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Adaptive correction of retardations with immunity to alignment errors for a channeled spectropolarimeter

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Retardation errors of high-order retarders will decrease the accuracy of a channeled spectropolarimeter. Taniguchi *et al.* have proposed a self-calibration method to calibrate the retardations [Opt. Lett. 31, 3279 (2006)]; however, they do not take into account the inevitable alignment errors of high-order retarders. In this paper, an adaptive correction method with immunity to alignment errors is proposed to reduce the effects of temperature variation on retardations. By separating and analyzing the amplitude terms and phase terms contained in the measurement data, the phase terms are utilized to correct the retardations, which makes the effectiveness of this adaptive correction method immune to the inevitable alignment errors of high-order retarders. The adaptive correction process can be accomplished in parallel to the measurement process without any auxiliary resources. The effectiveness and feasibility of this method is verified by simulations and experiments. The convenience and simplicity of the presented method make it extremely suitable for application on track.

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1. INTRODUCTION

The polarimetric spectral intensity modulation (PSIM) technique [1,2] utilized in channeled spectropolarimeters has several important advantages, such as the simplicity of the optical system, lack of mechanically movable components for polarization control or active devices for polarization modulation, and simultaneous measurement of the spectral content and all Stokes parameters in snapshot mode [1], and hence, they make channeled spectropolarimetry widely applicable in many application fields such as remote sensing and material characterization [3–8].

Owing to that, the high-order retarders are crystals, which are susceptible to temperature variation [9–13]. Therefore, in spite of the advantages mentioned above, in practical applications, reducing the effects of temperature variation on the retardations of high-order retarders (significant components of the PSIM module) is a noteworthy issue [10–13]. Lee *et al.* put forward an iterative reconstruction algorithm to mitigate the impacts of noise [10]. While it puts forth an advancement of being able to reconstruct signals containing more bandwidth compared with the Fourier reconstruction method [1], it needs the results of Fourier reconstruction to initialize the iterative reconstruction algorithm, which will restrict the effectiveness of the algorithm. In order to specifically address the problem caused by temperature variation, Snik *et al.* and Craven-Jones *et al.* proposed two similar methods using two uniaxial crystals or biaxial retarders, respectively, to produce thermally stable retarders [11,12]. While they are effective in some wave bands, their application will be limited by alternative suitable materials. Taniguchi *et al.* proposed a self-calibration method to compensate for the fluctuation of retardations [13]. While it is novel and ingenious, the whole process does not take into account the inevitable angle errors of the fast axis of high-order retarders [14–16]. The angle errors will cause the channeled spectropolarimeter to lose the inherent potential for self-calibration utilized in Ref. [13], which will be shown in Section 3.

To overcome the defects in the current methods, we put forward an adaptive correction method to reduce the effects of temperature variation on retardations for a channeled spectropolarimeter. By separating and analyzing the amplitude terms and phase terms contained in measurement data, the phase terms are utilized to correct the retardations. The effectiveness of this presented method is immune to alignment errors, which are inevitable in practical applications of the channeled spectropolarimeter. The whole adaptive correction process does not utilize any auxiliary resources, such as the reference beam or an extra retarder, which makes the presented method extremely suitable for application on track.

This paper is structured as follows. In Section 2, we first briefly review the principle of the channeled spectropolarimeter to illustrate that eliminating the phase factors is the most essential procedure during the measurement process of the channeled spectropolarimeter, and then the influence of the retardation errors introduced by temperature variation on the accuracy of a channeled spectropolarimeter are shown by simulations. Section 3 theoretically analyzes and summarizes the influence of alignment errors on the reconstruction model and the current method utilized to calibrate the phase factors and then proposes an adaptive correction method for reducing the effects of the temperature variation. Section 4 verifies the proposed method by numerical simulations. Section 5 further validates the proposed method by experimental tests, and conclusions are presented in Section 6.

2. EFFECTS OF THE RETARDATION ERRORS INTRODUCED BY TEMPERATURE VARIATION

In this section, we first briefly review the principle of channeled spectropolarimetry, which illustrates that eliminating the phase factors is the most essential procedure during the reconstruction process of Stokes parameters. Then, we utilize numerical simulations to show the significant influence of the retardation errors introduced by temperature variation.

A. Review of the Principle of Channeled Spectropolarimetry

Channeled spectropolarimetry is a technique that converts a spectrometer into a spectropolarimeter through the simple addition of a PSIM module to the optical system. The optical schematic of a spectrometer and PSIM module is shown in Fig. 1. The PSIM module consists of two high-order retarders R_1 and R_2, with thicknesses d_1 and d_2 and polarizer A [1,2]. In theory, as shown in Fig. 1, the transmission axis of polarizer A is horizontal and the fast axes of R_1 and R_2 are 0° and 45°, respectively. In fact, however, due to the alignment errors, the angle errors of fast axes of R_1 and R_2 are inevitable. ε_q $(q = 1, 2)$ is the angle error of the fast axis of high-order retarders R_1 and R_2, as depicted in Fig. 1, which will be utilized in subsection 3.A.

The polarization parameters of a light passing through a channeled spectropolarimeter can be most conveniently represented in terms of the Stokes vector representation $S(\sigma) = [S_0(\sigma)S_1(\sigma)S_2(\sigma)S_3(\sigma)]^T$. The Stokes vector of a target light launched into the spectrometer is expressed as

$$S_{\text{out}}(\sigma) = M_A(0°) \cdot M_{R_2}\{45°, \varphi_2(\sigma)\} \cdot M_{R_1}\{0°, \varphi_1(\sigma)\} \cdot S_{\text{in}}(\sigma), \tag{1}$$

where $S_{\text{in}}(\sigma)$ and $S_{\text{out}}(\sigma)$ denote the Stokes vectors of incident and transmitted target light, respectively, and σ is the wavenumber. M_{R_1}, M_{R_2}, and M_A stand for the Mueller matrices of R_1, R_2, and A, respectively. $\varphi_j(\sigma)$ $(j = 1, 2)$ is the phase retardation of R_1 and R_2. The spectrum obtained by the spectrometer is expressed as follows [1]:

$$\begin{aligned} B(\sigma) = {} & \frac{1}{2}S_0(\sigma) \\ & + \frac{1}{2}S_1(\sigma)\cos\{\varphi_2(\sigma)\} \\ & - \frac{1}{4}|S_{23}(\sigma)|\cos\{\varphi_2(\sigma) + \varphi_1(\sigma) - \arg[S_{23}(\sigma)]\} \\ & + \frac{1}{4}|S_{23}(\sigma)|\cos\{\varphi_2(\sigma) - \varphi_1(\sigma) + \arg[S_{23}(\sigma)]\}, \end{aligned} \tag{2}$$

where $S_{23}(\sigma) = S_2(\sigma) + iS_3(\sigma)$. $S_k(\sigma)$ $(k = 0\ldots3)$ denotes the Stokes parameters contained in $S_{\text{in}}(\sigma)$, and arg means the operator to take the argument. Computing the autocorrelation function of $B(\sigma)$ with the inverse Fourier transformation, when the thickness ratio of R_1 and R_2 is 1:2, the Stokes parameters are modulated to several different frequency domain regions, which are called "channels." The channels distributing in the frequency domain are given by

$$\begin{aligned} C(h) = {} & C_0(h) \\ & + C_1[h - (L_1 - L_2)] + C_1^*[-h - (L_1 - L_2)] \\ & + C_2(h - L_2) + C_2^*(-h - L_2) \\ & + C_3[h - (L_1 + L_2)] + C_3^*[-h - (L_1 + L_2)], \end{aligned} \tag{3}$$

where

$$C_0(h) = \mathcal{F}^{-1}\left\{\frac{1}{2}S_0(\sigma)\right\}, \tag{4}$$

$$C_1(h) = \mathcal{F}^{-1}\left\{\frac{1}{8}S_{23}(\sigma)\exp[i(\varphi_2(\sigma) - \varphi_1(\sigma))]\right\}, \tag{5}$$

$$C_2(h) = \mathcal{F}^{-1}\left\{\frac{1}{4}S_1(\sigma)\exp[i\varphi_2(\sigma)]\right\}, \tag{6}$$

$$C_3(h) = \mathcal{F}^{-1}\left\{-\frac{1}{8}S_{23}^*(\sigma)\exp[i(\varphi_1(\sigma) + \varphi_2(\sigma))]\right\}, \tag{7}$$

where $S_{23}^*(\sigma) = S_2(\sigma) - iS_3(\sigma)$, and $C_r^*(h)$ $(r = 1, 2, 3)$ is the conjugate parameter of $C_r(h)$, respectively. h is the variable in the frequency domain conjugate to σ under the Fourier transformation. L_p $(p = 1, 2)$ stands for the actual optical path difference (OPD) introduced by R_1 and R_2 in the central wavenumber [17]. The desired channels, C_0, C_2, and C_3 centered at $h = 0$, $h = L_2$, and $h = L_1 + L_2$, respectively, are then independently filtered out by the frequency filtering technique,

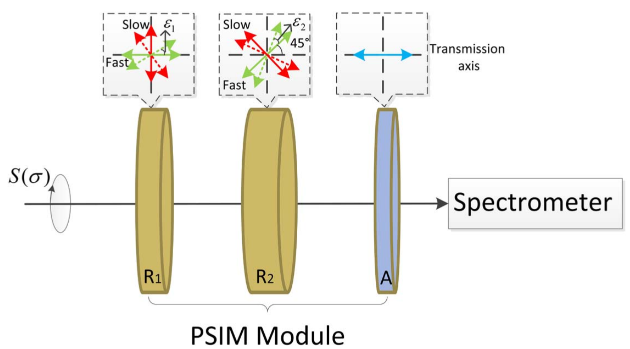

Fig. 1. Schematic of a channeled spectropolarimeter and angle errors of high-order retarders.

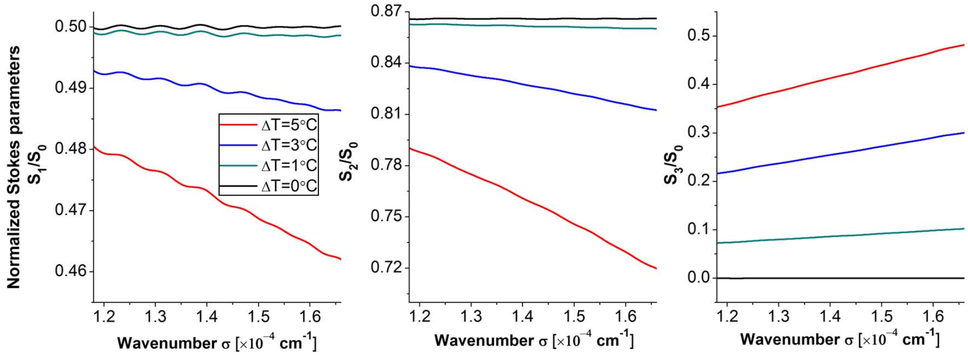

Fig. 2. Effects of temperature variation on the reconstructed normalized Stokes parameters. The reference values are $S_1/S_0 = 0.5$, $S_2/S_0 = 0.866$, and $S_3/S_0 = 0$.

and Fourier transformations are then performed. The results are expressed as

$$\mathcal{F}\{C_0(h)\} = \frac{1}{2} S_0(\sigma), \tag{8}$$

$$\mathcal{F}\{C_2(h)\} = \frac{1}{4} S_1(\sigma) \exp[i\varphi_2(\sigma)], \tag{9}$$

$$\mathcal{F}\{C_3(h)\} = -\frac{1}{8} S_{23}^*(\sigma) \exp[i(\varphi_1(\sigma) + \varphi_2(\sigma))]. \tag{10}$$

As shown in Eqs. (9) and (10), we must eliminate the phase factors $\exp[i\varphi_2(\sigma)]$ and $\exp[i(\varphi_1(\sigma) + \varphi_2(\sigma))]$ contained in the calculation results of channels C_2 and C_3 to reconstruct the Stokes parameters $S_1(\sigma)$ and $S_{23}^*(\sigma)$.

In general, the phase factors can be calibrated in advance by using a reference beam [13,18]. However, $\varphi_j(\sigma)$ $(j = 1, 2)$ is the function of the phase retardations of the higher-order retarders, which is susceptible to the variation of environmental temperature [9,11–13,18]. When the surroundings of measurement are inconsistent with calibration, the variation of the phase factors caused by temperature variation brings about considerable errors in the reconstructed Stokes parameters [18].

B. Influence of the Retardation Errors on the Reconstruction Accuracy of Normalized Stokes Parameters

Based on the research results in Ref. [9], the variation of retardation $\Delta\varphi(\sigma)$ depends on the initial retardation $\varphi(\sigma)$, which can be given by

$$\Delta\varphi(\sigma) = \gamma(\sigma) \cdot \varphi(\sigma) \cdot \Delta T, \tag{11}$$

where $\gamma(\sigma)$ is the temperature coefficient of the retarders and ΔT is the absolute value of the temperature variation. It is noteworthy that the retarders employed in the channeled spectropolarimeter are high-order retarders to increase the spectral resolution of reconstructed Stokes parameters. That is to say, according to Eq. (11), the retardations of high-order retarders are more susceptible to temperature variation.

We utilize numerical simulations to illustrate the influence of retardation errors on the reconstruction accuracy of polarization parameters. In the simulations, the target light is a linearly polarized light oriented at 30°. The wavenumber range is 11,854–16,609 cm^{-1}, and the thicknesses of R_1 and R_2 are 3.0 mm and 6.0 mm, respectively. The high-order retarders are made of quartz, whose birefringence in the selected waveband can be consulted in Ref. [19]. The variations of temperature are set as $\Delta T = 0°C$, 1°C, 3°C, and 5°C, respectively. The reconstructed normalized Stokes parameters in the presence of different temperature variations are shown in Fig. 2.

It is obvious that the reconstruction accuracy of the normalized Stokes parameters is susceptive to temperature fluctuation. Furthermore, the deviations of reconstructed normalized Stokes parameters grow larger as the temperature variation increases. Furthermore, we need know the real-time retardations during the whole measurement process, because the temperature may change at any moment in practical applications. Therefore, the influence of temperature variation cannot be ignored, and a real-time retardation calculation method should be applied to the channeled spectropolarimeter.

To overcome this problem, we propose an adaptive correction method to acquire the actual retardations for reducing the influence of temperature variation. The retardation errors introduced by temperature variation can be figured out merely using the measurement data. Then, the actual retardations can be utilized for reconstructing the true polarization contents of a target light. The convenience and simplicity of the proposed method make it extremely suitable for application on track.

3. ADAPTIVE CORRECTION OF RETARDATIONS WITH IMMUNITY TO ALIGNMENT ERRORS

Owing to the alignment errors of two high-order retarders being inevitable [14–16] in practical applications of a channeled spectropolarimeter, in this section, we first summarize the modified reconstruction model, considering the angle errors of the fast axis of high-order retarders presented in our previous literature, i.e., Ref. [16], and analyze the crucial influences of angle errors on the "self-calibration" method presented in Ref. [13] in Section 3.A. Then, by separating and analyzing the amplitude terms and phase terms contained in the measurement data, we put forward an adaptive correction method of retardations using the phase terms. It is effective for calculating the actual retardations without the influence of the angle errors of the fast axis of high-order retarders.

A. Influence of the Alignment Errors on the Reconstruction Model and Self-Calibration Method

The theoretical reconstruction model without alignment errors (used in Ref. [13]) can be expressed as

$$F_0(\sigma) = \frac{1}{2} S_0(\sigma), \tag{12}$$

$$F_2(\sigma) = \frac{1}{4} |S_1(\sigma)| \exp[i\{\varphi_2(\sigma) + \arg\{S_1(\sigma)\}\}], \tag{13}$$

$$F_-(\sigma) = \frac{1}{8} |S_{23}(\sigma)| \exp[i\{\varphi_2(\sigma) - \varphi_1(\sigma) + \arg\{S_{23}(\sigma)\}\}], \tag{14}$$

$$F_+(\sigma) = -\frac{1}{8} |S_{23}(\sigma)| \exp[i\{\varphi_2(\sigma) + \varphi_1(\sigma) - \arg\{S_{23}(\sigma)\}\}], \tag{15}$$

where $F'_t(\sigma)$ $(t = 0, 2, -, +)$ is complex representation of information contained in different channels in the spectral domain and the channels are called C_0, C_2, C_1, and C_3, respectively.

While the expressions above look neat and regular, in practical applications, due to the existence of angle errors of the fast axis of high-order retarders, the reconstruction model will be more complex than the theoretical reconstruction model. The modified reconstruction model, considering the angle errors of the fast axis of high-order retarders, is expressed as

$$F'_0(\sigma) = \Gamma_0, \tag{16}$$

$$F'_2(\sigma) = |\Gamma_2| \exp[i\{\varphi_2(\sigma) + \arg(\Gamma_2)\}], \tag{17}$$

$$F'_-(\sigma) = |\Gamma_1| \exp[i\{\varphi_2(\sigma) - \varphi_1(\sigma) + \arg(\Gamma_1)\}], \tag{18}$$

$$F'_+(\sigma) = |\Gamma_3| \exp[i\{\varphi_1(\sigma) + \varphi_2(\sigma) + \arg(\Gamma_3)\}, \tag{19}$$

$$F'_\#(\sigma) = |\Gamma_4| \exp[i\{\varphi_1(\sigma) + \arg(\Gamma_4)\}], \tag{20}$$

where

$$\Gamma_0 = \frac{1}{2} S_0(\sigma), \tag{21}$$

$$\Gamma_2 = \frac{1}{4} S_1(\sigma) + \frac{1}{2} \varepsilon_1 S_2(\sigma), \tag{22}$$

$$\Gamma_1 = \left\{\frac{1}{8} - \frac{1}{4}(\varepsilon_1 - \varepsilon_2)\right\} S_{23}(\sigma)) - \frac{1}{4} \varepsilon_1 S_1(\sigma), \tag{23}$$

$$\Gamma_3 = \left\{-\frac{1}{8} - \frac{1}{4}(\varepsilon_1 - \varepsilon_2)\right\} S^*_{23}(\sigma) + \frac{1}{4} \varepsilon_1 S_1(\sigma), \tag{24}$$

$$\Gamma_4 = -\frac{1}{2} \varepsilon_2 S^*_{23}(\sigma). \tag{25}$$

$F'_\#(\sigma)$ is the complex representation of the contents in the new channel, which will be called C_4. The new channel is created due to the existence of angle error ε_2. ε_q $(q = 1, 2)$ is the angle error of high-order retarders R_1 and R_2, which is shown in Fig. 1.

Comparing Eqs. (12)–(15) with Eqs. (16)–(25), owing to the existence of angle errors, first, the phase items $\arg(\Gamma_1)$ and $\arg(\Gamma_3)$ contained in $F'_-(\sigma)$ and $F'_+(\sigma)$ cannot be eliminated during the calculation process of $\exp[i\varphi_2(\sigma)]$, which causes the determination of $\varphi_2(\sigma)$ to depend on the state of polarization (SOP) of the target light; second, a new channel C_4 will be created, and it is almost overlapped with channel C_1 because of the thickness ratio of R_1 and R_2 being 1:2, which makes the problem more complex.

For the two reasons mentioned above, the channeled spectropolarimeter will lose the inherent potential for self-calibration utilized in Ref. [13]. To say the least, given that the angle errors can be calibrated in the laboratory, and in addition, we neglect the overlap error of channels C_1 and C_4, the influence of the angle errors on the self-calibration method is theoretically analyzed and summarized. According to the "self-calibration" method introduced in Ref. [13], the phase factor $\exp[i\varphi_2(\sigma)]$ can be calculated using Eqs. (16)–(25), expressed as

$$\begin{aligned} &16F'_0(\sigma)^2 - 64F'_+(\sigma) \cdot \{F'_-(\sigma) + F'_\#(\sigma)\} \\ &\quad = |\mathrm{T}| \exp[i\{2\varphi_2(\sigma) + \arg(\mathrm{T})\}]. \end{aligned} \tag{26}$$

By ignoring the second-order and higher-order small quantities, T can be expressed as

$$\begin{aligned} \mathrm{T} = {} & S_1^2(\sigma) + S_2^2(\sigma) + S_3^2(\sigma) - 4\varepsilon_2\{S_2^2(\sigma) - S_3^2(\sigma)\} \\ & + i8\varepsilon_2 S_2(\sigma) S_3(\sigma). \end{aligned} \tag{27}$$

It is apparent that even the angle errors can be calibrated in advance; owing to the existence of the angle error ε_2, the imagery part of T depends on the Stokes parameters $S_2(\sigma)$ and $S_3(\sigma)$ of the target light, which makes the determination of $\exp[i2\varphi_2(\sigma)]$ dependent on the SOP of the target light. Therefore, the effectiveness of the self-calibration method has been weakened by the angle errors.

B. Adaptive Correction of Retardations of Two High-Order Retarders

To overcome the above problems, we analyze the modified reconstruction model in the presence of the alignment errors and put forward a widely applicable adaptive correction method of retardations for reducing the effects of temperature variation. By separating and analyzing the amplitude terms and phase terms contained in different channels, expressed as in Eqs. (16)–(25), the phase terms are utilized to correct the retardations, which makes the effectiveness of this adaptive correction method immune to alignment errors.

Based on the introductions in Ref. [9], the retardation of high-order retarders $\varphi_j(\sigma)$ $(j = 1, 2)$ can be expressed as

$$\varphi(\sigma) = 2m(\sigma)\pi + \Phi(\sigma), \tag{28}$$

where $m(\sigma)$ denotes a series of positive integers, which is the order of high-order retarders corresponding to different wavenumbers, and $\Phi(\sigma) \in (-\pi, \pi]$ is the zero-order retardation varying with the wavenumber σ. In theory, $m(\sigma)$ and $\Phi(\sigma)$ can be calculated using the birefringence and thicknesses of the high-order retarders. However, in fact, owing to the influence of dispersion in the retarder material [20], the values of $m(\sigma)$ and $\Phi(\sigma)$ are calibrated and corrected by the results of extracting the argument of $\exp[i\varphi_2(\sigma)]$ and $\exp[i(\varphi_1(\sigma) + \varphi_2(\sigma))]$ obtained by the reference beam calibration technique.

It is noteworthy that considering the existence of manufacturing tolerance, the thickness of the retarders should be measured accurately using optical methods [21]. The results calibrated in the laboratory are expressed as $m_{j,22.5}(\sigma)$ and $\Phi_{j,22.5}(\sigma)$ ($j = 1, 2$), which will be utilized in the following discussion. As mentioned in Section 2.A, when the surroundings of the measurement are inconsistent with the calibration, the actual retardations are different from the calibration results, which will bring about considerable errors in the reconstructed Stokes parameters.

By analyzing Eqs. (17) and (22) contained in the modified model above, we realize that the angle error ε_1 only influences the amplitude term of the demodulation results of channel C_2. That is to say, first we can extract the phase terms of the demodulation results of channel C_2 to acquire $\Phi_{2,\mathrm{actual}}(\sigma) + \arg(\Gamma_2)$, where $\Phi_{2,\mathrm{actual}}(\sigma) \in (-\pi, \pi]$ is the actual zero-order retardation of R_2 in the measurement surroundings and $\arg(\Gamma_2)$ [contained in Eq. (17)] equals either 0 or π, depending on the sign of Γ_2. Therefore, the variation of $\varphi_2(\sigma)$ caused by the temperature change can be expressed as

$$\Delta\varphi_2(\sigma) = \Phi_{2,\mathrm{actual}}(\sigma) - \Phi_{2,22.5}(\sigma) + \arg(\Gamma_2). \quad (29)$$

In order to eliminate the influence of $\arg(\Gamma_2)$, we need judge the absolute value of $\Delta\varphi_2(\sigma)$ with a suitable threshold, such as $\pi/2$. The judgment results are utilized to determine the sign of Γ_2 and the variation of $\varphi_2(\sigma)$. It is important to emphasize that the algorithm is effective when an assumption is met, specifically, that the variation of $\varphi_2(\sigma)$ caused by the temperature change is far less than $\pi/2$ rad. According to the research results of Refs. [9] and [19], the assumption is quite easily met; for instance, as for a 6 mm retarder made of quartz, when the temperature varies 2°C, the maximum variation of retardation is approximately 0.148 rad in the wavenumber range of 11,854–16,609 cm^{-1}, which demonstrates that in practical applications the proposed method will be always effective.

In the following discussions, the situation where $\arg(\Gamma_2)$ equals 0 is employed to illustrate the correction procedure of the presented method. Therefore, in this situation, according to Eq. (29), the variation of $\varphi_2(\sigma)$ caused by temperature change can be expressed as

$$\Delta\varphi_2(\sigma) = \Phi_{2,\mathrm{actual}}(\sigma) - \Phi_{2,22.5}(\sigma). \quad (30)$$

However, the variation of phase retardation $\varphi_1(\sigma) + \varphi_2(\sigma)$ cannot be calculated using the same method, because the phase terms of the demodulation results of channel C_3 contain not only the phase retardations of R_1 and R_2 but also the argument introduced by the target light and the angle errors, which has been illustrated in Eqs. (19) and (24). Given that the two retarders are in contact with each other in actual applications, both retarders undergo the same environmental perturbations [13]. Considering the influence of temperature on the retardations of the high-order retarders introduced in Ref. [13], we can calculate the variation of $\varphi_1(\sigma) + \varphi_2(\sigma)$ between the measurement process and the calibration process, given by

$$\Delta\{\varphi_1(\sigma) + \varphi_2(\sigma)\} = \frac{[\varphi_1(\sigma) + \varphi_2(\sigma)]_{22.5}}{[\varphi_2(\sigma)]_{22.5}} \Delta\varphi_2(\sigma), \quad (31)$$

where $[\varphi_1(\sigma) + \varphi_2(\sigma)]_{22.5}$ and $[\varphi_2(\sigma)]_{22.5}$ are the retardations of high-order retarders calibrated using the reference beam, linearly polarized light oriented at 22.5°. Their values are calculated using the orders of high-order retarders $m_{j,22.5}(\sigma)$ ($j = 1, 2$) and the zero-order retardations $\Phi_{j,22.5}(\sigma)$ ($j = 1, 2$) according to Eq. (28). Since the variations of $\varphi_2(\sigma)$ and $\varphi_1(\sigma) + \varphi_2(\sigma)$ are settled, the actual retardations can be computed given by

$$[\varphi_2(\sigma)]_{\mathrm{actual}} = [\varphi_2(\sigma)]_{22.5} + \Delta\varphi_2(\sigma), \quad (32)$$

$$[\varphi_1(\sigma) + \varphi_2(\sigma)]_{\mathrm{actual}} = [\varphi_1(\sigma) + \varphi_2(\sigma)]_{22.5} + \Delta\{\varphi_1(\sigma) + \varphi_2(\sigma)\}. \quad (33)$$

It should be emphasized that the calibration results we utilized during the whole adaptive correction process are obtained in the laboratory, rather than measured on track, which means that the whole adaptive correction process merely utilizes the data measured online and calibrated in the laboratory. Furthermore, the adaptive correction of retardations is immune to the inevitable angle errors of high-order retarders, which makes the presented method absolutely independent of the target light in all angle error situations. In addition, the effectiveness of this presented method is also independent of the

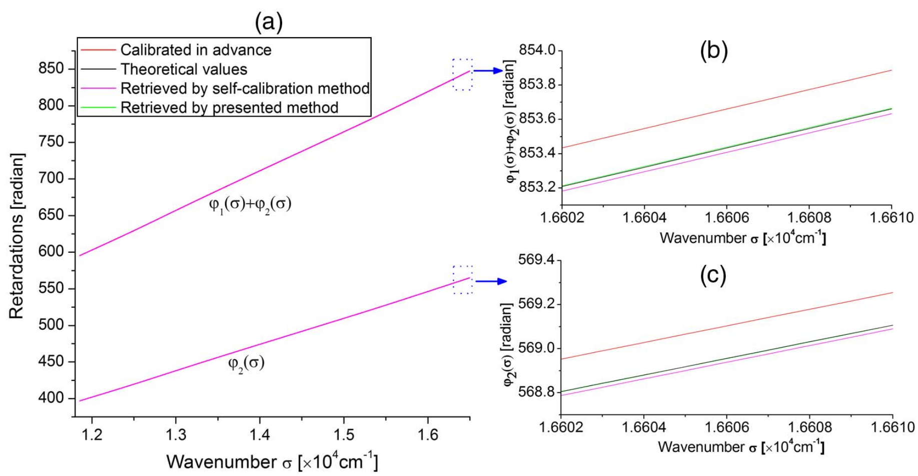

Fig. 3. Comparisons of the retardations acquired by different methods when the temperature goes up by 2°C and the angle errors are $\varepsilon_1 = 0.26°$ and $\varepsilon_2 = -0.42°$; (b) and (c) are the enlarged parts of the dotted boxes in (a), respectively.

Table 1. Comparison of Retardations Acquired by Different Methods in the Selected Wavenumber of $\sigma = 16609\ \mathrm{cm}^{-1}$ when the Temperature Variation is $\Delta T = 2°\mathrm{C}$ and the Angle Errors are $\varepsilon_1 = 0.26°$ and $\varepsilon_2 = -0.42°$

Parameters (Reference Values are the Theoretical Values)	Compared with the Calibration in Advance	Compared with the Self-Calibration Results	Compared with the Presented Method Results
$\Delta\varphi_2$	-1.48×10^{-1} rad	1.76×10^{-2} rad	6.47×10^{-4} rad
$\Delta(\varphi_1 + \varphi_2)$	-2.27×10^{-1} rad	2.64×10^{-2} rad	-4.77×10^{-3} rad

thickness ratio of two the high-order retarders, which makes it suitable for application in other channeled spectropolarimeters employing different retarder thickness ratios [22]. Using the presented adaptive correction method, we can acquire the actual retardations without sacrificing any other advantages, such as the simplicity of the optical system, the lack of a need for the mechanical or active elements, and the snapshot capability.

4. VERIFICATION BY NUMERICAL SIMULATIONS

The effectiveness of this presented method is first verified by numerical simulations. The Stokes parameters to be measured are set as $S_1 = S_2 = S_3 = \sqrt{3}/4S_0$. The wavenumber range is 11,854–16,609 cm^{-1}, and the thicknesses of R_1 and R_2 are 3.0 mm and 6.0 mm, respectively. The high-order retarders are made of quartz, whose birefringence in the selected waveband can be consulted in Ref. [19]. The two retardation calculation methods employed in the simulations are the self-calibration method introduced in Ref. [13] and the presented method introduced in this paper. Owing to that the alignment errors of the two high-order retarders are inevitable in practical applications, in the simulations, angle errors of the fast axes of the two high-order retarders are set to a general case as $\varepsilon_1 = 0.26°$ and $\varepsilon_2 = -0.42°$. Because the effectiveness of the presented method is immune to alignment errors, the angle errors of the retarders can be set as any values, and the specific values do not even need to be known.

The effects of temperature variation on the retardations and the effectiveness of the presented method for retrieving the actual retardations when the angle errors exist are shown in Fig. 3.

As shown in Fig. 2 and Table 1, the theoretical retardations of high-order retarders are different from the calibrated ones when the temperature changes, and the differences of $\varphi_2(\sigma)$ and $\varphi_1(\sigma) + \varphi_2(\sigma)$ at wavenumber $\sigma = 16609\ \mathrm{cm}^{-1}$ are -1.48×10^{-1} rad and -2.27×10^{-1} rad, respectively, which means that we cannot directly use the calibrated results acquired in advance to eliminate the phase factors mentioned above [13,18] in practical applications. The retrieval retardations obtained by the

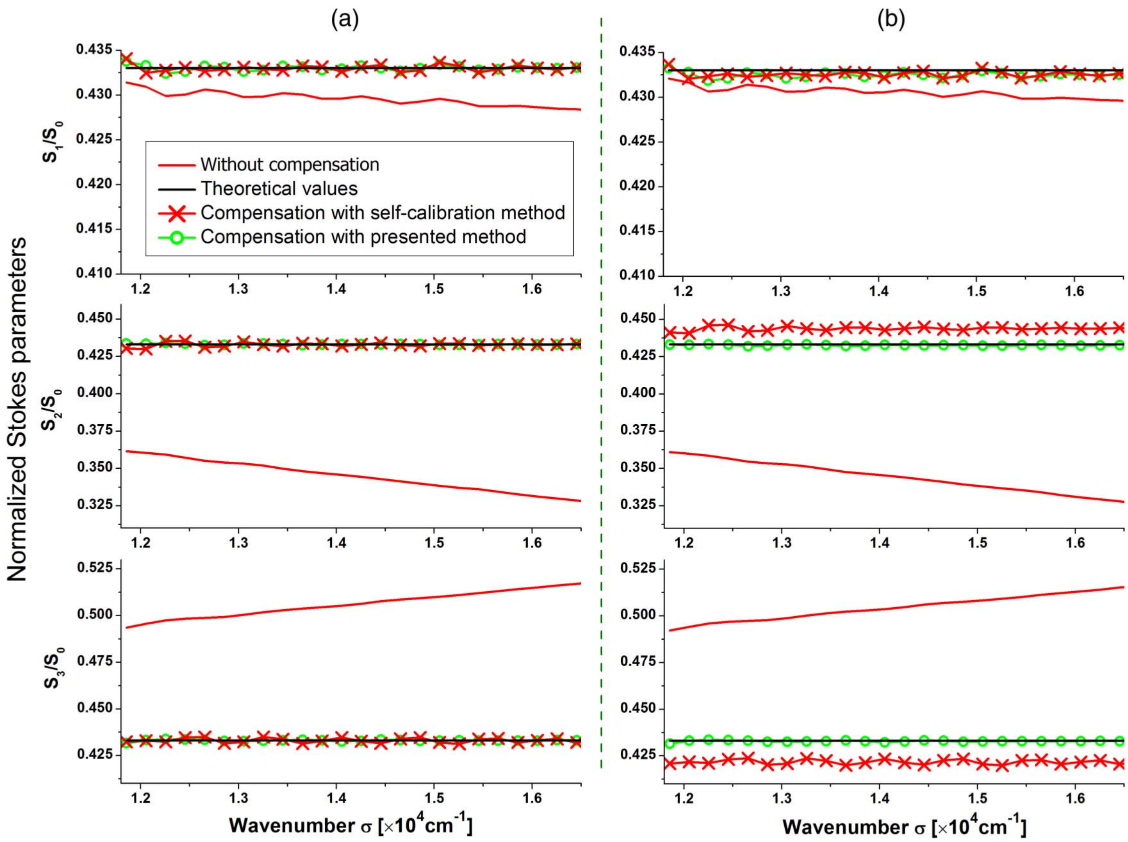

Fig. 4. Influence of retardation errors on the reconstructed normalized Stokes parameters and comparisons of compensation results using two methods in different situations (a) $\varepsilon_1 = \varepsilon_2 = 0°$, $\Delta T = 2°\mathrm{C}$, (b) $\varepsilon_1 = 0.26°$, $\varepsilon_2 = -0.42°$, $\Delta T = 2°\mathrm{C}$. The theoretical values are $S_1/S_0 = S_2/S_0 = S_3/S_0 = 0.433$.

Table 2. Reconstruction Errors of the Normalized Stokes Parameters Using Different Methods in the Selected Wavenumber of $\sigma = 16609\ \mathrm{cm}^{-1}$ when the Temperature Variation is $\Delta T = 2°\mathrm{C}$

Situation	Compensation Method	S_1/S_0 Error	S_2/S_0 Error	S_3/S_0 Error
Without angle errors	Self-calibration method	3.77×10^{-5}	-4.24×10^{-4}	3.91×10^{-4}
	Presented method	-3.14×10^{-5}	1.82×10^{-4}	-1.26×10^{-4}
With angle errors	Self-calibration method	-3.73×10^{-4}	1.04×10^{-2}	-1.10×10^{-2}
	Presented method	-5.46×10^{-4}	-3.39×10^{-4}	-2.99×10^{-4}

presented method are almost consistent with the theoretical values, and the differences of $\varphi_2(\sigma)$ and $\varphi_1(\sigma) + \varphi_2(\sigma)$ at wavenumber $\sigma = 16609\ \mathrm{cm}^{-1}$ are merely 6.47×10^{-4} rad and -4.77×10^{-3} rad, respectively, which verifies the effectiveness of our method. It is also clearly shown that owing to the existence of angle errors, the retardations acquired by the self-calibration method deviate from the theoretical retardations of high-order retarders. The differences of $\varphi_2(\sigma)$ and $\varphi_1(\sigma) + \varphi_2(\sigma)$ at wavenumber $\sigma = 16609\ \mathrm{cm}^{-1}$ are 1.76×10^{-2} rad and 2.64×10^{-2} rad, respectively, which means that the effectiveness of the self-calibration method has been weakened. Therefore, the adaptive correction method presented in this paper is a more suitable way to retrieve the actual retardations. It is effective to reduce the influence of temperature variation on retardations of high-order retarders, which is significant for keeping the accuracy and stability of the channeled spectropolarimeter in practical applications.

The variations of retardation introduced by temperature change may not be obvious enough, but their influence on the accuracy of the reconstructed polarization parameters is significant. The effects of retardation errors on the reconstructed normalized Stokes parameters and the effectiveness of the presented method to keep the accuracy while the angle errors exist are shown in Fig. 4.

It is shown in Fig. 4(a) that the relatively small variations of retardations introduced by temperature change can cause noteworthy reconstruction errors of the normalized Stokes parameters. Therefore, an effective method must be applied for reducing the influence of temperature variation in practical applications. When the angle errors of high-order retarders do not exist, the self-calibration method and the presented method are valid to compensate for the retardation errors to keep the reconstruction accuracy of the normalized Stokes parameters. However, as shown in Fig. 4(b) and Table 2, when the angle errors of high-order retarders exist, the effectiveness of the self-calibration method has been weakened, and, in contrast, the presented method is still valid. Comparing the results in Figs. 4(a) and 4(b), the presented method can reduce the influence of temperature variation greatly by retrieving the actual retardations. Furthermore, its effectiveness is immune to the angle errors of high-order retarders. The above results indicate that the presented method will play an important role in keeping the high precision and stability of a channeled spectropolarimeter in practical applications.

5. ANALYSIS OF EXPERIMENTAL RESULTS

The validity and feasibility of this presented method is further demonstrated by experimental tests. The photograph of experimental setup is shown in Fig. 5. The stabled light source, a collimator, and a rotatable polarizer P are used to generate the reference beam, linearly polarized oriented at 22.5°, and the target light, linearly polarized oriented at 30°. The PSIM module, i.e., the high-order retarders R_1 and R_2 and a polarizer A, along with a spectrometer (FieldSpec3, Analytical Spectral Devices) make up a channeled spectropolarimeter. The thicknesses of R_1 and R_2 and the wavenumber range are consistent with the simulation settings. The retarders R_1 and R_2 and polarizers A and P are placed in precision-adjusting racks for satisfying various experimental test conditions.

During the experimental process, the initial state after alignment is regarded as the situation $\varepsilon_1 = \varepsilon_2 = 0°$. We first use the reference beam to calibrate the retardations of two high-order retarders when the temperature is 20°C. Then, we artificially introduce the angle errors based on the initial state to $\varepsilon_1 = -\varepsilon_2 = 0.5°$ and we measure the modulated spectrum illuminating the experimental setup with the target light when the temperature is changed to 21°C, 23°C, 25°C by use of the temperature controller, respectively. The reconstructed normalized Stokes parameters measured in different situations and the results after compensation with the presented method are shown in Fig. 6.

As clearly shown in Fig. 6(a), the reconstruction deviations of the normalized Stokes parameters grow larger as the temperature variation increases. Therefore, to keep the accuracy of the channeled spectropolarimeter, the effects of the retardation errors caused by temperature variation cannot be ignored. Comparing the results in Fig. 6(a) with those in Fig. 6(b), it is apparent that the effects of temperature variation have been reduced effectively by the presented method, even when the angle errors exist. As shown in Table 3, using the presented method to compensate for the influence of temperature variation, the reconstructed deviations of the normalized Stokes parameters have been reduced by at least 1 order of magnitude. The accuracy of the experimental tests may be affected by the vibration of the reconstructed results, although we have alleviated the influences through introducing apodization using the

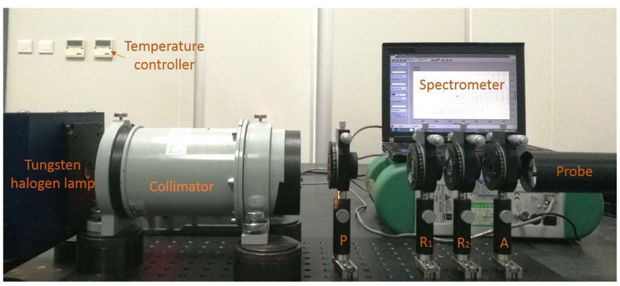

Fig. 5. Photograph of experimental setup.

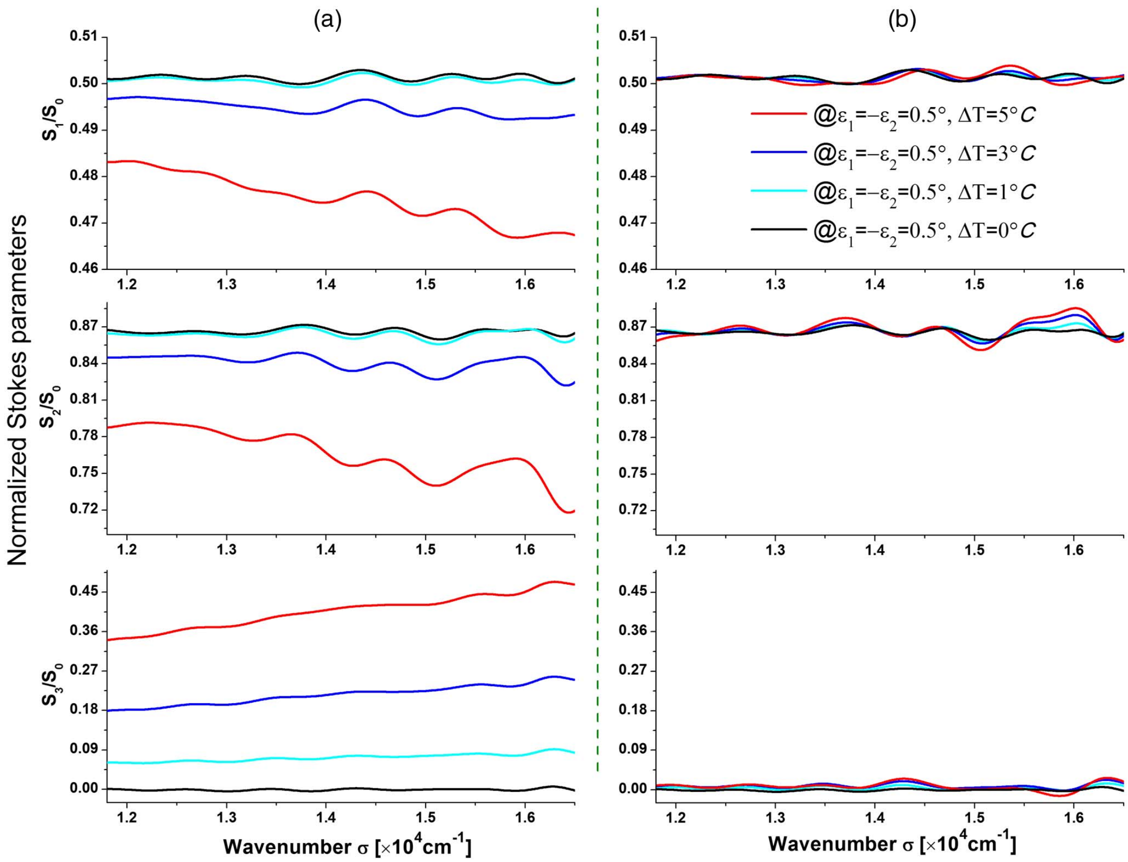

Fig. 6. Reconstruction results under different temperature variations when the angle errors exist (a) without compensation and (b) with compensation by the presented method. The theoretical values are $S_1/S_0 = 0.5$, $S_2/S_0 = 0.866$, and $S_3/S_0 = 0$, respectively.

Table 3. Reconstruction Errors of the Normalized Stokes Parameters in the Selected Wavenumber of $\sigma = 16609$ cm^{-1} when the Angle Errors are $\varepsilon_1 = -\varepsilon_2 = 0.5°$ and Temperature Variation is $\Delta T = 5°$C

Situation	S_1/S_0 Error	S_2/S_0 Error	S_3/S_0 Error
Without compensation	-3.38×10^{-2}	-1.37×10^{-1}	4.69×10^{-1}
With compensation	1.64×10^{-3}	2.94×10^{-3}	8.77×10^{-3}

Hann window [22]. On the whole, the experiment results demonstrate that by using the presented method to reduce the effects of temperature variation, the accuracy of the reconstructed polarization parameters can be improved under different situations of temperature variation. In addition, the effectiveness of this presented method is immune to the inevitable angle errors of high-order retarders, which makes this adaptive correction method of retardations more suitable to eliminate the phase factors for the channeled spectropolarimeter in practical applications.

6. CONCLUSIONS

Retardation errors of high-order retarders introduced by temperature variation apparently decrease the accuracy of a channeled spectropolarimeter. The effectiveness of the self-calibration method will be weakened by the alignment errors of high-order retarders. In this paper, an adaptive correction method of retardations has been presented to reduce the effects of temperature variation on retardations for a channeled spectropolarimeter. By separating the amplitude terms and phase terms contained in measurement data, the phase terms are utilized to correct the retardations of high-order retarders, which makes the effectiveness of this adaptive correction method immune to the inevitable alignment errors of high-order retarders. The effectiveness and feasibility of the presented method is verified by numerical simulations and experiments.

The adaptive correction process of retardations of high-order retarders can be completed simultaneously with the measurement process in practical applications without any auxiliary resources, such as the reference beam, extra retarders, or temperature monitors. By employing the presented method, we can relax the tolerance of the temperature requirement of the PSIM module elements on track. The convenience and simplicity of the presented method make it suitable for maintaining the accuracy and stability of the measurement of polarization parameters, which has an important significance for the application of a channeled spectropolarimeter.

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