



Spectroscopic Stokes polarimetry based on Fourier transform spectrometer

Yeng-Cheng Liu^a, Yu-Lung Lo^{a,b,*}, Chang-Ye Li^a, Chia-Chi Liao^a

^a Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan

^b Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan, Taiwan

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ABSTRACT

Two methods are proposed for measuring the spectroscopic Stokes parameters using a Fourier transform spectrometer. In the first method, it is designed for single point measurement. The parameters are extracted using an optical setup comprising a white light source, a polarizer set to 0°, a quarter-wave plate and a scanning Michelson interferometer. In the proposed approach, the parameters are extracted from the intensity distributions of the interferograms produced with the quarter-wave plate rotated to 0°, 22.5°, 45° and −45°, respectively. For the second approach, the full-field and dynamic measurement can be designed based upon the first method with special angle design in a polarizer and a quarter-wave plate. Hence, the interferograms of two-dimensional detection also can be simultaneously extracted via a pixelated phase-retarder and polarizer array on a high-speed CCD camera and a parallel read-out circuit with a multi-channel analog to digital converter. Thus, a full-field and dynamic spectroscopic Stokes polarimetry without any rotating components could be developed. The validity of the proposed methods is demonstrated both numerically and experimentally. To the authors' knowledge, this could be the simplest optical arrangement in extracting the spectral Stokes parameters. Importantly, the latter one method avoids the need for rotating components within the optical system and therefore provides an experimentally straightforward means of extracting the dynamic spectral Stokes parameters.

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1. Introduction

The problem of measuring the Stokes parameters has attracted significant attention in the literature. Hauge and Dill [1] developed a digital Fourier ellipsometer incorporating a rotating compensator and a fixed analyzer for measuring the state of polarization (SOP) of the light reflected from a sample. Lee et al. [2] presented a multi-channel spectroscopic ellipsometer based on a rotating-compensator for measuring the evolution over time of the Stokes parameters of the light reflected from the surface of a growing film. Oka [3] proposed a spectropolarimeter incorporating a pair of birefringent retarders for measuring all of the spectrally-resolved Stokes parameters of polychromatic light using a single-channeled spectrum. Kudenov et al. [4] presented a Fourier transform spectropolarimeter in which the channeled spectral method proposed in [3] was implemented using two Yttrium Vanadate (YVO₄) crystal retarders. In general, channeled spectropolarimetry techniques measure the complete SOP of a light beam by amplitude

modulating the Stokes parameters onto the spectral carrier frequencies. However, in such an approach, the high-frequency spectral features may cause interactions (aliasing) between adjacent carrier frequency channels and therefore result in false polarimetric signatures. Thus, a false-signature aliasing reduction technique is introduced to reduce and calibrate the error induced by these non-band-limited features [5,6].

In this study, two optical configurations are proposed for resolving the aliasing problem in channeled spectropolarimetry using a white light source and a scanning Michelson interferometer. White light Fourier transform spectrometers have a number of advantages over traditional dispersive spectrometers, including a higher signal-to-noise ratio and a faster measuring time. Thus, in the first configuration, a polarizer and quarter-wave plate are placed in front of the interferometer and the spectral Stokes parameters are extracted via Fourier transformation from the interferograms produced given four different rotational angles of the wave plate. It is especially designed for a full-field measurement in the second approach. Thus, in the second approach, the four interferograms required to compute the spectral Stokes parameters are obtained directly using a high-speed CCD camera with a pixelated phase-retarder and a polarizer array positioned behind the interferometer. It is noted that the technique can be

* Corresponding author at: National Cheng Kung University, Department of Mechanical Engineering, No. 1 University Road, Tainan, Taiwan.

E-mail address: loyl@mail.ncku.edu.tw (Y.-L. Lo).

utilized to measure spectral Stokes parameters both in reflection and transmission mode. In addition, it could be developed to obtain spectral information of birefringence, diattenuation and depolarization properties in anisotropic optical materials [7,8].

2. Theoretical analysis in the extraction of spectral Stokes parameters using scanning Michelson interferometer

Fig. 1 illustrates the first setup proposed in this study to measure the spectral Stokes parameters ($S_0(\sigma)$, $S_1(\sigma)$, $S_2(\sigma)$, and $S_3(\sigma)$) after the light passes through a sample is shown in Fig. 1 using a white light source and a scanning Michelson interferometer. In performing the measurement process, polarizer P is adjusted to 0° and quarter-wave plate Q is rotated to 0° , 22.5° , 45° or -45° , respectively. The corresponding interferograms are then obtained by driving the movable mirror (M_2) in the interferometer by means of a PZT stage.

The input light Stokes vector is given by

$$S_{in} = \begin{bmatrix} S_0(\sigma) \\ S_1(\sigma) \\ S_2(\sigma) \\ S_3(\sigma) \end{bmatrix} = \begin{bmatrix} I_x + I_y \\ I_x - I_y \\ I_{45^\circ} - I_{-45^\circ} \\ I_R - I_L \end{bmatrix}, \quad (1)$$

where σ is the wavenumber (defined as λ^{-1}), $S_0(\sigma)$ is the total light intensity, and $S_1(\sigma)$ is the light intensity obtained by subtracting the light intensity of linear polarization in the y direction (I_y) from that in the x direction (I_x). On the other hand, $S_2(\sigma)$ represents the light intensity obtained by subtracting the intensity of the light linearly polarized at -45° (I_{-45}) from that of the light linearly polarized at $+45^\circ$ (I_{45}). Finally, $S_3(\sigma)$ is the light intensity obtained by subtracting the intensity of the left-circular polarization light (I_L) from that of the right-circular polarization light (I_R). In general, the interferograms obtained by a Fourier transform spectrometer (FTS) [9] yield direct access to the spectral-carried frequencies containing the Stokes parameter information. In the present study, the spectropolarimetric data can be extracted from the Fourier domain via four different interferograms. The four different cases of optical arrangements with a scanning Michelson interferometer regarding to four interferograms are set as follows.

Arrangement 1: polarizer adjusted to 0° and slow axis of quarter-wave plate set to 45° . The Stokes vector of the light emerging from the polarizer has the form

$$S_{1,out} = [P_{0^\circ}][Q_{45^\circ}][S_{in}] = \frac{1}{2} \begin{bmatrix} S_0 + S_3 \\ S_0 + S_3 \\ 0 \\ 0 \end{bmatrix}, \quad (2)$$

Arrangement 2: polarizer adjusted to 0° and slow axis of quarter-wave plate set to 0° . The Stokes vector of the light

emerging from the polarizer has the form

$$S_{2,out} = [P_{0^\circ}][Q_{0^\circ}][S_{in}] = \frac{1}{2} \begin{bmatrix} S_0 + S_1 \\ S_0 + S_1 \\ 0 \\ 0 \end{bmatrix}, \quad (3)$$

Arrangement 3: polarizer adjusted to 0° and slow axis of quarter-wave plate set to -45° . The Stokes vector of the light emerging from the polarizer has the form

$$S_{3,out} = [P_{0^\circ}][Q_{-45^\circ}][S_{in}] = \frac{1}{2} \begin{bmatrix} S_0 - S_3 \\ S_0 - S_3 \\ 0 \\ 0 \end{bmatrix}, \quad (4)$$

Arrangement 4: polarizer adjusted to 0° and slow axis of quarter-wave plate set to 22.5° . The Stokes vector of the light emerging from the polarizer has the form

$$S_{4,out} = [P_{0^\circ}][Q_{22.5^\circ}][S_{in}] = \frac{1}{4} \begin{bmatrix} 2S_0 + S_1 + S_2 + \sqrt{2}S_3 \\ 2S_0 + S_1 + S_2 + \sqrt{2}S_3 \\ 0 \\ 0 \end{bmatrix}, \quad (5)$$

Note that in Eqs. (2)–(5), $[S_{in}]$ is the input light vector; $[Q_{45^\circ}, 0^\circ, -45^\circ, 22.5^\circ]$ represents the Mueller matrix of the quarter-wave plate with the slow axis set to 45° , 0° , -45° , and 22.5° , respectively, with respect to the x-axis; and $[P_{0^\circ}]$ is the Mueller matrix of the polarizer with its principal axis set to 0° with respect to the x-axis.

For **Arrangement 1**, the intensity distribution of the interferogram can be obtained via calculus in Mueller matrix [10] as

$$I_{1,out} = \int_0^{\sigma_{max}} C(1 + \cos 2\pi\sigma\Delta z) \left[\frac{1}{2}(S_0(\sigma) + S_3(\sigma)) \right] d\sigma, \quad (6)$$

where C is constant and can be normalized in the process of spectrum reconstruction. σ_{max} is maximum recovery wavenumber. Thus, it can be simplified as

$$I_{1,out} \propto \frac{1 + \cos(\phi_z)}{2} [S_0(\sigma) + S_3(\sigma)], \quad (7)$$

It is observed in Eq. (7) that Stokes parameters S_0 and S_3 are implicitly dependent on the wavenumber, σ . The phase term $\phi_z(\sigma)$ corresponding to the optical path difference (OPD) introduced by the Michelson interferometer is also dependent on the wavenumber, and has the form

$$\phi_z(\sigma) = 2\pi\Delta z\sigma, \quad (8)$$

where Δz is the OPD of the interferometer. It is noted that the constant offset in Eq. (7) can be blocked since it provides no useful spectral information in this theory. Thus, Eq. (7) can be simplified as the following form:

$$I_1(\sigma) \propto [S_0(\sigma) + S_3(\sigma)] \frac{\cos(\phi_z)}{2}, \quad (9)$$

Via an analogous treatment, the intensity distributions of the interferograms associated with Arrangements 2–4 can be derived respectively as

$$I_2(\sigma) \propto [S_0(\sigma) + S_1(\sigma)] \frac{\cos(\phi_z)}{2}, \quad (10)$$

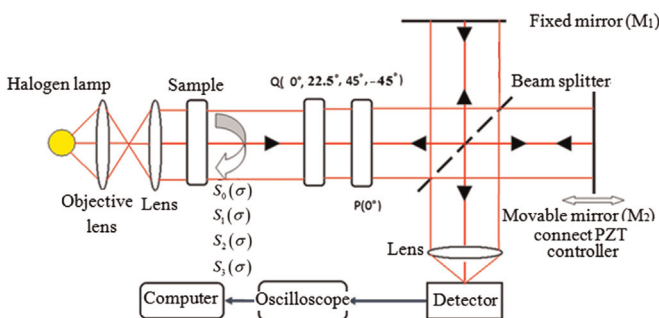


Fig. 1. Stokes parameter measurement using scanning Michelson interferometer.

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