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Dielectric traces of food materials in the terahertz region

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ABSTRACT

We investigated the feasibility of identifying food products using the complex dielectric constant of food materials, and insects as a foreign substance, in the terahertz (THz) frequency range from 0.3 to 1.2 THz. Although the food and insect materials have unique dielectric properties, several materials could not be distinguished by the dielectric constant. To discriminate all food materials completely, we obtained the dielectric traces, in which the real and imaginary parts of the values are plotted. Consequently, food materials and insects can be separated effectively using this analysis. Our results indicate that food materials and foreign substances can be unambiguously distinguished and detected according to the dielectric traces and independent parameters extracted from the complex dielectric constants, using THz time-domain spectroscopy.

1. Introduction

Food quality and safety issues are crucial in the life and health of consumers worldwide. Consequently, raising the living standards of consumers requires improving food quality and safety. Accordingly, many efforts have been made to develop new techniques that can be applied to food inspection. For a long time, destructive techniques, such as gas chromatography [1] and liquid chromatography [2], have been widely used to inspect food products. These techniques are easy to operate for food analysis but require a long acquisition time, sample preprocessing and a high maintenance cost.

Non-destructive measurements are an alternative to overcome the limitations of destructive methods. For example, ultraviolet spectroscopy [3], fluorescence spectroscopy [4–6] and Raman spectroscopy [7,8] are widely used for this purpose. In addition, near-infrared (NIR) hyperspectral imaging [9,10] and nuclear magnetic resonance (NMR) techniques [11,12] are also useful approaches to analyze food materials. The major merits of these non-destructive techniques include no sample preprocessing requirement and a rapid acquisition time compared to destructive methods. Moreover, a low maintenance cost is needed. Nonetheless, some of these non-destructive methods still have several hurdles, although their deployment to the industry has been commercially successful. For X-ray-based technologies, the radiation can ionize and damage food materials due to the high energy, and low-density material or soft matter cannot be analyzed by X-ray analysis. Ultraviolet spectroscopy is harmful to the active ingredients of food materials. Raman spectroscopy and NIR hyperspectral imaging techniques cannot penetrate into food materials so only the food surface can be investigated. In addition, fluorescence spectroscopy has limitations against samples containing fluorescent compounds, and NMR spectroscopy has a lower sensitivity than other techniques.

Unlike these non-destructive techniques, the terahertz (THz) technique has several advantages. THz spectroscopy provides detailed intermolecular information, such as hydrogen bonding, amorphous or crystalline structure, and molecular rotational or vibrational motion in molecules [13]. Low-density or soft matter materials, such as biological or chemical materials, can be analyzed because they show a high absorption coefficient in the THz region. Due to the low photon energy (1 THz = 0.004 eV), there is no ionization or damage during measurement using THz radiation. Besides, THz techniques provide a non-contact, non-destructive measurement. Consequently, various studies of biological and chemical issues using THz technologies are reported, such as pharmaceutical products, clinical diagnostics, tissue characterization and food safety monitoring [14–30].

In addition, the physical parameters, such as dielectric constants and refractive indices, can also be measured directly by the frequency-dependent phase and amplitude information, using THz spectroscopy. These physical values are valuable parameters in food engineering and technology because all food materials have unique physical features. Also, these properties are affected by food quality changes, where the optical properties of the food products can be described by an effective dielectric constant as the ratio of various components, such as carbohydrate, fat, protein and minerals. Thus, the resultant value provides valuable insight into the individual behavior of food material components. In addition, the dielectric relaxation, which is described by a real and imaginary part of the complex dielectric constant, can be analyzed

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and predicted by a dielectric relaxation model, such as the Cole–Cole or Cole–Davison model [31,32]. When chemical changes occur in food components, the dielectric relaxation may also change due to alterations in the electric fields inside foods. Consequently, it is possible to predict the state of food materials and their unique features by examining the dielectric properties.

Previously, we investigated the complex refractive index of food materials and identified food materials using the refractive index mapping [22]. In this study, we examined the dielectric properties of food products and several insects, which can be embedded as a foreign substance in food products, in the THz frequency region. Moreover, we obtained the dielectric properties from the real and imaginary parts of the dielectric constants. These values were then used to plot individual traces of selected food products.

2. Materials and methods

2.1. Food sample preparation

Dried food material samples were obtained from a local market in the Republic of Korea. We pulverized each food material into powder samples by using a commercial ball mill system (Pulverisette 23, Frisch, Germany). To avoid optical scattering, the food samples were crushed to an average particle size of approximately 1 μm in diameter. The ball mill machine used a ceramic grinding ball with a diameter of 15 mm, and the food samples were pulverized for 5 min at a regulated oscillation frequency of 50 Hz. For THz measurement, all the food samples were prepared as a pellet with a diameter of 10 mm and thickness of 2 mm by applying a pressure of 5000 kg/cm^2 for 10 min.

2.2. THz time-domain spectroscopy (THz-TDS)

The time-resolved THz pulse is generated by the THz-TDS system, which consists of a mode-lock Ti:sapphire femtosecond laser with a wavelength of 800 nm and a repetition rate of 80 MHz. Fig. 1(a) is the schematic of the THz-TDS system. The output laser beam is divided into a pump and two probe beams by a beam splitter. One of the beams is focused on a photoconductive antenna (PCA) fabricated with a Ti/Au dipole antenna to emit THz waves, and the other beam is used to detect THz pulses. The phase of the probe beam is modulated by the delay stage, and the waveform of the THz pulse is obtained by a time-domain scanning at the PCA detector [33]. The food samples were placed between the two off-axis parabolic mirrors. The humidity of the free space was maintained below 1% by using dry air to exclude the effect of water vapor. In our experiment, we used a commercial THz-TDS system (TPS-3000, Teraview, UK), illustrated in Fig. 1(b).

2.3. THz data processing

All materials have a unique dielectric constant, which is also termed the electric (complex) permittivity. The real and imaginary part of the dielectric constant $\tilde{\varepsilon}$ are represented by $\tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2$, where ε_1 and ε_2 are commonly called the dielectric constant and loss factor, respectively. The real part of the dielectric constant (ε_1) describes the ability of the material to store energy when it is exposed to an external electric field. The imaginary part (ε_2) influences both the energy absorption and attenuation of an external electric field and describes the ability to dissipate energy. Moreover, thermal energy in the food material can be converted in proportion to the imaginary part of the dielectric function.

The complex dielectric function $\tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2$ is equal to the square of the refractive index $\tilde{n}^2$. Hence, if the complex refractive index is known, the frequency-dependent real and imaginary parts of the complex dielectric function can be extracted from the equations below [34]:

$$\varepsilon_1(\omega) = n_1^2(\omega) - n_2^2(\omega) \tag{1}$$

$$\varepsilon_2(\omega) = 2n_1n_2 \tag{2}$$

The refractive index is also a physical value of materials and is represented by $\tilde{n} = n_1 + in_2$ where n_1 and n_2 are the real and imaginary parts, respectively. When a THz pulse travels through a sample, n_1 and n_2 are related to the refractive index (n) and absorption coefficient (α) of the materials. The refractive index is defined as the delay phase of the THz pulse between the air and sample, and the absorption coefficient is affected by the decreasing THz pulse intensity, as shown in Fig. 2(a). After fast Fourier transform, the frequency-domain amplitude can be extracted from the THz pulse, as illustrated in Fig. 2(b).

The output signal of the THz pulse $O(\omega)$ passing through a sample can be expressed by the input THz signal $I(\omega)$, as follows [21,34]:

$$O(\omega) = I(\omega)\exp\left[-\frac{d\alpha(\omega)}{2}\right]\exp\left[i\frac{2\pi}{\lambda}n_1(\omega)d\right] \tag{3}$$

where $I(\omega)$ is the input signal, $\alpha(\omega)$ is the absorption coefficient, d is the thickness of the sample, and λ is the wavelength. The absorption coefficient $\alpha(\omega)$ can be related to the imaginary part of the refractive index n_2 by

$$\alpha(\omega) = -\frac{2}{d}ln\left[\frac{O(\omega)}{I(\omega)}\right] = \frac{4\pi n_2}{\lambda} \tag{4}$$

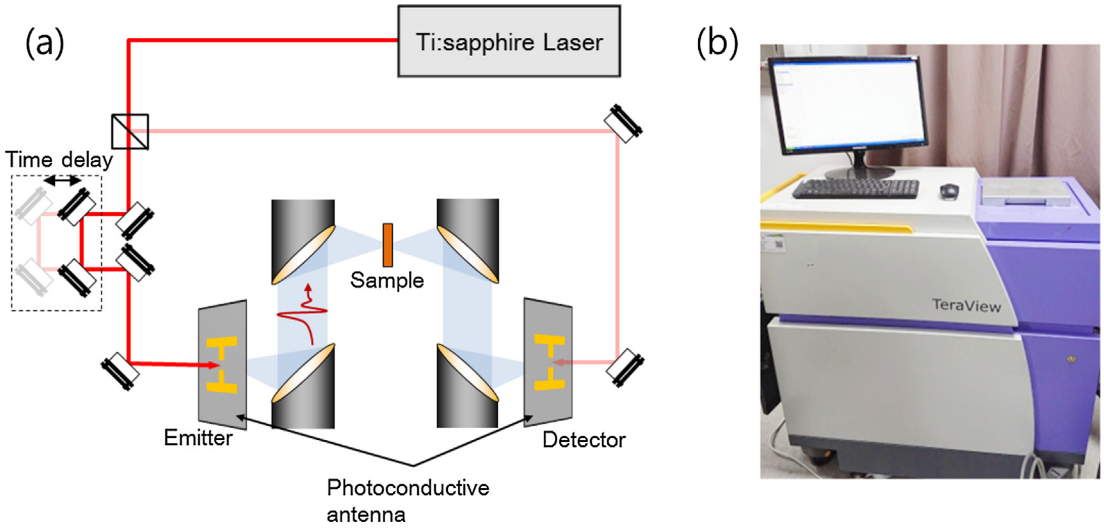

Fig. 1. (a) Schematic of the conventional THz time-domain spectroscopy and (b) the commercial THz system (TPS-3000, Teraview, UK).