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Desiccation of biological tissue measured by photonic millimeter-wave ellipsometry

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Abstract: The temporal variations of the complex relative dielectric constants for water-containing materials in the desiccation process have been measured by photonic millimeter wave ellipsometry. Both the real and imaginary parts decrease exponentially with time due to water evaporation from the samples. It is found that the variation of the imaginary part for a biological tissue sample is more gradual than that of the real part, reflecting the temporal change of the water distribution in the sample.

Keywords: ellipsometry, millimeter wave, UTC-PD, biological tissue

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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Millimeter/submillimeter (mm/sub-mm) waves have been used for a variety of applications, such as industrial inspections [1] and medical diagnoses [2]. These have been accomplished either by mm/sub-mm wave imaging or spectroscopy. The former measures the absorption and reflection of the mm/sub-mm waves by a sample, while the latter measures the resonant energy levels corresponding to various intermolecular forces in the sample. Especially for biological substances, a large water content is characteristic, and this content has a large absorption coefficient [3] as well as specific resonant energies in the mm/sub-mm wave range. These features are important for medical diagnoses since some diseases may influence water content in biological tissue [4].

There is another promising technique for measuring the properties of water-containing materials, that is, mm-wave ellipsometry [5], with which we can non-invasively measure the complex relative dielectric constant. This technique provides more quantitative information compared with imaging, and its system is simpler and less expensive compared with time-domain spectroscopy. In addition, the use of photonically generated continuous waves enables a shorter acquisition time and a compact measurement head for ellipsometry due to the system's relatively larger average power level than pulsed signals [6] and the feature of photonics devices of being connected with a flexible optical fiber.

In this paper, we report on an application of mm-wave ellipsometry in which photonically-generated continuous mm-waves were used on samples in the desiccation process. The obtained time dependences of the complex relative dielectric constant revealed the changes in the content and distribution of water in biological tissue.

Figure 1 shows a schematic diagram of the ellipsometry system we used in the experiments [5]. Two light signals generated by two laser diodes operating at around 1.55 μm with slightly different frequencies are combined by adjusting the polarizations with a polarization controller (PC) and amplified by an Erbium doped fiber amplifier (EDFA). Then, the optical signal is fed to an F-band waveguide-output uni-traveling-carrier photodiode (UTC-PD) module [7], and the UTC-PD module converts the optical signal to a mm-wave having a frequency corresponding to the frequency difference of the two light signals. The frequency of the mm-wave used in this study was 120 GHz. The linearly polarized mm-wave is emitted through a pyramidal horn antenna

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to a sample with an angle of 45 degrees against the plane of incidence, and an F-band Shottky barrier diode (SBD) module with a pyramidal horn antenna attached on a rotation stage detects the reflected signal. The output voltage of the SBD for a load resistance of 100 kΩ is recorded at each angle, and this angle dependence is numerically analyzed to obtain the complex relative dielectric constant for a certain time span. The power density of the incident mm-wave was sufficiently low, typically $3\sim4\,\mu W/(cm)^2$ at the sample surface, thus the rise of the sample temperature by the mm-wave irradiation is considered to be negligible.

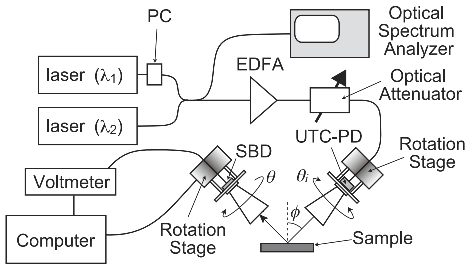

Fig. 1. Schematic diagram of the millimeter-wave ellipsometry system

To clarify the behavior of the relative dielectric constant in the basic desiccation process, we first measured a foamed polyurethane sample (5-mm thick) soaked with water. Due to the microscopic structure of the sample, only the near-surface regions of the sample absorbed moderate water content at the beginning. To decrease the evaporation speed, we covered the sample surface with a thin (10-μm thick) polyvinylidene chloride (PVDC) film having an array of small holes (0.5 mm in diameter at an interval of 5 mm). Figure 2 shows the obtained time dependence of the complex relative dielectric constant.

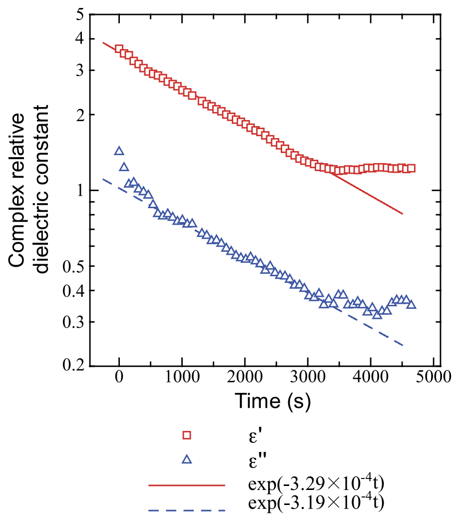

Fig. 2. Time dependence of the dielectric constant of a foamed polyurethane sample soaked with water

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Both the real (ϵ') and imaginary (ϵ'') parts decreased exponentially with time and became constant after about 3500 s. The solid and broken lines in the figure were fitted assuming the exponential decrease with time, and the obtained slopes for these log-log plots were nearly the same. The values after about 3500 s agreed well with the ones of the dry foamed polyurethane sample measured separately. We also confirmed that the sample used in Fig. 2 was dried after about 3500 s. These results indicate that the time dependence shown in Fig. 2 was basically due to the evaporation of the water from the sample surface.

The exponential decrease should be reasonable if the amount of evaporation is proportional to the total amount of the water in the sample. Meanwhile, the slopes of the real and the imaginary parts depend on the form of the water in the surface region. Generally, the imaginary part of the dielectric constant depends on both the total amount of the water and the conductivity of the sample, while the real part depends only on the total amount of the water. The almost the same slopes for the real and the imaginary parts in Fig. 2 suggest that the water was distributed sparsely in the sample. If the water existed as droplets with an average size much smaller than the wavelength of the incident mm-wave signal and with distances wide enough to suppress the capacitive coupling between droplets, the existence of the water would not significantly influence the conductivity of the sample. Such a situation will hold true in a relatively dried condition. Therefore, both the real and the imaginary parts of the dielectric constant should depend only on the total amount of the water, as shown in Fig. 2.

Next, as an example of biological materials, we measured the complex relative dielectric constants for a piece of bovine tissue (7-mm thick). As shown in Fig. 3, both the real and the imaginary parts of the relative dielectric constant decreased exponentially.

These results can also be explained by the evaporation of water from the

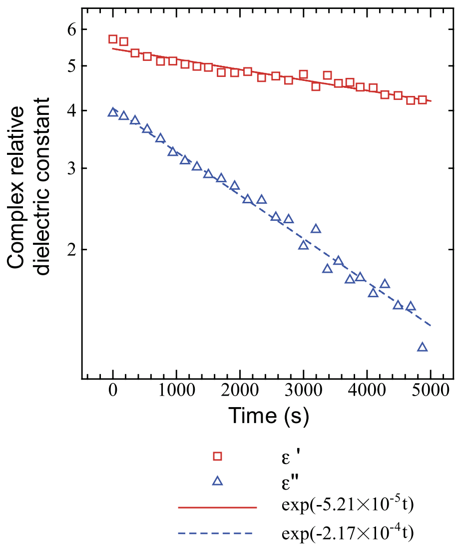

Fig. 3. Time dependence of the relative dielectric constant for bovine tissue

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sample. However, the slopes of the real and the imaginary parts in this log-log plot were apparently different. This is qualitatively different from the results shown in Fig. 2. The more rapid decrease of the imaginary part compared with the real part suggests that the conductivity of the sample decreased as the desiccation process advanced.

In biological tissue, water exists in cells (as intercellular fluid) and out of cells (as extracellular fluid). Those fluids are mostly constituted by water [8, 9], and thus the relative dielectric constants of both fluids are supposed to be nearly the same order as that of water ($\epsilon \sim 10$). Although cell membrane has relatively low conductivity, these intercellular and extracellular fluids make capacitive coupling and thus contribute to the conductivity, especially at higher frequencies. However, in the desiccation process, the extracellular fluid evaporates more rapidly than the intercellular fluid since the intercellular fluid is surrounded by the cell membrane. If the extracellular fluid were replaced by air ($\epsilon \sim 1$), the capacitive coupling among the cells would be decreased considerably. Although the actual decrease of the extracellular fluid would be more gradual and the cells would still maintain capacitive coupling among themselves due to their relatively short distances, the decrease in the extracellular fluid should gradually decrease the total conductivity of the tissue. This explains the more rapid decrease in the imaginary part of the relative dielectric constant than in the real part, as shown in Fig. 3.

These results indicate that information on the complex relative dielectric constant may provide insights into the conditions in biological materials through the behavior of water in the tissue. Thus, mm-wave ellipsometry is expected to become an important technique for future medical diagnoses.

In summary, we measured the time dependence of the complex relative dielectric constant for water-containing materials in the desiccation process by using mm-wave ellipsometry based on photonics technology. The relative dielectric constant was confirmed to decrease exponentially with time due to the evaporation of water from the sample. It was found that the temporal variation of the imaginary part for the bovine tissue sample was more gradual than that of the real part, indicating that the change in water distribution in biological tissue can be measured by mm-wave ellipsometry.

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