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Phase-shifting interferometry in fiber-based channeled spectropolarimeter

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ABSTRACT

Channeled spectropolarimetry measures the spectral dependence of the polarization states of light. This technique is marked by its snapshot feature, in that the complete polarization states can be determined simultaneously from a single intensity spectrum. However, without athermalization, it suffers from high sensitivity to temperature, which in turn, degrades the polarimetric reconstruction accuracy. In this paper, we present a calibration technique for a fiber-based channeled spectropolarimetry that leverages phase-shifting interferometry to accurately demodulate the retarders' phase, thereby improving the accuracy of the acquired Stokes parameters. Additionally, it enables robust spectropolarimetric performance that is insensitive to environmental perturbations. Experimental results demonstrate that calibrations using phase-shifting interferometry improve the Stokes reconstruction results by approximately a factor of 3 when compared to the reference beam calibration method.

1. INTRODUCTION

Spectropolarimetry measures the polarization states of light at different wavelengths. Among the different spectropolarimetric techniques, channeled spectropolarimetry (CSP) is particularly attractive because of its ability to provide time-resolved polarimetric measurements [1]. Traditionally, CSP methods utilize one or two high-order uniaxial crystal retarders, in conjunction with a polarization analyzer and a spectrometer [2,3]. This configuration permits the superposition of the polarization states of light (Stokes parameters) in a single intensity spectrum, where linear and elliptical Stokes information are amplitude modulated onto the retarders' spectral carrier frequencies.

One issue associated with the conventional CSP method is its high sensitivity to environmental perturbations, such as temperature changes in the modulating optics. This causes errors during the reconstruction of the Stokes parameters. Different calibration methods have been reported to reduce polarimetric errors, such as the reference beam and self-calibration techniques [4]. However, both methods show uncertainty in the reconstruction due to inaccurate demodulation of the retarders' phases. For high accuracy Stokes reconstruction, these two methods require that the modulating retarders experience no temperature changes, the retarders are in thermal contact or the use of athermalized retarders [5,6]. We have previously presented an alternative CSP calibration method that exploits the concept of phase-shifting interferometry (PSI) to accurately acquire the retarders' phases [7]. The PSI method allows robust CSP performance that is insensitive to environmental changes.

In this paper, we utilize the PSI calibration technique in a CSP system that incorporates optical fibers, instead of crystal retarders. The fiber's phase is acquired by implementing the four-step PSI algorithm, which requires collecting intensity measurements at four different analyzer's orientations [8]. We also provide experimental results of the Stokes reconstructions at room temperature using different polarization states inputs. Experimental results show that the use of PSI calibrations provides more accurate Stokes reconstructions as compared to the reference beam calibration (By approximately a factor of 3). Note that a fiber-based CSP structure has been previously reported in [9]. However, its approach in determining the fiber's phase retardation is based on interference fringes, which is conceptually different from our PSI approach. Additionally, Reference [9] did not experimentally provide any polarimetric reconstruction results.

This paper is organized as follows, Section 2 provides the theoretical system model of the fiber-based PSI-CSP system, and Section 3 describes our experimental setup and procedures and presents the experimental results.

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2. THEORETICAL SYSTEM MODEL

Figure 1 shows a basic setup of the fiber-based channeled spectropolarimeter system. The input light is assumed to have a broadband spectrum, with Stokes vector defined as $\vec{\mathbf{S}}(\sigma)=\left[S_0(\sigma)\ S_1(\sigma) S_2(\sigma)\ S_3(\sigma)\right]^T$, where σ is the wavenumber, S_0 is the total intensity of the light, S_1 is the difference between linear horizontal and vertical polarization, S_2 is the difference between linear $+45°$ and $-45°$ polarization, and S_3 is the difference between right and left circular polarization.

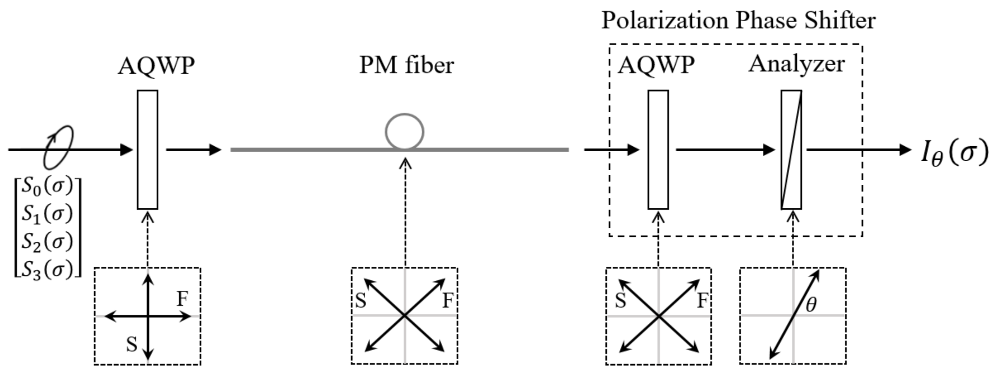

Figure 1. The basic setup of the fiber-based channeled spectropolarimeter.

The input light traverses an achromatic quarter-wave plate (AQWP) with its fast axes oriented at $0°$ relative to the horizontal and is then focused onto a single-mode polarization-maintaining (PM) fiber, with its fast axis oriented at $45°$. This combination of an AQWP with PM fibers allows both S_1 and S_2 to be modulated onto the fiber's spectral carrier frequency $\varphi(\sigma)$, defined as

$$\varphi(\sigma)=2\pi\sigma L\,B(\sigma), \tag{1}$$

where L is the optical fiber length and $B(\sigma)$ is the fiber's birefringence. The modulated light at the output of the PM passes through another AQWP, with its fast axis oriented at $45°$, followed by an analyzer oriented at an angle θ from the horizontal. The AQWP, together with the analyzer, act as a polarization phase shifter, where the spectral carrier frequency is phase-shifted by 2θ, given an analyzer angle of θ [10]. The intensity spectrum at the output of the analyzer is given by

$$I_\theta(\sigma)=\frac{1}{2}\left[S_0(\sigma)+S_1(\sigma)\cos(\varphi-2\theta)+S_2(\sigma)\sin(\varphi-2\theta)\right] \tag{2}$$

By applying the four-step PSI algorithm, the fiber's carrier phase φ can be accurately determined as follows,

$$\varphi=\tan^{-1}\left(\frac{I_{135}-I_{45}}{I_0-I_{90}}\right) \tag{3}$$

where I_0, I_{45}, I_{90} and I_{135} represent the spectral-domain intensity measurements, taken at analyzer orientations of 0°, 45°, 90°, and 135° respectively. Note that subtracting I_{90} from I_0, and I_{45} from I_{135} will automatically filter out S_0 from the intensity measurement. Once φ is determined, both S_1 and S_2 can be recovered by phase demodulation. The PSI calibration method will be experimentally used in our fiber-based channeled spectropolarimeter structure to accurately reconstruct the Stokes parameters at different input polarization states.

3. EXPERIMENTAL RESULTS

In this section, we present the polarimetric reconstruction results of the fiber-based channeled spectropolarimeter using the PSI calibration. Figure 2 depicts the experimental setup. A light-emitting diode (LED) was used at the input of the system, with an intensity spectrum, that ranges from 550 nm to 650 nm full width at half maximum (FWHM). A lens was placed in front of the LED to collimate the light, followed by a polarization state generator (PSG) to produce the desired input polarization states. The polarized light was then directed to a Fresnel rhomb, made of N-BK7 glass, which behaves as an AQWP through total internal reflection (TIR). The light at the output of the Fresnel rhomb was then focused onto a single-mode PM fiber (Thorlabs PM460-HP), with a spectral bandwidth of 460 to 700nm, a length of 30 cm and a birefringence that ranges from 0.0003 to 0.0005. The light at the output of the fiber was then directed to another AQWP followed by a polarization analyzer. A dispersive spectrometer, which consists of a Fresnel prism and a focal plane array (FPA), was used to measure the intensity spectrum. The FPA contains a camera (BFLY-U3-13S2M-CS) from FLIR Systems, Inc. and a Nikon lens (AF NIKKOR 50mm f/1.8D).

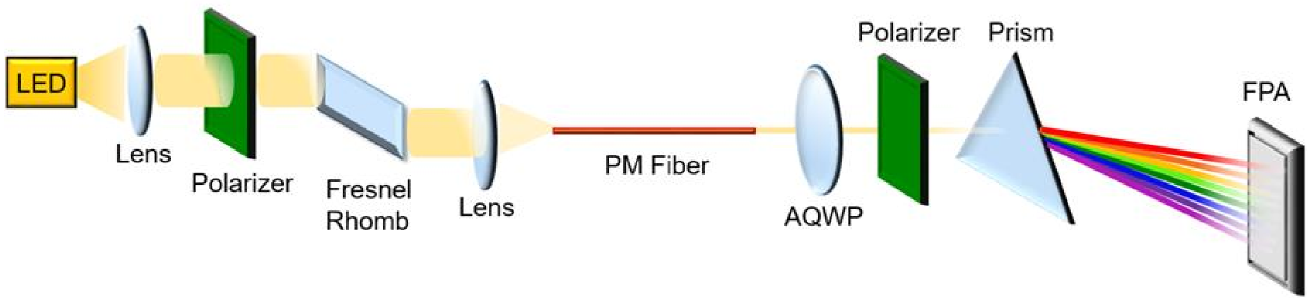

Figure 2. Experimental setup of the fiber-based channeled spectropolarimeter.

We determined the fast/slow axes of the optical fiber by using a common retarder characterization technique. We initially placed the optical fiber between two parallel polarizers, rotated both polarizers concurrently from 0° to 180° in 10° increments, recorded 19 intensity measurements for each polarizers' orientation and then applied a least-square fitting to the data in order to estimate the optical fiber's fast axis. This enabled us to set the fast axis of the fiber to 45° relatives to the horizontal polarization analyzer. Also, we calibrated and mapped the FPA camera pixels to wavelengths using Neon and Xenon gas discharge lamps. Once all the optical components in the experimental setup were correctly configured, we started taking multiple intensity measurements at PSG's orientations of 0°, 20°, 30°, 40°, 50°, and 60°. Table 1 provides the theoretical input Stokes parameters at the different polarizer's orientations.

Table 1. Theoretical stokes parameters at different input polarizer's orientations

Polarizer orientations	S_1/S_0 **amplitude**	S_2/S_0 **amplitude**
0	1	0
20	0.77	0.64
30	0.50	0.87
40	0.17	0.98
50	-0.17	0.98
60	-0.50	0.87

For a specific PSG orientation, intensity measurements were collected for analyzer orientations of 0° (horizontal), 45°, 90° (vertical), and 135°. Moreover, we calibrated the amplitude coefficients, introduced by the dispersive spectrometer at θ = 0°, 45°, 90°, and 135° so that all collected intensity spectrum measurements experience the same system response. Finally, we applied the phase-shifting algorithm provided in Eq. (3) to all the collected experimental data at the different PSG's orientations. Figure 3 and 4 show the polarimetric reconstruction results of S_1 and S_2 respectively, using the PSI calibration technique and at input linear polarization states of 0°, 20°, 30°, 40°, 50°, and 60°. The reconstruction results were collected over the spectral range spanning 550 to 650 nm, which was limited by the LED's spectrum FWHM as well as the optical fiber's spectral bandwidth.

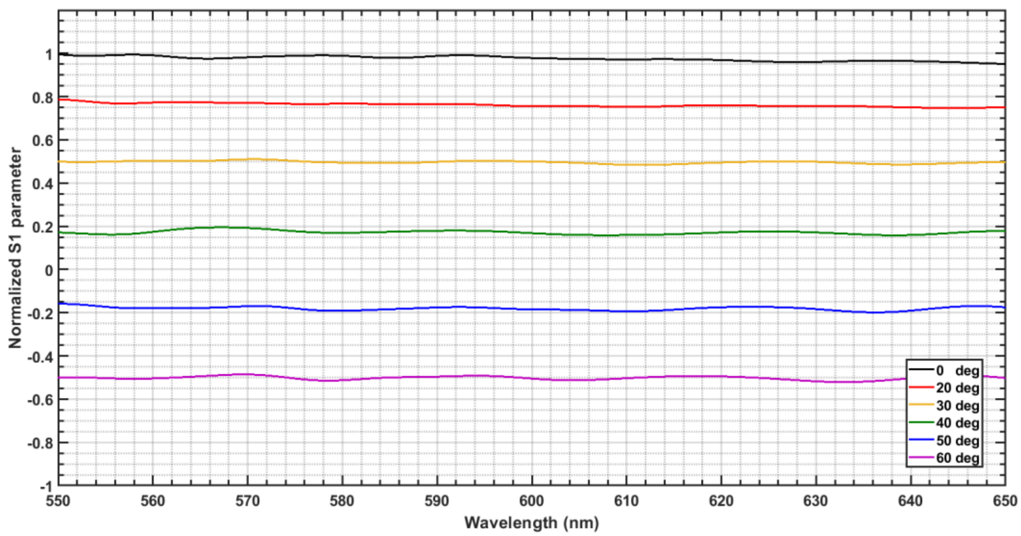

Figure 3. Normalized S_1 Stokes reconstruction results at input linear polarization states of 0° (Black), 20° (Red), 30° (Yellow), 40° (Green), 50° (Blue) and 60° (Magenta).

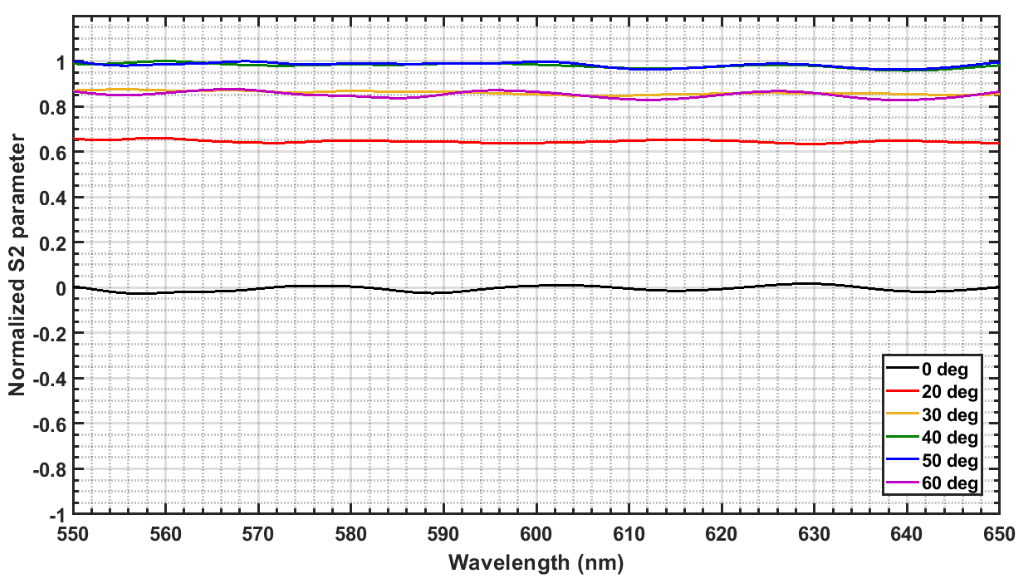

Figure 4. Normalized S_2 Stokes reconstruction results at input linear polarization states of 0° (Black), 20° (Red), 30° (Yellow), 40° (Green), 50° (Blue) and 60° (Magenta).

It can be observed from Figure 3 and Figure 4 that the polarimetric reconstructions of S_1 and S_2 are close to the theoretical values provided in Table 1. To determine the accuracy of the PSI calibration method, we perform the root mean square (RMS) error calculations relative to the theoretical Stokes parameters. For comparison, we also perform the RMS error calculations to the same data calibrated using the reference beam method, with a reference data collected at input polarizer's orientation of 22.5°. Table 2 provides the RMS error calculation for both the PSI and reference beam calibrations at the different PSG's orientations. These results show that the PSI calibration produces lower RMS errors in the polarimetric Stokes reconstructions as compared to the reference beam calibration for all input polarization states. When averaging the RMS error across the six input polarization states, the PSI calibration method provides an average RMS error of 0.96% and 1.1% in S_1 and S_2 respectively, whereas the reference beam method provides an average RMS error of 3.4% and 2.8% in S_1 and S_2 respectively. Future work will investigate the performance of the PSI as well as the reference beam calibrations at different optical fiber temperatures.

Table 2. RMS errors of the reconstructed Stokes parameters from the PSI and reference-beam calibrations

PSG's orientation (Deg.)	**S_1 RMS error (%) – PSI**	**S_2 RMS error (%) – PSI**	**S_1 RMS error (%) – Ref.**	**S_2 RMS error (%) – Ref.**
0	1.1	1.3	3.9	1.7
20	1.0	0.6	2.6	1.2
30	0.8	0.7	1.5	1.3
40	0.9	1.1	3.2	2.9
50	1.1	1.0	4.6	4.8
60	0.9	2.0	4.5	5.1

4. CONCLUSION

In this paper, a new PSI calibration method has been incorporated in a fiber-based CSP structure. This method accurately determines the fiber's phase retardation and hence enables higher accuracy in the polarimetric reconstructions. Experimental results show that the PSI calibration method provides higher accuracy in the Stokes reconstruction when compared to the reference beam calibration approach. The average RMS errors, using PSI calibration, are 0.96% and 1.1% in S_1 and S_2 respectively, whereas the average RMS errors, using the reference beam method, are 3.4% and 2.8% in S_1 and S_2 respectively.

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