Current measurement method based on magneto-optic rotation effect*

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Aiming at the approximate measurement of magnetic rotation angle in optical current sensor based on light intensity detection mode, this paper proposes a current measurement method based on triangular constant transformation to reconstruct magnetic rotation angle, so as to avoid the large current measurement error caused by the approximate measurement of the magnetic rotation angle. By extracting the direct current (DC) component and the alternating current (AC) component of the light intensity signal detected by the photoelectric detector (PD), the sine signal containing the magnetic rotation angle is directly obtained by dividing the two components, and then the triangular identity transformation method is used to linearly demodulate the magnetic rotation angle and reconstruct the current waveform. The experimental results show that the relative error of current measurement does not exceed 1.40% in the current range of 0.05—0.50 A, which is less than the approximate linear measurement (ALM) method, and the magnetic rotation angle and the current have a good linear relationship.

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With the rapid development of smart grid construction and the continuous improvement of voltage level, the traditional electromagnetic current transformer has seriously affected the development demand of modern power system due to the high insulation cost, magnetic saturation, slow dynamic response and other problems[1]. Compared with the traditional electromagnetic current transformer[2], the optical current transformer (OCT) has the advantages of good electrical insulation, response frequency bandwidth, non-magnetic saturation and ferromagnetic resonance, high safety performance and easy connection with the optical fiber communication system, and the measured output signal can realize informatization and digitalization, and has the potential to accurately obtain current-related information in real time[3].

Optical current sensors can be divided into all-fiber current sensors[4,5] and magneto-optical current sensors according to different sensing units. The all-fiber current sensor uses optical fiber as the sensing medium[6,7], which is limited in practical application due to the linear birefringence problem of the optical fiber itself, the low Verdet constant and the impact of environmental temperature problems[8-11]. The magneto-optical current sensor[12,13] often uses magneto-optic crystal or block glass as the sensor. Compared with optical fiber, magneto-optic crystal or block glass has the characteristics of high Verdet constant, low linear birefringence, simple structure and high sensitivity. Research has found that magneto-optical crystals have good applications in optical current sensors. However, the light intensity detection method based on the light polarization plane has nonlinear measurement problems, and the measurement results are affected by the fluctuation of output light intensity and temperature drift[14,15]. SHAO et al[16] designed a new magneto-optical current sensor using yttrium iron garnet (YIG) material, and proposed a dual-channel optical detection method and signal processing method for outputting the polarization state of light to realize the linear measurement of current in the measured wire. However, the mirror may cause a certain reflection phase shift of linearly polarized light. MIHAILOVIC et al[17] proposed a detection method for arbitrary magnetic induction and electric current waveform measurement that uses two orthogonally polarized light beams for sensing the Faraday rotation. A polarization scheme of orthogonal polarization detection is realized by using appropriate optical, photoelectric and electronic components to realize the normalization of a periodic signal and maintain the gain balance of the two channels to ensure the accuracy of the sensing system. WANG et al[18] proposed a method to detect weak current signal using spectrum analysis and phase-locked amplifier, and adopted a balanced detector to reduce the fluctuation of light source power, and introduced two beams of orthogonal polarized light for dual optical path signal detection. However, there is an imbalance of light intensity loss in dualbeam polarized

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light measurement, which affects the measurement results. CHEN et al[19] proposed a magneto-optic current sensor with two sensing arms. Through the normalization operation between the two arms, the temperature drift is adaptively compensated, and the sensing output proportional to the measured current is obtained. However, the magnetic rotation angle is approximately linear. LEONARDO et al[20] proposed a new optical sensing technology. Using the photoelectric characteristics of liquid crystals in the deformed spiral ferroelectric (DHF) mode, real-time measurement of the voltage and current of overhead power lines is performed. However, the properties of liquid crystals are temperature dependent. XU et al[21,22] proposed a linear photocurrent sensor based on wedge crystal imaging detection, which uses wedge crystal to convert the magneto-optical rotation angle into the horizontal displacement of light and dark interference fringe, and measures the current by calculating the displacement. HUANG et al[23] proposed a linear photocurrent sensor based on a strip aluminum polarization grating, which directly converts the magnetically induced rotation angle into synchronous linear motion of the light spot. The research on the horizontal displacement or spot location of light and dark interference fringes is based on imaging detection to achieve linear measurement of current. The processing of optical devices such as coherent optical fiber bundles and magneto-optical thin films is not only difficult but also costly. In summary, current research has not been able to break through the limitations of approximate linear measurement (ALM) caused by sinusoidal functions in the light intensity detection mode.

In this paper, a method of measuring the angle of magnetic rotation based on triangular identity transformation is proposed to avoid the current measurement error caused by the ALM of the angle of magnetic rotation. This method combines the trigonometric identity transformation (TIT) to process the single-line polarized light signal of the polarization beam splitter, to avoid the loss imbalance between the dual-beam line polarized light, and to solve the problem of current ALM caused by the nonlinear restriction of the sine function on the magnetic rotation angle. The theoretical derivation of the proposed method is carried out, and the feasibility of the proposed method is verified by building the relevant experimental platform, and the current value measurement error of the triangular identity transformation method and the ALM method is compared. The effectiveness of the proposed method is verified by theoretical analysis and experimental results.

Faraday magneto-optical rotation effect[24] is a physical phenomenon that magnetic field changes the properties of media, and its principle is shown in Fig.1. It shows that when a beam of linearly polarized light passes through the magneto-optic material placed in the magnetic field, the vibration surface of the linearly polarized light will produce a deflection proportional to the parallel component of the magnetic field (parallel to the direction of the light wave), and the deflection angle is called the magneto-optical rotation angle θ, which can be expressed as

$$\theta = V \cdot \int H \cdot \mathrm{d}L = V \cdot H \cdot L, \tag{1}$$

where V is the Verdet constant (rad/A) of magneto-optic material, H is the magnetic field strength (A/m), and L is the length of magnetic field path through which linearly polarized light passes (m). Since the magnetic field intensity is proportional to the current, current measurement can be achieved by measuring the magnetic rotation angle.

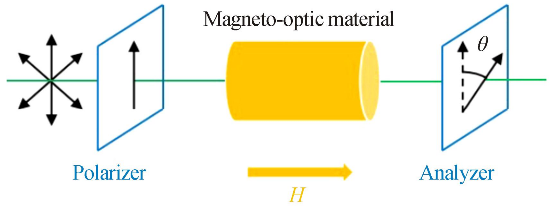


Fig.1 Faraday magneto-optical rotation effect

The measurement of magnetic rotation angle is based on Marius' law, and the light intensity mode is used to divide and detect the double optical paths. That is, the linearly polarized light with the initial light intensity of I_0 will be divided into two beams with mutually perpendicular polarization directions by using a polarizing prism after Faraday magneto-optical rotation effect occurs in magneto-optical glass. Since the included angle between the polarization direction of the two beams of light and the polarization direction of the polarizer is 45°, the intensity of the two beams of light is

$$\begin{aligned} I_1 &= I_0 \cdot \cos^2(45° - \theta) = \frac{I_0}{2} \cdot (1 + \sin 2\theta), \\ I_2 &= I_0 \cdot \cos^2(45° + \theta) = \frac{I_0}{2} \cdot (1 - \sin 2\theta). \end{aligned} \tag{2}$$

When the magnetic rotation angle θ is less than 1°, the signal processing method of difference division and sum is adopted:

$$\theta \approx \frac{1}{2} \cdot \sin 2\theta = \frac{I_1 - I_2}{I_1 + I_2}. \tag{3}$$

Eq.(3) realizes the measurement of the magnetic rotation angle, but it has the following defects. There is an imbalance in the intensity loss between the two orthogonal polarized optical paths output by the polarizing beam splitter prism. Use the ALM method, namely $\sin\theta \approx \theta$ to approximately measure the magnetic rotation angle, which leads to a large error in current measurement. In view of the above defects, this paper proposes a method to measure the magnetic rotation angle with a single optical path based on TIT. It can be seen from the above that the linearly polarized light with the intensity I_0 passes through the analyzer with an included angle of 45º with the polarization direction of the polarizer and is received by the photodetector, and the photodetector converts the light intensity into a photocurrent, and then converts it into a voltage $U(I)$ through a transimpedance amplifier:

$$U(I)=\frac{k\eta I_0}{2}\pm\frac{k\eta I_0}{2}\sin\left[2\theta(t)\right]=U_0\pm\Delta U(I),\quad(4)$$

where k is the photoelectric conversion coefficient of the photodetector, η is the optical path loss, and I_0 is the light source intensity. According to Eq.(4), the output voltage signal $U(I)$ consists of two parts: direct current (DC) output signal U_0 and alternating current (AC) output signal $\Delta U(I)$. In order to make the measurement result independent of the optical power and eliminate the uncertainty related to the change of optical path, divide the AC output signal $\Delta U(I)$ by the DC output signal U_0 to obtain the sine signal containing the magnetic rotation angle $\theta(t)$:

$$U_\mathrm{N}=\frac{\Delta U(I)}{U_0}=\sin\left[2\theta(t)\right].\quad(5)$$

Convert sine signal U_N to cosine signal U_M by trigonometric function identity transformation:

$$U_\mathrm{M}=\sqrt{1-U_\mathrm{N}^2}=\cos\left[2\theta(t)\right].\quad(6)$$

According to Eqs.(5) and (6), we can get

$$\theta(t)=\frac{1}{2}\cdot\arctan\frac{U_\mathrm{N}}{U_\mathrm{M}}.\quad(7)$$

The demodulation principle of the TIT method is shown in Fig.2.

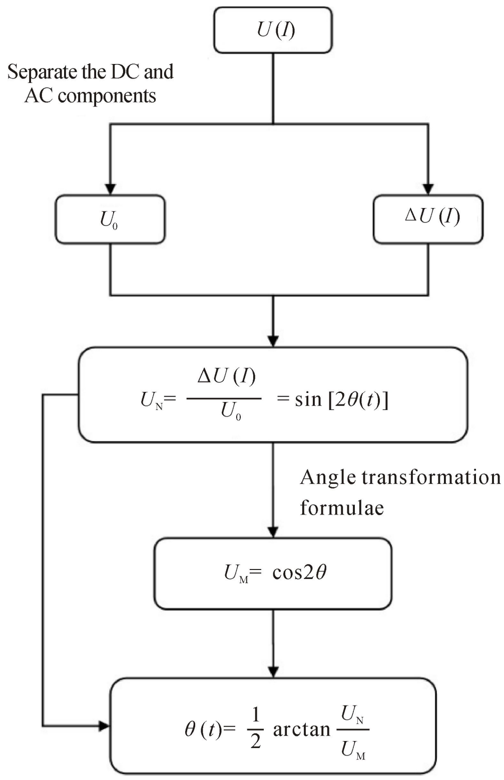


Fig.2 Process of TIT method

The excitation structure of the sensing part of the optical current sensor can be divided into current-carrying conductor, magnetic collecting ring and solenoid. The magnetic field around the current-carrying conductor structure is relatively scattered, and the magnetic field intensity under the excitation of small current is very weak. The magnetic collecting ring structure is made of ferromagnetic materials with high permeability, which cannot completely avoid magnetic saturation. Therefore, the excitation structure of the sensing part in this paper adopts a multi-layer close-turn solenoid model, as shown in Fig.3. The yellow area represents the magneto-optic glass, and the blue area represents the solenoid. Place the magneto-optic glass on the central axis inside the solenoid, and suppress the uneven distribution of magnetic field in the magneto-optic glass by designing the multi-turn coil and the length of the solenoid.

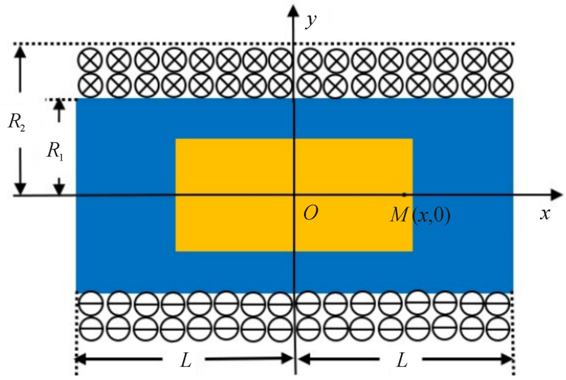


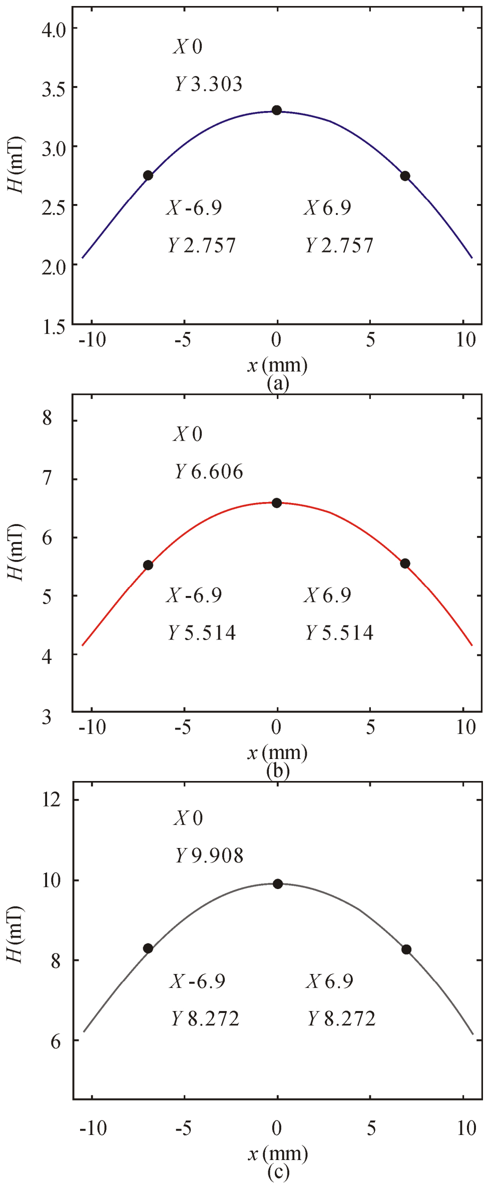
Fig.3 Cross-sectional view of multi-layer multi-turn solenoid model

In this paper, the inner radius of the solenoid is R_1=7 mm, the outer radius is R_2=13 mm, the length is L=21 mm, and the number of turns of the excitation coil is about 760 turns. Since the magneto-optic crystal is located at the center of the central axis of the solenoid, according to Biot-Savart law in the magnetic field, the magnetic field intensity (H) at any point M (x, y) in the axial direction of the solenoid can be obtained as[25]

$$H=\frac{NI}{4L\left(R_2-R_1\right)}\left[\left(x+L\right)\ln\frac{R_2+\sqrt{R_2^2+\left(x+L\right)^2}}{R_1+\sqrt{R_1^2+\left(x+L\right)^2}}-\left(x-L\right)\ln\frac{R_2+\sqrt{R_2^2+\left(x-L\right)^2}}{R_1+\sqrt{R_1^2+\left(x-L\right)^2}}\right],\quad(8)$$

where I is the current in the excitation coil. In order to specifically study the magnetic field distribution in the solenoid under the action of different currents, the magnetic field strength simulation is carried out in combination with Biot-Savart law and various parameters of the solenoid, as shown in Fig.4. Fig.4 shows the magnetic field intensity distribution in the solenoid with different currents. The simulation results of magnetic field intensity show that the magnetic field intensity inside the solenoid is symmetrically distributed about x=0 mm, and the magnetic field intensity decreases gradually from the center of the solenoid to the edges of both sides. In this paper, the magneto-optic glass is placed at the center of the solenoid, so the magnetic field intensity inside the magneto-optic glass is also symmetrically distributed about the center x=0 mm. It can be seen from the figure that the magnetic field strength at the center x=0 mm of the magneto-optic glass is greater than the magnetic field strength at the edge x=±6.9 mm on both sides, that is, the magneto-optic glass is in an uneven magnetic field environment. In order to reduce the deviation of the measurement results caused by the uneven distribution of the magnetic field strength, this experiment selects the average value of the magnetic field strength at each point as the uniform magnetic field to calculate and analyze the current.

To verify the effectiveness of the method in this paper, the structure of the experimental device is shown in Fig.5. The experimental laser source uses a laser diode (LD) (QL65D5SA, QSI). The output power of the LD is 5.0 mW and the wavelength is 650 nm. The LD is driven



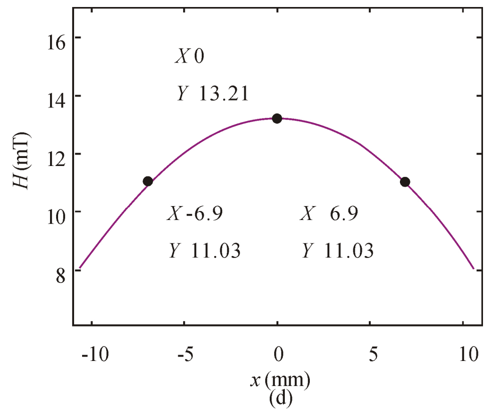


Fig.4 Simulation results of magnetic field strength: (a) *I*=0.10 A; (b) *I*= 0.20 A; (c) *I*=0.30 A; (d) *I*=0.40 A

by a constant current driver (THORLABS, LD1255R). A visible collimating lens (CL) is used to convert the divergent beam output by the LD into a collimating beam for easy alignment. The polarizer (P) is used to change the polarization state of the output light of the LD. The magneto-optic material is the magneto-optic glass MR-4 of Xi'an Aofa Optoelectronic Technology Co., Ltd., which is represented as a cylinder with a diameter of 3.50 mm and a length of 13.80 mm. The Verde constant V of the magneto-optic glass is about 109.08 rad/(T·m) at the wavelength of 632.8 nm. Polarization beam splitter (PBS) (reflectivity>99.5%, transmission>90%, and extrapolation ratio=1 000: 1) is used for polarization detection. Photoelectric detector (PD) (PDA36A-EC, Thorlabs) is used to detect light intensity signals, and collect data from the computer through data acquisition card (NI USB-4431) for processing and analysis. All experimental equipments are placed on the optical isolation platform (PTR52509, Thorlabs) to avoid vibration interference from the external environment.

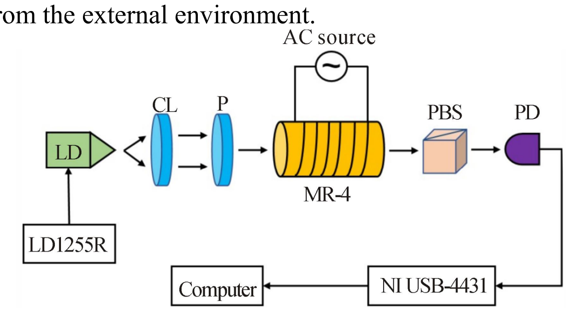
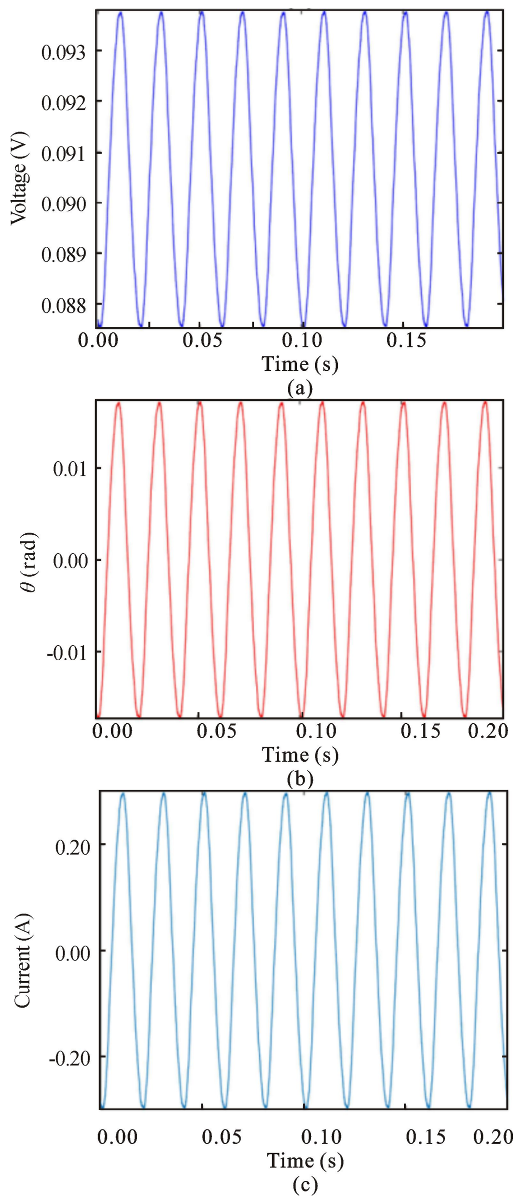


Fig.5 Experimental device structure

The power supply in the circuit is an AC with a frequency of 50 Hz. In this paper, a small single-phase adjustable transformer (input 220 V, output 0—250 V) is used in the circuit to adjust the power supply voltage, thus changing the current in the wire on the energized solenoid. The circuit uses a 6-bit half-high precision digital multimeter (34461A, Agilent) to monitor the current in real time. Since the current density J of the output of the small transformer is 2.50—4.00 A/mm^2, and the excitation coil on the energized solenoid is made of enameled wire with a diameter of 0.40 mm. According to the conductor current carrying formula $I=(d/2)^2\cdot\pi\cdot J$, the maximum excitation current I passing through the excitation coil is 0.50 A, so this experiment is measured in the range of AC frequency of 50 Hz and current I is 0.05—0.50 A. Fig.6 shows the measurement results of current I=0.30 A in the experiment.

Fig.6(a) shows the voltage signal received by the photodetector with current I=0.30 A. Through the signal processing method shown in Fig.2, the relevant magneto-optical rotation angle and current signal can be obtained, as shown in Fig.6(b) and (c), respectively. Fig.6(d) is the spectrum analysis of current signal. In Fig.6(d), the x-axis represents the frequency of the current, and the y-axis represents the peak value of the current. Since the six-and-a-half digital multimeter monitors the effective value of current in real time, we first convert the peak value of current into the effective value of current, and then calculate and analyze the relative measurement error and absolute measurement error of current.



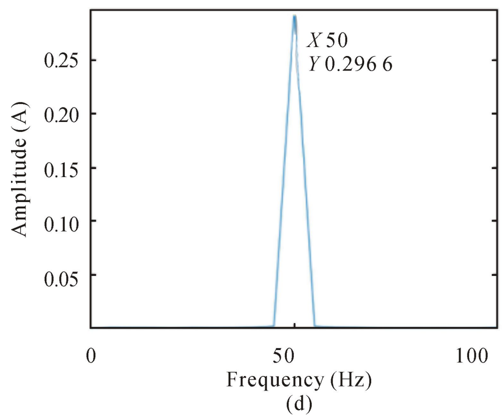


Fig.6 Measurement results of current of 0.30 A: (a) Voltage time-domain signal with current of 0.30 A; (b) Demodulated magnetic rotation angle signal; (c) Demodulated current signal; (d) Spectrum analysis of current signal

In order to explore the measurement error of the TIT method, the experimental measurement is carried out in the range of the current value I from 0.05 A to 0.50 A with the step size of 0.05 A. Repeat the measurement experiment for five times for each current measurement value. The results of absolute measurement error and relative measurement error of different currents are shown in Tab.1. The experimental results show that the absolute error of current is less than 6 mA and the relative error is less than 1.40% in the range from 0.05 A to 0.50 A.

Tab.1 Measured error of current with different values

Current values (A)	Absolute error (mA)	Relative error (%)
0.050	0.694	1.388
0.100	1.346	1.346
0.150	1.959	1.306
0.200	2.540	1.270
0.250	3.105	1.242
0.300	3.648	1.216
0.350	4.179	1.194
0.400	4.700	1.175
0.450	5.202	1.156
0.500	5.710	1.142

According to the measurement results in Tab.1, we use the linear fitting method to measure the magnetic rotation angle θ and current I, and the linear fitting coefficient is R^2=0.999 8. The fitting results are shown in Fig.7. It can be seen from Fig.7 that within the current value range of 0.05—0.50 A, the magneto-optical rotation angle has a good linear relationship with the current.

In order to compare the error of the ARM method and the TIT method on the demodulated current value, we selected five groups of experimental data in Tab.1 and analyzed them using the ARM method and the TIT method, respectively. The ARM method is mainly used to realize the ARM of current by precisely controlling the magnetic rotation angle ($\sin 2\theta \approx 2\theta$). The results of relative error analysis are shown in Fig.8. The red line marked with a diamond is the relative error measured by the ARM method. Therefore, the blue line with an asterisk is the relative error measured by the TIT method. The results of relative error analysis show that when the current is small, that is, when the angle of magnetic rotation is small, the measurement error of the TIT method is similar to that of the ALM method. When the current increases, that is to say, when measuring a larger magnetically induced rotation angle, the advantages of the triangular identity transformation method are more obvious. The experimental results show that the measurement accuracy of the TIT method is better than that of the ARM method.

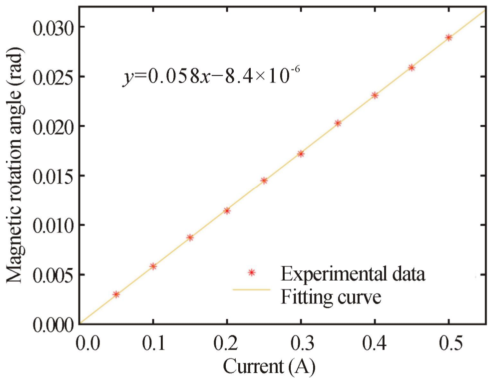


Fig.7 Linear relationship between magnetic rotation angle and current

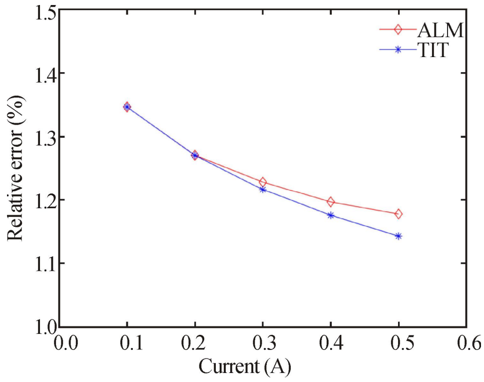


Fig.8 Relative error analysis of two measurement methods

In this paper, a method of measuring the magnetic rotation angle based on TIT is proposed. This method not only overcomes the limitation of ARM of magnetic rotation angle by light intensity demodulation mode, but also avoids the imbalance of light intensity loss in double-path detection. In addition, the magnetic field distribution of magneto-optical crystal in solenoid is analyzed by establishing the structural model of electrified solenoid, and repeated experiments are carried out by selecting currents with the same frequency and different amplitudes. The experimental results show that the maximum relative measurement error of the current does not exceed 1.40% in the range of 0.05—0.50 A, the measurement error is less than the ARM method, and the magnetic rotation angle and the current have a good linear relationship. The measurement error affecting the experiment in this paper is mainly caused by the following factors. On the one hand, there are some uncertain factors in the experimental measurement process, such as mechanical vibration, optical noise, etc. On the other hand, in the experiment, the angle between the polarization direction of the polarizer and the optical axis of the analyzer cannot be accurately adjusted, which will also lead to the reduction of current measurement accuracy, which is also the direction of our future work.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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