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Experimental verification of the uniaxial stress-optic law in the terahertz frequency regime

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ABSTRACT

The stress-optic law is fundamental to photoelasticity, and has been a prevalent method for measuring stress. However, its effectiveness in the terahertz (THz) regime has not been completely characterized. In this paper, the effects of uniaxial tensile stress on THz transmission through a polytetrafluoroethylene (PTFE) sample are investigated. Specifically, THz time domain spectroscopy (THz-TDS) has been used to measure the phase delay of transmitted THz radiation for different PTFE stress states. Differences in the refractive index of the PTFE are calculated from the measured phase delay. The calculated refractive index grows linearly with the applied stress, which can be considered a verification of the uniaxial stress-optic law in the terahertz frequency regime.

1. Introduction

As advanced materials research has provided new high power sources, terahertz (THz) technology has become widely used in diverse fields such as semiconductors, security, medical science, and manufacturing industries [1–3]. Time domain spectroscopy (TDS) is a widely used THz spectral analysis technique [4–6], where ultrafast laser pulses are used to generate and probe short pulses of broadband THz radiation. With the help of an optical or mechanical delay line, the THz pulses are sampled [7]. Because the transmitted THz pulses contain much information about the propagation medium, THz-TDS is widely used for materials characterization [8], nondestructive evaluation of composite structures [9], and label-free genetic analysis [10]. It has also been demonstrated that stress applied to the medium can affect terahertz emission [11,12].

Birefringence occurs in many transparent materials under loads. This phenomenon is called stress-birefringence or the stress-optical effect. Because of the stress-optic law, conventional photoelasticity has been the preferred experimental technique for stress analysis [13,14]. For stress analysis, a model of the investigated object is often manufactured with a material that has high photoelastic sensitivity, such as epoxy resin, so that stress-birefringence is readily detected [15]. However, the process of manufacturing models can be tedious.

THz radiation can penetrate many non-metallic materials [16]. Thus, if the stress-optic law is still observed in THz regime, a novel stress measurement technique similar to photoelasticity could be developed without the need for manufactured models. However, few experimental results have been reported on the effectiveness of the stress-optic law in the THz regime. In Ref. [17], the authors examined the THz stress-optic law with a polarization-sensitive THz-TDS system, but they did not provide a clear understanding of the basic principles.

In this paper, we present an experimental system based on THz-TDS to verify the uniaxial stress-optic law for the THz regime. The basic experimental principles are then discussed through the analysis of the electronic field strength of the transmitted THz radiation.

2. Experimental system

The experimental arrangement depicted in Fig. 1 includes two separate modules. The first is an improved THz-TDS system to measure phase delays of the THz radiation, while the other is a simple device to apply mechanical loads on the polytetrafluoroethylene (PTFE) sample. A femtosecond laser is used as the pump

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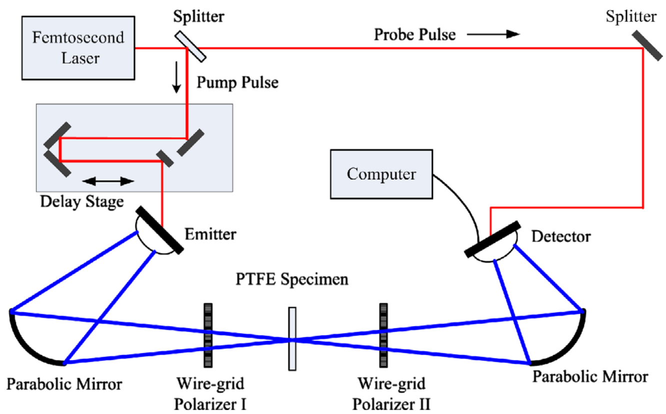

Fig. 1. Schematic diagram of the experimental setup.

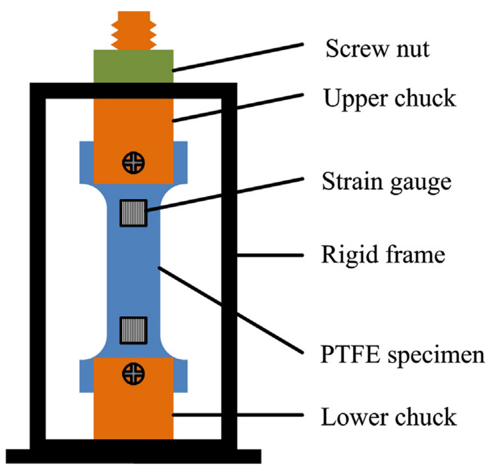

Fig. 2. Mechanical loading device.

source for both the THz emitter and detector, which are dipole-type photoconductive antennas. Two wire-grid polarizers generate and analyze polarized THz radiation in a bright-field path configuration. Polarizer I is used to polarize THz radiation along the direction of the applied stress in the sample, while Polarizer II is oriented in the same direction to analyze the transmitted THz radiation.

The mechanical loading device is shown in Fig. 2. It is easily integrated within the compact THz-TDS system. It consists of one rigid frame, two chucks, and one screw nut. The lower chuck is fixed on the rigid frame, while the upper chuck can be adjusted by the screw nut to apply tensile loading to the standard, dumbbell-shaped PTFE sample. Strain gauges are attached to the sample to measure the tensile strain. According to Hooke's Law, the applied stress can be calculated from the measured strain.

3. The basic experimental principles

During the experiments, the reference THz radiation is recorded before the sample is placed in the optical path. Then, THz radiation transmitted through the sample is recorded when the sample is unloaded and loaded. The phase delays of the THz radiation are determined by analyzing the recorded signals when the different stresses (loads) are applied.

The reference THz radiation detected by the detector antenna can be expressed as:

$$E_r = A_0 e^{i\delta_0} \tag{1}$$

where A_0 and δ_0 are the amplitude and initial phase, respectively. When the unloaded sample is placed in the optical path, the phase of the detected radiation will be delayed. The phase delay is given as:

$$\delta_1 = 2\Pi df(N_0 - N_a)/c \tag{2}$$

where N_a and N_0 are the refractive indices of air and the PTFE, respectively, d is the thickness of the sample, and c is the speed of light. Therefore, the detected radiation can be expressed as

$$E_0 = A_0 e^{i(\delta_0+\delta_1)} \tag{3}$$

The time required for the THz radiation to pass through the sample is

$$t_1 = N_0 d/c \tag{4}$$

As stress in the sample is increased, the phase difference between the reference and the radiation passing through the sample will change, as given by

$$\delta_2 = 2\Pi df(N_0 - N_a)/c \tag{5}$$

where N_1 is the refractive index of the loaded sample. Similarly, the radiation can be expressed as

$$E_1 = A_0 e^{i(\delta_0+\delta_2)} \tag{6}$$

From Eq. 4, the time required for transmission of the THz radiation through the sample will now be

$$t_2 = N_1 d/c \tag{7}$$

If $\Delta n = N_1 - N_0$ is the difference in refractive index, then the difference in transmission time can be written as

$$\Delta t = t_2 - t_1 = \Delta nd/c \tag{8}$$

Let $\Delta\delta = \delta_2 - \delta_1$ represent the phase difference for the unloaded and loaded situations. According to the relationship between time and phase, the difference in transmission time can also be written as

$$\Delta t = \Delta\delta/(2\pi f) \tag{9}$$

where f is the frequency of the detected radiation. According to Eqs. (8) and (9), the difference in refractive index can be obtained by

$$\Delta n = \frac{c}{2\pi d} \cdot \frac{\Delta\delta}{f} \tag{10}$$

Eq. (10) describes the relationship between the phase difference and the refractive index difference for one harmonic component. Thus, the refractive index difference can be determined by the phase difference, which is measured with the THz-TDS system.

According to the stress-optic effect, we know that the refractive index difference is a function of the applied stress:

$$N_1 - N_0 = A\sigma_1 + B(\sigma_2 + \sigma_3) \tag{11}$$

where σ_1, σ_2 and σ_3 are the three principle stresses, and A and B are the stress-optic constants. In our experiment, only one uniaxial tensile stress is applied. Thus, σ_1 is equal to the applied tensile stress, while σ_2 and σ_3 are zero. Therefore, the generalized stress-optic law can be simplified to:

$$\Delta n = N_1 - N_0 = A\sigma \tag{12}$$

where σ is the applied tensile stress. According to Eq. (12), and if the stress-optic law is still effective in the THz regime, *the applied tensile stress σ and the measured Δn obtained by Eq.* (10) *should have* a *linear relationship*. The proportionality coefficient will be the stress-optic constant A.

The refractive index difference can be measured with the THz-TDS system, while the applied stress can be measured with the strain gauge. Thus, we can verify whether there is a linear relationship between the two variables.