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Channeled polarimetric technique for the measurement of spectral dependence of linearly Stokes parameters

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HIGHLIGHTS

- An achromatic quarter wave plate, a high order retarder and a fixed polarizer can acquire linearly wavelength-dependent Stokes parameters.
- Laboratory experiments demonstrated the spectropolarimetric capability of the method.
- The presented method can improve the resolution of the reconstructed linearly spectrally resolved Stokes parameters and suppress reconstruction errors caused by aliasing between the channels.

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ABSTRACT

The principle and experimental demonstration of a method based on channeled polarimetric technique (CPT) to measure spectrally resolved linearly Stokes parameters (SRLS) is presented. By replacing front retarder with an achromatic quarter wave-plate of CPT, the linearly SRLS can be measured simultaneously. It also retains the advantages of static and compact of CPT. Besides, comparing with CPT, it can reduce the RMS error by nearly a factor of 2–5 for the individual linear Stokes parameters.

1. Introduction

Polarization information scattered or reflected from targets usually differs from that of background light and thus can offer targets' surface features, shape, shading, and roughness, while spectral information implies the targets' physical and chemical properties. Spectropolarimeter can acquire the spectral dependence of state of polarization (SOP) and improves the ability to effectively recognize the target with preferable accuracy [1–5].

Since conventional spectropolarimeters usually install polarization switching elements and microretarder or micropolarizer arrays in spectrometers, the sensors generally suffer from vibration, electrical noise, heat generation, and alignment difficulty [7]. CPT is first implemented by Oka and Kato, and can acquire all the spectrally resolved Stokes parameters at once without movable polarization components or micro-components [8]. Based on this concept, the CPT is incorporated into different imaging Fourier transform spectrometer to form Fourier transform channeled imaging spectropolarimeter (FTCISP) that has unique benefits due to the throughput (Jacquinot) and multiplex (Fellgett) advantages [9–16]. Recent progresses in imaging schemes arouse numerous potential applications of FTCISP in fields of target recognition [17,18], biomedical and material diagnosis [19,20], and atmospheric remote sensing [21]. Such sensor adds two thick retarders and an analyzer before imaging spectrometers or interferometers and yields direct access to the spectral carrier frequencies containing the spectrally resolved Stokes parameters. Since the interferogram recorded by the sensor usually contains seven interference channels, the spectral resolution of each spectral Stokes parameters is much lower than that of the interferometer. Besides, there is aliasing among the fringe patterns of different Stokes parameters, when a narrowband spectrum is measured by such sensor. An artifact reduction technique (ART) was addressed to eliminate the dominant aliasing between the interference channels. Since ART is performed by combining double measurements with orienting the analyzer in two orthogonal directions, a longer scanning time is needed, which makes the system more susceptible to temporal misregistration [13]. Recently, several improving aperture/amplitude division methods were proposed to modulate the Stokes

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parameters into imaging spectrometer to overcome the general drawbacks of the FTCISP [12,17,18]. However, differences in the distortion, focal length, and transmission coefficient of the optics necessitate sophisticated image registration algorithms. It is generally known that the measurement of S_3 is not necessary in most passive imaging scenarios that the obtaining linearly spectrally resolved Stokes parameters would satisfy several applications [6].

In this paper, we presented a method based on channeled polarimetric technique to measure spectrally resolved linearly Stokes parameters (namely, full linearly channeled polarimetric technique, FLCPT) that can increase spectral resolution of each measured Stokes parameter and restrain measurement error caused by aliasing between the channels. We describe the principle of the method in Section 2. The performance of the proposed method and conventional channeled polarimetric technique is compared through an experiment in Section 3, while our conclusion is contained in Section 4.

2. Principle of FLCPT

Optical schematic of the FLCPT is depicted in Fig. 1. The Stokes vector $S(\sigma)$ emitting from the target passes through achromatic quarter wave-plate AQWP, high-order retarder R and a linear analyzer, LA. The spectrum of the exiting light is then recorded by the spectrometer. The fast axis of AQWP is aligned with the transmission axis of LA, and R is oriented with its fast axis at 45° to the transmission axis of LA.

By using the Mueller calculus, the Stokes vector of the emergent light from analyzer LA can be described as [8,14]

$$\mathbf{S_{out}} = \mathbf{M_{LA}} \mathbf{M_R} \mathbf{M_{AQWP}} \mathbf{S_{in}} \tag{1}$$

where $\mathbf{M_{AQWP}}$, $\mathbf{M_R}$ and $\mathbf{M_{LA}}$ are the Muller matrices of the achromatic quarter wave plate AQWP, retarder R and the analyzer P_2, respectively. $\mathbf{S_{in}}$ is the spectrally resolved Stokes vector of the incident light and expressed by

$$S(\sigma) = \begin{bmatrix} S_0(\sigma) \\ S_1(\sigma) \\ S_2(\sigma) \\ S_3(\sigma) \end{bmatrix} = \begin{bmatrix} I_{0^\circ}(\sigma) + I_{90^\circ}(\sigma) \\ I_{0^\circ}(\sigma) - I_{90^\circ}(\sigma) \\ I_{45^\circ}(\sigma) + I_{-45^\circ}(\sigma) \\ I_R(\sigma) - I_L(\sigma) \end{bmatrix} \tag{2}$$

where σ is spectral variable, $S_0(\sigma)$ is the total intensity of the light, while $S_1(\sigma)$ denotes the part of 0° linear polarized light over 90°, $S_2(\sigma)$ for +45° over −45°, and $S_3(\sigma)$ for right circular over left circular.

The spectrometer responds to radiation intensity instead of polarization state, so only the first parameter of $\mathbf{S_{out}}$ can be measured. The recorded signal is varied with wavenumber and can be expressed as

$$S_0^{out}(\sigma) = \frac{1}{2}[S_0(\sigma) + S_1(\sigma) cos\varphi_R(\sigma) + sin\varphi_R(\sigma) S_2(\sigma)] \tag{3}$$

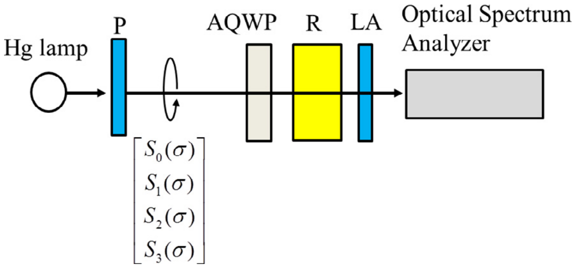

Fig. 1. Optical schematic of FLCPT.

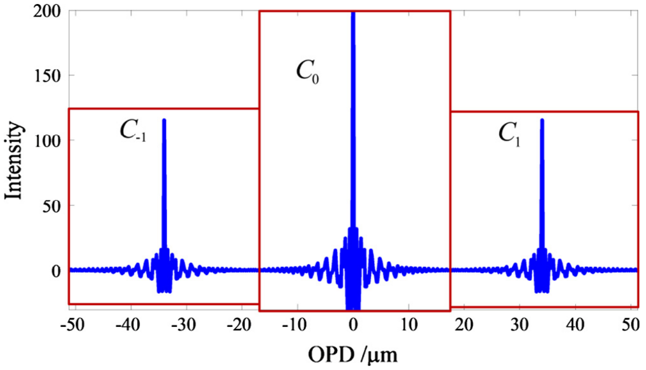

Fig. 2. Simulated interferogram for a 0° linear incident polarization state.

The phase term is presented as $\varphi_R(\sigma) = 2\pi\sigma B(\sigma)D$, where $B(\sigma)$ and D is birefringence of the crystal and thickness of the retarder R, respectively. It should be noted that such a cosinusoidally modulated spectrum is the channeled spectrum that is frequently used in the field of frequency-domain interferometry. Expanding Eq. (3) yields three frequency channels that contain the polarimetric information

$$S_0^{out}(\sigma) = \frac{1}{2} S_0(\sigma) + \frac{S_1(\sigma) - iS_2(\sigma)}{4} e^{i\varphi} + \frac{S_1(\sigma) + iS_2(\sigma)}{4} e^{-i\varphi} \tag{4}$$

The inverse Fourier transformation of $S_0^{out}(\sigma)$ gives an interferogram with the intensity varied with optical path difference:

$$C(z) = \frac{1}{2} C_0(z) + \frac{1}{4} C_1(z - L_2) + \frac{1}{4} C_1^*(-z - L_2) \tag{5}$$

where z and L_2 denotes the optical path difference (*OPD*) produce by the spectrometer and the retarder R, respectively. The three components included in $C(z)$, centered at $z = 0$ and $\pm L_2$, are separated from one another over the *OPD* axis if the retarder thickness D is properly selected. These separated channels can be seen from a simulated interferogram shown in Fig. 2, where the input radiation is a 0° linear incident polarization state and a broad band source.

By filtering the desired channels C_0 and C_{-1} (fringe patterns in the left two red boxes shown in Fig. 2) and taking Fourier transform, the linearly spectrally-dependent Stokes parameters can be reconstructed:

$$S_0(\sigma) = \Im\{C_0\} \tag{6}$$

$$S_1 = \mathrm{real}[2\Im\{C_1\} e^{i\varphi}] \tag{7}$$

$$S_2 = \mathrm{imag}[2\Im\{C_1\} e^{i\varphi}] \tag{8}$$

where real[ ] and imag[ ] denotes taking the real part and imaginary part of an imaginary parameter. In Eqs. (6)–(8), $S_0(\sigma)$ can be demodulated directly, the phase factor φ modulated $S_1(\sigma)$ and $S_2(\sigma)$ can be calibrated by using a reference beam [8,13,14].

3. Experiment and discussion

We carried out an experiment to demonstrate the validity of our method. Polychromatic light from an Hg lamp is transmitted by a polarizer (P) located in front of the AQWP to create a controlled SOP. The polarizer and the analyzer are α-barium borate (α-BBO) Glan-Taylor prisms (extinction ratio $\geq 10^5$) from Union Optic, Inc. AQWP is the product AQWP05M-600 supplied by Thorlabs, Inc with flat retardance of 90° over 400–800 nm. The quartz prism with thickness of 9 mm fabricated by Keelaser, Inc is used for the retarder. Spectrum $S_0^{out}(\sigma)$ of the light transmitted by LA is