Novel High-Speed Photopolarimeter Based on a Metallic Grating

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Abstract. A novel high-speed photopolarimeter is presented in this paper, which is composed by the optical system, electronics system and PC. This instrument uses a metallic grating that can produce both reflective diffraction and transmission diffraction as a beam splitter to divide the incident light into many components, and the light fluxes of the four 1st order diffracted beams are converted linearly into four electrical signals by four photodiodes. After going through a signal conditioning circuit, these electrical signals are converted into digital values by high-speed A/D converters that can implement synchronous multi-channels sampling, and then the data sampled are high-speedily transmitted into the PC via a USB2.0 interface. The electrical signal vector $I$ composed by the four electrical signals possesses the linear relationship with the incident light Stokes vector $S$. The nonsingular instrument matrix $A$ of this instrument can be obtained by the calibration, and then the unknown Stokes vector $S$ of the incidence light can be obtained from the equation $S = A^{-1}I$. The testing results show that the mean deviations of the measured Stokes parameters compared with the predicted values are less than 1% at 632.8nm. It is compact and easy to be installed, and can be used as a polarization state detector in real-time polarimetry and ellipsometry.

1. Introduction
The light polarization is a rich resource from which we can obtain lots of valuable information. Light polarization is very important in many applications. Because the traditional methods of the measurement of light polarization adopt general movable parts or modulators, their applications are limited in the field of rapid change of polarization, such as the study of the physical chemistry reaction on the sample surface. In 1982, Azzam introduced the division-of-amplitude photopolarimeter (DOAP), which can implement the simultaneous detection of multi-signal channel using the division-of-amplitude method, which can obtain nearly instantaneous and simultaneous measurements of the four Stokes parameters. [1-5]

In this paper we designed a special metallic grating that can produce both reflective diffraction and transmission diffraction, utilized it as a beam splitter to present a novel photopolarimeter base on the principle of the DOAP.

2. Principle
We use the method of vacuum sputtering, splutter the metallic chromium on the optical glass, and then sculpture the diffraction grating that is shown in figure 1 on the metal surface. It can generate both...
reflective diffraction and transmission diffraction, and the intensities of reflective diffraction beam and transmission diffraction beam at the same order are approximately equal.

**Figure 1.** Metallic Grating.

**Figure 2.** Schematic drawing of measuring the polarization state of light using a metallic grating. P: Polarizer, D: Detector.

It is illustrated in figure 2, a collimated light beam incident on a metallic grating, and then we can observe the reflective diffraction and the transmission diffraction. Because they are vertical between the incident plane and the grating grid, all diffraction beams are in the same plane. The polarization state of the incident light is analyzed in terms of ±1st order beam both reflective diffraction and transmission diffraction, here, marks these beams with \( m, m = 0,1,2,3 \). The light fluxes of the four diffracted beams are converted linearly into four electrical signals \( i_m(m=0,1,2,3) \) by four photodiodes \( D_m(m=0,1,2,3) \). Polarizer with azimuth \( A_m(m=0,1,2,3) \) fronts each detector. The output electrical signal \( i_m \) is a linear combination of all four Stokes parameters of the incident light; i.e.,

\[
i_m = a_{m0}S_0 + a_{m1}S_1 + a_{m2}S_2 + a_{m3}S_3 \quad m = 0,1,2,3.
\]

Consequently, row vector \( \mathbf{I} = [i_0, i_1, i_2, i_3]^t \) composed by four electrical signals has the following linear relationship with incident light Stokes vector \( \mathbf{S} = [S_0, S_1, S_2, S_3]^t \) (where \( t \) denotes the transpose)

\[
\mathbf{I} = \mathbf{A} \mathbf{S},
\]

where

\[
\mathbf{A} = \begin{bmatrix}
    a_{00} & a_{01} & a_{02} & a_{03} \\
    a_{10} & a_{11} & a_{12} & a_{13} \\
    a_{20} & a_{21} & a_{22} & a_{23} \\
    a_{30} & a_{31} & a_{32} & a_{33}
\end{bmatrix}
\]

called the instrument matrix and that is the function of wavelength. If it is nonsingular, which has inverse matrix \( \mathbf{A}^{-1} \), consequently, the incident light Stokes vector \( \mathbf{S} \) can be expressed like this

\[
\mathbf{S} = \mathbf{A}^{-1} \mathbf{I}.
\]

After obtaining instrument matrix \( \mathbf{A} \), the unknown Stokes vector that describes the incident light polarization can be obtained from equation (4). In the practical application, the instrument matrix \( \mathbf{A} \) is determined by calibration not by calculation.

**3. Experimental setup**

Based on the above principle, we have studied the instrument that can measure the state of polarization, as shown in figure 3. The photopolarimeter is composed of three function modules, which are the optical system, the electrics system and the personal computer.
3.1. Optics System

3.1.1. Polarizations State Generator (PSG). The polarization state generator (PSG) can generate any complete polarization state to be used for calibration, after the calibration it may remove. In this instrument, the PSG is mainly consisted of a He-Ne laser (632.8nm, <2mW), a linear polarizer and a quarter-wave retarder (QWR). The polarizer and the QWR were mounted separately in the precision motorized rotators, the rotators revolved round the optical axis with the use of two stepper motors.

After the non-polarization light goes through the ideal polarizer and the QWR, the normalized Stokes vector of output is

\[
\mathbf{S}_{\text{PSG}} = \mathbf{M}_{\text{QWR}}(Q)\mathbf{M}_P(\theta)\mathbf{S}_{\text{un}} = \begin{bmatrix}
1 \\
\cos 2Q \cdot \cos(2Q - 2\theta) \\
\sin 2Q \cdot \cos(2Q - 2\theta) \\
\sin(2Q - 2\theta)
\end{bmatrix},
\]

where \(\mathbf{S}_{\text{un}}\) is the Stokes vector of the non-polarization light, \(\mathbf{M}_p(\theta)\) is Mueller matrix of polarizer with azimuth \(\theta\); \(\mathbf{M}_{\text{QWR}}(Q)\) is Mueller matrix of QWR with azimuth \(Q\). From the equation (5), we know that the PSG can generate any complete polarization states by adjusting the azimuth \(\theta\) of polarizer and azimuth \(Q\) of the QWR.

3.1.2. Polarization State Detector (PSD). The polarization state detector is mainly consisted of the metallic grating, the polarizer and the QWR. ±1st order beams both reflective diffraction and transmission diffraction which are generated by metallic grating, are converted linearly into electrical signals by four photodiodes, polarizer with azimuth 0°, 45°, 90° and -45° is placed in front of each detector. To improve the discrimination of the instrument to right-handed and left-handed circularly polarization, the second QWR is placed in front of the polarizer \(P_3\), the inclination is 45° between its quick axis direction and transmission axis of the polarizer \(P_3\). When instrument is working, it is very important to aiming extremely between the incoming beam and the PSD, here, we use a silicon quadrant photocell to measure 0 order transmission diffracted beam to complete the aiming.

3.2. Electronics

The electronics system is studied based the MCU platform, as shown in figure 4. Its basic function is: (1) the multi-channel photo electricity transformation and the signal processing; (2) multi-channel analog signals high-speed high-resolving A/D converters; (3) rotation control of 2 stepper motors; (4) high speed data transmit between the electronics system and PC. The microcontroller is CY7C68013 of Cypress Corporation, it carries on the data exchange through the USB2.0 interface with the PC, and
receives the command from the PC, completes the control of electric stepper motors and the data acquisition and so on. A/D converter is MAX1316 of Maxim Corporation, it can simultaneous fast sample to 8 channels (or below 8) analog signals.

![Schematic block diagram of the electronics system.](image)

3.3. Software
This instrument software includes firmware, device driver and client application.

3.3.1. Firmware. The firmware is the program stored in the microcontroller. Using the Keil uVision2 IDE, the firmware code for the G-DOAP is written in C. The main function of firmware is to initialize various hardware units, control stepper motors, control data acquisition and communicate with PC. In terms of EP2 and EP6 of CY7C68013, we can realize the data transfer between the microcontroller and PC. Set the EP2 as an IN endpoint and the EP6 as an OUT endpoint, and set their transfer type as bulk transfers.

3.3.2. Device Driver. Under the Windows operating system, the USB device that has the specific function requires to be provided its driver by the designer. Cypress Corporation has provided a USB2.0 developer’s kit (USB Developer’s uStudio) under the Windows operating system. In uStudio, it contains a general USB device drivers CyUSB.Sys, user only need to modify the CyUSB.inf file, do not need to compile again and make any USB2.0 device to match with this driver.

We modified the CyUSB.inf file, and used CyUSB.Sys as the driver of the G-DOAP on the PC.

3.3.3. Client Application. The main function of client applications includes: (1) Controlling the rotation of stepper motors, (2) Multi-channel high-speed data acquisition, (3) Data processing and displaying.

The key of compiling client applications is that how to receive the data from the USB equipment and to send data to it. uStudio has contained a storehouse of C++ CyAPI.Lib that aim at the special object, which as one kind of Windows API scheme instead, it provides an advanced and simple interface of application for the driver of CyUSB.sys. It is very easy to grasp the use method of CyAPI for user who is familiar with USB equipment.

Under the Borland C++ 6.0, using the functions in CyAPI.lib, we can achieve the data transfer between PC and microcontroller, and compiled the client application program of this instrument.
4. Results and analysis
The testing results show that the mean deviations of the measured Stokes parameters compared with the theoretical values are less than 1% at 632.8nm.

The main reasons that result the deviation are: (1) optic components is imperfect in the PSG, especially in QWR; (2) light beam deviation error; (3) polarizer in PSG and azimuth angle in QWR have deviation; (4) the nonlinearity of the photo detector and the signal conditioning circuit.

5. Conclusion
A novel photopolarimeter was introduced in this paper. This instrument uses a metallic grating as its beam splitter. Four diffracted beams intercepted by photodiodes are used to determine the state of polarization of the incident light. This instrument uses neither movable parts nor modulator; the measure speed is only determined the response of the photodetectors and their associated electronics. It is compact, easy to be installed, and can be used as a polarization state detector in real-time polarimetry and ellipsometry.

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