Sensitive measurement of water content in dry material using low-frequency terahertz time-domain spectroscopy system equipped with micro-structured photoconductive antennas

Takeshi Yasui\textsuperscript{1,2} and Tsutomu Araki\textsuperscript{2}

\textsuperscript{1}Inst. Tech. Sci., Univ. Tokushima, Japan
\textsuperscript{2}Grad. Sch. Engg. Sci., Osaka Univ., Japan

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What is THz electromagnetic pulse?

THz region: 0.1~10 THz (30μm~3mm)
(undeveloped electromagnetic region)

THz electromagnetic pulse (THz pulse)
triggered by femtosecond pulse laser

- Free-space propagation
- Excellent transmittance to nonmetal material
  - (paper, ceramics, plastic, tissue, etc)
- Coherent beam
- Considerably low scattering
  - because of λ in THz wave = sub-mm~mm
- Low energy and low invasion
- Ultrashort pulse
- Wide spectral width
- Strong absorption of water
  - due to orientation polarization of polar water molecule
- Spectroscopy and imaging

Blue characteristics are advantageous to water content measurement in dried material!
Sensitive measurement of water content is required for quality control of dry materials (dried foods, industrial products, etc).

Conventional methods

1. Weight measurement with electronic balance
   Non-contact, remote monitoring of water content is difficult!

2. IR spectroscopy
   Strong IR absorption due to vibrational polarization of water molecule!
   Limited to transparent materials because of scattering in turbid material!

3. THz time-domain spectroscopy (THz-TDS) New!
   Strong THz absorption due to orientation polarization of polar water molecule!
   Considerably low scattering are effective for turbid material!
   Too strong THz absorption of water (= 230 cm\(^{-1}\) at 1 THz) at high-frequency THz region (>1 THz)
   often demands on limitations on samples, such as considerably thin or dry.

To improve limitations on samples using moderate absorption of water at low-frequency THz region

Present talk
Sensitive measurement of water content in dry materials based on low-frequency THz-TDS
Experimental setup

Use of bow-tie shape antenna as a THz emitter and detector to achieve sensitivity in the low-frequency THz region less than 0.3 THz

Major modification

Δτ=80fs, λ_c=808nm, P=300mW, f=87 MHz
Basic performance

Water content measurement

THz Time-Domain Spectroscopy (THz-TDS)

Fourier Transform

Amplitude spectrum

Phase spectrum

Temporal waveform
Transmittance spectrum of pure water

THz wave over 0.1 THz is disappeared by broadband, strong absorption of water. THz absorption at 0.07 THz is used for quantification of water content.
Good correlation between water thickness and THz absorption at 0.07 THz. Amount of water content is calibrated from THz absorption using this relationship.
Drying progress of wet tissue paper

To evaluate performance of THz-TDS for water content measurement

Comparison with an weight method using an electronic balance
Good correlation between the two methods indicates good performance of water content measurement using THz-TDS.
Water content in adhesive for wood

Evaluation of hardening degree of adhesive

Hardening caused by evaporation of water @ adhesive for wood

Non-contact monitoring of adhesive hardening using THz absorption of water
Difference of THz absorption spectra before and after hardening of the adhesive is obvious.
Gradual decrease of THz absorption indicates slow evaporation of water, and hence slow hardening of adhesive. Temporal change of THz absorption is stopped at 70 min, which implies completion of adhesive hardening.
Water content in instant coffee powder

Excessive water content in dried food

Rotting or mold of food!

In-process monitoring of a very small amount of water content is required for strict quality control of dried food!

Direct, remote monitoring of water content in bottled instant coffee powder
Water content in instant coffee powder (1)

THz transmittance spectra

Empty glass bottle strongly absorbs THz wave > 0.1 THz because of water in the glass.

THz wave < 0.1 THz is not significantly absorbed and scattered by coffee powder.

Low-frequency THz-TDS is available for water content measurement.
Water content in the bottled coffee powder increased by forced humidifying

THz transmittance spectra of bottled coffee powder

Before forced humidifying

Water content=7.5mg/cm$^3$
Detection limit=1.0mg/cm$^3$

After forced humidifying for 3.5h (>90%RH)
Summary

(1) Sensitive measurement of water content in dried materials using low-frequency THz-TDS

(2) Basic performance
   >High correlation with a electronic-balance weight method
   >Detection limit = 1mg/cm$^3$ at coffee powder measurement

(3) Application
   >Hardening monitoring of adhesive for wood
   >Quality control of instant coffee powder in a glass bottle

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