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A FOUR-CHANNEL POLARIMETER TO MEASURE NANOSECOND LASER PULSES

JUN 1978

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INTRODUCTION

With the advent of nanosecond lasers, new opportunities have arisen as well as problems of scientific and military interest. One problem is the measurement of the polarization state of nanosecond laser pulses. We solved this problem by developing a novel four-channel polarimeter which simultaneously measures the four Stokes polarization parameters of an optical pulse. This design is enhanced by proper selection of the polarization state of the transmitted beam, which makes it possible to determine the ABCD polarization matrix of an optical system, using a single optical pulse.

The polarimeter is automated, has no moving parts, and is controlled by a Hewlett Packard (HP) 9825A desk calculator and an HP-IB Interface Bus System with an HP 6940B multiprogrammer.

Two important factors were critical to the adoption of this polarimeter design. The first was the realization that if an optical system was illuminated with a nanosecond laser pulse, the traditional methods for measuring the polarization state, or equivalently the Stokes polarization parameters, are completely inadequate. In order to measure the Stokes parameters, four distinct settings of a wave-plate/polarizer combination are needed. It is obviously impossible to do this in such a short time frame when dealing with nanosecond pulses. Since four distinct settings must be made, a polarimeter must contain four separate channels in which the wave plate/polarizer is preset and permanently fixed. With this design it is then possible to determine the Stokes polarization parameters simultaneously.

We wish to emphasize, however, that this arrangement allows us to measure the Stokes parameters of an optical beam irrespective of any time duration of the signal.

The second important factor in the design of the polarimeter was the fact that most optical systems of military interest contain only polarizing and phase shifting elements, as we shall show in the following sections. This being the case, it is possible to show that the 4x4, sixteen-element, Mueller-Stokes polarization matrix has only four unknown matrix elements, A, B, C, and D. This specialized matrix form is called the ABCD polarization matrix. Further analysis shows that if an optical component or system is illuminated with either circularly polarized or linearly polarized light, each of the detected Stokes parameters is equal to one of the A, B, C, or D matrix elements.

The design and operation of the polarimeter are directly related to the polarizing behavior of optical systems. Consequently, we first devote several sections of the paper to a detailed mathematical discussion of the polarization behavior.

DISCUSSION

Mueller-Stokes Matrices for Optical Components

The basic properties of the Stokes polarization parameters have been described in the classic texts by Chandrasekhar[1] and Born and Wolf.[2] Futher properties, as well as their relation to the Mueller-Stokes polarization matrices, have been treated by Shurcliff and other authors.[3,4,5]

There are three types of optical components that can change the state of polarization of an optical beam. These components are 1) a polarizer, 2) a compensator (phase shifter), and 3) a rotator. In this section we present the Mueller-Stokes matrix for each of these components and refer the reader to the referenced works for their derivation.

Polarizer

$$M_{pol}(p_x,p_y) = 1/2 \begin{pmatrix} p_x^2 + p_y^2 & p_x^2 - p_y^2 & 0 & 0 \\ p_x^2 - p_y^2 & p_x^2 + p_y^2 & 0 & 0 \\ 0 & 0 & 2p_xp_y & 0 \\ 0 & 0 & 0 & 2p_xp_y \end{pmatrix}, \quad (1)$$

where $0 \leq p(x,y) \leq 1$. For $p(x,y) = 1$ we have perfect transmission, while $p(x,y) = 0$ corresponds to no transmission (total absorption). For example, $p_y = 0$ for a Nicol prism or Polaroid, so

$$M_{POL}(p_x, p_y = 0) = p_x^2/2 \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \tag{2}$$

Compensator (Phase Shifter)

$$M_{COMP}(\phi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\phi & -\sin\phi \\ 0 & 0 & \sin\phi & \cos\phi \end{pmatrix}, \tag{3}$$

where ϕ is the total phase shift between the orthogonal axes. Specifically, for a quarter-wave plate, $\Phi = \pi/2$, so

$$M_{COMP}(\phi = \pi/2) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix}. \tag{4}$$

Rotator

$$M_{ROT}(2\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\theta) & \sin(2\theta) & 0 \\ 0 & -\sin(2\theta) & \cos(2\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{5}$$

where θ is the angle of rotation.

These expressions are valid only if the axes of the components are aligned with those of the incident beam. If the optical device is rotated through an angle θ then the transformed matrix is given by

$$M(2\theta) = M_{ROT}(-2\theta)\ M\ M_{ROT}(2\theta) \quad . \tag{6}$$

It is possible to construct an eigenvector which provides a simultaneous diagonal basis for the Mueller-Stokes matrices for the polarizer and the phase shifter, but not the rotator. To show this, the Stokes parameters are defined in terms of the optical field by

$$S_o = E_x E_x^* + E_y E_y^* = I_{xx} + I_{yy}$$

$$S_1 = E_x E_x^* - E_y E_y^* = I_{xx} - I_{yy}$$

$$S_2 = E_x E_y^* + E_y E_x^* = I_{xy} + I_{yx}$$

$$S_3 = i(E_x E_y^* - E_y E_x^*) = i\ (I_{xy} - I_{yx}). \tag{7}$$

The eigenvector that allows Eq 1 and 3 to be written in a diagonalized form is

$$\begin{pmatrix} I_{xx} \\ I_{yy} \\ I_{xy} \\ I_{yx} \end{pmatrix} , \tag{8}$$

and the diagonalized polarization matrices for the polarizer and the phase shifter are, respectively,

$$\widetilde{M}_{POL}(p_x,p_y) = \begin{pmatrix} p_x^2 & 0 & 0 & 0 \\ 0 & p_y^2 & 0 & 0 \\ 0 & 0 & p_x p_y & 0 \\ 0 & 0 & 0 & p_x\,p_y \end{pmatrix} \quad (9)$$

and

$$\widetilde{M}_{COMP}(\phi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & e^{-i\phi} & 0 \\ 0 & 0 & 0 & e^{+i\phi} \end{pmatrix} . \quad (10)$$

where *the tilde, ~, stands* for diagonalized matrix representation. The relation between the diagonalized forms, Eq 9 and 10, and the nondiagonalized Mueller-Stokes matrices, Eq 1 and 3, is

$$M = M_D^{-1}\ M\ M_D \quad , \quad (11)$$

where

$$M_D = (1/2) \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & i \\ 0 & 0 & 1 & -i \end{pmatrix} \quad (12)$$

and

$$M_D^{-1} = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & -i & i \end{pmatrix} . \quad (13)$$

The use of a diagonalized matrix representation allows us to write the total system matrix for a system with m polarizing surfaces and n phase-shifting elements. This is found to be

$$M_{POL}(m) = \begin{pmatrix} P_{x_1}^2 & 0 & 0 & 0 \\ 0 & P_{y_1}^2 & 0 & 0 \\ 0 & 0 & P_{x_1}P_{y_1} & 0 \\ 0 & 0 & 0 & P_{x_1}P_{y_1} \end{pmatrix} \cdot \begin{pmatrix} P_{x_m}^2 & 0 & 0 & 0 \\ 0 & P_{y_m}^2 & 0 & 0 \\ 0 & 0 & P_{x_m}P_{y_m} & 0 \\ 0 & 0 & 0 & P_{x_m}P_{y_m} \end{pmatrix} , \quad (14)$$

or

$$\tilde{M}_{POL}(m) = \begin{pmatrix} \prod_{i=1}^{m} P_{x_i}^2 & 0 & 0 & 0 \\ 0 & \prod_{i=1}^{m} P_{y_i}^2 & 0 & 0 \\ 0 & 0 & \prod_{i=1}^{m} P_{x_i}P_{y_i} & 0 \\ 0 & 0 & 0 & \prod_{i=1}^{m} P_{x_i}P_{y_i} \end{pmatrix} . \quad (15)$$

Similarly,

$$\widetilde{M}_{COMP}(n) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \exp -i \sum\limits_{j=1}^{n} \phi_j & 0 \\ 0 & 0 & 0 & \exp -i \sum\limits_{j=1}^{n} \phi_j \end{pmatrix}. \tag{16}$$

In terms of the non-diagonalized Mueller-Stokes matrices, we can then write

$$\widetilde{M}_{POL}(m) = \frac{1}{2} \begin{pmatrix} \prod\limits_{i=1}^{m} P_{x_i}^2 + \prod\limits_{i=1}^{m} P_{y_i}^2 & \prod\limits_{i=1}^{m} P_{x_i}^2 - \prod\limits_{i=1}^{m} P_{y_i}^2 & 0 & 0 \\ \prod\limits_{i=1}^{m} P_{x_i}^2 - \prod\limits_{i=1}^{m} P_{y_i}^2 & \prod\limits_{i=1}^{m} P_{x_i}^2 + \prod\limits_{i=1}^{m} P_{y_i}^2 & 0 & 0 \\ 0 & 0 & 2 \prod\limits_{i}^{m} P_{x_i} P_{y_i} & 0 \\ 0 & 0 & 0 & 2 \prod\limits_{i}^{m} P_{x_i} P_{y_i} \end{pmatrix} \tag{17}$$

and

$$M_{COMP}(n) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\left(\sum\limits_{j=1}^{n} \phi_j\right) & -\sin\left(\sum\limits_{j=1}^{n} \phi_j\right) \\ 0 & 0 & \sin\left(\sum\limits_{j=1}^{n} \phi_j\right) & \cos\left(\sum\limits_{j=1}^{n} \phi_j\right) \end{pmatrix}. \tag{18}$$

By direct matrix multiplication, the total system matrix is found to be

$$M = \frac{1}{2} \times$$

$$\begin{pmatrix} \prod_{i=1}^{m} P_{x_i}^2 + \prod_{i=1}^{m} P_{y_i}^2 & \prod_{i=1}^{m} P_{x_i}^2 - \prod_{i=1}^{m} P_{y_i}^2 & 0 & 0 \\ \prod_{i=1}^{m} P_{x_i}^2 - \prod_{i=1}^{m} P_{y_i}^2 & \prod_{i=1}^{m} P_{x_i}^2 + \prod_{i=1}^{m} P_{y_i}^2 & 0 & 0 \\ 0 & 0 & 2\prod_{i=1}^{m} P_{x_i}P_{y_i}\cos\left(\sum_{j=1}^{m}\phi_j\right) & -2\prod_{i=1}^{m} P_{x_i}P_{y_i}\sin\left(\sum_{j=1}^{m}\phi_j\right) \\ 0 & 0 & 2\prod_{i=1}^{m} P_{x_i}P_{y_i}\sin\left(\sum_{j=1}^{m}\phi_j\right) & 2\prod_{i=1}^{m} P_{x_i}P_{y_i}\cos\left(\sum_{j=1}^{m}\phi_j\right) \end{pmatrix} . \tag{19}$$

The reader should note carefully the form of Eq 19.

<u>The ABCD Polarization Matrix</u>

Equations 1, 3, and 19 are seen to have the form

$$M = \begin{pmatrix} A & B & 0 & 0 \\ B & A & 0 & 0 \\ 0 & 0 & C & -D \\ 0 & 0 & D & C \end{pmatrix} . \tag{20}$$

Thus, for the polarizing matrix, Eq 1, we see that A, B, C, and D of Eq 20 are

$$A = (1/2)\ (p_x^2 + p_y^2) \qquad B = (1/2)\ (p_x^2 + p_y^2)$$

$$C = 2\ p_x\ p_y \qquad D = 0, \tag{21}$$

while for the compensator, Eq 3, we have

$$A = 1,\ B = 0,\ C = \cos\phi,\ \text{and}\ D = \sin\phi. \tag{22}$$

Henceforth, Eq 20 will be called the ABCD polarization matrix, or simply the ABCD matrix.

We can show that the following equation holds for the Stokes parameters for a perfectly polarized beam:

$$S_o^2 = S_1^2 + S_2^2 + S_3^2 \quad . \tag{23}$$

Using Eq 20 and 23, we readily find that the following relation exists between the A, B, C, and D parameters:

$$A^2 = B^2 + C^2 + D^2. \tag{24}$$

In practice, this relation is very useful since it obviously allows us to find the fourth matrix element if the other three are known. Moreover, the relation can serve as a useful check on all four measured or calculated elements.

Consider that we now illuminate a system described by the ABCD matrix with linearly $+45^o$ polarized light. The Stokes vector for the incident light is $\{1, 0, 1, 0\}$. Matrix multiplication with Eq 20 yields

$$\begin{pmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{pmatrix} = \begin{pmatrix} A & B & 0 & 0 \\ B & A & 0 & 0 \\ 0 & 0 & C & -D \\ 0 & 0 & D & C \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}, \tag{25}$$

so

$$\begin{pmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{pmatrix} = \begin{pmatrix} A \\ B \\ C \\ D \end{pmatrix}. \tag{26}$$

Thus we have the very useful result that if an optical system consists only of polarizers and/or phase shifters and if the optics are illuminated with linearly +45° polarized light, each of the measured Stokes parameters is equal to one of the ABCD matrix elements.

The ABCD matrix elements can also be extracted using right circularly polarized light. In this case, the incident Stokes vector is {1, 0, 0, 1} , so

$$\begin{pmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{pmatrix} = \begin{pmatrix} A & B & 0 & 0 \\ B & A & 0 & 0 \\ 0 & 0 & C & -D \\ 0 & 0 & D & C \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \tag{27}$$

and

$$\begin{pmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{pmatrix} = \begin{pmatrix} A \\ B \\ -D \\ C \end{pmatrix} . \tag{28}$$

We note that D and C are interchanged when Eq 28 is compared with the result for linearly +45° polarized light, Eq 27.

The previous analysis assumes that the axes of the transmitted field and the optical system being illuminated are aligned. In general, this is not true. Nevertheless, the A, B, C, D parameters can still be determined. This can be done by transmitting two sequential orthogonally polarized pulses. The optimum choices are either right and left circularly polarized light or linearly +45° and -45° polarized light. The angle of rotation between the axes can then be determined and the A, B, C, D parameters found. In practice, this operation is always done with the polarimeter.

Measurement of the Stokes Polarization Parameters and the ABCD Matrix Elements

We have seen that each of the Stokes parameters is equal to one of the ABCD matrix elements for polarizing and/or phase-shifting systems. In this section we discuss the measurement of the Stokes parameters, or equivalently, the ABCD matrix elements.

The Stokes parameters of an optical beam can be measured by the appropriate positioning of a wave plate followed by a polarizer, set at an angle θ. This arrangement is shown below in Fig. 1.

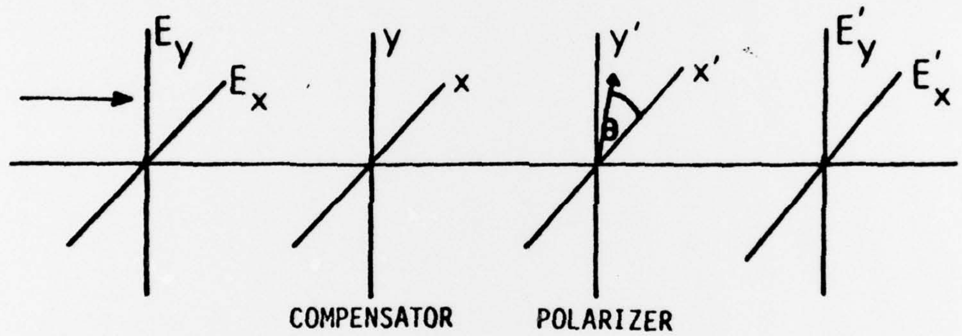

Figure 1. Measurement of the Stokes polarization parameters.

A straightforward analysis shows that the detected intensity, $I(\theta, \phi)$, is

$$I(\theta, \phi) = (1/2)\, [S_0 + S_1 \cos(2\theta) + S_2 \sin(2\theta)\cos\phi - S_3 \sin(2\theta)\sin\phi], \quad (29)$$

where S_o, S_1, S_2, and S_3 are the detected Stokes parameters, θ is the angle between the horizontal x-axis and the polarizer transmission axis, and ϕ is the phase shift between the orthogonal axes of the wave plate.

The Stokes parameters can be obtained by sequentially setting θ to either 0, $\pi/2$, or $\pi/4$ and inserting or removing a quarter-wave plate in the optical train. The respective detected intensities will be

$$I(0,\ 0) = (1/2)[S_0+S_1], \tag{30a}$$

$$I(\pi/2,\ 0) = (1/2)[S_0-S_1], \tag{30b}$$

$$I(\pi/4,\ 0) = (1/2)[S_0+S_2], \text{ and} \tag{30c}$$

$$I(\pi/4,\ \pi/2) = (1/2)[S_0-S_3], \tag{30d}$$

from which the Stokes parameters or the equivalent A, B, C, D parameters are found to be

$$S_0 = I(0,\ 0) + I(\pi/2,\ 0) \tag{31a}$$

$$S_1 = I(0,\ 0) - I(\pi/2,\ 0) \tag{31b}$$

$$S_2 = 2I(\pi/4,0) - I(0,0) - I(\pi/2,\ 0) \tag{31c}$$

$$S_3 = I(0,\ 0) + I(\pi/2,\ 0) - I(\pi/4,\ \pi/2) \tag{31d}$$

In the measurement shown in Fig. 1, the assumption was made that the source of radiation was continuous. This allows time for selective setting of the polarizer/wave plate. We can represent the continuous beam measurement schematically, as shown in Fig. 2, below.

Figure 2. Sequential measurement of the Stokes

Thus an incident beam propagates through a single optical train (referred to as a single channel), and four sequential settings and measurements are then made.

It is clear that the CW method for determining the Stokes parameters for a nanosecond pulse is inappropriate, and, therefore, a different arrangement is required. This can be accomplished by introducing four separate channels, which correspond to each of the equations in Eq 30 . This four-channel polarimeter, shown in Fig. 3, permits the simultaneous measurement of the Stokes parameters, A, B, C, and D elements.

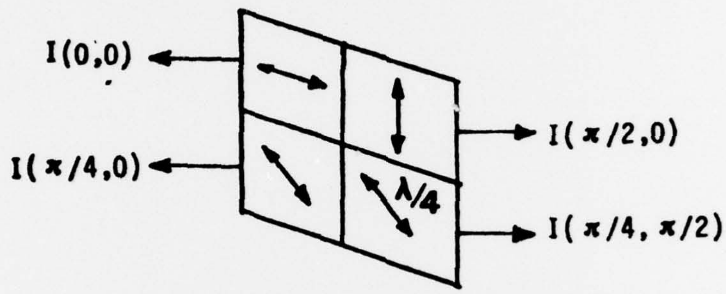

Figure 3. Parallel measurement of the Stokes polarization parameters.

A quarter-wave plate is placed over the fourth channel, $I(\pi/4, \pi/2)$.

The arrangement shown in Fig. 3 can be schematically represented by

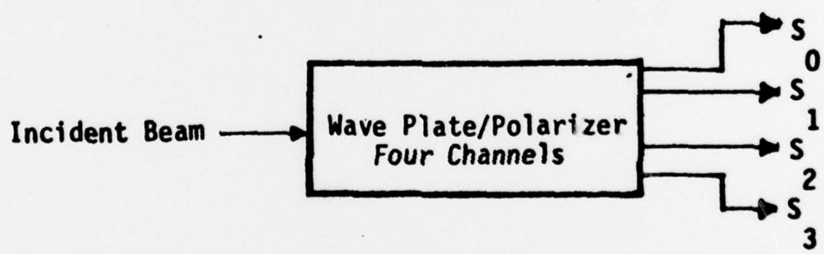

Figure 4. Configuration of the four-channel analyzer.

We emphasize that this arrangement of the polarimeter has no moving parts and, therefore, allows either continuous or pulsed polarized radiation to be measured. Because we actually use the polarimeter to measure the ABCD parameters, the polarimeter is known as either the four-channel polarimeter or the ABCD polarimeter.

In the following and final section we describe the implementation of the polarimeter and its integration into an automatic measurment system. This is done using an HP 9825A desk calculator and a Hewlett-Packard Interface Bus System, in conjunction with the HP 6904B multiprogrammer.

Computer Interfacing in the Four-Channel Polarimeter

During the past decade there has been remarkable progress in the development of minicomputers, desk calculators, and interfacing equipment. In view of this fact and the large amount of data to be collected and analyzed, the Hewlett-Packard 9825A desk calculator was selected to operate the four-channel polarimeter.

The interfacing between the calculator and the polarimeter was accomplished using the Hewlett-Packard Interface Bus System (HP-IB). Briefly, the HP-IB transfers data and commands in parallel between the components of an instrumentation system and the HP 9825A calculator. There are 16 signal lines, of which eight are data input/output (I/O) lines reserved for the transfer of data and other messages in a byte-serial, bit-parallel manner. The remaining eight signal lines are used for data byte transfer control (3) and general interface management (5).

In order to provide even greater flexibility, Hewlett-Packard has developed a general laboratory instrument known as the HP 6940B multiprogrammer. The system is placed in parallel on the HP-IB. This device allows a wide choice of measurements or instrument controls to be made. The HP 6940B multiprogrammer holds up to 15 plug-in cards for various purposes; e.g., control of stepper motors, voltage monitoring, relay control, etc. In our system, an HP 693330A relay card was inserted into the multiprogrammer and used to sequentially open and close relays connecting the detector/ amplifiers to a digital voltmeter.

While a voltage monitor card is available for use in the multiprogrammer and permits readings of 150 times per second, it is limited to 12-bit analog to digital conversion. Since resolution is of greater interest than speed, an HP 3490A digital voltmeter, which has a resolution of 1 microvolt on a 100-millivolt scale, was used on the HP-IB. Because of this much greater resolution, the number of readings per second, however, is reduced to 5 per second.

Finally, the HP-IB Interface Bus uses an 8-bit ASCII coded output. This must be converted to the HP 6940B multiprogrammer

16-bit format. In order to make this conversion, an HP 595000A interface unit must be used between the calculator and the multiprogrammer.

We pointed out earlier that the configuration of the four-channel polarimeter can be used with a CW optical source as well as a pulsed optical source. A description of the CW mode will be given first.

To illustrate the basic technique of determining the Stokes parameters, a block diagram of the four-channel polarimeter and the computer/interfacing is shown in Fig. 5. Several versions of the four-channel optical head were built, using Polaroids initially and precisely mounted calcite prisms and quarter-wave plates later. Each Polaroid was cut from the same sheet, and each channel normalized to the first channel. The same was done to the detector/amplifier channels. The alignment of the Polaroids was measured to be within 10′ of arc, while the calcite prisms polarizers were measured to be within 2′ of arc.

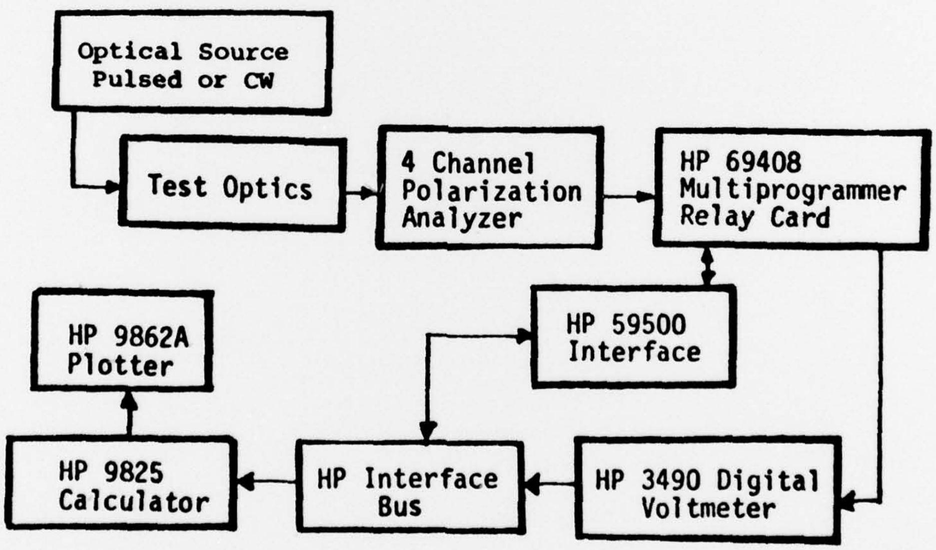

Figure 5. Block diagram of the computer-controlled polarimeter.

The four channels of the optical head were uniformly illuminated, detected, and converted from a current to a voltage signal, using UDT 101A transimpedance amplifiers. By programming the calculator, each relay was closed for N seconds, and a maximum of five readings per second was made on each channel. This was done for all four channels and the measured data were then stored in the calculator. At the end of the read cycle, the average intensity reading in each channel was determined and converted to the Stokes parameters, or equivalently, to the A, B, C, and D parameters. The results were then printed out on an HP 9871A impact printer. In some instances it was more useful to display the corresponding polarization ellipse, using an HP 9862A plotter. At a future date a CRT will be used to speed up the data presentation.

The system configuration for a pulsed source is similar to that of the CW operation. The difference is the increase in complexity of the detection circuit, Fig. 5, and the addition of an HP 69434A Event Sense Card and an HP 69600B Programmable Timer Card in the multiprogrammer.

The detection circuit converts the nanosecond pulse current to a voltage that is held by the peak detector. The laser is fired once per second, and a trigger is sent to the Event Sense Card. The output of this card initiates the calculator for reading each of the relays. Each relay is programmed to be closed for 100 milliseconds and sequentially read at the beginning of each 200-millisecond interval. All four relays have then been read at the end of 800 milliseconds. During the last 200 milliseconds of the 1-second cycle, a single 1-millisecond pulse is sent to field effect transistors from the HP 6900B Programmable Timer Card. This pulse discharges the capacitors in the detection circuit. Finally, after the laser has fired N times, usually taken at N-20, the data are averaged and the A, B, C, D parameters printed out.

CONCLUSIONS

We have shown that a four-channel polarimeter can be used to determine the polarization characteristics of optical components, systems, and other related phenomena. While the primary purpose of the four-channel configuration is to measure the four Stokes polarization parameters in a nanosecond duration, there is an additional benefit to the design. This is shown by illuminating an optical system with right circularly polarized light or linearly $+45^{\circ}$ polarized light. Each of the measured Stokes parameters is then equal to one of the unknown A, B, C, D matrix elements. In many situations of military interest this property could be invaluable.

The development of the polarimeter described in this paper evolved from the recognition that all optical beams carry polarization information. If this information is processed in real time in the manner described, then it may be possible to provide significantly improved performance of military systems.

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