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Two-states method for polarization dependent loss measurement

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Abstract

We report a two-states method for measuring polarization dependent loss (PDL) in an optical fiber system. Based on the property that the Mueller matrix governing the transmission property of any linear, time-invariant optical system with birefringence and PDL satisfies Lorentz transformation, we prove that PDL depends on the first column of the Mueller matrix. Hence only two orthogonal input polarization states are required to explicitly determine PDL. Experiment results show the agreement of our method with previously reported methods.

Keywords: Polarization dependent loss; Mueller matrix; State of polarization

1. Introduction

Determination of polarization dependent loss (PDL) in optical devices in an optical fiber system is very important due to its adverse effect on both analog and digital optical signals [1,2]. Combined effect of PDL and polarization mode dispersion (PMD) gives rise to anomalous pulse spreading and deteriorates the bit error rate [3,4]. There exist a few techniques to measure PDL, including deterministic all-states, pseudorandom all-states, deterministic fixed-states techniques [5], unpolarized light [6] and interferometric method [7]. The first two techniques sample a large number of subsets over the entire polarization-state space in a repeatable or pseudorandom way, respectively [5]. The traditional deterministic fixed-states techniques employ three [8] or four [5] well-defined input states of polarization (SOP) to derive PDL. The unpolarized light method measures PDL through depolarizing input light while the interferometric method is based on the interference between multiple light paths. Because the deterministic fixed-states techniques depend on the properties of the transmission matrix, the prior knowledge about the transmission matrix determines the detailed technique one can employ. In [5], the polarization dependent transmission (loss or gain) extrema are derived from the first row elements of the Mueller matrix. In this paper, we first derive the theoretical result that the polarization dependent transmission of an optical device can be expressed by the first column; this result is based on the Lorentz transformation property of the Mueller matrix which was presented in [9]. We then propose another polarization dependent transmission measurement technique, which employs only two orthogonal input SOPs. We name this technique as two-states method. This technique has the potential advantage of faster measurements. Experiment results on a spool of polarization-maintaining fiber (PMF) with bending induced PDL [10] and side-polished single mode fiber (SMF) demonstrate the validity of the proposed measurement method.

2. Theory

The input and output SOPs of an optical device can be related by

$$\begin{pmatrix} S_{\text{out}0} \\ S_{\text{out}1} \\ S_{\text{out}2} \\ S_{\text{out}3} \end{pmatrix} = \mathbf{M} \begin{pmatrix} S_{\text{in}0} \\ S_{\text{in}1} \\ S_{\text{in}2} \\ S_{\text{in}3} \end{pmatrix}, \tag{1}$$

where $\mathbf{M}$ is 4×4 Mueller matrix, $S = (S_0\ S_1\ S_2\ S_3)^{\mathrm{T}}$ is Stokes parameter matrix, S_0 is the optical power, $S_0 = \sqrt{S_1^2 + S_2^2 + S_3^2}$ for fully polarized light, and superscript T denotes matrix trans-

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pose. For an optical fiber system which has loss, birefringence and PDL simultaneously, there exist two orthogonal input polarization states which correspond to maximum and minimum transmission [5]. When two polarization states are orthogonal in Jones sapce, their inner product is 0 in Stokes space, e.g., $(S_0\ S_1\ S_2\ S_3)^{\mathrm{T}}$ and $(S_0\ -S_1\ -S_2\ -S_3)^{\mathrm{T}}$ for fully polarized light. For the two input SOPs that are aligned with the two transmission extrema states, the output SOPs are also orthogonal but the length of output Stokes vectors (optical power) will be less than that for the input SOPs and the output SOPs will be located inside the Poincaré sphere. Further, PDL is the power difference (in dB) between the two output SOPs. On the other hand, if the two input SOPs are orthogonal but are not aligned with the transmission extrema states, the output SOPs will not be orthogonal. Even under this condition, as shown later on, one can calculate the system PDL using the Stokes parameters of the output light.

Based on the property that the Mueller matrix governing the transmission property of any linear, time-invariant optical system with birefringence and PDL satisfies Lorentz transformation, we have [9,11]

$$\mathbf{M}^{\mathrm{T}}\mathbf{G}\mathbf{M} = \sqrt{\det \mathbf{M}} \cdot \mathbf{G}. \tag{2}$$

Here

$$\mathbf{G} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

is called Minkowski metric and $\det \mathbf{M}$ is the determinant of matrix $\mathbf{M}$. Based on Eq. (2), we can obtain the inverse matrix of $\mathbf{M}$, under the condition that $\det \mathbf{M} \neq 0$, as follows [11]:

$$\mathbf{M}^{-1} = \frac{1}{\sqrt{\det \mathbf{M}}}\mathbf{G}\mathbf{M}^{\mathbf{T}}\mathbf{G} = \begin{pmatrix} m_{11} & -m_{21} & -m_{31} & -m_{41} \\ -m_{12} & m_{22} & m_{32} & m_{42} \\ -m_{13} & m_{23} & m_{33} & m_{43} \\ -m_{14} & m_{24} & m_{34} & m_{44} \end{pmatrix} \Big/ \sqrt{\det \mathbf{M}}, \tag{3}$$

where m_{ij} are the elements of the Mueller matrix.

Thus, we have one bilinear equation from $\mathbf{M}\mathbf{M}^{-1} = \mathbf{I}$ ($\mathbf{I}$ is a 4×4 identity matrix) as [12]

$$m_{11}^2 - m_{21}^2 - m_{31}^2 - m_{41}^2 = m_{11}^2 - m_{12}^2 - m_{13}^2 - m_{14}^2. \tag{4}$$

Next, PDL (in dB) is defined as

$$\mathrm{PDL} \equiv 10\log\left(\frac{T_{\max}}{T_{\min}}\right), \tag{5}$$

where $T_{\max}$ and $T_{\min}$ are the transmission extrema. It has been proven that [5]

$$\begin{cases} T_{\max} = m_{11} + \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}, \\ T_{\min} = m_{11} - \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}. \end{cases} \tag{6}$$

Using Eqs. (4) and (6), we can easily get

$$\begin{cases} T_{\max} = m_{11} + \sqrt{m_{21}^2 + m_{31}^2 + m_{41}^2}, \\ T_{\min} = m_{11} - \sqrt{m_{21}^2 + m_{31}^2 + m_{41}^2}. \end{cases} \tag{7}$$

To measure m_{11}, m_{21}, m_{31}, and m_{41}, two orthogonal input SOPs are required. We write these as $S_{\mathrm{in}0a}(1\ S_{\mathrm{in}1}\ S_{\mathrm{in}2}\ S_{\mathrm{in}3})^{\mathrm{T}}$ and $S_{\mathrm{in}0b}(1\ -S_{\mathrm{in}1}\ -S_{\mathrm{in}2}\ -S_{\mathrm{in}3})^{\mathrm{T}}$ where $S_{\mathrm{in}0a}$ and $S_{\mathrm{in}0b}$ denote the corresponding input optical powers. From Eq. (1), assuming that the corresponding output SOPs are $S_{\mathrm{out}0a} \times (1\ S_{\mathrm{out}1a}\ S_{\mathrm{out}2a}\ S_{\mathrm{out}3a})^{\mathrm{T}}$ and $S_{\mathrm{out}0b}(1\ S_{\mathrm{out}1b}\ S_{\mathrm{out}2b}\ S_{\mathrm{out}3b})^{\mathrm{T}}$, we obtain

$$\begin{aligned} S_{\mathrm{out}0a}\begin{bmatrix} 1 \\ S_{\mathrm{out}1a} \\ S_{\mathrm{out}2a} \\ S_{\mathrm{out}3a} \end{bmatrix} &= S_{\mathrm{in}0a}\begin{bmatrix} m_{11} + S_{\mathrm{in}1}m_{12} + S_{\mathrm{in}2}m_{13} + S_{\mathrm{in}3}m_{14} \\ m_{21} + S_{\mathrm{in}1}m_{22} + S_{\mathrm{in}2}m_{23} + S_{\mathrm{in}3}m_{24} \\ m_{31} + S_{\mathrm{in}1}m_{32} + S_{\mathrm{in}2}m_{33} + S_{\mathrm{in}3}m_{34} \\ m_{41} + S_{\mathrm{in}1}m_{42} + S_{\mathrm{in}2}m_{43} + S_{\mathrm{in}3}m_{44} \end{bmatrix}, \\ S_{\mathrm{out}0b}\begin{bmatrix} 1 \\ S_{\mathrm{out}1b} \\ S_{\mathrm{out}2b} \\ S_{\mathrm{out}3b} \end{bmatrix} &= S_{\mathrm{in}0b}\begin{bmatrix} m_{11} - S_{\mathrm{in}1}m_{12} - S_{\mathrm{in}2}m_{13} - S_{\mathrm{in}3}m_{14} \\ m_{21} - S_{\mathrm{in}1}m_{22} - S_{\mathrm{in}2}m_{23} - S_{\mathrm{in}3}m_{24} \\ m_{31} - S_{\mathrm{in}1}m_{32} - S_{\mathrm{in}2}m_{33} - S_{\mathrm{in}3}m_{34} \\ m_{41} - S_{\mathrm{in}1}m_{42} - S_{\mathrm{in}2}m_{43} - S_{\mathrm{in}3}m_{44} \end{bmatrix}. \end{aligned} \tag{8}$$

Then, by solving the equations in (8), we can get the first column of Mueller matrix

$$\begin{bmatrix} m_{11} \\ m_{21} \\ m_{31} \\ m_{41} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\left(\frac{S_{\mathrm{out}0a}}{S_{\mathrm{in}0a}} + \frac{S_{\mathrm{out}0b}}{S_{\mathrm{in}0b}}\right) \\ \frac{1}{2}\left(\frac{S_{\mathrm{out}1a}S_{\mathrm{out}0a}}{S_{\mathrm{in}0a}} + \frac{S_{\mathrm{out}1b}S_{\mathrm{out}0b}}{S_{\mathrm{in}0b}}\right) \\ \frac{1}{2}\left(\frac{S_{\mathrm{out}2a}S_{\mathrm{out}0a}}{S_{\mathrm{in}0a}} + \frac{S_{\mathrm{out}2b}S_{\mathrm{out}0b}}{S_{\mathrm{in}0b}}\right) \\ \frac{1}{2}\left(\frac{S_{\mathrm{out}3a}S_{\mathrm{out}0a}}{S_{\mathrm{in}0a}} + \frac{S_{\mathrm{out}3b}S_{\mathrm{out}0b}}{S_{\mathrm{in}0b}}\right) \end{bmatrix}. \tag{9}$$

Thus, from Eqs. (5), (7), and (9), PDL can be derived explicitly using any two input SOPs as long as they are orthogonal as shown below:

$$\mathrm{PDL} = 10\log\left(\frac{R_a + R_b + \sqrt{R_a^2 + R_b^2 + 2R_aR_b\chi}}{R_a + R_b - \sqrt{R_a^2 + R_b^2 + 2R_aR_b\chi}}\right), \tag{10}$$

where $R = S_{\mathrm{out}0}/S_{\mathrm{in}0}$ is the power ratio between output and input; and $\chi = \sum_{i=1}^{3} S_{\mathrm{out}ia}S_{\mathrm{out}ib}$ is the dot product between the two normalized output SOP vectors which is the cosine of the angle between the two output SOPs in Stokes space.

3. Experiment results and discussion

We have performed some experiments to verify the method of measurement of PDL proposed above. The devices under test (DUT) are one spool of PMF with bending-induced PDL and a side polished SMF. The experiment setup is shown in Fig. 1. In our setup, the in-line polarimeter (polarization analyzer) 1 is used to monitor the input SOPs and input optical powers, and polarimeter 2 measures the corresponding output Stokes

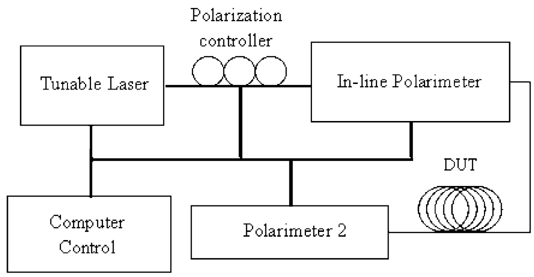
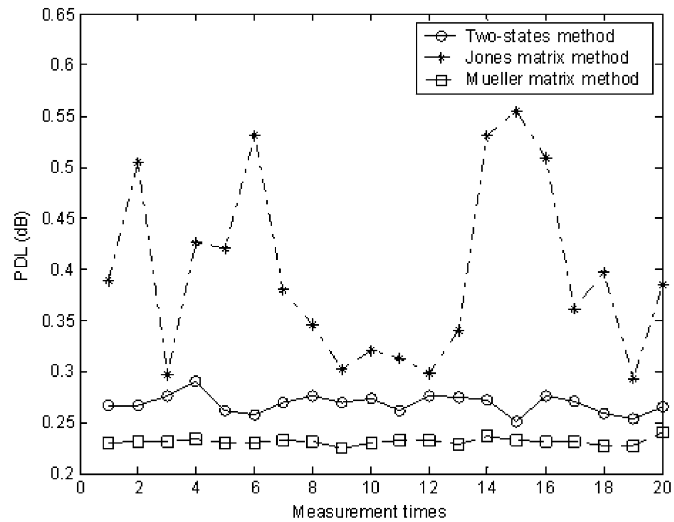


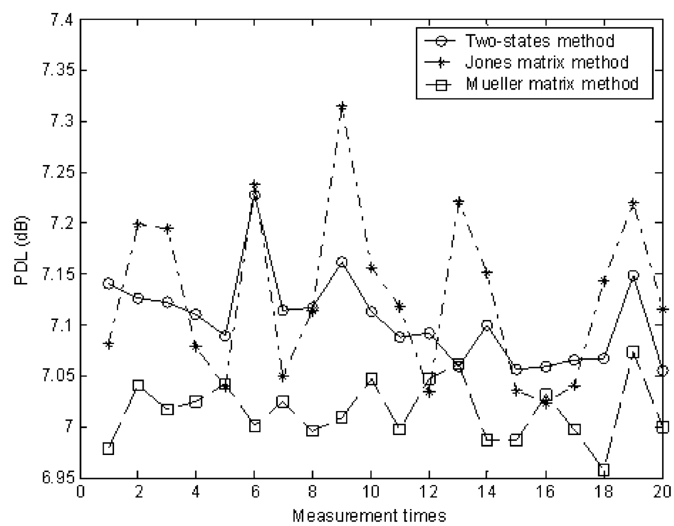
Fig. 1. Experiment setup for PDL measurement.

parameters. In order to generate two orthogonal input SOPs, a polarization controller (PC) is employed. The first SOP is generated arbitrarily and is measured by polarimeter 1. For the second SOP, one tunes the PC until polarimeter 1 indicates that the SOP is orthogonal to the first one. The tunable DFB laser is used as the fully-polarized light source. The whole system is controlled and synchronized by a computer. We name our measurement method as two-states method. For convenience, we call the other two deterministic fixed-states techniques as Jones matrix [8] and Mueller matrix [5] methods which use, respectively, 3 and 4 fixed states of SOP. We compare the measurement results obtained using our method with the Jones and Mueller matrix methods. All the methods are implemented with the same setup. The results of 20-time measurement for the two DUTs, measured at 1550 nm wavelength, are shown in Fig. 2. For each DUT, the 20-time measurement took about 40 min with an interval of 2 min between each measurement. In order to make the comparison between the three methods more clear, we list the mean values and standard deviations for the measured PDL values in Table 1.

It is obvious that the results of our method are in close agreement with those obtained using the other two methods. Since the Mueller matrix method has been adopted by the international standards bodies [13,14], we can consider that it is more accurate than the Jones matrix method. In Table 1, we find that the mean values for our method are closer to those for the Mueller matrix method. Further, the standard deviation of measurements using our method are much smaller than those for the Jones matrix method because our method only needs two input SOPs and thus entails a smaller measurement error. The standard deviation for our method is slightly larger than that for the Mueller matrix method. A possible reason for this is that in our method and the Jones matrix method, one measures the output SOPs while in the Mueller matrix method one measures the output power. The SOPs can be affected by the change of birefringence induced by environment variation during the measurement, but the power does not get affected [15]. On the other hand, the measurement speed of our method is much faster compared with that for the Mueller matrix method which needs 4 input SOPs. Figures 3a and 3b present the measured PDL values for the same DUTs over a wavelength range 1510–1580 nm. Once again, results based on all the three methods are included. A close match is observed between the results from these methods. For both Figs. 2 and 3, the measured results for our method lie in between those for the other two methods. This further confirms the validity of our proposed two-states method.



(a)



(b)

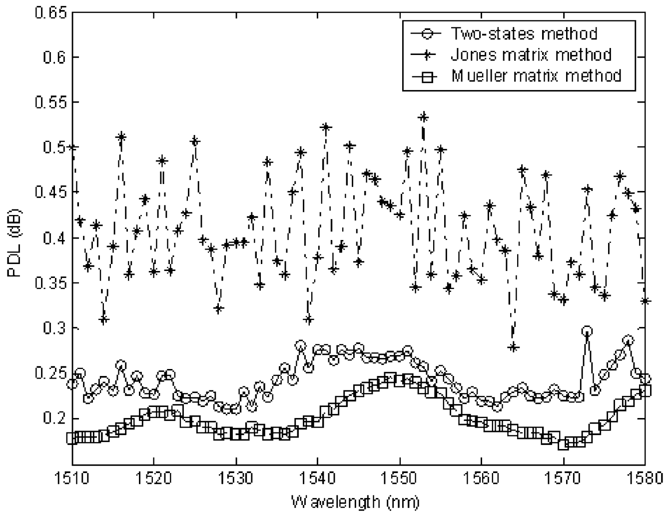
Fig. 2. PDL measurement results for two DUTs; (a) side-polished fiber and (b) PMF with bending-induced PDL.

Table 1
Mean value and standard deviation of PDL measurement results for two samples using three different methods

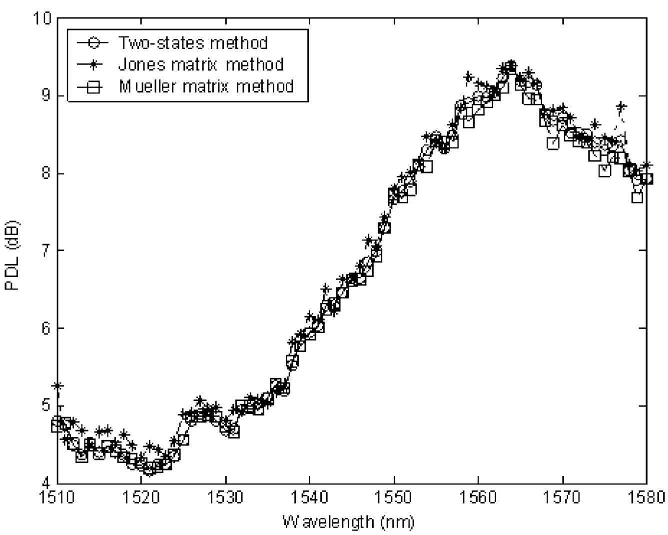
Method	Side-polished fiber (dB)	Spooled PMF (dB)
Two-states method	0.268 ± 0.009	7.105 ± 0.043
Jones matrix method	0.395 ± 0.088	7.128 ± 0.083
Mueller matrix method	0.231 ± 0.003	7.016 ± 0.030

4. Conclusion

A PDL measurement method, called two-states method, was presented. This method is based on the Lorentz property of Mueller matrix of optical devices with both PDL and birefringence. Since we demonstrated that PDL depends on the first column of Mueller matrix, the traditional Jones matrix and Mueller matrix techniques can be simplified to a two-states technique. As the proposed method only requires any two orthogonal input SOPs, it has the potential advantage of



(a)



(b)

Fig. 3. PDL vs wavelength for two DUTs; (a) side-polished fiber and (b) PMF with bending-induced PDL.

higher measurement speed and reduced error. Experiment results demonstrated the validity of our method.

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