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# Development of spectroscopic transmission-type four detector polarimeter

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ABSTRACT

We have developed a spectroscopic transmission-type four detector polarimeter (T-FDP). It consists of a detector head and a multichannel spectrometer equipped with a two-dimensional CCD detector. Inside the T-FDP, three cubic beam splitters are aligned in a straight line and they are rotated relative to each other. From the responses of the spectroscopic T-FDP to five inputs with known polarization states it is possible to determine the characteristic matrices of the T-FDP at various wavelengths. The trajectories of the experimentally measured polarization states on the Poincaré sphere agree well with theoretical predictions. These results demonstrate the feasibility of using the T-FDP for spectroscopic ellipsometry.



## 1. Introduction

Ellipsometry can be used to easily and non-destructively measure film thickness with an accuracy on the order of nanometers [1–3]. It is highly sensitive to the thickness and the optical properties of a film. Ellipsometry can also be used for *in-situ* observation of the dynamic behavior of liquid crystals [4]. Consequently, ellipsometry is widely utilized for investigating surfaces and the optical properties of thin films. One of the authors (T. Tsuru) has developed an automatic null ellipsometer that has a picometer thickness sensitivity and can determine the complex refractive index and the thicknesses of nanometer-period multilayers using layer-by-layer analysis [5–7]. Thus, ellipsometry is a promising tool for nanoscience and nanotechnology.

Recently, several novel static polarimeters have been proposed that do not involve mechanical movement or electrical modulation [8–12]. They can perform high-speed measurements since their performance is limited only by the data acquisition speed of their electronics. As a static polarimeter, Azzam proposed a four-detector polarimeter (FDP) [8,9], which is a useful and a powerful instrument for measuring the polarization state of light. The FDP contains four custom-made photodetectors that are rotated relative to each other to alter the plane of incidence of the photodetector. To simplify the optical alignment and calibration of the FDP, one of the authors (S. Kawabata) developed a transmission-type FDP (T-FDP) by modifying the design of the original FDP [13,14]. The T-FDP has three beam splitters with 45° surfaces aligned in a straight line and rotated at an angle relative to each other. The beam splitter added to the T-FDP as an extra output ejects light with the same polarization state as the incident light. The beam splitters split the incident light into five beams, which are detected using commercially available photodetectors.

The present paper describes the construction and the characteristics of a spectroscopic T-FDP. Procedures for aligning and calibrating the spectroscopic T-FDP are also proposed. Finally, measurements of the polarization states are performed as a practical application of the spectroscopic T-FDP to spectroscopic ellipsometry.

## 2. Spectroscopic T-FDP

Fig. 1 shows a schematic diagram of the spectroscopic T-FDP. It consists of a T-FDP head [13,14], a multichannel spectrometer (MK-302, Bunkoukeiki Co., Ltd.), and a cooled two-dimensional CCD detector with a 16-bit A/D converter (ST-8XME, Santa Barbara Instrument Group). The T-FDP head is connected to the spectrometer by multimode optical fibers. Light from the T-FDP head is transferred to the entrance slit of the spectrometer and is recorded as spectral distributions on the two-dimensional CCD detector. Since the multimode fiber completely depolarizes the transmitted light, the polarization efficiency of the spectrometer can be disregarded. The spectral intensities of each channel are fed to the computer and the polarization state of the light for each wavelength is determined.

The T-FDP head consists of three cubic beam splitters ($BS_1$, $BS_2$, and $BS_3$) that are aligned along the optical axis. Beam splitters $BS_2$ and $BS_3$ are rotated by 45 and 90° about the optical axis, respectively. Beam splitter $BS_0$ is placed on top of the $BS_1$ as an extra output for monitoring the incident light intensity. $BS_0$ is twisted by 90° with respect to $BS_1$ so that the p- and s-components of the incident light are interchanged [14]. Therefore, after being reflected from $BS_1$ and $BS_0$, the light emerging from $BS_0$ has the same polarization state as the incident light. Each beam splitter consists of two right-angle prisms, one of which is coated with chromium on its hypotenuse face. The

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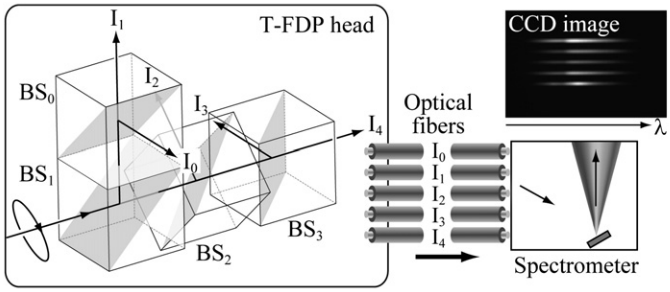


**Fig. 1.** Schematic diagram of the spectroscopic transmission-type four detector polarimeter (T-FDP).

input light is split into reflected and transmitted beams at a ratio of approximately 1:1. The T-FDP head generates five output signals $I_0$–$I_4$ that depend on the polarization state of the incident light. As mentioned above, the output signal $I_0$ reflected at $BS_0$ has the same polarization state as the incident light and it is used to normalize other output signals $I_1 - I_4$ when both calibrating the system and performing measurements. Fig. 2 shows a photograph of the T-FDP housing.

The spectrometer contains a 50 grooves/mm grating and it can measure the full visible light range (340 to 1200 nm) with a spectral resolution of approximately 0.6 nm. The beam spot separation at the entrance slit of the spectrometer is 500 μm. The astigmatism of the multichannel spectrometer is compensated to obtain finely separated images of the optical fibers on the CCD. Fig. 3(a) shows a single-shot spectral image of the output light from the T-FDP head. It shows that each spectral line from the optical fiber is clearly separated. Fig. 3(b) shows the line profiles of the image. The data acquisition time depends on the specifications of the CCD detector and the intensity of the incident light; we achieved a sampling rate of 0.12 s using our spectroscopic T-FDP. The spectral range of the spectroscopic T-FDP is mainly limited by the quantum efficiency of the CCD; in our case, it was approximately 400 to 1000 nm.

The relationship between the output light intensities $I(\lambda)$ and the polarization state $S(\lambda)$ of the incident light with wavelength λ is expressed by the following linear relation in matrix form [8].

$$I(\lambda) = A(\lambda) \cdot S(\lambda), \tag{1}$$

where $S(\lambda)$ is the Stokes vector $(S_0, S_1, S_2, S_3)$ of the incident polarized light and $A(\lambda)$ is a $4 \times 4$ characteristic matrix of the T-FDP at the wavelength λ. If $n$ measurements are performed in calibration, the measured intensities and the input Stokes vectors will both be rectangular $4 \times n$ matrices with generic elements of $I_{c,\ i}$ and $S_{c,\ j}$, respectively (where $c$ denotes the $c$th measurement of the $n$ measurements, $i$ denotes the detector number and $j = 0$ to 3). If four

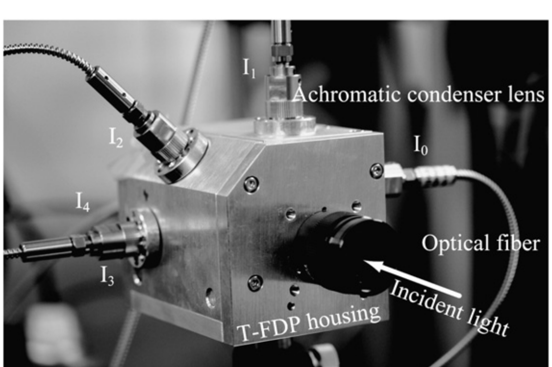


**Fig. 2.** Photograph of the T-FDP head.

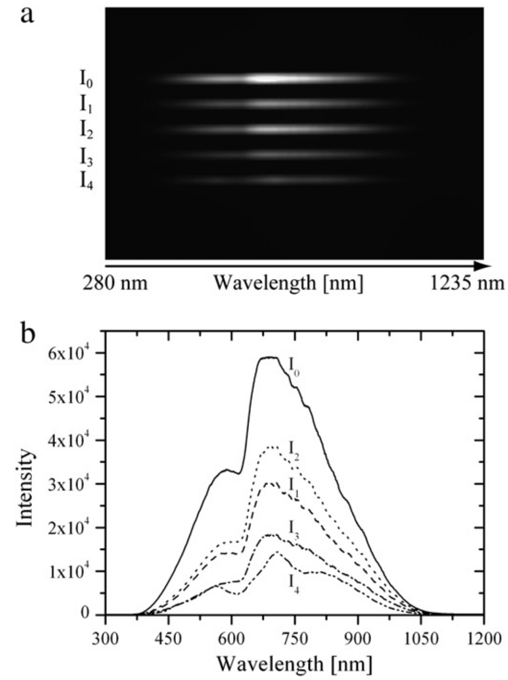


**Fig. 3.** (a) Single-shot spectral image of output beams from the T-FDP head that passed through five optical fibers and a multichannel spectrometer and were recorded using a cooled CCD camera. (b) Line profiles of the spectral image in (a).

measurements are made, $I(\lambda)$ and $S(\lambda)$ will be square matrices and $A(\lambda)$ can be expressed in terms of the nonsingular matrix $S(\lambda)$ as

$$A(\lambda) = I(\lambda) \cdot S(\lambda)^{-1}. \tag{2}$$

If the characteristic matrix $A(\lambda)$ is known, the polarization state of the incident light can be determined from the output intensities using the following equation.

$$S(\lambda) = A(\lambda)^{-1} \cdot I(\lambda). \tag{3}$$

Here, $A(\lambda)^{-1}$ is the inverse matrix of the characteristic matrix $A(\lambda)$.

If $n>4$ (as is the case in our calibration procedure), $S(\lambda)^{-1}$ in Eq. (2) is replaced by $S(\lambda)^{+}$, which is known to be:

$$S(\lambda)^{+} = S(\lambda)^{T} \cdot \left\{ S(\lambda) \cdot S(\lambda)^{T} \right\}^{-1}. \tag{4}$$

Note that the characteristic matrix $A(\lambda)$ is determined for the whole of the T-FDP system. Thus, it expresses not only the characteristics of the T-FDP head but also the gain properties of the optical fibers, the spectrometer, and the CCD detector.

## 3. Calibration procedure

The characteristic matrix $A(\lambda)$ at wavelength λ in Eq. (1) can be determined by using four elliptically polarized beams whose polarization states are known as incident beams. In this study, to reduce the number of chromatic polarization states in the calibration procedures, three linear polarized lights with $P = 0$, 60, and 120° and two circular polarization sets of $(P, C) = (0°, 45°)$ and $(0°, -45°)$ are employed, where $P$ and $C$ are respectively the azimuths of the polarizer and the quarter-wave plate for 633 nm. Linearly polarized light with a different azimuthal angle can be generated by the Glan–Thompson prism regardless of the wavelength. In contrast, the elliptical polarization including the circular polarization at each wavelength must be