave an effective approach to characterize the woven fabric.

Acknowledgements

A part of this study is the result of "Fundamental Research and Human Resources Development Program for Nuclear Decommissioning related to Integrity Management of Critical Structures including Primary Containment Vessel and Reactor Building, and Fuel Debris Processing and Radioactive Waste Disposal" carried out under the Center of World Intelligence Project for Nuclear S&T and Human Resource Development by the Ministry of Education, Culture, Sports, Science and Technology of Japan. Besides, a part of the fiber samples were provided by Watalis Co., Ltd. (Miyagi pref. Japan, URL: http://watalis.co.jp/). The authors would like to thank prof. Narita from Tohoku University for instructions.

References

[1] R. Sen, G. Mullins, K. Suh, D. Winters, FRP application in underwater repair of corroded piles, Special Publ 230 (2005) 1139–1156.
[2] Z. Zhou, J. Ou, B. Wang, Smart FRP-OFGB bars and their application in reinforced concrete beams, In: Proceedings of the first international conference on structural health monitoring and intelligent structure, 2003, pp. 13–15.
[3] R.J. Roe, W. Krigbaum, Description of crystallite orientation in polycrystalline materials having fiber texture, J Chem Phys 40 (1964) 2608–2615.
[4] C.-S. Wu, H.-T. Liao, Polycaprolactone-based green renewable ecocomposites made from rice straw fiber: characterization and assessment of mechanical and thermal properties, Ind Eng Chem Res 51 (2012) 3329–3337.
[5] J.A. Olson, A. Robertson, T. Finnigan, R. Turner, An analyzer for fibre shape and length, J Pulp Pap Sci 21 (1995) J367.
[6] J.-i. Nishizawa, K. Suto, T. Sasaki, T. Tanabe, T. Kimura, Spectral measurement of terahertz vibrations of biomolecules using a GaP terahertz-wave generator with automatic scanning control, J Phys Appl Phys 36 (2003) 2958.
[7] J.-i. Nishizawa, T. Sasaki, K. Suto, T. Yamada, T. Tanabe, T. Tanno, T. Sawai, Y. Miura, THz imaging of nucleobases and cancerous tissue using a GaP THz-wave generator, Optic Commun 244 (2005) 469–474.
[8] S. Ragam, T. Tanabe, Y. Oyama, K. Watanabe, H. Dezaki, Comparison of CW THz wave spectrometer with laser diode excitation and pulsed THz wave spectrometer with Cr: forsterite sources based on difference frequency generation of near-infrared lasers in GaP, J Infrared, Millim Terahertz Waves 31 (2010) 1164–1170.
[9] K. Suto, T. Sasaki, T. Tanabe, K. Saito, J.-i. Nishizawa, M. Ito, GaP THz wave generator and THz spectrometer using Cr: forsterite lasers, Rev Sci Instrum 76 (2005) 123109.
[10] E. Dan Hirleman, Modeling of multiple scattering effects in Fraunhofer diffraction particle size analysis, Part Part Syst Char 5 (1988) 57–65.
[11] J.-i. Nishizawa, T. Sasaki, K. Suto, M. Ito, T. Yoshida, T. Tanabe, High-resolution GaP terahertz spectrometer and its application to detect defects in gamma-irradiated glucose crystal, Int J Infrared Millimet Waves 29 (2008) 291–297.
[12] J.-i. Nishizawa, T. Tanabe, K. Suto, Y. Watanabe, T. Sasaki, Y. Oyama, Continuous-wave frequency-tunable terahertz-wave generation from GaP, IEEE Photon Technol Lett 18 (2006) 2008–2010.