Stokes Polarimetry

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INSTRUMENTS

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James Kemp's version of the photoelastic modulator was invented for use as a polarimeter, particularly for use in astronomy. The basic problem is measuring net polarization components in what is predominantly an unpolarized light source. Dr. Kemp was able to measure a polarization component of light less than 10^6 below the level of the total light intensity.

The polarization state of a light source is represented by four numerical quantities called the "Stokes parameters".[1,2] These correspond to intensities of the light beam after it has passed through certain devices such as polarized prisms or films and wave plates. These are defined in Figure 1.
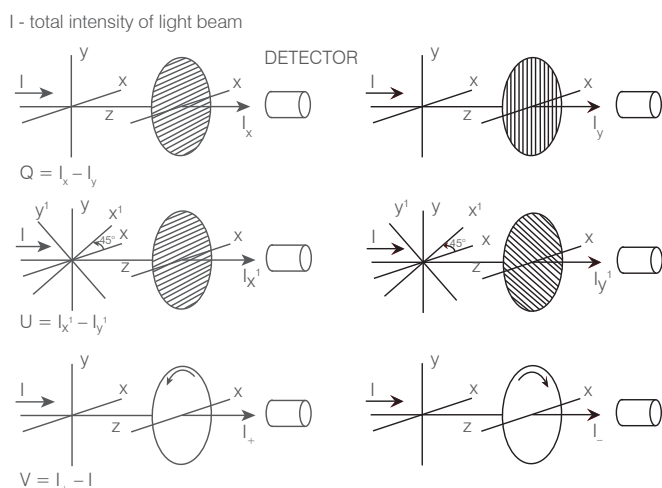
I - total intensity of light beam

Figure 1. Definition of the Stokes Parameter

To many scientists a polarimeter is a device for measuring a change in the plane of polarization of a linearly polarized light beam. For small angle rotations, this measurement can be done more simply and with greater precision using the techniques described in the application note "Optical Rotation."

SIMPLIFIED POLARIMETER

A simplified polarimeter optical setup is shown in Figure 2. This setup would be suitable for situations in which the direction of the linear polarization component is known beforehand. The polarimeter should be aligned so that the passing axis of the modulator is at 45 degrees to the known linear polarization direction, as shown. The polarizer is oriented at right angles to the plane of the incident linear polarization component.

The circular polarization component will produce a signal at the modulator frequency, 1f. If the sense of the circular polarization is reversed, this will be shown by an output of opposite sign from the lock-in amplifier. This signal is proportional to Stokes Parameter V.

The linear polarization component will give a signal at twice the modulator frequency, 2f. A linearly polarized component at right angles to the direction shown will produce a lock-in output with opposite sign. This signal is proportional to Stokes Parameter U.

A linear component of polarization which is at 45 degrees to the direction shown will produce no 2f signal in the lock-in amplifier. If there is no such component, the Stokes parameter Q is zero. If there is such a component, this simplified polarimeter cannot detect it.

Figure 2 assumes that the light source is monochromatic or nearly so. PEM-based modulators need some spectral selection of the light being measured. If a wavelength selecting device such as a monochromator or interference filter is used, it should be placed between the polarizer and the detector.
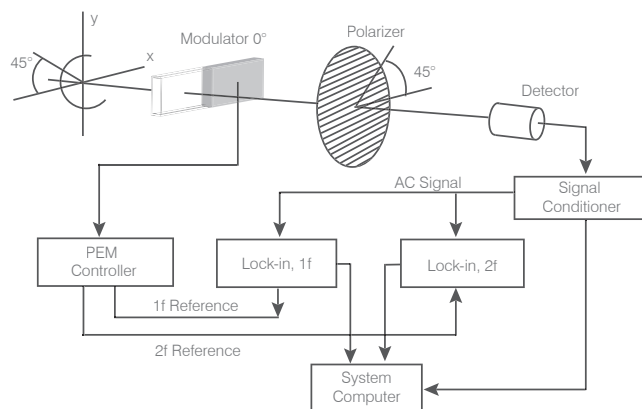

Figure 2. Simplified Polarimeter Set-up

Stokes Polarimetry

GENERAL POLARIMETERS

Rotator-Based Polarimeter

The setup above is not sufficient for determining the complete polarization state in situations where the linear polarization direction is not initially defined. Thus, two measurements at 45 degrees with respect to each other must be made. This is a requirement of all general purpose polarimeters.

With a PEM, there are at least two ways of accomplishing this. The first method is to provide a means of rotating the entire polarimeter apparatus (Figure 2) through 45 degrees. A measurement in each of the two positions must be made. This is an acceptable and straightforward method provided that the light source is steady and does not change over the time required for both measurements.

For a rotator-based polarimeter, the modulator, polarizer and other detector would be mounted so they can be rotated together. Two measurements would be taken, with the angular positions of the polarimeter assembly differing by 45 degrees. Modern systems would utilize a computer which would drive a motorized rotator and also process the data from the lock-in amplifiers and the DC meter.

The relationships between the electronic outputs of the lock-ins and the DC meter, and the polarization state of the light source are given in Table 1.

By using computer control of a single lock-in amplifier, it would be possible to make both 1f and 2f measurements sequentially.

FRACTIONAL POLARIZATIONS:

$$Q \; \alpha \; V_{2f} \, (0°) \qquad \left| \frac{\text{linear}}{\text{polarization}} \right| = \frac{\sqrt{Q_2 + U_2}}{I}$$

$$U \; \alpha \; V_{2f} \, (45°) \qquad \theta = \frac{1}{2} \tan^{-1} \left(\frac{U}{Q} \right)$$

$$V \; \alpha \; V_{1f} \, (0°) = V_{1f}(45°) \qquad \left| \frac{\text{circular}}{\text{polarization}} \right| = \frac{V}{I}$$

Table 1. Stokes Parameters with Rotating Polarimeter

Dual Modulator Polarimeter

Two photoelastic modulators may be used to provide a polarimeter with "real time" measurement capability. The two modulators are mounted with their modulator axes at 45 degrees with respect to each other.

The polarizer is mounted with its passing axis between the two modulator axes, or at 22.5 degrees with each modulator axis. The modulators must operate at different frequencies, typically a frequency separation of 2 to 5 kHz is used.

Figure 3 shows the optical configuration for a dual-modulator polarimeter. As mentioned, the modulator axes of the two modulators are at 45 degrees, with the polarizer passing axis at 22.5 degrees with each modulator. The angular designations for each modulator are determined by which angular direction of polarized light each modulator subsystem is sensitive to.
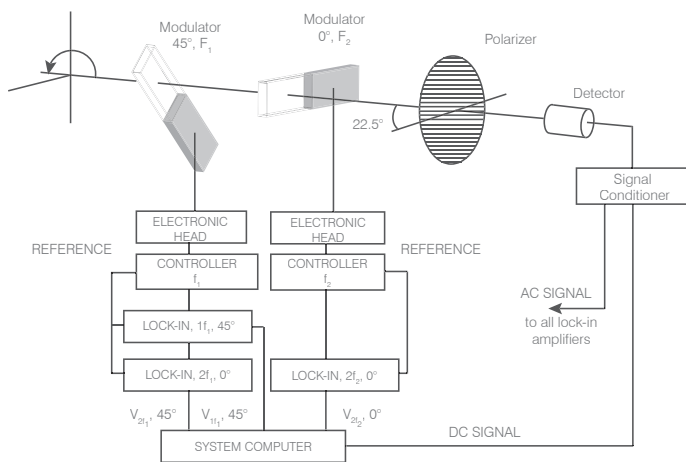

Figure 3. Dual Modulator Polarimeter Set-up

The relationships between the electronic output voltages and the appropriate polarization parameters are given in Table 1. The outputs of the two modulator systems are equivalent to the two measurements with the rotator-based system.

The measurement of the Stokes parameter I could in principle be accomplished by using a single detector with an optical system to restrict the field of view and to select the appropriate spectral bandwidth. There is much benefit to measuring I through the same

optical system as the polarimeter.

To measure I with this setup, it is important that the retardation amplitude of both PEMs be adjusted to a specific value. This value is A = 0.383 waves = 2.405 radians. For these PEM retardation values, the intensity at the detector is independent of PEM retardation and VDC is proportional to the Stokes parameter I.

USE OF WAVEPLATES

If the light source being measured is monochromatic or nearly so, waveplates may be used to simplify the polarimeter system significantly. Two such uses are described below.

Polarimeter Using Half-Wave Plate

Rotating a small component such as a waveplate is much simpler than rotating a whole polarimeter apparatus. The half-wave plate exhibits the property of rotating any linear polarization component to the opposite side of the fast axis.

The half-wave plate is placed initially with its fast axis parallel to the modulator axis. In this position Q and V may be measured, although the algebraic signs of the lock-in outputs will be reversed, compared with the polarimeter without the waveplate.

The waveplate is then rotated by 22.5 degrees for the measurement of the Stokes parameter U. Thus the 45 degree component is at 0 degrees with respect to the modulator axis, the 0 degree component is at 45 degrees. Thus the two measurements are sufficient for measuring the two linear parameters Q and U.

Linear Polarimeter Using Quarter-Wave Plate

If linear polarimetry is intended and there is no desire to measure the circular polarization components, the addition of a quarter-wave plate can be used to make a linear polarimeter which has no moving parts.

The waveplate is then placed with the fast axis at 45 degrees with the modulator axis. The 45 degree polarization component (Stokes parameter U) is unaffected, and is detected by a lock-in amplifier at twice the modulator frequency.

The component at 0 degrees (Stokes parameter Q) is converted by the waveplate to circularly polarized light. This circular light is then detected by the lock-in amplifier at the modulator frequency.

References:

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4. Kemp, James C. and Barbour, Mark. *A Photoelastic Modulator Polarimeter at Pine Mountain Observatory*, Publication of the Astronomical Society of the Pacific, 93:521-525, August 1981.

5. Kemp, James C., Henson, G.D., and Powell, E.R. "*The optical polarization of the sun measured at a sensitivity of parts in 10 million*," Nature, V. 326, No. 6110, pp. 270-273, March 19, 1987.

6. Kemp, James C. "*Detecting polarized light at levels below 1 ppm*". SPIE Conference, Los Angeles, January 1988.