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Thermally controllable filter at terahertz region

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HIGHLIGHTS

- Thermally controlled filter is demonstrated at terahertz range.
- The characteristics of filter can be controlled by using dodecanoic acid and polyethylene.
- The granular scattering by air voids due to melting of dodecanoic acid is main factor of the characteristics of filter.

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ABSTRACT

We experimentally investigated terahertz (THz) filters fabricated using dodecanoic acid (DDA) particles and polyethylene (PE) by performing THz time-domain spectroscopy. Since the refractive indices of DDA and PE are the same in the THz range, no optical scattering occurred when they were mixed. However, heating caused air voids to replace the DDA particles, and the DDA melted into the spaces between the PE particles. Furthermore, as the DDA particle size, heating time, and DDA content increased, the THz band width became narrower. Based on the results, we propose a new, low-cost type of THz filter with a simple manufacturing method.

1. Introduction

For a few decades, terahertz (THz) technologies have primarily been employed for basic science research as well as optical technology development and applications. Consequently, THz techniques have contributed significantly to the resolution of important scientific issues. For instance, the development of THz electromagnetic radiation sources and detectors has motivated numerous fundamental studies on the properties of materials such as semiconductors, organic materials, metallic films [1], and biochemicals [2–4] and even medical science [5,6]. In addition, THz techniques have been used in numerous applications such as THz imaging [7,8], communication [9,10], and food research [11,12]. However, technical limitations still exist due to the lack of THz functional devices that can control and modulate THz electromagnetic radiation. Hence, THz technology remains underdeveloped. As one type of THz optical component that could be employed to overcome this hurdle, THz filters are becoming essential for THz wave modulation. Many prior filter studies have focused on the development of artificial structures, such as metamaterials (e.g., split-ring resonators and metal hole arrays) [13,14], photonic crystals [15,16], and surface plasmons [17,18], which could provide new means of THz wave control. However, these artificial structures are accompanied by problems such as long fabrication times and, consequently, high costs.

Meanwhile, conventional THz systems, such as THz time-domain spectroscopy (THz-TDS) systems, also require filtering of specific frequencies to select target frequency bands to reject thermal radiation, which can saturate sensitive detectors. In addition, THz filters can be also used for communication to select specific frequency and frequency modulated imaging investigation. Several types of THz filters have been studied previously, including low-pass [19,20], high-pass [21], band-pass [22], and band-stop [23] filters. In addition, there are various investigations reports of optically, electrically, mechanically and thermally tuned terahertz filters [24–30]. Although various THz filters have been developed, more easy-to-build THz filters are required to improve THz techniques.

In this article, a thermally controllable, easily manufacturable THz filter based on dodecanoic acid (DDA) is introduced. The DDA particle size can be varied to fabricate THz filters due to the optical granular scattering effect (OGSE). In this study, we employed THz-TDS to investigate the properties of the proposed

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THz filters. The low cost and simplicity of manufacturing such filters further increase their potential for use in THz wave control and applications.

2. Materials and methods

2.1. Sample preparation

Crystalline DDA was purchased from Sigma-Aldrich (St. Louis, MO, USA). The granular DDA was crushed with a mortar and sieved through 105, 425, 600, and 850 μm meshes. The penetrated micro-particles were collected, milled with polyethylene (PE) powder, and pressed into 300 mg, 2-mm-thick, 10-mm-diameter pellets with DDA concentrations of 10% under a pressure of 5000 kg/cm^2. PE is a suitable filling material for THz (far-infrared) spectroscopy because it is very transparent at such frequencies. Melting and recrystallization of the DDA micro-particles was induced by heating the pellets at 70 °C for 10 min and subsequent cooling at room temperature. Fig. 1 illustrates the processing method, including images of the DDA particles in the PE powder before and after heating. Heating caused air voids to be generated at the positions of the DDA particles.

2.2. THz time-domain spectroscopy

The THz transmission spectra of the DDA were measured from 0.2 THz to 3 THz (6–100 cm^{-1}) using a commercial THz-TDS system (TPS-3000, Teraview, UK) at room temperature and less than 1% humidity. THz electromagnetic pulses were generated by a coplanar photoconductive antenna pumped by a Ti : sapphire femtosecond laser with a repetition rate of 80 MHz and center wavelength of 800 nm. The beam from the laser source was divided into two paths to generate and detect THz pulse signals. Fig. 2 depicts typical THz pulse signals in the time domain, and THz spectrum in the frequency domain.

2.3. X-ray diffraction

Powder X-ray diffraction (XRD) patterns were collected from 2θ = 15° to 30° using Cu Kα radiation and a Bruker D8 Advance diffractometer (Bruker, Karlsruhe, Germany). The XRD samples were prepared using the same procedure that was employed to produce the PE pellets containing DDA micro-particles. Pure granular DDA was also investigated, and the effect of thermal treatment on the crystallinity of the DDA microstructure was monitored.

2.4. Scanning electron microscopy

The morphologies of the PE pellets containing DDA micro-particles were visualized using a field-emission scanning electron microscope (FE-SEM, Leo Supra 55, Genesis 2000, Carl Zeiss, Oberkochen, Germany) with an accelerating voltage of 5 kV. Cross-sectional views were obtained by cutting the PE pellets using a razor blade.

3. Results and discussion

The morphologies of the DDA crystals sieved through the different meshes were examined using the SEM (Fig. 3(a)). Self-associated crystalline structures were observed in all of the samples even after crushing, as shown in the inset. The crystalline granules were composited into the pure PE pellets and recrystallized by heating to above the melting point and subsequent cooling down at room temperature. In this demonstration, the DDA particles were heated by 70 °C for 10 min. After recrystallization of the DDA granules, air voids were formed in PE pellets, which were examined by performing cross-sectional SEM. This finding indicates that the melted DDA granules were pulled by the capillary force into the confined spaces between the PE particles and could be solidified. The DDA granules remaining in the voids were also recrystallized and settled on the interfaces of the voids, as shown in the inset images in Fig. 3(b). The sizes of the voids produced in the PE pellets depended upon the incorporated DDA granules. Therefore, the void size could be controlled easily by preparing PE pellets using differently sized DDA granules.

The DDA was characterized to identify the crystal structure changes by performing XRD measurements. DDA has a polymorphic molecular structure that exhibits monoclinic and triclinic characteristics. The XRD results, which are presented in Fig. 4, display the standard peaks of the monoclinic and triclinic structures at 2θ = 16.3, 21.5, and 24.0 and 19.2, 20.0, 21.9, 23.5, and 24.5, respectively. These spectra indicate that pre- and post-heated DDA have XRD peaks matching those of the triclinic and monoclinic structures, respectively [31,32]. Accordingly, it can be inferred that the structure of the melted and re-crystalized DDA was changed from triclinic to monoclinic by heating. The peaks at 2θ = 21.5 and 21.9 correspond to the 4.11 Å and 4.38 Å intermolecular distances, respectively, in carbon chains. Thus, the intermolecular interactions in carbon chains are increased by heating.

We investigated the THz spectra of the filter samples using the THz-TDS system. As shown in Fig. 5, we prepared samples using 105, 425, 600, and 850 μm DDA particles and obtained their frequency-domain THz spectra. Fig. 5(a) and (b) present the frequency-domain THz transmittances of the filters before and after heating at 70 °C for 10 min, respectively. As expected, no significant differences between the THz transmittances of the filters are evident before DDA particle melting, as shown in Fig. 5(a). However, after heating, the THz transmittances differ significantly, revealing the relationship between THz transmittance and DDA particle size. The THz transmittance at high frequencies is

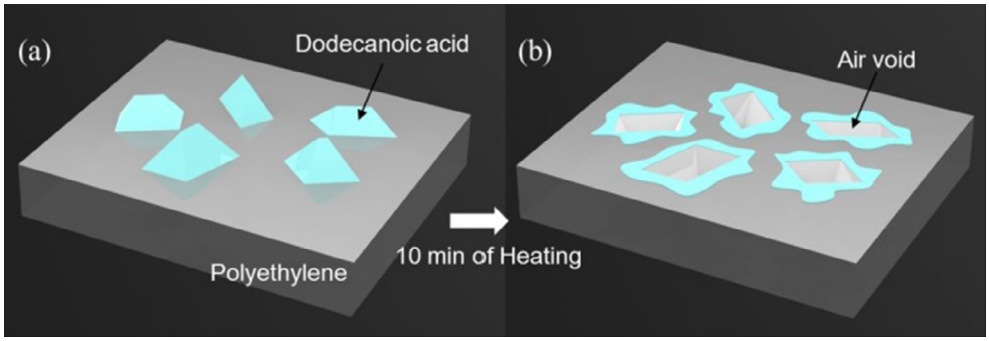

Fig. 1. Scheme of the processing method (a) before and (b) after heating and cooling DDA particles.