

Research Article

Terahertz Characteristics of Magnetic Fluid Based on Microfluidic Technology

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Magnetic fluid is a new functional material with both liquid fluidity and solid magnetism, which has important application value in medicine, biology, and so on. In this study, terahertz technology and microfluidic technology were combined to investigate the terahertz transmission characteristics of a magnetic fluid in different magnetic fields and different electric fields. In the external magnetic field, the intensity of the terahertz spectrum increased with an increase in the magnetic field intensity, and the response to the magnetic field in different directions was different. Under the applied electric field, the intensity of the terahertz spectrum decreased with an increase in the electric field intensity. This method is convenient for studying the terahertz characteristics of magnetic fluid and provides technical support for in-depth studies of magnetic fluid.

1. Introduction

The terahertz (THz) refers to the frequency range of 0.1–10 THz and wavelength range of 3 mm to 30 μm of the electromagnetic spectrum [1]. The traditional free-space terahertz time domain spectroscopy (THz-TDS) system [2–5] is a typical representative of THz technology. Over the years, THz technology and its applications have made great progress in many fields. The artificial electromagnetic materials, such as plasmonic devices [6], metamaterials [7], and photonic crystals (PCs) [8], have been extensively investigated to manipulate THz waves. Shuvaev et al. [9] reported the observation of a giant Faraday effect, using THz spectroscopy on epitaxial HgTe thin films at room temperature. Kitamura et al. [10] used THz technology to detect various copolymers (e.g., polydimethylsiloxane (PDMS), Polycarbonate, and Polyethylene terephthalate). Magnetic fluid is a new type of functional material because it breaks the solid state of traditional magnetic material and becomes a liquid state. Thus, it has many characteristics. It is a colloidal

suspension composed of magnetic nanoparticles in a carrier liquid, of which optical and magneto-optical (MO) properties have been extensively investigated in the optical frequency range [11, 12]. Shalaby et al. [13] demonstrated that the ferrofluid has a very low absorption loss and a certain MO activity under a low external magnetic field (EMF) in the THz regime. Jiang et al. [14] demonstrated that the low-frequency oscillating magnetic field applied perpendicularly on the magnetic fluid thin film can form ordered columnar lattice structures. Shalaby et al. [15] realized a polarization sensitive magnetic modulator operating at THz wavelength by using 10 nm Fe_3O_4 . Fan et al. [16] investigated terahertz (THz) magneto-optical properties of magnetic fluid and magnetic fluid-filled photonic crystal (FFPC) by using the THz-TDS system. This shows that THz technology can be used to study magnetic fluid, but there are few reports on the combination of THz technology and microfluidic technology to study the characteristics of magnetic fluid. At present, microfluidic technology has been widely used in chemical, physical, and biological detection and other fields because of

its low reagent consumption, fast detection speed, and easy operation. Fan et al. [17] used the microfluidic sensing based on the photonic crystal (PC) pillar array that was investigated in the terahertz (THz) region. They fabricated the silicon PC sensors and experimentally and theoretically demonstrated their resonances by using the THz-TDS system. Fan et al. [18] designed a sandwich THz microfluidic chip suitable for detecting different solutions, which expanded the application range of microfluidic technology. The above studies show that the terahertz characteristics of magnetic fluid are of far-reaching research value. Besides, combining microfluidics with terahertz technology is an effective research method. In this study, THz technology and microfluidic technology were combined to investigate the THz characteristics of magnetic fluid, and the THz time domain and frequency domain spectra of the magnetic fluid changed with different magnetic field and electric field strengths and directions.

2. Experimental Light Path

The THz time domain spectral system in this experiment used a self-mode-locked fiber femtosecond laser independently developed by Peking University as its laser source (the center wavelength was 1550 nm, the pulse repetition frequency was 100 MHz, the pulse width was 75 fs, and the pulse power was 130 mW). Figure 1 shows the experimental light path diagram. The self-mode-locked laser output occurs after the half-wave plate and PBS polarization splitting prism is divided into two beams with one beam as a pump pulse after the mechanical moving table is coupled into a fiber-optic photoconductive antenna (BATOP company bPCA-100-05-10-1550-c-f), which is used to generate the THz waves. The other serves as a detection pulse, which is converged through the lens and coupled into the fiber-optic photoconductive antenna (BATOP company bPCA-180-05-10-1550-c-f) to detect the THz waves. The microfluidic chip, which was filled with magnetic fluid, was placed between two off-axis projectile mirrors and carries information about the magnetic fluid as THz waves pass through. Then, it is received by the detection antenna, the signal is amplified by the phase-locked amplifier, and the data are collected and processed by a computer.

3. Manufacturing of the Microfluidic Chips

Cyclic olefin copolymer (COC) has a high transmittance to terahertz wave and transparent to visible light, which makes it an ideal material for the preparation of the microfluidic chip. However, for the study of the THz properties of magnetic fluids, the magnetic fluid in the base of organic solution can react with COC and affect the experiment results. Thus, we chose quartz glass as the material for the preparation of the microfluidic chip. In this experiment, two pieces of quartz glass with a size of $3\text{ cm} \times 3\text{ cm} \times 2\text{ mm}$ were used as the substrate and the cover, and then, square areas with a length and width of 2 cm were carved onto 3M double-sided tape with a thickness of $50\text{ }\mu\text{m}$. Then, the double-sided tape was bonded with the substrate and the

cover. Finally, the microfluidic chip was made, and the production process is shown in Figure 2. To detect the transmittance of the THz microfluidics chip made of quartz glass, the chip without the sample was first placed into the optical path and detected by the THz-TDS system. The transmittance of the chip remained above 85% with a high transmittance. Then, the sample of the magnetic fluid was injected into the chip through the liquid inlet and left standing for 24 h. It did not react with the microfluidic chip. Thus, this THz microfluidic chip provides a solid foundation for studying the THz transmission characteristics of the magnetic liquid. Microfluidic chips made of quartz glass are cheaper than those made of COC, and this opens up new avenues for the detection of many organic liquids that react with COC.

4. External Magnetic Field System

Many studies have shown that several characteristics of magnetic fluid can only be displayed under an external magnetic field. The magnetic field varies in strength, and it has different effects. In this experiment, a tiny electromagnet was used to provide the magnetic field. It was powered by a WYJ-9B-type transistor-regulated power supply by adjusting the output voltage of the transistor-regulated power supply (output voltage range: 1–30 V) to change the working voltage of the electromagnet and then adjust the size of the magnetic field strength. When the microfluidic chip with magnetic fluid is placed in a stable external environment with different magnetic field intensities, the THz wave passes through the sample, and the THz time domain and frequency domain spectra have certain variation rules. Figure 3 shows the magnetic field system parallel to the THz transmission direction, and Figure 4 shows the magnetic field system perpendicular to the THz transmission direction.

5. External Electric Field System

In this study, a set of applied electric field systems was designed, which have the function of changing the size and direction of the electric field. The shelf material used to fix the microfluidic chip and electrode plate was Plexiglas. Figures 5 and 6 show the experimental devices with the electric field direction parallel to the THz transmission direction and perpendicular to the THz transmission direction, respectively. The high-voltage power supply module (DW-P153-05C51) provides the voltage for the electrode plate, and its output voltage can be changed between 0 and 15,000 V by adjusting the potentiometer.

6. Experiment and Results

6.1. THz Spectral Characteristics of Magnetic Fluid in an External Magnetic Field. First, some magnetic fluid with a concentration of 35% was injected into the THz microfluidic chip to form a $50\text{ }\mu\text{m}$ magnetic fluid film, which was placed into the THz-TDS system. In the absence of an external magnetic field, the time domain spectrum was obtained first,

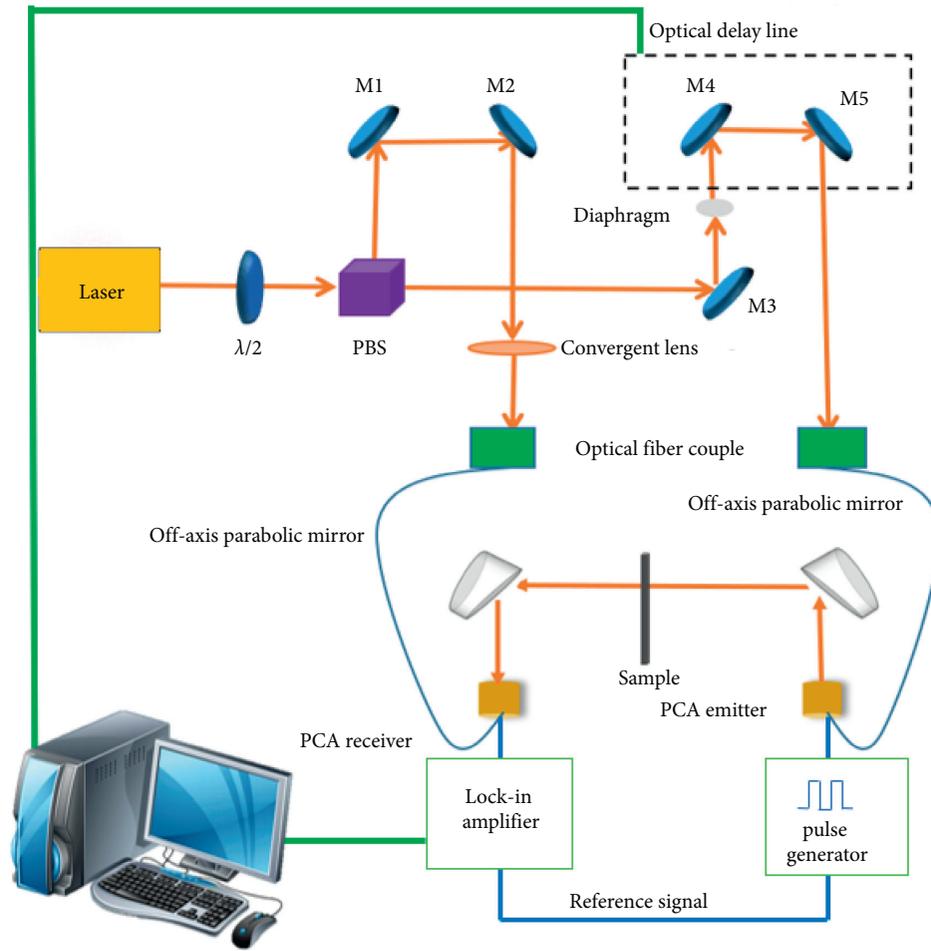


FIGURE 1: Experimental light path diagram.

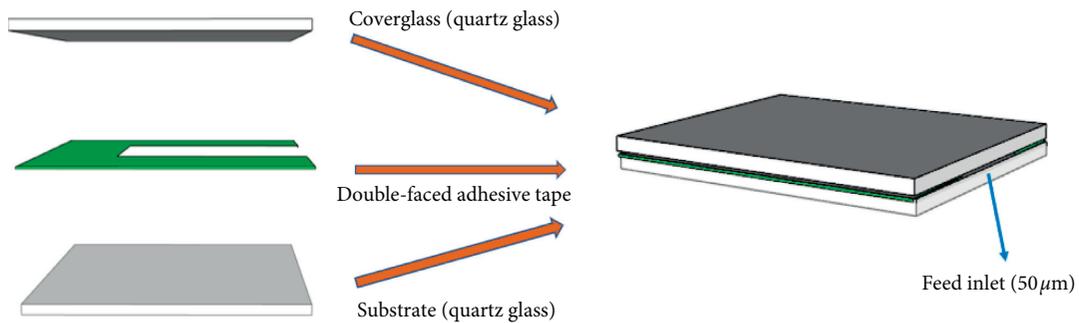


FIGURE 2: Schematic of microfluidic chip fabrication.

and then, the frequency domain spectrum was obtained by Fourier transform. Afterwards, the microfluidic chip injected with magnetic fluid was placed in the magnetic field system, as shown in Figure 3, and then tested by the THz-TDS system. The magnetic field around the microfluidic chip was changed by changing the voltage. The spectrum of magnetic field intensity from 75.1 and 48.2 mT was obtained, as shown in Figure 7. According to the time domain spectrum, when the parallel magnetic field is applied, the

THz pulse shifts to the left, and the external magnetic field changes the arrangement of magnetic fluid molecules, making it easier for THz waves to pass through. According to the frequency domain spectrum, under the action of an external parallel magnetic field, the spectrum intensity of the magnetic fluid increases, and the spectrum intensity increases with an increase in magnetic field intensity. We conjectured that the internal shape of the magnetic fluid is a chain-like structure caused by the external magnetic field,

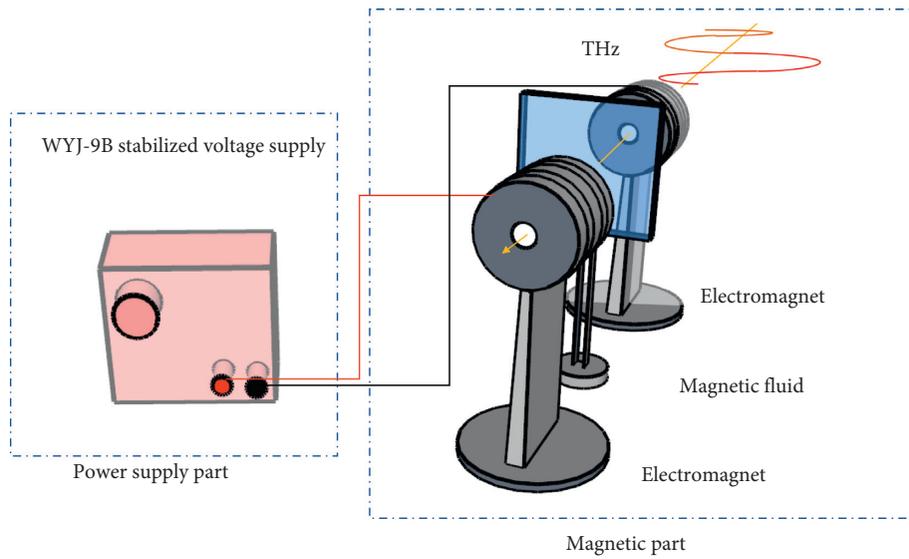


FIGURE 3: Diagram of a parallel magnetic field system.

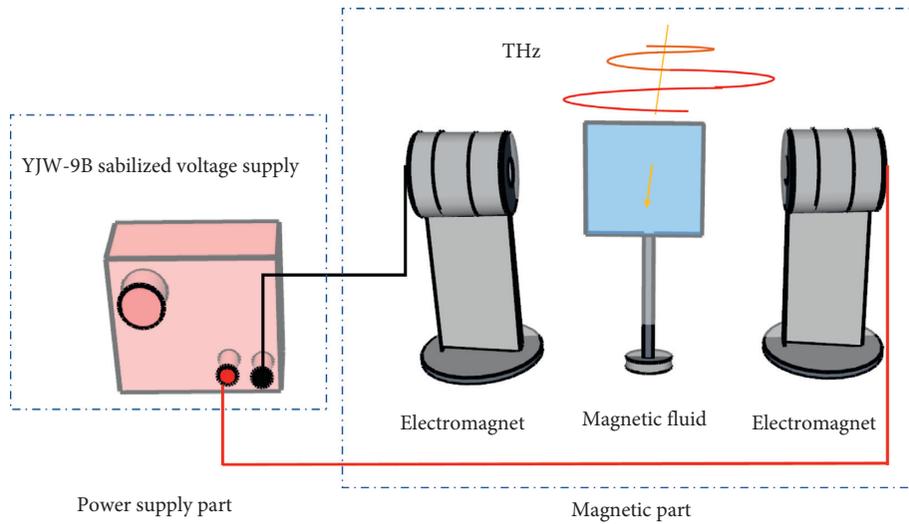


FIGURE 4: Diagram of a vertical magnetic field system.

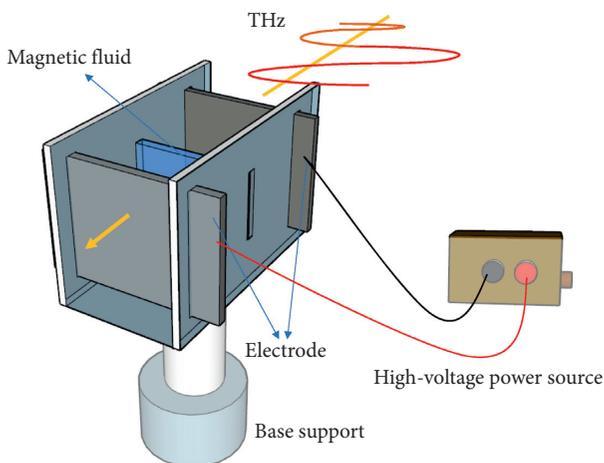


FIGURE 5: Diagram of the parallel electric field system.

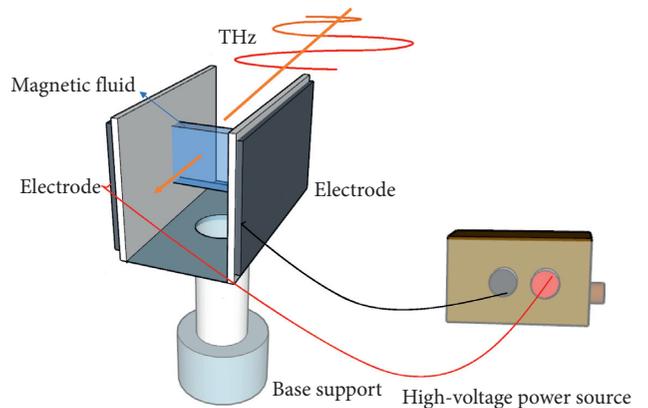


FIGURE 6: Diagram of the vertical electric field system.

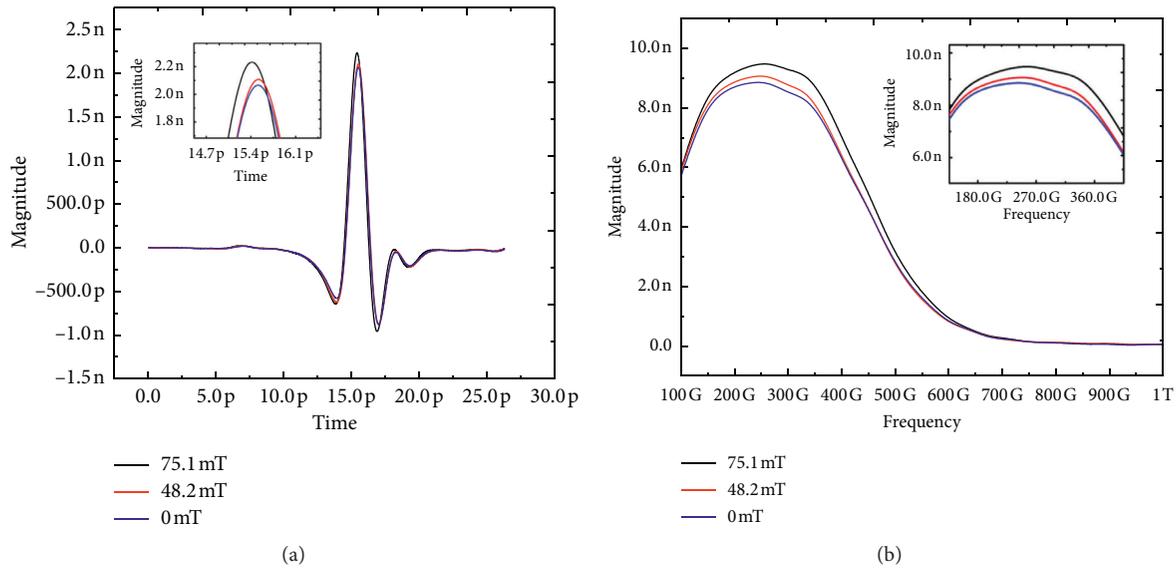


FIGURE 7: Time domain spectrum (a) and frequency domain spectrum (b) of magnetic fluid under different magnetic fields.

which leads to a change in the spectrum intensity. Additionally, in this study, we also converted the two electromagnets perpendicular to the THz wave, i.e., the magnetic field direction was perpendicular to the THz transmission direction, and we found that the time domain and frequency domain spectrum of THz waves did not produce significant changes.

6.2. THz Spectral Characteristics of Magnetic Fluid in an External Electric Field. The magnetic fluid THz microfluidic chip was placed in the THz-TDS system. Under the condition of no applied electric field, the THz-TDS system was used to obtain the time domain and frequency domain spectra. Then, an electric field of 1000 V/cm, 1250 V/cm, 1500 V/cm, 1750 V/cm, and 2000 V/cm was applied parallel to the THz transmission direction. The electric field was applied to each sample for 5 minutes at each electric field strength. After that, the switch was disconnected, and the electrode plate was removed. The time domain and frequency domain spectra were obtained by the THz-TDS system. After each experiment, we disconnected the power supply and left the microfluidic chip which was filled with magnetic fluid to stand for 5 minutes so it could return to the original state as much as possible. Figure 8 shows the experimental results. According to the time domain spectrum, when a parallel electric field was applied, the THz pulse was delayed. According to the frequency domain spectrum, the spectral intensity of the magnetic fluid decreased under the action of the applied parallel electric field, and the spectral intensity decreased more with an increase in the electric field intensity. A similar change was observed when the electrode plate was placed vertically with the microfluidic chip, as shown in Figure 9.

6.3. THz Spectrum of the Substrate Solution. The magnetic fluid in this experiment was composed of Fe_3O_4 and a carrier

solution (an organic solution composed of mineral oil). Mineral oils are a mixture of long-chain alkanes and base oils. To explore whether the presence of the base carrier fluid would affect the experimental results, several experiments were performed on the base carrier fluid according to the operating methods described in Sections 6.1 and 6.2. The spectral information did not change significantly; thus, interference by the base carrier fluid could be eliminated.

7. Discussion

7.1. THz Spectral Characteristics of Magnetic Fluid in an External Magnetic Field. In the experiment of applying a magnetic field to magnetic fluid, from the time domain spectrum, we found that the THz pulse shifted to the left when the parallel magnetic field was applied. According to the frequency domain spectrum, under the action of an external parallel magnetic field, the spectrum intensity of the magnetic field increased, and the spectrum intensity increased with an increase in the magnetic field intensity. When the magnetic field direction was perpendicular to the THz transmission direction, no significant change was found.

First, we built the physical model shown in Figure 10. The magnetic fluid forms a $50\ \mu\text{m}$ thin film in the THz microfluidic chip. In the x - y plane, the THz waves are incident into the magnetic fluid along the z -direction. If the external magnetic field in the z -direction is extended (parallel to the THz transmission direction), the external magnetic field in the z -direction causes the nanoscale Fe_3O_4 particles in the magnetic fluid to gather along the z -direction and form a chain structure. This leads to an increase in the number of particles in the z -direction and a decrease in the area of Fe_3O_4 particles in the x - y plane perpendicular to the z -direction, which increases the probability of THz passing through the magnetic fluid. Then, the intensity of the THz frequency domain spectrum increases, and the effect

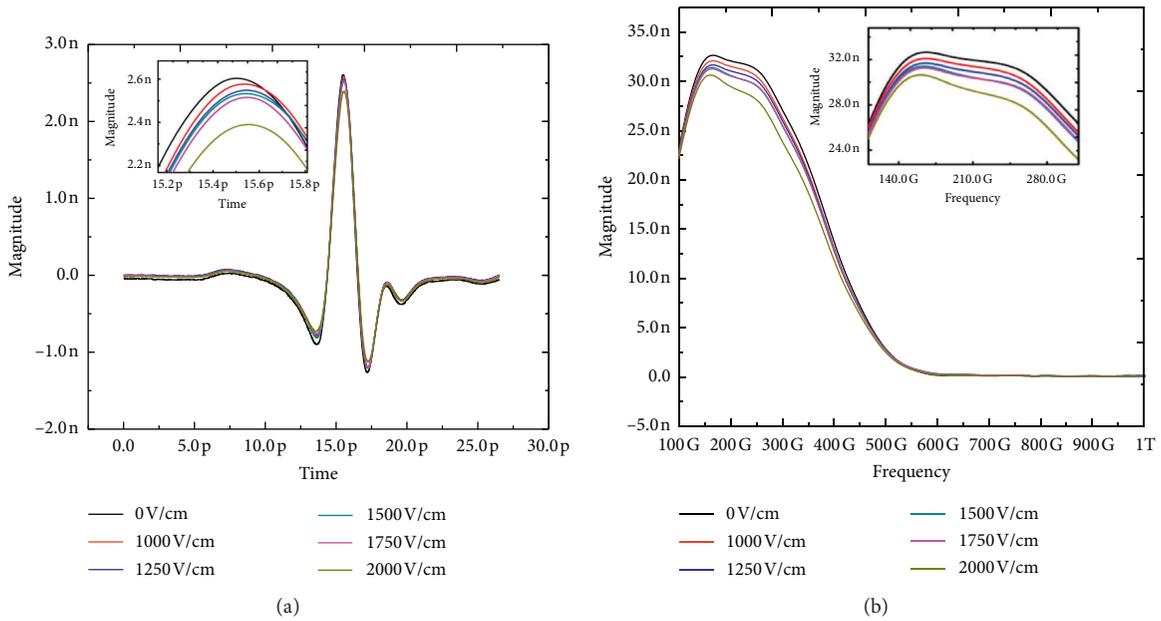


FIGURE 8: THz time domain spectrum (a) and frequency domain spectrum (b) with an applied parallel electric field.

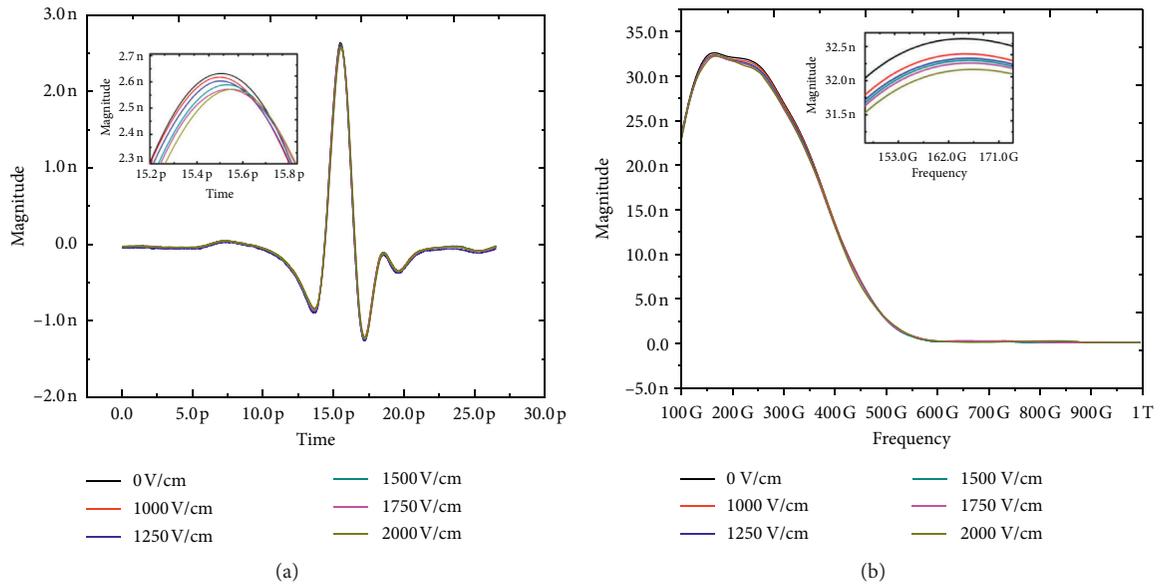


FIGURE 9: THz time domain spectrum (a) and frequency domain spectrum (b) with an applied vertical electric field.

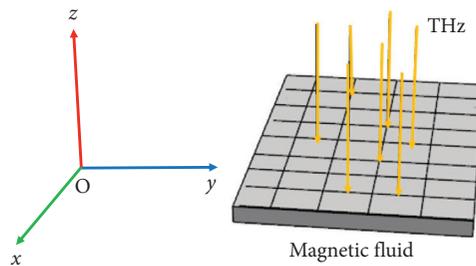


FIGURE 10: Magnetic fluid model of THz passing through an applied magnetic field.

becomes more obvious with an increase in the magnetic field intensity. According to the THz time domain spectrum, the THz pulse appears to shift left, which indicates that the external magnetic field changes the arrangement of the molecules in the magnetic fluid, making it easier for the THz pulse to pass through; thus, the THz pulse appears as a left shift phenomenon. If the external magnetic field in the y -direction is extended (perpendicular to the THz transmission direction), the external magnetic field in the y -direction causes the nanoscale Fe_3O_4 particles in the magnetic fluid to converge along the y -direction to form a chain-like structure. The formation of this chain-like structure does not reduce the area occupied by Fe_3O_4 particles in the x - y plane. Therefore, when the direction of the external magnetic field is perpendicular to the THz transmission direction, there is no significant change in the time domain and frequency domain spectral intensity. This result is consistent with the theoretical analysis obtained by Fang et al. [19] using visible light, indicating the feasibility of using microfluidic technology to study the THz transmission characteristics of magnetic fluid with an external magnetic field.

7.2. THz Spectral Characteristics of Magnetic Fluid in an External Electric Field. In the experiment of using an applied electric field on the magnetic fluid, the time domain spectrum showed that the THz pulse was delayed when we applied a parallel electric field. According to the frequency domain spectrum, under the action of an external parallel electric field, the spectral intensity of the magnetic fluid decreased, and with an increase in the electric field intensity, the spectral intensity decreased more. The above phenomenon was also observed when the electric field direction was perpendicular to the THz transmission direction.

Because magnetic fluid is a stable colloid, it has some basic properties of a colloid. The colloidal particles in the magnetic fluid were Fe_3O_4 , and the spacing of particles was large when there was no applied electric field. When an external electric field is applied, particles want to reach equilibrium under the action of electric field forces, electrostatic repulsion force, and the magnetic dipole between particles. When they get close to each other, the distance between particles decreases and the electrostatic repulsion force increases, thus reducing the influence of the external electric field. With an increase in the electric field intensity, the particles become arranged more and more densely, as shown in Figure 11. Because of the smaller particle spacing, the THz light did not easily pass through, which led to the decrease in the spectral intensity of the magnetic fluid compared with the condition of no electric field, and the decrease in the spectral intensity was larger with an increase in the electric field intensity. Additionally, the THz time domain spectrum showed that the THz pulse was delayed, indicating that the THz waves could accurately detect the variation in Fe_3O_4 nanoparticle spacing in the magnetic fluid.

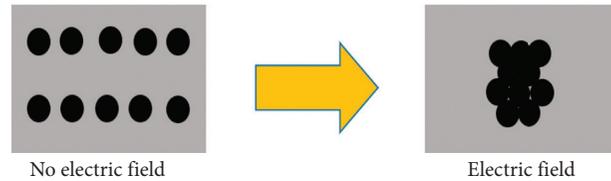


FIGURE 11: Internal variation of magnetic fluid in an applied electric field.

8. Conclusions

A THz microfluidic chip for organic solvent detection was designed in this study. The THz transmission characteristics of the magnetic fluid under different magnetic field intensities and directions were studied using the microfluidic chip. When the magnetic field direction was parallel to the THz transmission direction, the THz pulse shifted to the left when the magnetic field was applied. According to the frequency domain spectrum, the spectral intensity of magnetic fluid increased, and the spectral intensity increased with an increase in the magnetic field intensity. When the magnetic field direction was perpendicular to the THz transmission direction, no obvious phenomenon was found. The main reason was that the external magnetic field in different directions caused the nanoscale Fe_3O_4 particles in the magnetic fluid to gather in different directions and form a chain-like structure. Thus, THz waves likely had different responses to the magnitude and direction of the applied magnetic field of magnetic fluid. Then, the THz transmission characteristics of the magnetic fluid under different electric field intensities and directions were studied using the microfluidic chip. When the electric field direction was parallel to the THz transmission direction, the time domain spectrum showed that the THz pulse was delayed. According to the frequency domain spectrum and compared with the condition without electric field, the spectral intensity of the magnetic fluid decreased, and the spectral intensity decreased more with an increase in the electric field intensity. This phenomenon was also found when the electric field direction was perpendicular to the THz transmission direction. The main reason for this phenomenon was the change in the spacing of particles inside. This method is convenient for studying the terahertz characteristics of magnetic fluid and provides technical support for in-depth studies of magnetic fluid. In the next phase, we will focus on how to relate the above findings to biomedicine.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed to the theoretical analysis, calculations, experiment, and preparation of the manuscript.

Acknowledgments

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