High-speed polarization mode dispersion measurement using digital polarization-state generators and Mueller matrix method

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A polarization-mode dispersion (PMD) measurement system using a pair of polarization-state generators (PSGs) is demonstrated. Based on the saturation characteristics of magneto-optic rotators, the PSG can be digitally controlled, ensuring high-speed and highly repeatable generation of five distinct polarization states. Thus, the PSG can make full use of the advantage of the Mueller matrix method of PMD measurement. The experimental result shows that the system has good measurement repeatability and potential for field testing.

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Single-mode fibers are always birefringent because they are non-ideal. For instance, these fibers have imperfectly rounded symmetrical cores; they also receive additional stress from their manufacture and installation, and field circumstances. Birefringence leads to the variation of the propagation constant with different polarization modes. Its effect on the broadening of optical pulses is called polarization-mode dispersion (PMD). PMD deteriorates system performance in high-speed optical transmission[1,2]; hence, it is important to measure PMD.

Widely accepted PMD measurement techniques include Jones matrix eigenanalysis (JME)[3], Poincare sphere (PS) method[4], fixed polarizer (FP) method[5], interferometric (IF) method[6,7], and non-intrusive coherent detection[8]. JME, PS, and IF methods based on a swept optical local oscillator can offer complete characterizations of PMD. The FP, IF, and non-intrusive coherent detection methods can provide in-field measurements; however, they yield only an average differential group delay (DGD)[9].

The Mueller matrix method was first proposed by Jopson *et al.*, but a suitable device to make full use of the advantages was not provided[10]. Polarization-state generators (PSGs) based on rotating quarter-wave and half-wave plates[11], or based on ferroelectric liquid crystals[12], have therefore been proposed. However, the former PSG suffers from the disadvantages of low repeatability, short lifetime, and high-cost because of its mechanical nature, while the latter PSG has issues on temperature stability and reliability. $LiNbO_3$-based polarization controller has been used for polarization tracking and PMD compensation because of its high speed. A 56-krad/s polarization tracking speed using an 8-stage $LiNbO_3$-based polarization controller with an analog voltage control and with less than 10-ns response time has been reported[13]. Recently, Yao *et al.* proposed a novel high-speed all-solid-state digital PSG as a polarization-state analyzer (PSA)[14,15]. In this letter, we combine the advantages of the digital PSG and the Mueller matrix method to establish a low-cost measurement system that provides high-speed PMD measurement with complete PMD characterization. In addition, an all-fiber swept laser compact light source with an available scan rate of 370 kHz over a 100-nm wavelength range has been developed[16].

Mueller matrix method establishes a relationship between two polarization states at adjacent optical frequencies after transmission through fiber by rotation matrices[10]. This is expressed as

$$\mathbf{S}(\omega + \Delta\omega) = \mathbf{R}(\omega + \Delta\omega)\mathbf{R}^{\mathrm{T}}(\omega)\mathbf{S}(\omega), \tag{1}$$

where $\mathbf{R}$ is the 3×3 rotation matrix characterizing fiber at a given optical frequency ω, $\Delta\omega$ is the optical frequency interval, and $\mathbf{S}$ is the normalized Stokes vector. Information about the rotation angle and rotation axis, such as the PMD vector, is extracted from matrix $\mathbf{R}(\omega + \Delta\omega)\mathbf{R}^{\mathrm{T}}(\omega)$. Obviously, this method is an extension of the PS method; however, it avoids determining the rotation angle and rotation axis from geometric relations, which is somewhat more complex to some extent. The problem is therefore focused on determining the rotation matrix $\mathbf{R}$.

We used a pair of PSGs to establish a PMD measurement system, as shown in Fig. 1. The PSG consists of a polarizer, two pairs of magneto-optic (MO) rotators, and a quarter-wave plate. Each MO rotator can rotate the state of polarization (SOP) with an angle of approximately 22.5° when magnetic field is applied above a saturation field threshold. The direction of SOP rotation is determined by the direction of the magnetic

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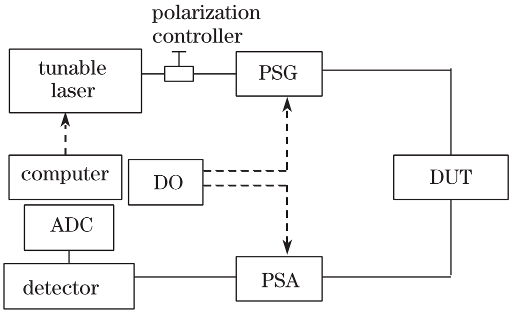

Fig. 1. Configuration of PMD measurement system.DO: digital output, ADC: analog-to-digital conversion, DUT: device under test.

field. When two MO rotators rotate towards the same direction, the net rotation is 45° or −45°; the net rotation is 0° when two MO rotators rotate in opposite directions. Thus, five polarization states (0°, ±45°, left hand circular, and right hand circular) can be generated from the different rotation combinations of the MO rotators. The saturation characteristic of the MO rotators enables the digital binary bit control of the rotation angle. This avoids the inaccuracy and drift that accompany analog control, ensuring high repeatability. Concurrently, the parallel digital binary bit control of MO rotators provides a high-speed SOP switch of less than 250 μs.

If three polarization states that are orthogonal between any two polarization states in the Stokes vector space are launched into the fiber under test, the solution of the rotation matrix $\mathbf{R}$ can be simplified. From the foregoing PSG analysis, we can see that this condition can be easily fulfilled with the novel PSG. For example, we can choose PSG to generate SOP of 0°, 45°, and right hand circular with high repeatability. Then,

$$\mathbf{R} = [\mathbf{S}_{\text{out}}^1 \quad \mathbf{S}_{\text{out}}^2 \quad \mathbf{S}_{\text{out}}^3], \tag{2}$$

where $\mathbf{S}_{\text{out}}^1, \mathbf{S}_{\text{out}}^2$, and $\mathbf{S}_{\text{out}}^3$ are the normalized output polarization states after transmission through the fiber under test.

The problem of rotation matrix $\mathbf{R}$ calculation is transformed to obtain the Stokes vector of the output polarization states. When the input polarization state of the PSA is $\mathbf{S} = (S_0, S_1, S_2, S_3)^{\text{T}}$, the detected optical power P is expressed as

$$P = \frac{1}{2}[S_0 - \cos 2\alpha \cos 2\beta \cdot S_1 + \cos 2\alpha \sin 2\beta \cdot S_2 + \sin 2\alpha \cdot S_3], \tag{3}$$

where α is the net rotation angle of the pair of MO rotators near the polarizer, and β is the net rotation angle of the other pair. We can choose a minimum of four combinations of α and β:

$$\mathbf{P} = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} = \begin{bmatrix} W_{11} & W_{12} & W_{13} & W_{14} \\ W_{21} & W_{22} & W_{23} & W_{24} \\ W_{31} & W_{32} & W_{33} & W_{34} \\ W_{41} & W_{42} & W_{43} & W_{44} \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \mathbf{WS}, \tag{4}$$

where W_{ij} are the coefficients determined by Eq. (3).

We transform Eq. (4) and consider the situation of having three SOPs,

$$\begin{bmatrix} S_{\text{out},0}^1 & S_{\text{out},0}^2 & S_{\text{out},0}^3 \\ S_{\text{out},0}^1 \cdot \mathbf{S}_{\text{out}}^1 & S_{\text{out},0}^2 \cdot \mathbf{S}_{\text{out}}^2 & S_{\text{out},0}^3 \cdot \mathbf{S}_{\text{out}}^2 \end{bmatrix} = \mathbf{W}^{-1} \begin{bmatrix} P_1^1 & P_1^2 & P_4^3 \\ P_2^1 & P_2^2 & P_4^3 \\ P_3^1 & P_3^2 & P_4^3 \\ P_4^1 & P_4^2 & P_4^3 \end{bmatrix} = \mathbf{W}^{-1}[\mathbf{P}^1 \quad \mathbf{P}^2 \quad \mathbf{P}^3], \tag{5}$$

where P_i^j represents the ith output optical power under the jth input SOP. The rotation matrix $\mathbf{R}$ is obtained from Eqs. (2) and (5). If we use more than four combinations of α and β to obtain better results, only $\mathbf{W}^{-1}$ is replaced by $(\mathbf{W}^{\text{T}}\mathbf{W})^{-1}\mathbf{W}^{\text{T}}$[11]. With the scanning optical frequency of a tunable laser, a series of $\mathbf{R}$ can be obtained and used for PMD calculation.

The experimental setup was established according to Fig. 1. An Agilent 81640A tunable laser source (TLS) module with 40-nm/s maximum tuning speed was used for the scanning of optical frequency. A data acquisition card with 12-bit resolution and 120-kHz acquisition frequency was used. The acquisition time was far less than the SOP switching time of PSG. One PSG was used to generate three SOPs; the other PSG was used as a PSA and was set with four SOP switches. This means that only 3 ms is needed at each optical frequency during the measurement process. To mitigate deterioration caused by too much wavelength change during SOP switching, the wavelength scanning speed should be limited. For example, to limit the wavelength change to less than 15 pm in 3-ms SOP switching time, the scanning speed should be less than 5 nm/s. Generally, the number of optical frequencies used in PMD measurement can be less than 1000, and the measurement time of the experimental system can be less than 10 s considering the calculation time and other factors.

To demonstrate, three segments of polarization-maintaining fiber (PMF) with lengths of 1.76, 5.91, and 14.60 m were measured with the experimental system. Measurement wavelength intervals were 0.5, 0.2, and 0.1 nm, respectively. The results are 3.637, 11.510, and 29.068 ps, respectively. Figure 2(a) shows the DGD measurement result of 1.76-m PMF as a function of wavelength. Figure 2(b) shows the PMD vector variation with wavelength; the PMD vector changes only slightly with different wavelengths for PMF. For comparison, the same PMFs were measured using a commercial PMD instrument (NEXUS-PMD-C-X) based on the IF method. The IF method has a 1% PMD value with ±0.05 ps of measurement repeatability and a measurement speed of 12 s for 1-ps PMD value. The PMD values measured through the IF method are 3.502, 11.620, and 28.880 ps, respectively, consistent with our results.

In order to investigate the long-term stability of the system, the 1.76-m PMF was again measured after four months; the result is shown in Fig. 3. The measurement repeatability is 0.0158 ps, which is 0.44% of the PMD value. The maximum difference is 0.055 ps, and it is less than the error limit of 2% PMD value determined by the relative wavelength accuracy of TLS,

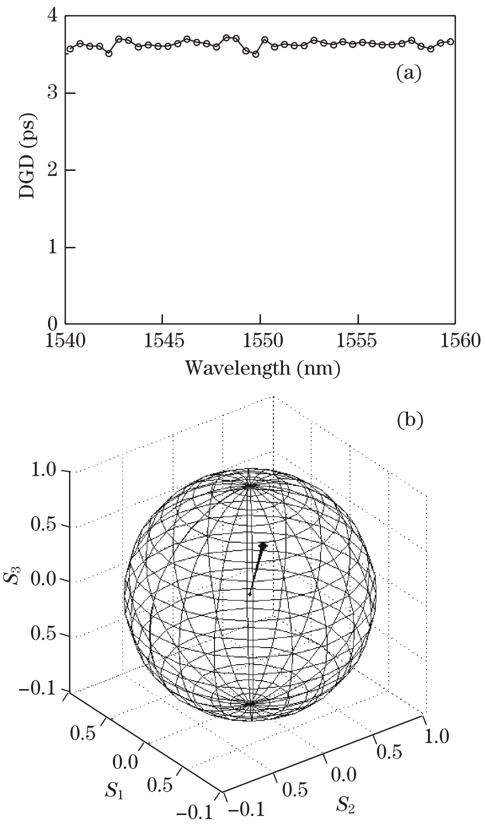

Fig. 2. Measured results of 1.76-m PMF as a function of wavelength. (a) DGD and (b) PMD vector.

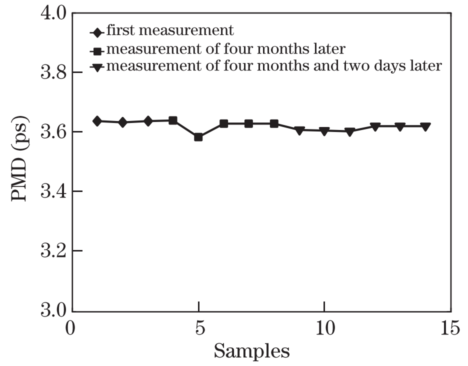

Fig. 3. Measured PMD values of 1.76-m PMF at different periods.

showing that the system has good long-term stability.

In conclusion, the PSG based on MO rotators is very suitable for the Mueller matrix method of PMD measurement. The speed and stability of the novel PMD measurement system are better than those of the IF method. Moreover, it offers complete PMD information because it can provide the PMD vector. These advantages make the novel system a potential candidate for detailed field testing or for mass measurements in factories.

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