Functional assessment of water sorption–desorption for frequency-dependent skin penetration depth of terahertz radiation

Borwen You[1], Ja-Yu Lu[2], Chin-Ping Yu[3], Pei-Hwa Wang[4]

[1]Department of Applied Physics, Faculty of Pure and Applied Sciences, University of Tsukuba, Ibaraki 305–8573, Japan
[2] Department of Photonics, National Cheng Kung University, Tainan 70101, Taiwan
[3]Department of Photonics, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan
[4]Department of Animal Science and Technology, National Taiwan University, 106 Taipei, Taiwan
E-mail: you.borwen.gt@u.tsukuba.ac.jp

1. Introduction

Terahertz (THz) radiation can be applied to distinguish diseased skin from normal skin based on its water-sensitive response, which appears in the time-domain waveforms or dielectric constant spectra of skin in a reflective THz time-domain spectroscopy (TDS) [1]. The skin penetration depth of THz radiation determines the sensitivity of the THz–TDS system to pathological tissues. The high sensitivity of the THz–TDS system, in particular, is required for the early diagnosis of skin cancer. The skin penetration depth of THz radiation is determined as the reciprocal of THz absorption coefficients measured from THz wave transmission in the skin [2]. However, THz absorption coefficients that are derived from reflected THz waveforms cannot provide the exact skin penetration depth of THz radiation. The issue is that the Fresnel reflection principle of a single-layer skin surface, used to analyze the reflected waveforms, ignores wave interference in the multilayered internal structure of the skin [3]. Moreover, the frequency-dependent skin penetration depth of THz radiation has not been explored through reflective THz–TDS. In the presentation, the frequency-dependent skin penetration depths of THz radiation are experimentally characterized by analyzing the interference effects of THz waves in a multilayered water–skin structure and are numerically verified through finite-element method simulation.

2. Sample preparation for water sorption–desorption

To easily observe the THz interference effect in the multilayered skin structure, a water overlayer is dripped on the surface of a porcine skin sample. Figures 1(a) and 1(b) show the sample cell to load a porcine skin and there is one operation window to expose the skin surface for one water overlayer and THz radiation. When the water overlayer gradually desorbs or evaporates with time, the dynamic variations of THz wave reflectivity from the water–skin composite medium are measured. Based on the condition without damaging the skin, the inner water contents of the skin were further treated by the hot air flow (40 °C) to observe THz reflectivity as shown in Fig. 1(c).

To modify the dielectric properties of skin samples, we damaged the skin layers that include the stratum corneum (SC) and partial epidermis through treatments with boiling water, freezing at −85 °C and thawing. The SC contains a dense network of keratin, a type of protein that prevents water evaporation from the skin [4]. Keratin can be denatured through boiling, and the formation of ice crystals through freezing at −85 °C causes massive membrane disruption. Hence, the damaged skin surface after thawing drastically shrinks upon exposure to ambient atmosphere. Figure 1(d) shows that the damaged skin surface shrinks and darkens during water evaporation. By contrast, the undamaged (normal) skin exhibits completely preserved surface morphology and does not shrink during natural evaporation.

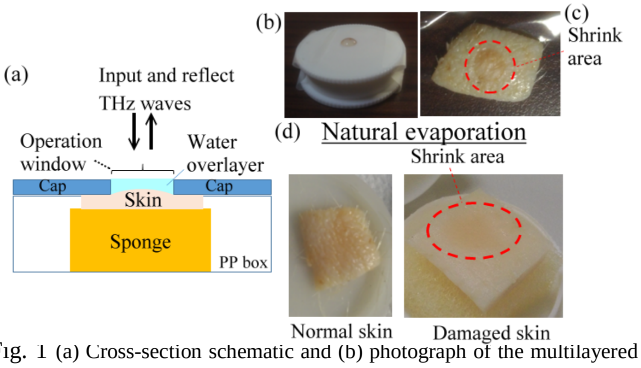

Fig. 1 (a) Cross-section schematic and (b) photograph of the multilayered water–skin sample in a sample holder. (c) Photograph of skin sample dried under hot air flow. (d) Photographs of normal and damaged skin samples during natural evaporation.

3. Sensing results

The sensing results show that the 0.1–0.9 THz waves have skin penetration depths of 0.1–0.3 mm and those waves with 0.4–0.6 THz frequencies especially have the maximum skin penetration depth of 0.3 mm. To confirm the maximum penetration depths of THz waves and to validate the multilayered skin model, the skin surface is further damaged with boiling water and freezing at –85 °C to induce massive membrane disruption [Fig. 1(d)], thereby forming a large porous space in the skin surface with a high water content. The porosity or water content of the damaged skin tissue with a thickness of 0.1 mm is nearly 80% and thus approximates a water-like tissue layer at the skin surface. The observation thus shows that 0.4–0.6 THz waves can pass through the outermost water-like tissue layer without obvious wave amplitude fluctuation during the water desorption on the damaged skin.

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