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INFLUENCE OF TERAHERTZ WAVES ON THE FIBER DIRECTION OF CFRP COMPOSITE LAMINATES

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ABSTRACT. The importance of Carbon-fiber reinforced plastics (CFRP) are widely utilized due to more high performance in engineering structures. It was well known that a nondestructive technique would be very beneficial. A new terahertz radiation has been recognized for their importance in technological applications. Recently, T-ray (terahertz ray) advances of technology and instrumentation has provided a probing field on the electromagnetic spectrum. The THz-TDS can be considered as a useful tool using general non-conducting materials; however it is quite limited to conducting materials. In order to solve various material properties, the index of refraction (n) and the absorption coefficient (α) are derived in reflective and transmission configuration using the terahertz time domain spectroscopy. However, the T-ray is limited in order to penetrate a conducting material to some degree. Here, the T-ray would not go through easily the CFRP composite laminates since carbon fibers are electrically conducting while the epoxy matrix is not. So, investigation of terahertz time domain spectroscopy (THz TDS) was made and reflection and transmission configurations were studied for a 48-ply thermoplastic PPS (poly-phenylene sulfide)-based CFRP solid laminate. It is found that the electrical conductivity of CFRP composites depends on the direction of unidirectional fibers. Also, the T-ray could penetrate a CFRP composite laminate a few ply based on the E-field (Electrical field) of carbon fibers. The terahertz scanning images were made at the angles ranged from 0° to 180° with respect to the nominal fiber axis. So, the images were mapped out based on the electrical field (E-field) direction in the CFRP solid laminates. Also, using two-dimensional spatial Fourier transform, interface C-scan images were transformed into quantitatively angular distribution plots to show the fiber orientation information therein and to predict the orientation of the ply.

Keywords: Terahertz Radiation, Fiber Direction, CFRP Composites, C-scan Images
PACS: 81.70.-g

INTRODUCTION

It is well known that terahertz zone lies between the microwave and infrared zone of the electromagnetic spectrum. Also, recent advances of technology and instrumentation in terahertz radiation have provided a probing field on the electromagnetic spectrum because the terahertz radiation has a shorter wavelength, relatively higher resolution and lower attenuation. The terahertz radiation is of critical importance in the spectroscopy evaluation of airport security screening, medical imaging, polar liquids, industrial systems and composites as well [1]. Also the terahertz time
domain spectroscopy (TDz-TDS) is leading noncontact accurate detection of flaws and impact damages in composites, in which the TDz-TDS is based on photoconductive switches, which rely on the production of few-cycle terahertz pulses using a femtosecond laser to excite a photoconductive antenna [2-5]. This can generate sub-picosecond bursts of THz radiation, and subsequently detect them with high signal-to-noise. With the emitted power distributed over several terahertz, they consequently span a very broad bandwidth. A transient change of the emitter occurs in the resistance of a photoconductive switch on a terahertz timescale. An external dc bias can create a current flow that contains components at terahertz frequencies[6-7].

So, the chemical property of materials is of great interest and the study presents many challenges. In this paper, we will report a few of the most interesting applications of THz ‘T-ray’ radiation for the nondestructive evaluation of composite materials and structures. These methods include both a reflection and through-transmission mode, where the THz pulses was set up for scanning image reconstruction. A new measurement technique of refractive index will be discussed, which can be used to resolve on reflection and through-transmission modes. The refractive index data measured by a new measurement technique was compared with the existing data for PMMA and Fused quartz. It was found that the data of refractive index were well agreed with the existing data. The penetration ability of T-ray waves has a limit to the conducting carbon fiber composites. The experimentation of THz TDS testing was extensively performed on one-ply CFRP laminate ate the different angles based on the E-filed [8-10]. So, the influence and limitations of terahertz radiation will be discussed for the NDE direction of composites. Thus, the THz effective scan images can be made according to the angels at the orientation of carbon fibers. It follows that the higher contrast images are being governed by the E-field direction. Also, T-ray C-scan images were obtained and then 2-D FFT was utilized to show the fiber direction information and predict the ply orientation.

THEORY AND EXPERIMENT

The THz TDS configuration system is shown in Fig.1 in order to collect the material parameter data and perform the images as a mode of through-transmission. A mode-locked, 100fs, Ti: Sapphire laser drove a photoconductive switch using a lock-in amplifier. The THz pulse was reflected at 17o from the sample and was detected using an electro-optic technique (Zn Te crystal).

![Diagram showing the geometry of the through-transmission mode.](image-url)
**Reflection Mode**

This method was to determine the index of refraction used to calculate the optical path length different between the front and back reflections in the time domain [11].

\[ n^4 - A n^2 - A \sin^2 \theta_p = 0 \]  \[
\text{where } A = \left( \frac{T^2 V_{\text{air}}^2}{(4d)^2} \right) \]

where \( T \) is the transmission time of the sample, \( d_2 \) is the sample thickness, \( V_{\text{air}} \) is the light speed in air and \( \theta_p \) is the incident angle of the sample.

**Through-Transmission Mode**

In through-transmission mode, the index of refraction (n) could be calculated using the following equation [11].

\[ n = 1 + \frac{\Delta t V_{\text{air}}}{d} \]  \[
\text{Where } \Delta t \text{ is the difference time between with sample and without sample, } d \text{ is the sample thickness, } V_{\text{air}} \text{ is the light speed in air.} \]

**RESULTS AND DISCUSSION**

**Measurement of Refractive Index**

In preparation for measuring material parameters, we first measured a THz pulse transmitted from GFRP composites. In Fig. 2 one can clearly see the initial signal without sample (see Fig.2 (a)) ; and the other signal was captured as shown in Fig.2 (b). A method to determine the index of refraction was used to calculate the time delay \((\Delta t = T_2 - T_1)\) based on the optical path length difference using the through-transmission mode as shown in Table 1. It is found that those data were agreed with the known data for through-transmission mode.

![FIGURE 2. THz TDS pulses transmitted from without sample and with sample.](image-url)

\[ T_1 = 275.15 \text{ ps} \]
\[ T_2 = 298.0 \text{ ps} \]
\[ \Delta t = T_2 - T_1 \]
TABLE 1. Average THz refractive indices of the material studied.

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive index(n) in Through-transmission mode</th>
<th>Refractive index(n)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fused quartz</td>
<td>1.60 ± 0.09</td>
<td>1.60 ± 0.08</td>
</tr>
<tr>
<td>PMMA</td>
<td>1.96 ± 0.05</td>
<td>1.95 ± 0.05</td>
</tr>
<tr>
<td>GFRP composites</td>
<td>2.12 ± 0.06</td>
<td>-</td>
</tr>
</tbody>
</table>

*Known data by References [8-9].

E-Field Characterization in Carbon Fiber

Terahertz waves can penetrate dielectric materials quite easily but not electrically conducting materials. The application of terahertz waves to the inspection of carbon composites is mentioned in the literature [8,11] but there has not been in depth studies. Carbon fiber reinforced polymer composites (CFRP) are poor conductors for electricity and the conductivity is anisotropic, so it is worthwhile to quantify the penetration of terahertz waves in carbon composites. The carbon fibers used in the manufacturing of CFRP are highly anisotropic microscopically; the electrical conductivity along the fiber axis is about three orders of magnitude greater than that in the radial direction. In a unidirectional laminate of carbon fiber composite, the transverse electrical conductivity is further impeded by the lack of continuity.

The conduction mechanism in the transverse direction (perpendicular to the fiber axis) is a percolation process that relies on the random contact between adjacent fibers. In the literature, the electrical conductivity data for carbon composites are somewhat sparse [9].

Experimentally, we have measured the angular dependence of the power transmission through a 1-ply unidirectional carbon composite laminate using the CW terahertz system. Near the low end of the frequency spectrum \( f \sim 0.1 \) THz, the transmitted power is more than 30 dB above the noise floor. The angular dependence of the transmitted power at 0.1 THz is shown in Fig. 3.

![FIGURE 3. Angular peak-to-peak amplitude of transmitted power of THz terahertz waves through a 1-ply unidirectional CFRP laminate.](image-url)
The transmission powers were measured at every 15 degree angles. Fig. 3(a) shows the highest transmission power amplitude; however Fig. 3 (g) does lowest amplitude. And the measured power amplitudes were plotted as a function of angles as shown in Fig. 4. When compared to the theory prediction [10] based on the angular dependent conductivity, the measured power transmission at angles away from 90 degree much higher the predicted. The value would have the unidirectional carbon composites behaving like a polarizer with a sharp cut-off under the assumptions that the incident terahertz ray is linearly polarized and that the fiber axes in the laminate are all parallel. It seems that the discrepancy in some angles contributes to the above involved things. However, it is found that the transmission of terahertz power depend on the fiber direction of conducting CFRP composite laminates.

When compared to the theory prediction based on the angular dependent conductivity, the measured power transmission at angles away from 90 degree much higher the predicted. The value would have the unidirectional carbon composites behaving like a polarizer with a sharp cut-off under the assumptions that the incident terahertz ray is linearly polarized and that the fiber axes in the laminate are all parallel. It seems that the discrepancy in some angles contributes to the above involved things. So, it is assumed that the E-field direction is normal to the carbon fiber direction as shown in Fig.4 (b).

**THz Images in PPS CFRP Solid Laminate**

A reflective TDS system was utilized in order to evaluate the effect of E-filed direction on PPS CFRP solid laminate. A PPS CFRP solid laminate was scanned at different angles. Sample’s layup is [45/0/-45/90]_{6s} and 114 x 355 x 6.8 mm in size. Fig. 5 shows a sample set up of TDS system for scanning. A scan configuration and direction was made based on the E-field direction.
TDS scan images were made at the different time gates and best combination of E-field directions. These images were mapped out based on the E-field direction in the CFRP solid laminates. Scan size is 60 x 60 mm and step size is 0.5 mm. These images are based on a reflection mode at the scan range of $\Delta t$ (scan gate length) = 10 ps. Especially, at $\theta = -45^\circ$, this image to be considered clear and higher contrast as shown in Fig. 5(a). Here, there are some lines in the angle of $\theta = -45^\circ$ due to the E-field direction of THz wave. It is thought that the THz wave penetrated a couple of a CFRP prepreg sheet called a scan depth.

THz Image Processing on PPS CFRP Solid Laminate

A PPS CFRP solid laminate was consisted with the different angles in each ply and the laminate was scanned by a reflection THz-TDS system as shown in Fig. 6. The scanned images showed the ply lay-up direction of the laminate based on the E-field. It was difficult to determine the fiber angles of the angular components in the THz-TDS C-scan images simply by visual observation as shown in Fig. 6(a). So, the information of fiber angles needed to be analyzed quantitatively which describes the angular components in the THz-TDS C-scan images. The approach taken was to use a two-dimensional fast Fourier transform (2-D FFT). An example that illustrates the image processing procedure is given in Fig. 6. The original C-scan image is shown in Fig. 6(a).

To process this image, a two-dimensional Hanning window was first applied to reduce the edge effects on its spatial Fourier transform. A 2-D FFT was then performed and the resulting spatial spectrum is shown in Fig. 6(b), where the grayscale is proportional to the magnitude of the spectrum in dB. The THz-TDS C-scan method was then used to determine the orientation of all the plies in a 48-ply laminate that had a layup of [(0/45/90/-45)]. It is confirmed that there is different at the location of peak amplitude for the surface of a specimen. The angular spectrum for fiber effect was shown in Fig. 6(b). Here X-axis means angle of function and Y-axis is a peak signal of ply-error location in the laminates. Take a look of Fig. 6, for example, the angular distribution plot.
of the first interface (between the 0° and 45° plies) showed that the highest peak was at 0° (see Fig. 6(a)). This could be due to the fact that the dark dot of the images caused from waviness of ply. Lay-up of the first ply in CF/Epoxy composites was usually easy to determine due to resultant THz-TDS C-scan image containing almost exclusively the orientation of the ply at the different angles. It is found that variations happen in amplitude when the THz-TDS waves go through a couple of ply of composites and so the signal change makes ply-layup orientation of plies determined.

CONCLUSION

Recently, terahertz radiation can show unique characteristics for nondestructive evaluation on the composites. It was found that the index of refraction of samples could be easily measured using a transmission configuration. Also, the index of refraction in the terahertz frequency range for composite was measured using a conventional equation based on the transmission configuration. However, it is recommended that a reflection mode is certainly a more likely candidate for a maintenance technique due to access to unknown body.

The ply-layup orientation of the laminates at the surface can be mapped out by performing a THZ-TDS C-scan image of the T-ray signals reflected from the laminate and using an image processing procedure based on two-dimensional Fourier transform.

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