



Increase the sensitivity of terahertz liquid detection using a triple attenuated total reflection probe

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Abstract: Terahertz attenuated total reflection (ATR) technique serves as a pivotal tool for the spectroscopic analysis of liquids. However, when measuring liquids, conventional single internal reflection probes exhibit low sensitivity and detection accuracy due to the limited interaction between the evanescent wave and the sample. To address this limitation, we designed and constructed a terahertz liquids ATR probe utilizing a triple internal reflection prism, which effectively enhances the interaction between the evanescent wave and the liquid by increasing the number of reflections within the prism. Experimental results demonstrate that the terahertz triple ATR probe achieves high accuracy in measuring the sample's optical constants. By exploiting the differences in terahertz wave absorption among different polar solvents, the proposed probe effectively recognizes polar solvents such as ethanol, water, isopropanol, and acetone. In terms of sensor performance, the sensitivity of our probe, which employs a triple internal reflection scheme, is three times that of a conventional single internal reflection probe. This increased sensitivity further enhances the accuracy of measuring small changes in solution composition.

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1. Introduction

Terahertz waves typically refer to electromagnetic radiation with frequencies ranging from 0.1 to 10 THz. Over the past two decades, terahertz time-domain spectroscopy (THz-TDS) has become increasingly popular for nondestructive testing applications, due to its low energy, high temporal resolution, and strong penetration capabilities. In pharmaceutical manufacturing, THz-TDS is used to detect defects in tablets or composite structures [1–3], which aids in the evaluation of compression quality. For composite materials, it measures the thickness of specialized components [4–6], which facilitates the evaluation of the uniformity of material thickness. THz-TDS can be categorized into transmission and reflection modes, depending on the properties of the test object. Transmission systems are primarily used for low-absorption samples, such as organic compounds and semiconductors [7–9]. Recently, THz-TDS combined with metasurfaces has been utilized for high-absorption samples in the transmission mode due to enhanced light-matter interaction [10,11]. However, micro-scale metasurfaces involve complex fabrication and high costs. Initially, terahertz time-domain attenuated total reflection (THz TD-ATR) systems were developed for analyzing liquids or biological solutions with high terahertz absorption [12,13]. Recently, these systems have been adapted for measuring powdery substances and low-absorbing liquids in laboratory settings, due to their minimal sample handling requirements [14,15]. THz TD-ATR spectroscopy represents a significant advancement over traditional methods by providing enhanced sensitivity through asymptotic field detection

[16]. In commercial applications, Hamamatsu Photonics' ATR products are now being used in production sites for chemicals and food products, demonstrating the potential of ATR technology for real-world applications.

In 2006, Nagai et al. first proposed the THz TD-ATR system [17], which comprises a THz-TDS system and an ATR prism configured in the transmitted light path. A liquid sample is added dropwise into the cell above the prism. The terahertz beam strikes the prism at a specific angle, causing total internal reflection at the prism-sample interface. By detecting and analyzing the reflected terahertz beam, optical information about the sample can be extracted. Subsequently, various research groups have developed different systems around ATR sensors. In 2012, Nakanishi et al. proposed an integrated prism system to reduce Fresnel loss at the interface [18]. In 2016, Soltani et al. introduced an ATR system based on Dowell prisms for online monitoring of industrial high-absorption liquids [19]. In 2019, Huang et al. proposed a dual prism system for rapid measurements [20]. In 2023, Fu et al. developed a microfluidic ATR system specifically designed to minimize fluid consumption [16]. During the same year, the research team further utilized this system and successfully investigated the effects of nicotine on normal and cancerous neural cells [21]. As analytical techniques gradually transition from laboratory settings to industrial manufacturing processes, traditional single reflection methods exhibit limitations in detection. Firstly, single reflection probes demonstrate low spectral contrast for samples with low absorption [22,23], posing challenges for analysis because the intensity of the evanescent wave at the interaction interface decays exponentially at very shallow surface depths, with interaction distances on the order of wavelengths [24]. Secondly, lower spectral intensities result in a decrease in sensitivity, as evidenced by a diminished ability to recognize subtle variations in the sample components and an increased susceptibility of the system to ambient noise and instrumental fluctuations. Therefore, there is a need to enhance the signal intensity of the samples acquired in the system of interest, in order to augment the sensitivity of the internal reflection spectroscopy.

To improve the sensitivity of ATR spectroscopy for liquid detection, we designed and constructed a liquid probe utilizing the principle of multiple reflection. The probe employs a unique prism structure featuring triple internal reflection, specifically designed to enhance the interaction between the evanescent wave and the sample, thereby elevating its sensitivity. In practical applications, the probe demonstrates the ability to measure the optical constant of the sample with high accuracy and to distinguish among commonly encountered polar liquids. In terms of sensing performance, our novel probe demonstrates a sensitivity that is three times higher than that of conventional ATR probe with the same reflection setup. This clear improvement enables it to detect subtle compositional differences in mixed solutions more effectively.

2. System and methods

2.1. Experimental setup

We designed and constructed a terahertz liquid probe using triple attenuated total reflection spectroscopy. The THz-TDS utilizes BT-FTS5500 chassis from B-THz Co., Ltd (Wuhan, China) [25], housing essential optical components, including an all-fiber femtosecond laser, a mechanical delay line, and an acquisition board. Figure 1(A) shows the all-fiber femtosecond laser emitting a pulse with a central wavelength of 1550 nm and an average power of 17 mW. Subsequently, the pulse is converted into a picosecond p-polarized terahertz pulse by an InGaAs photoconductive transmitting antenna. The terahertz pulse is collimated by a TPX lens with a 50 mm focal length and directed by planar metal mirrors onto the incident plane of the ATR prism. Each internal reflection within the ATR prism generates an evanescent wave that interacts with the sample, enhancing the absorption of terahertz waves. After interaction, the terahertz pulse, now containing sample information, exits the prism and is detected by the InGaAs receiving antenna along a symmetric path. The ATR accessory allows for handheld measurements for field testing.

As shown in Fig. 1(B), the ATR probe incorporates a metal base plate, a triple reflection prism, planar metal mirrors, an adjusting bracket, TPX lenses, lens mounts, and antenna mounting sleeves. To ensure high-quality measurements, a metal fixture with an adjustment mechanism was used, and alignment holes on the base plate were incorporated to reduce alignment errors. The ATR prism at the front end of the ATR probe, as shown in Fig. 1(C), is a 7-sided prism with dimensions of 63.6 mm in length, 30 mm in width, and 42.4 mm in height. The propagation length within the prism measures approximately 15 cm. All five optical surfaces of the prism are polished, and it is designed with all three internal reflection angles set at 45 degrees. The prism is securely mounted to the mounting frame using UV adhesive and is connected to the base plate through threaded holes. Constructed from floating-zone high-resistance silicon, the ATR prism exhibits high hardness and chemical resistance, thereby fulfilling the requirements of various industrial applications. Additionally, its high relative refractive index of 3.42 and broad spectral range fulfill the optical requirements necessary for the measurements. Finally, we utilized the blade method to measure the diameter of the terahertz spot incident upon the prism, which was found to be approximately 18.6 mm. Upon emerging from the prism, the diameter of the outgoing spot was approximately 19 mm. The incorporation of the prism into the device led to an attenuation of the terahertz amplitude by roughly 8%.

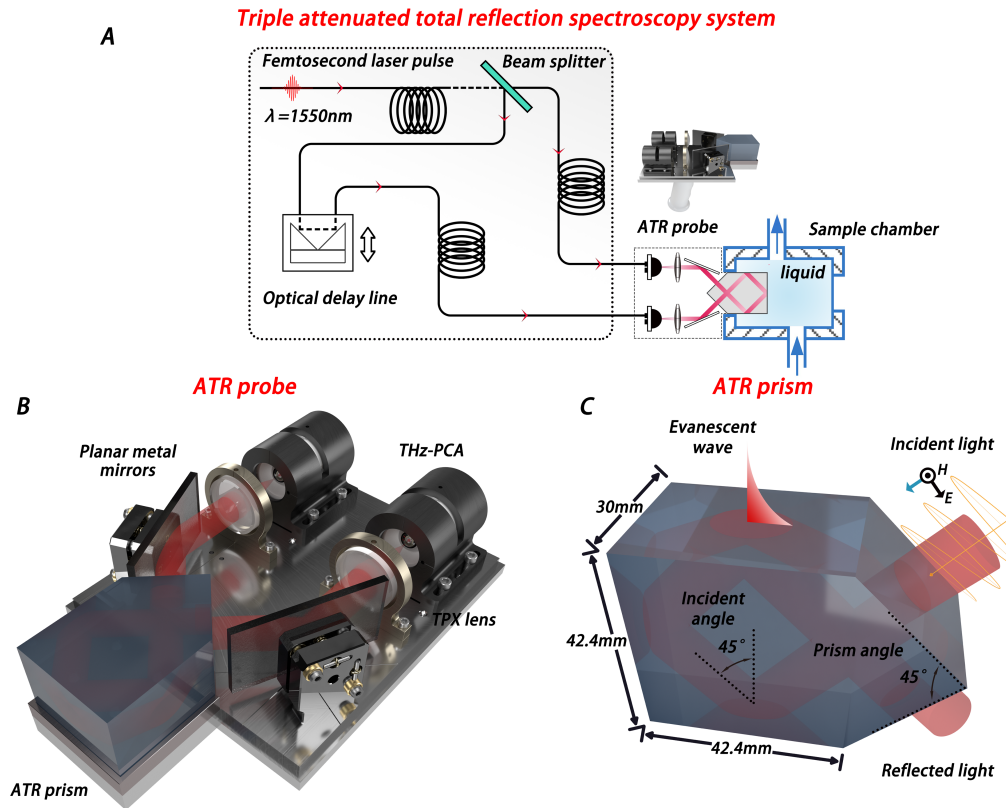


Fig. 1. The THz TD-ATR system (A), ATR probe (B), and ATR prism (C) used in experiments.

After constructing the THz TD-ATR system, we meticulously aligned the planar mirrors and focusing lenses within the ATR probe to ensure that the beam's average angle of incidence on the ATR closely matched the design value. Consequently, by averaging the time-domain signals 1024 times in an indoor environment, our system achieved a terahertz time-domain pulse width of

620 fs and a signal-to-noise ratio of 70 dB (see Fig. 2(A)). In the frequency domain, it exhibited a spectral width of 3.6 THz and a dynamic range of 73 dB (see Fig. 2(B)). The observed spectral depression corresponds to the absorption peak of atmospheric water vapor [26].

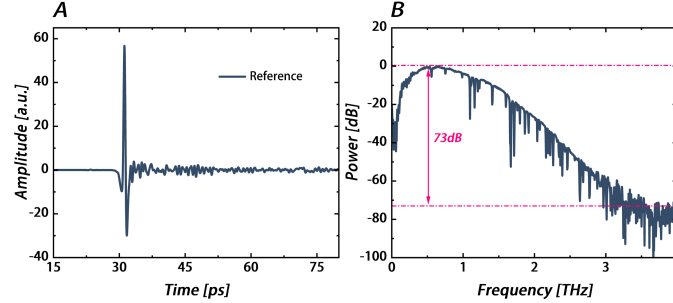


Fig. 2. Terahertz time-domain pulse (A) and frequency-domain spectrum (B) of the reference signal.

2.2. Analytical method

To extract optical information from the sample using signal from multiple internal reflections, the ATR device needs to independently measure both the reference and sample signals. These signals are then transformed into their respective frequency-domain representations, $\tilde{E}_{ref}$ and $\tilde{E}_{sam}$, using a fast Fourier transform. The frequency-domain complex electric field is subsequently calculated as described by Eq. (1), where N denotes the number of internal reflections.

$$\tilde{H}(\omega) = \frac{\tilde{E}_{sam}(\omega)}{\tilde{E}_{ref}(\omega)} = \frac{\tilde{E}_{in}(\omega) \cdot (\tilde{r}_{sam})^N}{\tilde{E}_{in}(\omega) \cdot (\tilde{r}_{ref})^N} = \left(\frac{\tilde{r}_{sam}}{\tilde{r}_{ref}} \right)^N \quad (1)$$

Terahertz waves incident in the p-polarization direction are utilized. The reflection coefficient $\tilde{r}_{sam}$ and $\tilde{r}_{ref}$ are described by the Fresnel equation (Eq. (2)). Here, θ_i denotes the incidence angle of the terahertz wave at the interface, and, θ_t represents its emergence angle.

$$\tilde{r} = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \quad (2)$$

To simplify the equation, we introduce the variable q , defined as $(1 - \tilde{H}(\omega))/(1 + \tilde{H}(\omega))$ [18]. Consequently $\tilde{H}(\omega)$ can be expressed as shown in Eq. (3).

$$\left(\frac{\tan(\theta_i - \theta_{sam})}{\tan(\theta_i + \theta_{sam})} \cdot \frac{\tan(\theta_i + \theta_{ref})}{\tan(\theta_i - \theta_{ref})} \right)^N = \frac{1 - q}{1 + q} \quad (3)$$

Applying a series of mathematical transformations to Eq. (3) yields the result given in Eq. (4), where $\sin \theta_{ref} \cdot \cos \theta_{ref}$ is abbreviated as A and $\sin \theta_i \cdot \cos \theta_i$ is abbreviated as B .

$$\sin \theta_{sam} \cdot \cos \theta_{sam} = \frac{\sqrt[N]{1 - q(A - B)} + \sqrt[N]{1 + q(B + A)}}{\sqrt[N]{1 + q(A + B)} + \sqrt[N]{1 - q(B - A)}} \cdot B \quad (4)$$

Finally, according to Fresnel's law, the complex permittivity $\tilde{\epsilon}_{sam}$ of the sample is given by Eq. (5) [18], where n_{prism} represents the refractive index of the prism.

$$\tilde{\epsilon}_{sam} = \frac{\sin^2 \theta_i \cdot \left(1 - \sqrt{1 - 4(\sin \theta_{sam} \cdot \cos \theta_{sam})^2} \right)}{2(\sin \theta_{sam} \cdot \cos \theta_{sam})^2} \cdot n_{prism}^2 \quad (5)$$

The refractive index n_{sam} and extinction coefficient k_{sam} of the sample can be derived from Eqs. (6) and (7), where ϵ_{sam} and ϵ'_{sam} denote the real and imaginary parts of the complex permittivity, respectively.

$$n_{sam} = \sqrt{\frac{\sqrt{\epsilon_{sam}^2 + \epsilon_{sam}'^2} + \epsilon_{sam}}{2}} \quad (6)$$

$$k_{sam} = \sqrt{\frac{\sqrt{\epsilon_{sam}^2 + \epsilon_{sam}'^2} - \epsilon_{sam}}{2}} \quad (7)$$

Using the extinction coefficient k_{sam} provided in Eq. (7), the absorption coefficient α_{sam} presented in Eq. (8) can be calculated. Here, ω represents the angular frequency, and c represents the propagation speed of terahertz wave in vacuum [27].

$$\alpha_{sam} = \frac{2\omega k_{sam}}{c} \quad (8)$$

The penetration depth d_p is an important parameter for evanescent waves. Terahertz waves undergoing internal reflection interact with the sample, causing the reflected beam to attenuate at specific frequencies, which in turn results in the absorption fingerprint of a particular substance. The expression for d_p is given by Eq. (9) [28].

$$d_p = \frac{\lambda}{2\pi\sqrt{n_{prism}^2 \sin^2 \theta_i - n_{sam}^2}} \quad (9)$$

where λ represents the wavelength of the incident light, the penetration depth of the evanescent wave, as given by Eq. (9), depends on the angle of incidence, the wavelength of the incident light, and the refractive indices of the media adjacent to the interface. When the opposite side of the reflective interface is air, the penetration depth of the evanescent field extending from the reflective surface during a single internal reflection at a frequency of 0.3 THz is approximately 72 μm . With triple internal reflection, the interaction length increases to 216 μm . Given that absorbance is proportional to the concentration of the substance and linearly dependent on the thickness of the sample, this enhancement effect increases the absorbance to three times its original value. Additionally, since the device undergoes three identical instances of single internal reflection, the overall reflectivity of the system is equivalent to the cube of the reflectivity of single reflection.

3. Experiments

3.1. Extraction of optical constants

Optical constants are universal properties of the material under study and can therefore be employed to compare the measurement accuracy of different sensors. We selected pure water, glycerin, and insulating oil as the subjects for comparison in single internal reflection and triple internal reflection measurements, respectively. In the experiments, triple internal reflection measurements were conducted by immersing all three sensing surfaces of the ATR prism in the liquid. For single internal reflection measurements, the same ATR accessory was utilized, but only the outermost sensing surface of the ATR prism was in contact with the liquid. Consequently, the parameters associated with single internal reflection, including the incident spot radius, reflection angle, polarization state, amplitude, and time delay of the reference signal, are nearly identical to those of triple internal reflection. Furthermore, the depth of the liquid exceeded the penetration depth of the evanescent wave in both measurement scenarios [29]. The time-domain signals of these three solvents (see Figs. 3(A), 4(A), and 5(A)) were first measured under indoor

ambient conditions using the constructed probe. We averaged the terahertz reference and sample signals 1024 times, and the measurement for one set of samples can be completed within 4 minutes. The single internal reflection exhibits smaller time-domain amplitude attenuation and changes in time delay. In contrast, the triple internal reflection, with its extended evanescent wave path, provides more pronounced measurements for liquids with weaker absorption. The time-domain signals were processed using the method described in Eqs. (1) to (8). Subsequently, Figs. 3(B) and 3(C), 4(B) and 4(C), and 5(B) and 5(C) present the refractive indices, extinction coefficients, and absorption coefficients of pure water, glycerin, and insulating oil, respectively, in the 0.2-1.6 THz frequency range. The results demonstrate that the refractive indices, extinction coefficients and absorption coefficients obtained from the triple internal reflection are nearly identical to those from the single internal reflection, indicating the high precision of the triple ATR accessory in extracting optical constants.

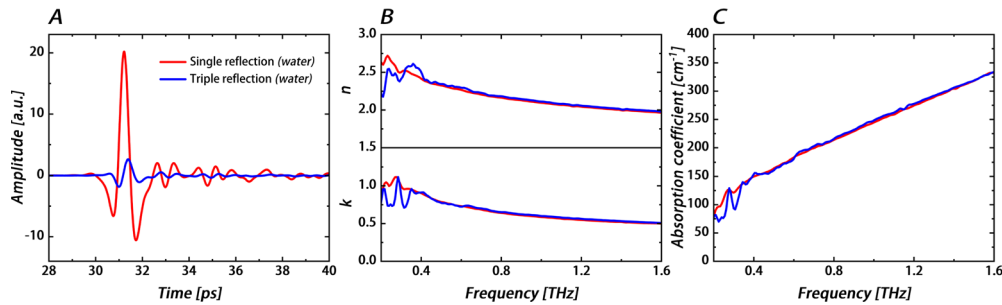


Fig. 3. Terahertz time-domain pulses (A), refractive indices, extinction coefficients (B), and absorption coefficients (C) of pure water, measured using both triple and single internal reflection.

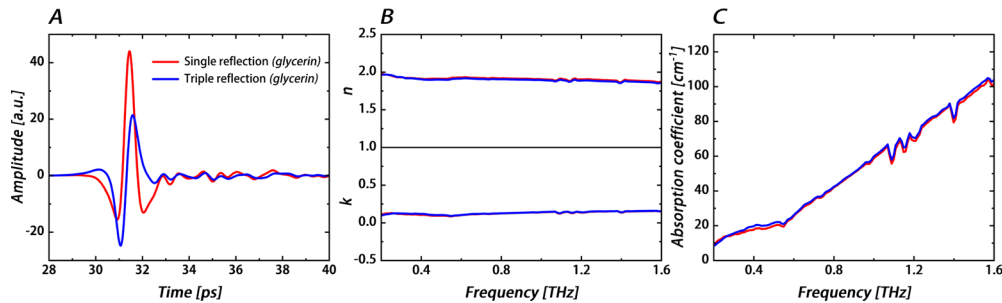


Fig. 4. Terahertz time-domain pulses (A), refractive indices, extinction coefficients (B), and absorption coefficients (C) of glycerin, measured using both triple and single internal reflection.

3.2. Liquid recognition

The above analysis confirms the effectiveness of our proposed method and device for extracting optical constants from multiple internal reflections. In realistic sensing scenarios, the selectivity of the sensor is very important. Depending on the frequency of hydrogen bond breaking and formation events resonate at THz frequencies [30], the number and lifetime of hydrogen bonds in different polar solvents lead to differences in absorption. This property can therefore be utilized for the identification of different polar solvents. We measured pure water, acetone, ethanol, and isopropanol at room temperature using the designed ATR probe, and plotted their

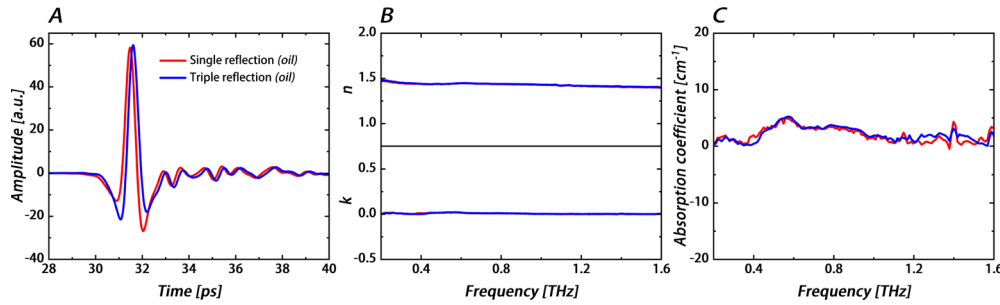


Fig. 5. Terahertz time-domain pulses (A), refractive indices, extinction coefficients (B), and absorption coefficients (C) of insulating oil, measured using both triple and single internal reflection.

absorbance and transmittance curves in the range of 0.2 to 1.6 THz. The absorbance is calculated as $Absorbance = -\log(I(v)/I_0(v))$ [31], where $I(v)$ and $I_0(v)$ denote the intensity responses of the sample signal and the reference signal, respectively, at frequency v . From the absorbance spectra (Fig. 6(A)) and amplitude transmission spectra (Fig. 6(B)) of these four liquids, it is evident that within the frequency range of 0.2-1.6 THz, the amplitude transmittance of water is confined to the range of 0-0.12 due to its strong absorption of terahertz radiation. In contrast, isopropanol exhibits the weakest terahertz absorption among the four solutions, and consequently, the amplitude transmittance of the isopropanol solvent remains within the range of 0.7-0.81. Although the absorption spectra of these four solvents (Fig. 6(A)) do not show a clear fingerprint in the terahertz range, there are significant differences in their absorption rates and absorption trends and magnitudes. Therefore, they can be distinguished from each other by their unique absorption properties in this spectral region.

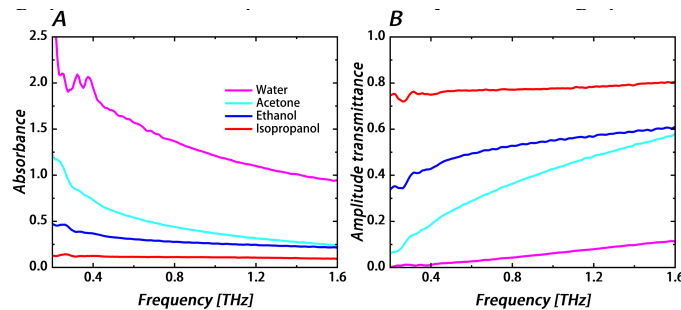


Fig. 6. Absorbance spectra (A) and amplitude transmittance spectra (B) of pure water, acetone, ethanol and isopropanol obtained from measurements at the proposed probe.

Many samples contain moisture during the actual testing process [32]. Therefore, it is necessary to evaluate the enhanced sensitivity of the triple internal reflection probe compared to the single internal reflection probe. We prepared ten aqueous ethanol solutions using room-temperature purified water, with concentrations ranging from 0% to 100% in increments of 10%. The average absorbance of these solutions was measured within a frequency range of 0.4 to 1.4 THz. As illustrated in Fig. 7(A), the average absorbance of the samples progressively decreased with increasing ethanol concentration for both types of reflection probes. We conducted a numerical comparison of the $\Delta A/\Delta C$ ratios for both reflection probes, where ΔC represents the change in concentration and ΔA represents the corresponding change in absorbance. Within the concentration range of 40% to 50%, the sensitivities of the triple and single internal reflection

probes were 0.011 and 0.0036, respectively. This indicates that the triple internal reflection probe is approximately three times more sensitive than the single internal reflection probe, thereby demonstrating its enhanced sensitivity to variations in solution water content. Additionally, we narrowed the concentration range between adjacent solutions to 2% and prepared ethanol-water solutions with concentrations ranging from 100% to 90%. Figures 7(B) and 7(C) present the absorbance profiles for the triple and single internal reflection over the 0.4 to 1.6 THz frequency range. The data reveal a gradual decrease in the slopes of the absorbance curves as frequency increases for all ethanol concentrations. Furthermore, absorbance values within this frequency range increased with increasing water content in the ethanol solutions. Notably, the discrimination between neighboring absorbance spectra improved significantly under triple internal reflection conditions, enhancing the accuracy of identifying subtle changes in solution concentration.

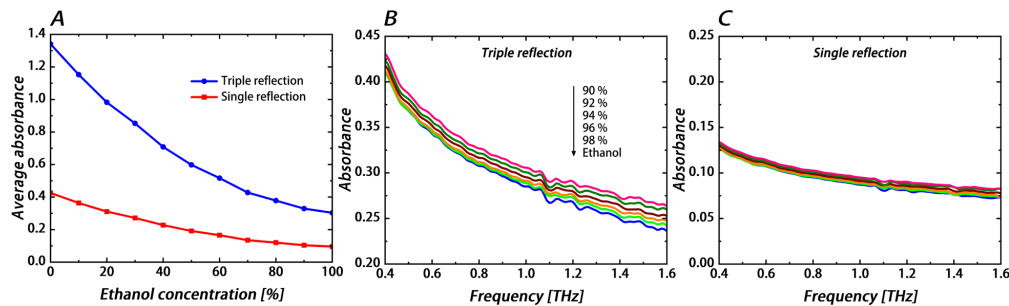


Fig. 7. Average absorbance of ethanol solutions at ten concentrations with 10% increments (A), and absorbance of ethanol solutions at five concentrations with 2% steps between adjacent levels under triple (B) and single (C) internal reflection.

4. Conclusion

This work introduces a THz TD-ATR probe based on triple attenuated total reflection to enhance the sensitivity of ATR spectroscopy for liquid sensing applications. The accessory employs triple internal reflection to extend the interaction distance between the evanescent wave and the liquid, thereby enhancing the sensitivity during the testing process. Under identical 45° setup conditions, the refractive indices, extinction coefficients, and absorption coefficients obtained from triple internal reflection exhibited high consistency with those derived from single internal reflection, as tested with pure water, glycerin, and insulating oil. Further testing was conducted with four polar solvents—pure water, ethanol, isopropanol, and acetone—demonstrating that the designed triple reflection ATR probe could distinguish among them based on their differences in terahertz wave absorption. Finally, we prepared aqueous ethanol solutions with concentrations ranging from 0% to 100% in 10% increments. The results indicated that the slope of the absorbance response of the triple reflection probe to changes in ethanol concentration was approximately three times greater than that of the single reflection probe, suggesting a higher sensitivity of the triple reflection probe to variations in solution concentration. When the concentration range of the ethanol solutions was narrowed down to 90–100% in 2% increments, the increased sensitivity of the triple reflection probe allowed for clearer distinction among these concentrations compared to single reflection, thereby improving the accuracy of identifying solutions with subtle differences.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References

1. P. Bawuah, N. Tan, S. N. A. Tweneboah, *et al.*, "Terahertz study on porosity and mass fraction of active pharmaceutical ingredient of pharmaceutical tablets," *Eur. J. Pharm. Biopharm.* **105**, 122–133 (2016).
2. C. H. Ryu, S. H. Park, D. H. Kim, *et al.*, "Nondestructive evaluation of hidden multi-delamination in a glass-fiber-reinforced plastic composite using terahertz spectroscopy," *Compos. Struct.* **156**, 338–347 (2016).
3. M. Anuschk, A. L. Skelbaek-Pedersen, T. K. Vilhelmsen, *et al.*, "Terahertz time-domain spectroscopy for the investigation of tablets prepared from roller compacted granules," *Int. J. Pharm.* **642**, 123165 (2023).
4. B. Cao, T. Deng, M. Fan, *et al.*, "Physical constraints-based terahertz thickness measurement method of thermal barrier coating," *NDT E Int.* **143**, 103058 (2024).
5. L. Liebermeister, S. Nellen, R. B. Kohlhaas, *et al.*, "Terahertz Multilayer Thickness Measurements: Comparison of Optoelectronic Time and Frequency Domain Systems," *J. Infrared, Millimeter, Terahertz Waves* **42**, 1153–1167 (2021).
6. F. Sun, M. Fan, B. Cao, *et al.*, "Terahertz Based Thickness Measurement of Thermal Barrier Coatings Using Long Short-Term Memory Networks and Local Extrema," *IEEE Trans. Ind. Inform.* **18**(4), 2508–2517 (2022).
7. J. Hu, W. Liu, L. Yang, *et al.*, "Research on classification methods for rubber based on terahertz time-domain spectroscopy with data fusion strategy," *Infrared Phys. Technol.* **139**, 105324 (2024).
8. H. Kim, I. Maeng, C. Kang, *et al.*, "Characterization of proton beam-irradiated silicon using terahertz time-domain spectroscopy," *Curr. Appl. Phys.* **51**, 34–38 (2023).
9. R. Ulbricht, E. Hendry, J. Shan, *et al.*, "Carrier dynamics in semiconductors studied with time-resolved terahertz spectroscopy," *Rev. Mod. Phys.* **83**(2), 543–586 (2011).
10. J. Lyu, L. Huang, L. Chen, *et al.*, "Review on the terahertz metasensor: from featureless refractive index sensing to molecular identification," *Photonics Res.* **12**(2), 194–217 (2024).
11. J. Lv, S. Shen, L. Chen, *et al.*, "Frequency selective fingerprint sensor: the Terahertz unity platform for broadband chiral enantiomers multiplexed signals and narrowband molecular AIT enhancement," *Photonix* **4**, 28–41 (2023).
12. M. Grognot and G. Gallot, "Quantitative measurement of permeabilization of living cells by terahertz attenuated total reflection," *Appl. Phys. Lett.* **107**(10), 103702–103705 (2015).
13. J. Qin, L. Xie, and Y. Ying, "Rapid analysis of tetracycline hydrochloride solution by attenuated total reflection terahertz time-domain spectroscopy," *Food Chem.* **224**, 262–269 (2017).
14. K. Hashimoto and S. R. Tripathi, "Non-Destructive Identification of Drugs in Plastic Packaging Using Attenuated Total Reflection Terahertz Time Domain Spectroscopy," *Optics* **3**(2), 99–106 (2022).
15. D. Crompton and A. Vickers, "Assigning the characteristics of an ATR dove prism for use with terahertz frequencies: supplemented with molecular dynamic simulations," *2012 4th Computer Science and Electronic Engineering Conference*, 47–52 (2012).
16. Y. Fu, T. Chen, L. Chen, *et al.*, "Terahertz time-domain attenuated total reflection spectroscopy integrated with a microfluidic chip," *Front. Bioeng. Biotechnol.* **11**, 1143443 (2023).
17. M. Nagai, H. Yada, T. Arikawa, *et al.*, "Terahertz time-domain attenuated total reflection spectroscopy in water and biological solution," *Int. J. Infrared Millimeter Waves* **27**(4), 505–515 (2006).
18. A. Nakanishi, Y. Kawada, T. Yasuda, *et al.*, "Terahertz time domain attenuated total reflection spectroscopy with an integrated prism system," *Rev. Sci. Instrum.* **83**(3), 033103 (2012).
19. A. Soltani, S. F. Busch, P. Plew, *et al.*, "THz ATR Spectroscopy for Inline Monitoring of Highly Absorbing Liquids," *J. Infrared, Millimeter, Terahertz Waves* **37**(10), 1001–1006 (2016).
20. H. Huang, Q. Liu, L. Zhu, *et al.*, "Dual-prism based terahertz time-domain attenuated total reflection spectroscopy and its application to characterise the hydration state of L-threonine in solution," *Opt. Commun.* **437**, 133–138 (2019).
21. M. Tang, M. Zhang, Y. Fu, *et al.*, "Terahertz label-free detection of nicotine-induced neural cell changes and the underlying mechanisms," *Biosens. Bioelectron.* **241**, 115697 (2023).
22. F. M. Mirabella, "History of Internal Reflection Spectroscopy," in *Internal Reflection Spectroscopy: Theory and Applications* (CRC Press, 1992), pp. 1–16.
23. M. Milosevic, "Introduction to Spectroscopy," in *Internal Reflection and ATR Spectroscopy* (John Wiley & Sons, Inc, 2012), pp. 1–19.
24. Dexheimer, "Terahertz time domain spectroscopy with photoconductive antennas," in *Terahertz Spectroscopy: Principles and Applications*, S. L. Dexheimer, ed. (CRC Press, 2008), pp. 1–39.
25. <https://www.b-thz.com>.
26. L. Liebermeister, S. Nellen, R. B. Kohlhaas, *et al.*, "Optoelectronic frequency-modulated continuous-wave terahertz spectroscopy with 4 THz bandwidth," *Nat. Commun.* **12**(1), 1071–1080 (2021).
27. W. Yu, J. Shi, G. Huang, *et al.*, "THz-ATR Spectroscopy Integrated with Species Recognition Based on Multi-Classifer Voting for Automated Clinical Microbial Identification," *Biosensors* **12**(6), 378–389 (2022).
28. Y. Wang, Z. Jiang, D. Xu, *et al.*, "Study of the dielectric characteristics of living glial-like cells using terahertz ATR spectroscopy," *Biomed. Opt. Express* **10**(10), 5351–5361 (2019).
29. Y. Liao, M. Zhang, M. Tang, *et al.*, "Label-free study on the effect of a bioactive constituent on glioma cells in vitro using terahertz ATR spectroscopy," *Biomed. Opt. Express* **13**(4), 2380–2392 (2022).
30. D. Crompton and A. J. Vickers, "THz spectroscopic studies of biomolecules," *2012 13th Biennial Baltic Electronics Conference* 13–20 (2012).

31. I. L. Jernelv, K. Strom, D. R. Hjelm, *et al.*, “Infrared Spectroscopy with a Fiber-Coupled Quantum Cascade Laser for Attenuated Total Reflection Measurements Towards Biomedical Applications,” *Sensors* **19**(23), 5130–5143 (2019).
32. J. Xu, D. G. Liao, M. Gupta, *et al.*, “Terahertz Microfluidic Sensing with Dual-Torus Toroidal Metasurfaces,” *Adv. Opt. Mater.* **9**(15), 2100024 (2021).