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An optical temperature measurement method based on magneto-optical Kerr rffect of metal nanofilms

Lan Li[a,b,*] · Wenzhong Liu[a,b] · Jingjing Cheng[a]

[a]School of Artificial Intelligence and Automation, Huazhong University of Science and Technology, Wuhan,China
[b]China-Belt and Road Joint Laboratory On Measurement and Control Technology, Huazhong University of Science and Technology, Wuhan, China
[*]Corresponding author, email: d202180958@hust.edu.cn

Abstract

In this study, we demonstrate a novel magneto-optical thermometer using a Magneto-optical Kerr Effect (MOKE) system optimally configured with a photoelastic modulator (PEM) that combines the optical and pyro effects of magnetic metal nanofilms to detect transient surface temperatures with high sensitivity and temporal resolution. The temperature-induced Kerr signal of the metal nanofilms is finally transformed into the AC-DC harmonic ratio. By innovatively configuring the analyzer axis close to the extinction position, the signal gain of the harmonic ratio can be increased while reducing the background signal, thus significantly improving the SNR of the temperature measurement. This magneto-optical thermometer combines the high spatial and temporal resolution of MOKE to provide a possible method for non-invasive and fast temperature measurements on the micro- and nanometer scales, and is expected to be useful in temperature imaging applications in conjunction with optical imaging techniques.

I. Introduction

Micro- and nanoscale temperature measurements play a critical role in biology[1–4], industrial manufacturing[5] and other fields. Combining metal nanofilms with magnetism and optics for measurements is becoming increasingly popular due to its non-invasiveness and high temporal resolution. The magneto-optical Kerr effect (MOKE)[6, 7], which describes the change in the polarization and intensity of light before and after its reflection on the surface of a magnetic medium, exhibits promising potential in field of temperature measurement at the micron-nanometer scales owing to their attractive non-invasiveness, excellent temporal resolution and spatial resolution[8–10]. Due to the temperature-induced Kerr signal is very weak, the Kerr rotation angle and typical ellipticity were approximately 10^{-3} rad. Thus, it is essential to find a method to improve the magneto-optical Kerr signal gain.

This study proposes an optical temperature measurement method based on Magneto-optical Kerr Effect of metal nanofilms. The method innovatively sets the analyzer axis at a small angle a close to 0°, which significantly increases the harmonic ratio in the case of detecting light near extinction, resulting in higher sensitivity of temperature measurements. Thus MOKE-based magneto-optical thermometers not only enable non-invasive and fast temperature measurements, but can also be combined with optical imaging techniques for temperature imaging in the future.

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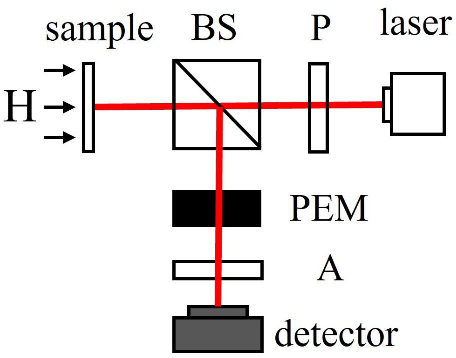

Figure 1: Schematic diagram of the experimental setup. Components: P Polarizer. BS Beam splitter. A analyzer.

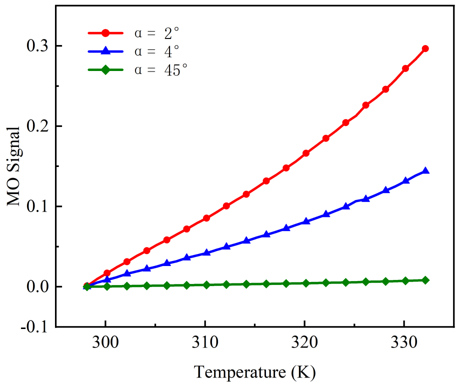

Figure 2: Experimental results of the MO signal for the different configurations. The temperature dependence of the MO signal. The MO signal is normalized to zero against 302 K.

II. Working principle

In this study, the temperature-induced magneto-optical Kerr signal was measured by a typical optical system, and the schematic diagram of the experimental setup is shown in Figure. 1. The linearly polarized light that passes through the polarizer becomes elliptically polarized light after reflecting on the surface of the metal nanofilms, and this elliptically polarized light, which carries the magnetization information of the sample, passes through the PEM and becomes periodically modulated elliptically polarized light, and the light intensity of the linearly polarized light that passes through the polarizer is finally received by the photodetector. The PEM (Hinds PEM-50) generates a periodic retardation with f as the frequency and β as the maximum amplitude as $\delta = \beta(sin(2\pi f t))$. The Kerr signal is modulated to each harmonic of the PEM's modulation frequency.

In our system, the axis of polarizer and PEM was set 90° to and 0°, correspondingly, and the Jones matrix method was used to derive a theoretical model of the temperature-induced Kerr signal from the intensity to the electrical signal. It can be inferred that the detected electric field light intensity I for different analyzer orientation angles α can be given by:

$$I = I_0|r_{ss}|\left\{\left(\theta_k^2+\varepsilon_k^2\right)cos^2\alpha + sin^2\alpha + (\theta_k cos\delta + \varepsilon_k sin\delta)sin2\alpha\right\} \quad (1)$$

Where I_0 is the initial intensity of the incident light, the θ_k corresponds to the Kerr rotation and the ε_k corresponds to the Kerr ellipticity. DPSD algorithm is used to determine the amplitude of each harmonic of light intensity at the modulating frequency: DC amplitude V_{DC}, first harmonic amplitude V_{1f}, and second harmonic amplitude V_{2f}:

$$V_{DC} = I_0|r_{ss}|K_{DC}\left[\left(\theta_k^2+\varepsilon_k^2\right)cos^2\alpha + sin^2\alpha + J_0(\delta)\theta_k sin2\alpha\right] \quad (2)$$

$$V_{1f} = I_0|r_{ss}|K_{1f}2J_1(\delta)sin2\alpha\varepsilon_k(T) \quad (3)$$

$$V_{2f} = I_0|r_{ss}|K_{2f}2J_2(\delta)sin2\alpha\theta_k(T) \quad (4)$$

where K_{DC} ,K_{1f} and K_{2f} represent the amplification of the photodetector circuit at various frequencies of the DC, first harmonic, and second harmonic, respectively. Further, $J_i(\delta)$ is $cos(\delta)$ and $sin(\delta)$ Bessel function at the order i. The expression for the ratio of the first and second harmonics are:

$$\frac{V_{1f}}{V_{DC}} = \frac{K_{1f}}{K_{DC}}\frac{sin2\alpha}{sin^2\alpha}2J_1\varepsilon_k(T) \quad (5)$$

$$\frac{V_{2f}}{V_{DC}} = \frac{K_{2f}}{K_{DC}}\frac{sin2\alpha}{sin^2\alpha}2J_2\theta_k(T) \quad (6)$$

Because amplification, or Bessel function, is a temperature-independent fixed value. The AC/DC harmonic ratio is called the magneto-optical (MO) signal, which enables temperature measurements to be achieved. As a single-valued function of the temperature, the harmonic ratio can be used as a magneto-optical signal to measure the temperature.

III. Results and discussion

The response of the MO signal to the temperature for different configurations is shown in Figure. 2. The MO signals of the near-extinction configurations were all much higher than typical configuration, and it can be seen that the signal gains of MO signal increase with decreasing analyzer angle. The simulation results of the amplitude at different analyzer angles when the weak Kerr signal (assuming to be 10^{-6} rad) caused by 0.1°C temperature change acts on the harmonics of the light intensity are shown in Figure. 3. The simulation conditions are that the initial light intensity is 1 µW and the amplification is 100 kV/W.

The results show that the smaller the analyzer angle, the greater the signal gain of the harmonic ratio, which enables highly sensitive temperature measurements. It's worth noting that in the conventional configu-

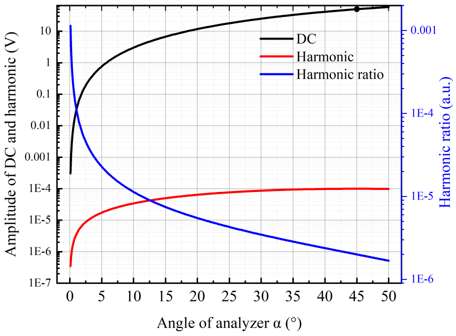

Figure 3: Simulation results for DC, harmonic amplitude and harmonic ratio at different α.

ration $\alpha = 45°$, the difference between DC and harmonics is 6 orders of magnitude, so it's difficult to achieve a high SNR measurement of harmonics with such a large background signal. However, the closer the analyzer angle is to extinction, the difference between harmonics and DC will become smaller and smaller, e.g., for $\alpha = 2°$, the difference narrows to 4 orders of magnitude. This means that by reducing the analyzer angle, the component of the harmonic signal in the total light intensity can be further amplify, attenuating the problem of big background disturbance during the measurement. The limitations of this approach depend on the high SNR detection of weak light by detectors, implying the need to achieve high-gain and low-noise optical measurements.

We set the optical axis of the analyzer at a small angle so that the detected light intensity is close to extinction, and thus the harmonic amplitude can be enhanced with bigger initial light intensity and amplification of photodetector.

IV. Conclusion

The near extinction method proposed in this paper can effectively improve the temperature resolution compared to the conventional magneto-optical Kerr detection method with a photoelastic modulator, and fast temperature measurements have been achieved. Future work is expected to achieve higher resolution optical temperature sensing by increasing the magnification of the photodetection and setting a higher intensity extinction angle, etc., or temperature imaging by combining optical imaging techniques is also very promising.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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