Development of a High-Precision DOP Measuring Instrument

by Tatsuya Hatano *, Takeshi Takagi *, Kazuhiro Ikeda * and Hiroshi Matsuura *

ABSTRACT In response to the need for higher speed and greater capacity in optical communication, studies are being carried out on high-speed digital transmission technologies, but at rates of 40 Gbps specifically, the deterioration in transmission characteristics due to the effect of polarization mode dispersion (PMD) has led to a need for PMD compensators. It is known that the amount of PMD and the degree of polarization (DOP) are interrelated, so that it is possible to compensate for PMD by monitoring the DOP of the signal light. Accordingly, in an effort to devise a PMD monitor for PMD compensators, we have developed a high-precision DOP measuring instrument that is low in cost and accommodated in a compact package. This paper reports on the results obtained by producing a prototype of this instrument.

1. INTRODUCTION

In response to the need for higher speed and greater capacity in optical communication, studies are being carried out on high-speed digital transmission technologies. Deterioration in transmission characteristics (bit error rate, or BER) due to the effect of polarization mode dispersion (PMD) is not a significant problem at the bit rates used heretofore, but at 40 Gbps specifically, this has led to a need for PMD compensators. PMD occurs as a result of a difference in group delay between two orthogonal polarization modes due to increased ellipticity of the single-mode fiber core, lateral pressure or localized temperature change. A PMD compensator is a device that compensates for the effects of PMD occurring in the transmission path, and to do this the amount of PMD must be monitored. Since in general there is a correlation between PMD and DOP, a DOP monitor may be considered a PMD monitor. Figure 1 shows an example of PMD compensation.

In a 10-Gbps transmission testing system, PMD was produced by actually using a variable DGD, and the DOP of the signal light was measured. At 10 Gbps the time interval between adjacent bits is 100 psec, but even when a PMD of 50 psec--half that value--is applied, DOP is in the area of 80 %, not much of a deterioration. The BER, however, does deteriorate significantly, and so in considering its use to improve BER as the PMD monitor of the PMD compensator, it is necessary that DOP be measured with high precision at conditions when it is greater than 80 %. Accordingly the authors have developed a compact, high-performance, low-cost DOP measuring instrument as a PMD monitor for a PMD compensator, and report on it herewith.

* Optical Components Development Dept., FITEL-Photonics Lab.

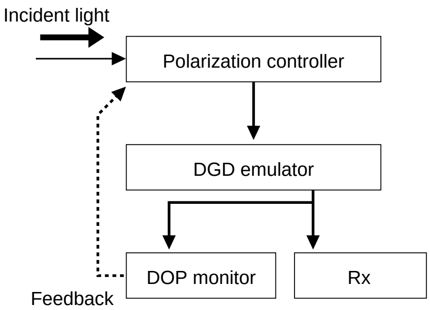

Figure 1 Example of PMD compensation.

2. OPERATING PRINCIPLE OF HIGH-PRECISION DOP MEASURING INSTRUMENT

The high-precision DOP measuring instrument represents the state of polarization of incident light by Stokes parameters (S_0, S_1, S_2, S_3) that are defined by Equation (1), and outputs S_0, S_1 and S_2. The Stokes parameters are calculated by using, together with Equation (2), four values of current (I_t, I_0, I_{45}, I_{q45}) that are output from the structure described in the following.

In this, the expressions indicating the electrical currents obtained by photoelectric conversion of the light incident on the DOP measuring instrument are: I_t for the totality of all incident light, I_0 for the light of one of the four split beams of incident light that has been passed through a 0-deg polarizer, I_{45} for the light that has been passed through a 45-deg polarizer, and I_{q45} for light passed through the 1/4 wave plate and 45-deg polarizer. Here the relative angle between the crystal axes of the 0-deg and 45-deg polarizers is 45 deg, and the setting for the reference angle is arbitrary.

Following is an explanation of Poincare sphere representation. This is used because, as all states of polarization (SOP) are represented in a single coordinate system,

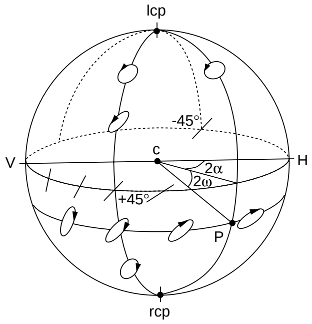

Figure 2 Poincare sphere representation.

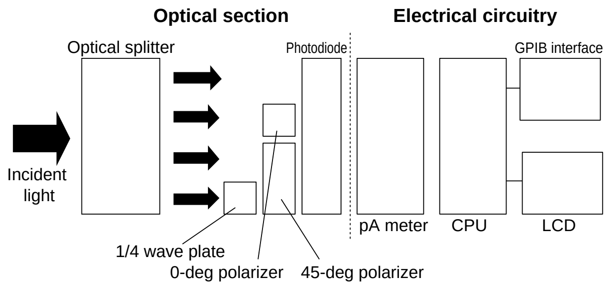

Figure 3 Schematic diagram of high-precision DOP measuring instrument.

it makes it easier to comprehend changes in the SOP. Figure 2 shows a Poincare sphere representation in which the axes of the rectangular coordinates are defined as S_1 for the horizontal linearly polarized component, S_2 for the linearly polarized component at 45 deg from the horizontal, and S_3 for the right-handed circularly polarized component.

$$\begin{aligned} S_0 &= <|E_x|^2> + <|E_y|^2> \\ S_1 &= <|E_x|^2> - <|E_y|^2> \\ S_2 &= <2 \cdot E_x \cdot E_y \cdot \cos\delta> \\ S_3 &= <2 \cdot E_x \cdot E_y \cdot \sin\delta> \end{aligned} \quad (1)$$

where: $\delta = \Phi_y - \Phi_x$
S_0 is the total intensity
S_1 is the horizontal linearly polarized component
S_2 is the linearly polarized component at 45 deg from the horizontal
S_3 is the right-handed circularly polarized component

$$\begin{aligned} S_0 &= I_t \\ S_1 &= 2 \cdot I_0 - I_t \\ S_2 &= 2 \cdot I_{45} - I_t \\ S_3 &= 2 \cdot I_{q45} - I_t \end{aligned} \quad (2)$$

$$\mathrm{DOP} = \{(S_{12} + S_{22} + S_{32})^{1/2}\} / S_0 \quad (3)$$

Figure 3 is a schematic diagram of the high-precision DOP measuring instrument, which is divided into the optical section and the electrical circuitry.

The optical section comprises an optical fiber collimator (not shown), an optical splitter, polarizers, and four photodiodes (PD), enclosed in a modular package measuring 70 mm in length, 26 mm in width, and 8 mm in height (Figure 4).

From their definitions, the Stokes parameters can be calculated based on measurements of the intensity of the four transmitted light beams. The following description of the optical section and electrical circuitry is based on Figure 3.

The incident light is fed by the optical fiber collimator to the splitter, where it is split into four. The first of these is received directly by the photodiode resulting in the output I_t. The second passes through the polarizer having a crystal angle of 0 deg and impinges on the photodiode resulting in output I_0. The third passes through the polarizer having a crystal angle of 45 deg and impinges on the photodiode resulting in output I_{45}. The fourth passes through the 1/4 wave plate and the polarizer having a crystal angle of 45 deg and impinges on the photodiode, resulting in output I_{q45}. At this point the crystal axis of the polarizer that is at a 45-deg angle to that of the 0-deg polarizer is rotated by an angle of 45 deg in a plane perpendicular to the direction of travel of the incident light. The crystal axis of the 1/4 wave plate agrees with that of the 0-deg polarizer.

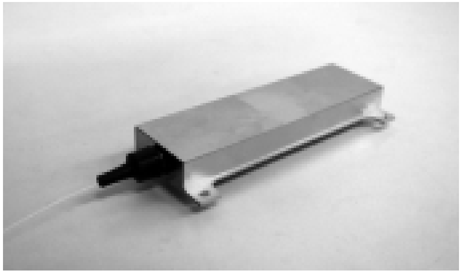

Figure 4 Appearance of Stokes analyzer module.

The four current outputs described above (I_t, I_0, I_{45} and I_{q45}) are then measured by the pA meter on the electrical side. The CPU performs the calculations shown in Equations (2) and (3) to find the Stokes parameters and DOP, and the results are output from the GPIB interface and displayed on the LCD panel.

The electrical circuitry primarily comprises a 32-bit CPU, EPROM, GPIB controller, and equipment for measuring minute currents (a pA meter with 4-channel measuring capability, minimum resolution of 100 pA, maximum current of 1 mA and maximum sampling rate of 1 msec). These elements are mounted on a circuit board measuring 257 mm in length and 182 mm in width. To further economize on space, the optical section module is also mounted on the same circuit board. The board on which the optical module is mounted is enclosed in a casing, shown in Figure 5, together with a power supply, LCD panel, and various setting switches.

Figure 5 Appearance of high-precision DOP measuring instrument.

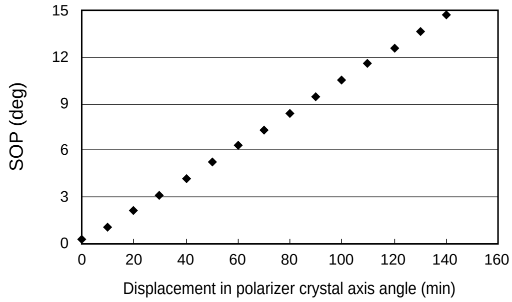

Figure 8 Simulation result 2 (on SOP).

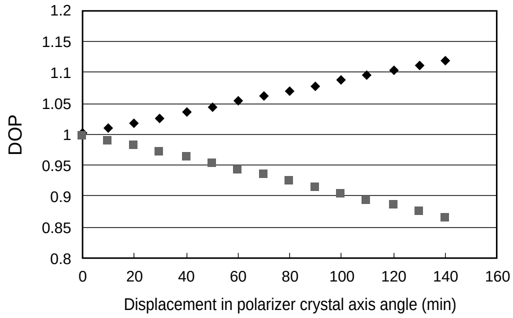

Figure 9 Simulation result 2 (on DOP).

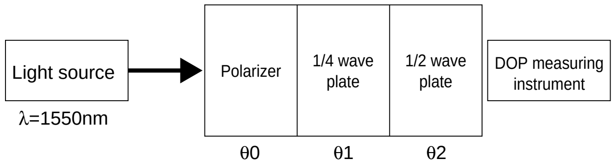

Figure 10 Measurement system for evaluation.

3. ASSEMBLY

In assembling the optical section of this instrument the precision with which the crystal axes of its 1/4 wave plate and the 0-deg and 45-deg polarizers has a major impact on DOP precision.

We therefore conducted a simulation of the effect on SOP and DOP precision of a displacement in the rotational angle of the 1/4 wave plate, in a case in which there was no displacement in the crystal axis angles of two 45-deg polarizers and a 10-minute displacement between the crystal axes of a 0-deg polarizer and 45-deg polarizer. The results are shown in Figures 6 and 7.

We also conducted a simulation of the effect on SOP and DOP precision of a displacement in the crystal axes of a 0-deg polarizer and 45-deg polarizer, in a case in which there was no displacement in the crystal axis angles of two 45-deg polarizers and a 20-minute displacement in the rotational angle of the 1/4 wave plate. The results are shown in Figures 8 and 9.

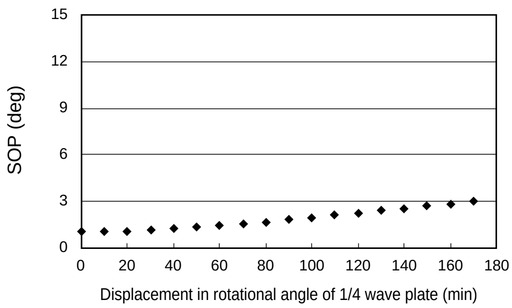

Figure 6 Simulation result 1 (on SOP).

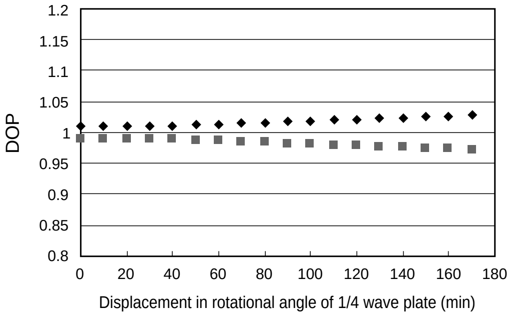

Figure 7 Simulation result 1 (on DOP).

As a result of these simulations it was found that to achieve a DOP precision of ±1 %, the displacement must be within 20 min for the rotational angle of the 1/4 wave plate and within 10 min for polarizer angle. The method of alignment currently in use involves determining the angle of the crystal axis with respect to the 1/4 wave plate and polarizer holders, with respect to the configurations of the respective components.

4. EVALUATION

Direction and size are both related to Stokes parameter precision, and the evaluation was performed as shown in Figure 10. With respect to SOP, which indicates direction, the 1/4 wave plate and 1/2 wave plate were rotated sequentially by angles θ_1 and θ_2 from a certain Stokes vector reference state (1, 0, 0), and a comparison was made between the rotational angles on a Poincare sphere calculated from angles θ_1 and θ_2 and the SOP rotation angles measured on a Poincare sphere using the DOP measuring instrument developed here. With respect to

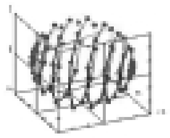

Figure 11 Changes in measured Stokes parameter.

Table 1 Performance of developed DOP measuring instrument.

Measured wavelengths	1480~1640 nm
Input power	-35 to 0 dBm
Sampling time	8 msec (typ)
DOP precision	±2.5 %
SOP precision	±2 deg
Interface	GPIB
Power consumption	7.5 W
Power supply	100 VAC
Overall dimensions	210×99×350 mm
Output data	Stokes parameter, DOP

DOP, which represents size, after the state of polarization of the light emitted by the light source (DOP = 1) rotated on a Poincare sphere, the DOP was measured and was compared with the original DOP that is unity, as shown in Figure 11.

Figure 11 shows the changes, represented on a Poincare sphere, in a Stokes parameter measured by the DOP measuring instrument when the 1/4 wave plate rotational angle θ_1 shown in Figure 10 was set at 0 deg, ±10 deg, ±20 deg, ±30 deg, ±40 deg, and ±45 deg, and the 1/2 wave plate rotational angle θ_2 was increased from 0 deg to 90 deg in 10-deg steps.

The Stokes parameter obtained by the DOP measuring instrument developed here and the angular displacement with respect to the calculated values found from angles θ_1 and θ_2 of the crystal axes of the 1/4 wave plate and 1/2 wave plate respectively were from +1.2 deg to -2.0 deg, and the results of DOP measurement were from 0.973 to 1.016. Table 1 shows the performance of the DOP measuring instrument developed here.

5. APPLICATIONS

As a typical application for the DOP measuring instrument developed here, we designed a PMD measuring system. As shown in Figure 12 it comprises a variable-wavelength light source, the device under test (DUT), the DOP measuring instrument and a controller computer. Using the program shown in Figure 13, measurements were made by the Poincare sphere method, in which PMD is determined by applying a 360-deg phase difference to a cycle of the path traced by SOP on the sphere. By means of the wavelengths at any two arbitrary points on the Poincare sphere and the rotational angles of the corresponding Stokes vectors, PMD, $\Delta\tau$ may be calculated using Equation (4). Polarization maintaining fibers (PMFs) with lengths of 9.5 m and 50 m were used as the DUT.

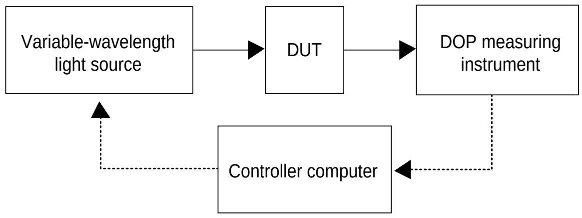

Figure 12 PMD measuring system.

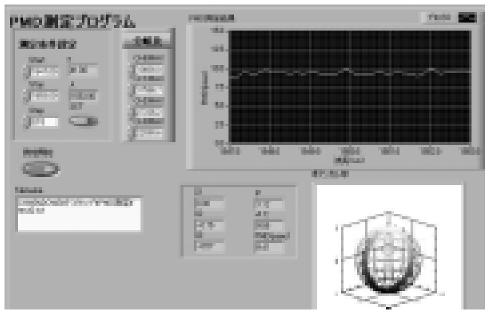

Figure 13 Program for PMD measurement.

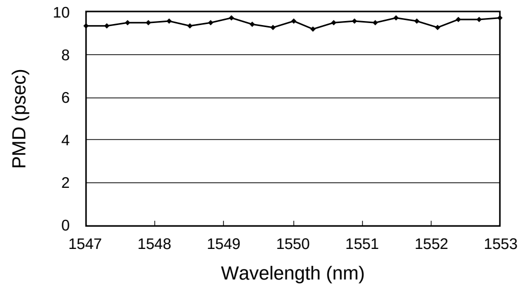

Figure 14 Results of PMD measurements using 9.5-m PMF.

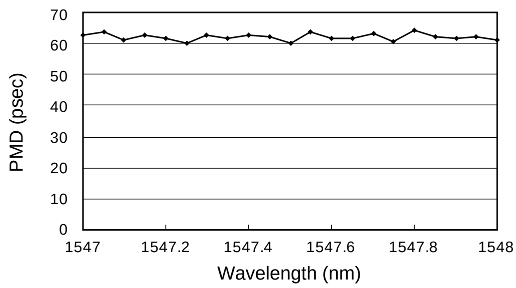

Figure 15 Results of PMD measurements using 50-m PMF.

The results of these measurements are shown in Figures 14 and 15, and Table 2.

$$\Delta\tau=(\Delta\Phi/360)\cdot(\lambda_n\cdot\lambda_{n+1}/C\cdot(\lambda_{n+1}-\lambda_n)) \qquad (4)$$

where: $\Delta\Phi$ is the rotational angle on the Poincare sphere of the Stokes vectors corresponding to two wavelengths (deg)

Table 2 Comparison of values of PMD using different measuring instruments.

DUT		PMD (psec) By Furukawa instrument	PMD (psec) By other manufacturer's instrument
9.5-m PMF	1st try	9.70	9.37
	2nd try	9.66	9.46
50-m PMF	1st try	62.28	63.32
	2nd try	62.20	63.45

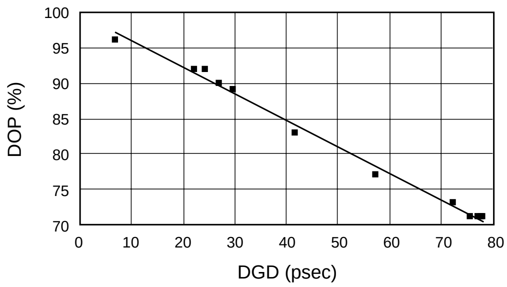

Figure 16 Change in DOP with respect to DGD.

Figure 17 Appearance of PMD compensator.

C is the speed of light (3.0×10^8 m/s)
λ_n is the light source wavelength
n is the n-th wavelength

Another promising application of the DOP measuring instrument developed here is as the monitor in a PMD compensating system. Figure 16 shows changes in DOP with respect to DGD. In the measuring system a 10-Gbps signal is input sequentially to a polarization controller and a variable DGD, and then goes to the DOP measuring instrument for measurement. There is a correlation between DGD and DOP, and a PMD compensator finds applications as a PMD monitor. Figure 17 shows the appearance of a PMD compensator.

The incident light is passed through the polarization controller, PMF and optical coupler, and then output. The beams split by the optical coupler are received by the Stokes analyzer module, DOP is monitored and applied as feedback to the polarization controller.

6. CONCLUSION

A low-cost, high-precision DOP measuring instrument has been developed, comprising a Stokes analyzer module having an optical fiber collimator, optical splitter, 1/4 wave plate, polarizers and photodiodes, which, together with the electrical circuitry, comprising a 32-bit CPU, EPROM, GPIB controller and equipment for measuring minute currents, is mounted on a single circuit board, and packaged with the power supply, LCD panel, setting switches, etc. in a compact unit casing. It is expected to be in demand as a PMD monitor for PMD compensators.