Nondestructive measurement of layer structures in dielectric substrates by collimated terahertz time domain spectroscopy

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Abstract: This paper reports the measurement results, obtained by terahertz (THz) time-domain spectroscopy (TDS), for a dielectric substrate used in high-frequency components. The results demonstrate that the present THz-TDS measurement system, which uses collimated THz waves, can be used to nondestructively observe the layer structure of the substrate. The measured layer thicknesses agree with the values obtained through cross-sectional optical micrographs of the dielectric substrate. The relative dielectric constant of the substrate is also estimated from the time-of-flight of the observed waves reflected at the front and back of the substrate surfaces.

Keywords: THz, time-domain spectroscopy, TDS, substrate

Classication: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

The recent explosive growth in communication traffic has increased the demand for the use of high-frequency bands for wireless communication systems. A higher accuracy is required for antennas and radio frequency (RF) components using high-frequency bands than those using low-frequency bands [1, 2]. Thus, there is a need to characterize the state of the dielectric substrate used for high-frequency antennas and components [3]. Terahertz (THz) radio waves have received much attention in the sensing of various materials because THz waves are situated in between radio and light waves and there are many materials that exhibit specific reflection and diffraction characteristics for THz waves [4]. Many studies have been conducted on THz imaging [5], and THz time-domain spectroscopy (TDS) has been recognized as an effective measurement method to characterize materials nondestructively [6, 7, 8, 9, 10]. In THz-TDS, the target is irradiated with THz pulses, and the time-of-flight characteristics of the pulses, which pass through the dielectric substrate or are reflected on and in the substrate, are analyzed.

For a detailed characterization of substrates that are widely used for RF components and planar antennas, this paper reports the bulk properties of a conventional substrate, as measured by THz-TDS. In this measurement, the collimated THz pulse wave is used as the transmitting wave illuminating the substrate, and the THz pulse reflected by the substrate is analyzed.

2 Measurement setup

Fig. 1 shows the configuration and a photograph of the measurement setup. Details of the measurement system have been described in [11]. As mentioned above, the present THz-TDS system uses collimated THz waves, instead of focused THz waves. The use of collimated waves increases the measurement area and depth in each measurement. In this measurement, the transmitter (TX) and receiver (RX) are located at $\theta_T = 30^\circ$ and $\theta_R = -30^\circ$, respectively, and the distance between the substrate and TX $r_T$ and that between the substrate and RX $r_R$ are both 120 mm.
The substrate under test is irradiated with impulse THz waves collimated by the lens, and the reflected waves were received at the receiver. The half-value angles of both the TX and RX antennas are about 3.0°.

![THz-TDS measurement system](image)

**Fig. 1.** THz-TDS measurement system: (a) configuration, (b) photograph.

Fig. 2 shows an example of the illuminated time pulse signal and its amplitude spectrum. This was measured with the TX and RX in a straight-line alignment such that the RX directly receives the transmitting wave from the TX. The distance between the TX and RX antennas is measured to be 200 mm. As can be seen in Fig. 2, the spectrum of the pulse extends to around 1.7 THz and the peak of the amplitude spectrum is observed at about 0.4 THz, which corresponds a wavelength of 0.75 mm.

![Injected pulse](image)

**Fig. 2.** Injected pulse: (a) time pulse signal, (b) amplitude spectrum.

### 3 Measured substrates

The substrate used in this measurement is made of a ceramic-filled, glass-reinforced hydrocarbon-based material (hereafter, “hydrocarbon substrate”). Its thickness is 1.6 mm. A 2-mm-thick acrylic plate is also measured for comparison. Photographs
of the hydrocarbon substrate and the acrylic plate are shown in Fig. 3. The dielectric constant of the hydrocarbon substrate is 3.3 at 10 GHz, and the typical dielectric constant of acrylic ranges roughly between 3 and 5. In the present measurements, the cases in which the metal plate is placed behind the hydrocarbon substrate or acrylic plate are tested as well.

![Photograph of target substrate: (a) hydrocarbon substrate, (b) acrylic plate.](image)

Fig. 3. Photograph of target substrate: (a) hydrocarbon substrate, (b) acrylic plate.

### 4 Derivation of dielectric constant

In this paper, the dielectric constant of the hydrocarbon substrate is examined on the basis of the measured pulse. The dielectric constant is obtained as follows. Since the THz wave radiating from the TX antenna hits the substrate with an incident angle $\theta_T$, as shown in Fig. 1 and 4, and the refractive index of air is 1, the angle of refraction $\theta_1$ of the hydrocarbon substrate satisfies Eq. (1) via Snell’s law.

\[
\sqrt{\varepsilon_1} \sin \theta_1 = \sin \theta_T,
\]

where $\varepsilon_1$ is the dielectric constant of the hydrocarbon substrate. Since $\theta_T$ is 30° in this measurement, Eq. (1) can be rewritten as

\[
\sin \theta_1 = \frac{1}{2 \sqrt{\varepsilon_1}}.
\]

Fig. 4. Path of the THz pulse wave in the substrate.

Here, the path length and time of the THz pulse traveling in the hydrocarbon substrate are denoted by $2r$ and $\Delta t$, respectively, and the thickness of the substrate
is denoted by \( d \), as shown in Fig. 4. The relationship between \( r \) and \( d \) can be expressed by

\[
d = r \cos \theta_1. \tag{3}
\]

Substituting Eq. (2) into Eq. (3) by using the relationship \( \cos \theta_1 = \sqrt{1 - \sin^2 \theta_1} \),

\[
r = \frac{d}{\sqrt{1 - \frac{1}{4\varepsilon_1}}}. \tag{4}
\]

On the other hand, the following relationship is satisfied between the path length \( 2r \) and time \( \Delta t \) in the substrate.

\[
2r = \frac{c\Delta t}{\sqrt{\varepsilon_1}}, \tag{5}
\]

where \( c \) is the speed of light. Substituting Eq. (5) into Eq. (4), the dielectric constant of the hydrocarbon substrate can be obtained via

\[
\frac{c\Delta t}{2\sqrt{\varepsilon_1}} = \frac{d}{\sqrt{1 - \frac{1}{4\varepsilon_1}}}. \tag{6}
\]

Taking the square of Eq. (6),

\[
\frac{(c\Delta t)^2}{4\varepsilon_1} = \frac{d^2}{1 - \frac{1}{4\varepsilon_1}}
= \frac{4d^2}{(c\Delta t)^2} \cdot \frac{1}{4\varepsilon_1 - 1}
= \left( \frac{4d}{c\Delta t} \right)^2 \cdot \frac{\varepsilon_1}{4\varepsilon_1 - 1}
= a \cdot \frac{\varepsilon_1}{4\varepsilon_1 - 1}, \tag{7}
\]

where \( a = (4d/(c\Delta t))^2 \). Eq. (7) can be reorganized as a quadratic equation in \( \varepsilon_1 \):

\[
a\varepsilon_1^2 - 4\varepsilon_1 + 1 = 0. \tag{8}
\]

The dielectric constant is the solution to this quadratic equation. Thus, the dielectric constant can be obtained if \( d \) and \( \Delta t \) are known.

### 5 Results

Fig. 5 shows the received time pulses during measurement of the hydrocarbon substrate and acrylic plate by the THz-TDS system. Figs. 5(a) and (b) are the cases of the hydrocarbon substrate and acrylic plate, respectively. The black solid line represents the case with a metal plate behind the hydrocarbon substrate or acrylic plate, and the red dotted line represents the case without the metal plate. The first peak in the pulse corresponds to the reflected wave on the front surface of the substrate or plate. In the case of the acrylic plate, another response is observed at around 30 ps. The fact that this response is magnified and reversed upon placing the metal plate confirms that this is the response at the other side of the plate surface.
On the other hand, many responses are observed in the case of the hydrocarbon substrate. The case with the metal plate behind the substrate in Fig. 5(a) reveals that the response at the opposite surface is roughly at 30 ps, while in the absence of the metal plate, the response at the opposite surface is not clear.

Fig. 6 shows a cross-sectional optical micrograph of the hydrocarbon substrate. Seven layers can be observed in this figure. The dielectric constant of the hydrocarbon substrate is calculated from the received pulse response via Eq. (8). The time difference between the pulses reflected on the front and back surfaces of the substrate is 19.5 ps. Thus, the dielectric constant of the hydrocarbon substrate is found to be 2.99. This is smaller than the value at 10 GHz.

The magenta dots in Fig. 5(a) represent the estimated arrival times of the pulses reflected at the front and back sides, and the boundaries between the layers of the hydrocarbon substrate calculated from the optical micrograph. The estimated dielectric constant is used to calculate the arrival times. As shown in this figure, the estimated arrival times from the boundaries between the layers agree with the lower-side peaks of the received pulse response. Table I shows the thickness of each layer, estimated by the peaks close to the magenta dots in the measured pulse. The table also shows the thicknesses obtained from the optical micrograph. The differences between these two sets of thickness values are less than 0.02 mm, which
corresponds to 0.03 wavelengths at the peak frequency (0.4 THz) in the pulse spectrum. Since the boundaries between adjacent layers are not clear in the micrograph, there will be errors associated with the thicknesses obtained from the micrograph. In addition, since the hydrocarbon substrate is composed of several distinct layers, the dielectric constant of each layer may be different. These factors can help to explain the discrepancy between the thickness values. However, since the difference is within 0.02 mm, the dielectric constant of each layer is almost the same. Thus, it can be said that the layers in the hydrocarbon substrate can be measured nondestructively by using the THz-TDS measurement system.

### Table I. Layer thicknesses estimated from pulse peaks and micrograph

| Layer number | Thickness (pulse) | Thickness (micrograph) |
|--------------|-------------------|------------------------|
| #1           | 0.17 mm           | 0.16 mm                |
| #2           | 0.26 mm           | 0.24 mm                |
| #3           | 0.25 mm           | 0.26 mm                |
| #4           | 0.26 mm           | 0.24 mm                |
| #5           | 0.26 mm           | 0.28 mm                |
| #6           | 0.27 mm           | 0.26 mm                |
| #7           | 0.16 mm           | 0.18 mm                |

6 Conclusion

This paper reported the measurement results obtained by THz time-domain spectroscopy for a hydrocarbon substrate used for high-frequency components. By using collimated THz waves in the THz-TDS measurements, the layer structure of the hydrocarbon substrate was observed. The comparison between the cross-sectional optical micrograph of the substrate and the pulse response demonstrated that the layer structure can be characterized nondestructively through THz-TDS measurement.

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