Research Article

A Contactless Liquor Level Detection Method Using Terahertz Time-Domain Spectroscopy

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In this paper, we proposed the terahertz technique to measure the liquid level of Chinese liquor in sealed pots. We analyzed the transmission process of terahertz pulse in the sealed pots and established a model of the relationship between terahertz pulse interval and liquor level. The measurement results are in good agreement with the theoretical model. The results show that the terahertz technique can realize the high precision measurement of liquor level. The absolute and relative errors are less than $\pm 40 \mu\text{m}$ and 0.014%, respectively. In addition, we also evaluated the influence of dewdrop on the measurement accuracy. The results show that dewdrop only leads to a deviation of $18 \mu\text{m}$. The results prove the value of terahertz technology in the field of liquid level monitoring.

1. Introduction

Chinese liquor is one of the oldest distillates in the world and has been popular in China for centuries. The growing sales indicated liquor still plays a major social role in China [1, 2]. Before being sold, the liquor is commonly stored in the ceramic pot for the hoard to improve its taste and enhance its value. In this process, the liquid level of the liquor in the pot is one of the key indicators that represent its states. Since hundreds to thousands of pots are sealed with polyethylene (PE) films, it is challenging to find an appropriate method and adequate instruments to measure the liquid level of the liquor. Firstly, the fragility of the ceramic pots requires a contactless measurement method. Additionally, it is better not to remove the PE film that ensures that the liquor in the cylinder is in a stable state when measuring the liquid level of the liquor. Finally, measurement methods with low energy consumption and high precision are needed to avoid damaging the product. Therefore, the liquid level measurement is of great significance in the liquor-brewing process.

At present, most liquid level sensors are in contact, including pressure liquor meters [3], magnetostriction liquid meters [4], floating sensors [5], capacitance sensors [6, 7], and fiber optic liquid meters using an in-fiber Mach-Zehnder interferometer [8–10], an in-fiber Fabry-Perot interferometer [11, 12], or fiber Bragg gratings [13–15]. All the contact-based methods are unable to meet the requirements for a satisfactory measurement of the liquid level of the liquor. And the contactless sensors include ultrasonic liquid meters [16], radar liquid meters [17], microwave liquid meters [18–20], and optical liquid meters [21], of which are easily perturbed by dust, steam, bubbles, and the variations in the dielectric constant of the liquid and the temperature, which leads to large uncertainties in the measurement.

Terahertz (THz) radiation, which refers to the region of 0.1–10 THz, has the advantage of directivity and low photon energy. Thus, the terahertz time-domain spectroscopy (THz-TDS) technology has become widely used in the non-destructive field [22, 23]. In this study, we developed the research of liquor level measurement using THz-TDS technology. The liquor level measurement model is established,

FIGURE 1: The schematic diagram of the experimental setup.

FIGURE 2: The transmission model of THz wave in the sealed pot.

which has a good consistency with the experimental results. Additionally, we evaluated the stability of the system. The results show that THz-TDS has application value in the field of liquor level monitoring.

2. Theory of Liquor Level Measurement

2.1. Experimental Setup. The traditional THz-TDS mainly includes a femtosecond laser, a THz source, a THz detector, and a time-delay stage. Generally, the femtosecond laser is focused on the THz source to produce THz pulses. The pump-probe technology is employed to detect ultrafast THz pulses. The THz-TDS setup in this study is plotted in Figure 1. The femtosecond pulses (MaiTai SP, Spectra-Physics) are divided into pump and probe pulses by a half-wave plate (HWP) and a polarization beam splitter (PBS), with an energy ratio of 5:1. The pump pulses are reflected by M1-M3 and then focused onto a photoconductive antenna (PCA-LTGAAS-LT50, Zomega) to produce THz pulses.

The THz pulses are collected with a lens (TL1) to form a parallel beam. Then, the parallel beam is reflected vertically by a THz mirror (TM1) for object detection. The reflective THz beam is collected with beam splitter mirror (TBS), THz mirrors (TM2 and TM3), and then focused on the ZnTe (110, 2 mm). The probe pulses are collected with mirrors (M4, M5, and M6) and silicon chip and finally focused on the ZnTe collinearly with THz beam. The probe pulses modulated by the THz beam are measured by a Wollaston prism and a balanced detector. The output signal from the detector is amplified by a phase-locked amplifier (SR830, SRS). The time-delay stage is realized with two mirrors (M1 and M2) and a motorized linear stage (GTS150, Newport). In the experiment, the motion control and signal acquisition are realized by the LabVIEW software.

2.2. Theoretical Analysis. Figure 2 shows the transmission model of the THz wave in the sealed pot. The THz wave ($E_i(\omega)$) generated by the photoconductive antenna is normal

FIGURE 3: (a) The comparison of the predictive model with measured results. (b) Error analysis.

incidence on the sealed pot. Part of the THz wave is reflected from the air-PE interface, and the rest of the THz wave penetrates the air-PE interface. According to the Fresnel equation [24], the propagation coefficient $P_p(\omega, h + d_a)$ inside the air and the reflection coefficient $R_{ap}(\omega)$ of the air-PE film interface are

$$P_a(\omega, h + d_a) = \exp[-i\tilde{n}_a(\omega)\omega(h + d_a)/c], \quad (1)$$

$$R_{ap}(\omega) = \frac{\tilde{n}_a(\omega) - \tilde{n}_p(\omega)}{\tilde{n}_a(\omega) + \tilde{n}_p(\omega)}, \quad (2)$$

The part of the wave reflected from the air-PE film interface serves as the reference signal $E_r(\omega)$, which is described by

$$E_r(\omega) = E_i(\omega)P_a^2(\omega, h + d_a)R_{ap}(\omega). \quad (3)$$

To simplify the calculation, we ignore the effect of the frequency on the refractive index. Equation (3) is transformed by a Fourier inversion as

$$E_r(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} R_{ap}E_i(\omega) \exp\left[-i\frac{2n_a\omega(h + d_a)}{c}\right] e^{i\omega t} d\omega,$$

$$d\omega = R_{ap}E\left[t - \frac{2n_a(h + d_a)}{c}\right],$$

$$R_{ap} = \frac{n_a - n_p}{n_a + n_p}.$$

(4)

Another part of wave penetrating the air-PE interface transmits into two media (PE film and ethanol gas): the transmission coefficient $T_{ap}(\omega)$ at the air-PE film interface, propagation coefficient $P_p(\omega, d_p)$ inside the PE film, and

FIGURE 4: Twenty times repeated measurements of the liquor level signal.

transmission coefficient $T_{pe}(\omega)$ of the PE film-ethanol gas interface are

$$T_{ap} = \frac{2\tilde{n}_a(\omega)}{\tilde{n}_a(\omega) + \tilde{n}_p(\omega)}, \quad (5)$$

$$P_p(\omega, d_p) = \exp(-i\tilde{n}_p(\omega)\omega d_p/c), \quad (6)$$

$$T_{pe} = \frac{2\tilde{n}_p(\omega)}{\tilde{n}_p(\omega) + \tilde{n}_e(\omega)}. \quad (7)$$

Additionally, it is reflected (by ethanol gas-liquor interface) back into ethanol gas and PE film again, which the liquor level signal $E_o(\omega)$ is obtained. According to the Fresnel equation, the propagation coefficient $P_e(\omega, d_e)$ inside the ethanol gas, reflection coefficient $R_{el}(\omega)$ of the ethanol gas-liquor interface, transmission coefficient $T_{ep}(\omega)$ of the ethanol gas-PE film interface, and transmission coefficient $T_{pa}(\omega)$ of the PE film-air interface are

$$P_e(\omega, d_e) = \exp(-i\tilde{n}_e(\omega)\omega d_e/c), \quad (8)$$

$$R_{el}(\omega) = \frac{\tilde{n}_e(\omega) - \tilde{n}_l(\omega)}{\tilde{n}_e(\omega) + \tilde{n}_l(\omega)},$$

$$T_{ep} = \frac{2\tilde{n}_e(\omega)}{\tilde{n}_e(\omega) + \tilde{n}_p(\omega)}, \quad (9)$$

$$T_{pa} = \frac{2\tilde{n}_p(\omega)}{\tilde{n}_p(\omega) + \tilde{n}_a(\omega)}. \quad (10)$$

According to Equations (1) and (5)–(10), the liquor level signal $E_o(\omega)$ is expressed as

$$E_o(\omega) = E_i(\omega)T_{ap}(\omega)T_{pe}(\omega)R_{el}(\omega)T_{ep}(\omega)T_{pa}(\omega) \cdot P_a^2(\omega, h + d_a)P_p^2(\omega, d_p)P_e^2(\omega, d_e). \quad (11)$$

Ignoring the effect of the frequency on the refractive index, Equation (11) is transformed by a Fourier inversion as

$$E_o(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} kE_i(\omega)e^{i\omega t}e^{-i2\omega n_a(h+d_a)+n_p d_p+n_e d_e/c},$$

$$d\omega = kE \left[t - \frac{2(n_a h + n_a d_a + n_p d_p + n_e d_e)}{c} \right], \quad (12)$$

$$k = \frac{16n_a n_p^2 n_e (n_e - n_l)}{(n_a + n_p)^2 (n_p + n_e)^2 (n_e + n_l)}.$$

As Equations (4) and (12) show, by comparing $E_o(t)$ with $E_r(t)$, the time-domain spectroscopy moves to the right $2(n_p d_p + n_e d_e)/c$, where c indicates the speed of light, n_p , d_p , and n_e are known quantities, and only d_e is unknown. The terahertz pulse interval Δt between the reference signal $E_r(t)$ and the liquor level signal $E_o(t)$ is

$$\Delta t = \frac{(n_p d_p + n_e d_e)}{c}. \quad (13)$$

According to Equation (13), the liquor level d_l can be written as

$$d_l = L - d_e = L - \frac{c\Delta t - 2n_p d_p}{2n_e}, \quad (14)$$

where $c = 3 \times 10^8 \text{ m/s}$, $n_e \approx 1$, $n_p = 1.518$ [25], $d_p = 0.1 \text{ mm}$, and L is the depth of container.

3. Experimental Results and Discussion

In this research, we adopted a cylindrical glass container (the diameter and height are 116.19 mm and 300 mm, respectively) and a PE film (the thickness is 0.1 mm, the state of PE film is dry) to simulate the storage conditions of liquor. To simulate the variations of liquor level, we used a pipette to inject 10 mL liquor into the container each time with a liquor level change (Δd_l) of 0.943 mm. Here, we measured the liquor level with a path of approach 120 mm.

In Section 2.2, we established a predictive model based on the Δt between the reference signal $E_r(t)$ and the liquor level signal $E_o(t)$. Figure 3(a) plots the comparison of the predictive model with measured results. The measured results have a good consistency with the predictive model in both intercept and slope. Further, Figure 3(b) shows that the absolute and relative errors are less than

(a)

(b)

(c)

(d)

FIGURE 5: The influence of dewdrop phenomenon: (a) dewdrop phenomenon on the PE film's inside, (b) THz time-domain spectra for 20 times repeated measurements with dewdrops of the PE film, (c) comparison of peak terahertz signal intensity between dry and dewy PE films, and (d) comparison of peak position between dry and dewy PE films.

$\pm 40 \mu\text{m}$ and 0.014%, respectively. This indicated that the THz-TDS method is of high precision in liquor level measurement.

To evaluate the systematic error on measurement accuracy, we performed 20 times repeated measurements of the liquor level signal with dry of PE film. As Figure 4 shows, the maximum and the minimum peak positions are 5.86 ps

and 5.82 ps, respectively, with a mean value of 5.84 ps. The standard deviation is 0.012 ps, which indicates that the measurements are of high repeatability.

As mentioned, the dewdrop is one of the major factors that affect measurement accuracy. After being stored for two days, dewdrops have occurred on the PE film's inside as shown in Figure 5(a). The reflected signal of the liquor

surface has been measured repeatedly for 20 times, as illustrated in Figure 5(b). Comparing with Figures 4 and 5(b), it could be seen that the terahertz signal intensities are reduced from 2.35×10^{-4} to 1.99×10^{-4} (Figure 5(c)), due to the extra absorption of dewdrops. Meanwhile, the average peak position is delayed 0.06 ps from 5.78 ps to 5.84 ps (Figure 5(d)), which gives rise to about 18 μm measuring error. Since terahertz waves have longer wavelengths than visible-infrared rays and better penetration than microwaves, the dewdrop of the PE film has less effect on measurement accuracy and error. This indicates that the THz technology has the advantage of field detection.

4. Conclusion

To meet the demand for liquor level measurements of stored liquor, we proposed a new liquor level detection method using the THz technology. Firstly, we designed a reflective THz-TDS system for measurements. Secondly, we deduced the predictive model of THz signals with the liquor level based on the propagation coefficients of the multilayered medium. Finally, we verified the model with the measurements. The results show that the predictive model has a good consistency with measurements in both intercept and slope. Additionally, the absolute and relative errors are less than $\pm 40 \mu\text{m}$ and 0.014%, respectively, which indicates that this method is of high accuracy. Moreover, we also evaluated the effects of systematic error and dewdrop. The repeatable experiment shows that the system has good repeatability with a small standard deviation of 0.012 ps, and the dewdrop results in an 18 μm measuring error. This indicates that the THz-TDS method is an accurate, nondestructive tool for the liquor level measurements.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] Y. Niu, J. Kong, Z. Xiao, F. Chen, N. Ma, and J. Zhu, "Characterization of odor-active compounds of various Chinese "Wuliangye" liquors by gas chromatography-olfactometry,

gas chromatography-mass spectrometry and sensory evaluation," *International Journal of Food Properties*, vol. 20, Supplement 1, pp. S735–S745, 2017.

- [2] Z. Li, P. P. Wang, C. C. Huang, H. Shang, S. Y. Pan, and X. J. Li, "Application of Vis/NIR spectroscopy for Chinese liquor discrimination," *Food Analytical Methods*, vol. 7, no. 6, pp. 1337–1344, 2014.
- [3] J. Y. Kim, J. H. Lee, S. E. Bae et al., "Automated high-temperature liquid level measurement system using a dynamic tube pressure technique," *Journal of Industrial and Engineering Chemistry*, vol. 49, pp. 30–35, 2017.
- [4] B. Jin, X. Liu, Q. Bai, D. Wang, and Y. Wang, "Design and implementation of an intrinsically safe liquid-level sensor using coaxial cable," *Sensors*, vol. 15, no. 6, pp. 12613–12634, 2015.
- [5] S. E. Woodard and B. D. Taylor, "A wireless fluid-level measurement technique," *Sensors and Actuators A: Physical*, vol. 137, no. 2, pp. 268–278, 2007.
- [6] F. Reverter, X. Li, and G. C. M. Meijer, "Liquid-level measurement system based on a remote grounded capacitive sensor," *Sensors and Actuators A: Physical*, vol. 138, no. 1, pp. 1–8, 2007.
- [7] E. dos Reis and D. da Silva Cunha, "Experimental study on different configurations of capacitive sensors for measuring the volumetric concentration in two-phase flows," *Flow Measurement and Instrumentation*, vol. 37, pp. 127–134, 2014.
- [8] C. E. S. Castellani, H. C. B. Ximenes, R. L. Silva, A. Frizzera-Neto, M. R. N. Ribeiro, and M. J. Pontes, "Multi-parameter interferometric sensor based on a reduced diameter core axial offset fiber," *IEEE Photonics Technology Letters*, vol. 29, no. 2, pp. 239–242, 2017.
- [9] C. A. Rodríguez, M. R. N. Ribeiro, A. Frizzera-Neto, C. E. S. Castellani, and M. J. Pontes, "Envelope-based technique for liquid level sensors using an in-line fiber Mach-Zehnder interferometer," *Applied Optics*, vol. 55, no. 34, pp. 9803–9809, 2016.
- [10] M. Sun, Y. Jin, and X. Dong, "All-fiber Mach-Zehnder interferometer for liquid level measurement," *IEEE Sensors Journal*, vol. 15, no. 7, pp. 3984–3988, 2015.
- [11] W. Wang and F. Li, "Large-range liquid level sensor based on an optical fibre extrinsic Fabry-Perot interferometer," *Optics and Lasers in Engineering*, vol. 52, pp. 201–205, 2014.
- [12] M. de Fatima F Domingues, T. de Brito Paixao, E. Fernandes Teixeira Mesquita et al., "Liquid hydrostatic pressure optical sensor based on micro-cavity produced by the catastrophic fuse effect," *IEEE Sensors Journal*, vol. 15, no. 10, pp. 5654–5658, 2015.
- [13] C. A. F. Marques, G. D. Peng, and D. J. Webb, "Highly sensitive liquid level monitoring system utilizing polymer fiber Bragg gratings," *Optics Express*, vol. 23, no. 5, pp. 6058–6072, 2015.
- [14] E. Vorathin, Z. M. Hafizi, A. M. Aizzuddin, M. K. A. Zaini, and K. S. Lim, "A novel temperature-insensitive hydrostatic liquid-level sensor using chirped FBG," *IEEE Sensors Journal*, vol. 19, no. 1, pp. 157–162, 2019.
- [15] M. Zhang, R. Yu, Y. du, J. Zou, and L. Wang, "Liquid-level sensor based on reflective mechanically induced long-period grating using double-cladding fiber," *IEEE Sensors Journal*, vol. 18, no. 23, pp. 9568–9575, 2018.
- [16] P. Li, Y. Cai, X. Shen, S. Nabuzaale, J. Yin, and J. Li, "An accurate detection for dynamic liquid level based on MIMO

- ultrasonic transducer array,” *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 3, pp. 582–595, 2015.
- [17] A. Maunder, O. Taheri, M. R. Ghafouri Fard, and P. Mousavi, “Calibrated layer-stripping technique for level and permittivity measurement with UWB radar in metallic tanks,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 7, pp. 2322–2334, 2015.
- [18] A. J. Cole and P. R. Young, “Chipless liquid sensing using a slotted cylindrical resonator,” *IEEE Sensors Journal*, vol. 18, no. 1, pp. 149–156, 2018.
- [19] H. Guo, L. Yao, and F. Huang, “A cylindrical cavity sensor for liquid water content measurement,” *Sensors and Actuators A: Physical*, vol. 238, pp. 133–139, 2016.
- [20] H. Moghadas, M. Daneshmand, and P. Mousavi, “A passive non-contact microwave loop resonance sensor for liquid interface,” *Sensors and Actuators B: Chemical*, vol. 241, pp. 96–98, 2017.
- [21] S. A. Reza and N. A. Riza, “Agile lensing-based non-contact liquid level optical sensor for extreme environments,” *Optics Communication*, vol. 283, no. 18, pp. 3391–3397, 2010.
- [22] B. M. Fischer, H. Helm, and P. U. Jepsen, “Chemical recognition with broadband THz spectroscopy,” *Proceedings of the IEEE*, vol. 95, no. 8, pp. 1592–1604, 2007.
- [23] P. U. Jepsen, D. G. Cooke, and M. Koch, “Terahertz spectroscopy and imaging—modern techniques and applications,” *Laser & Photonics Reviews*, vol. 5, no. 1, pp. 124–166, 2011.
- [24] H. Tuononen, K. Fukunaga, M. Kuosmanen, J. Ketolainen, and K. E. Peiponen, “Wiener bounds for complex permittivity in terahertz spectroscopy: case study of two-phase pharmaceutical tablets,” *Applied Spectroscopy*, vol. 64, no. 1, pp. 127–131, 2010.
- [25] D. R. Smith and E. V. Loewenstein, “Optical constants of far infrared materials. 3: plastics,” *Applied Optics*, vol. 14, no. 6, pp. 1335–1341, 1975.