Quasi-monochromatic fiber depolarizer and its application to polarization-dependent loss measurement

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We theoretically derive the relationship between the degrees of polarization (DOPs) of input and output for an optical component with polarization-dependent loss (PDL) and birefringence. Based on the theoretical result, we propose a novel depolarizer for quasi-monochromatic light that can depolarize a fully polarized light with a 50 MHz linewidth to less than 0.2% in the DOP. The depolarized light is then used to measure PDL in a single-mode optical fiber link. To the best of our knowledge, our new PDL measurement method is significantly faster than all known methods. Experimental results show excellent agreement with other methods. © 2006 Optical Society of America

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A nondepolarizing optical system with polarization-dependent loss (PDL) has no depolarization effect on a fully polarized light. However, such a system can change the degree of polarization (DOP) of a partially polarized or unpolarized light.[1] In other words, a partially polarized or unpolarized light can be depolarized or polarized by a PDL component. This property implicates some novel applications in polarization optics. In this Letter, first we derive the equation governing the relation between the input and output DOPs of a light traveling through a PDL component. Based on the properties of this equation, we propose a novel depolarizer for quasi-monochromatic light and a single-input PDL measurement method that uses the depolarized quasi-monochromatic output from the depolarizer.

Our proposed narrowband depolarizer can successfully depolarize a fully polarized light from a distributed feedback (DFB) laser diode (LD) with a 50 MHz linewidth to a DOP value less than 0.2%. In contrast, the traditional Lyot depolarizer cannot depolarize quasi-monochromatic light; even the Mach–Zehnder-interferometer-based depolarizer cannot effectively depolarize light with linewidths less than 100 MHz.[2] The unpolarized quasi-monochromatic light is then used for a novel deterministic technique for PDL measurement, whose principle is based on the same governing equation. There are several known PDL measurement methods, including deterministic all-states, pseudorandom all-states, and deterministic fixed-states techniques.[3] The deterministic all-states and pseudorandom all-states techniques sample a large number of subsets over the entire polarization-state space in a repeatable or pseudorandom manner, respectively.[3] The previously reported deterministic fixed-states techniques employ three or four well-defined input states of polarization (SOP) to derive PDL.[3,4] All these techniques require multi-SOP inputs, which tend to induce errors and result in longer measurement time. Our proposed PDL measurement method employs only one input; hence it is faster and has fewer error sources.

We begin by expressing the Mueller matrix that relates optical fields at two positions in a non-image-forming optical system. In Stokes space, the input and output Stokes parameters for quasi-monochromatic light are related by a Mueller matrix **M** as

$$\begin{pmatrix} s_{\text{out0}} \\ s_{\text{out1}} \\ s_{\text{out2}} \\ s_{\text{out3}} \end{pmatrix} = \mathbf{M} \begin{pmatrix} s_{\text{in0}} \\ s_{\text{in1}} \\ s_{\text{in2}} \\ s_{\text{in3}} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \begin{pmatrix} s_{\text{in0}} \\ s_{\text{in1}} \\ s_{\text{in2}} \\ s_{\text{in3}} \end{pmatrix}. \tag{1}$$

It has been found that an arbitrary **M** can be decomposed into three parts, which represent, respectively, a depolarizer, a retarder, and a diattenuator.[5] If the depolarizer is absent, it has also been proved that **M** is just a Lorentz transformation [Lorentz Group $O(3,1)$],[6] which means[7]

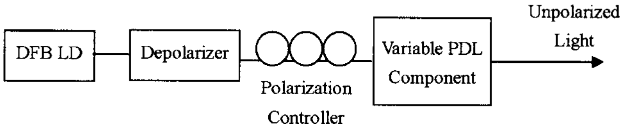

Fig. 1. Configuration of a quasi-monochromatic light depolarizer.

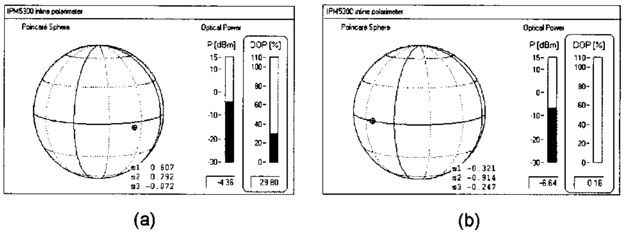

Fig. 2. DOPs measured at (a) the output port of traditional depolarizer and (b) after the variable PDL component.

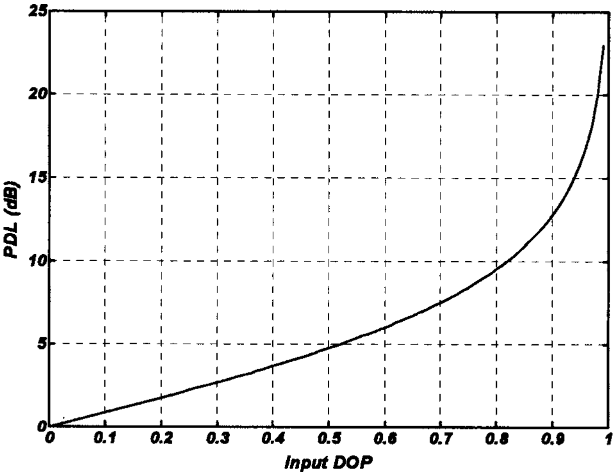

Fig. 3. Relation between the input DOP and the required PDL value for fully depolarizing the input.

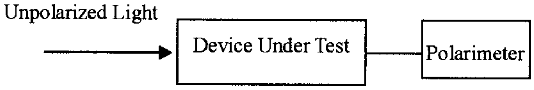

Fig. 4. Experimental configuration for PDL measurement using unpolarized light.

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

Here $\mathbf{G}=\mathrm{diag}(1,-1,-1,-1)$ is the Minkowski metric. Based on Eqs. (1) and (2), we can easily obtain

$$s_{\mathrm{out0}}^2-s_{\mathrm{out1}}^2-s_{\mathrm{out2}}^2-s_{\mathrm{out3}}^2=\sqrt{\det \mathbf{M}}(s_{\mathrm{in0}}^2-s_{\mathrm{in1}}^2-s_{\mathrm{in2}}^2-s_{\mathrm{in3}}^2). \tag{3}$$

Defining $\mathrm{DOP}_{\mathrm{out}}=\sqrt{s_{\mathrm{out1}}^2+s_{\mathrm{out2}}^2+s_{\mathrm{out3}}^2}/s_{\mathrm{out0}}$ and $\mathrm{DOP}_{\mathrm{in}}=\sqrt{s_{\mathrm{in1}}^2+s_{\mathrm{in2}}^2+s_{\mathrm{in3}}^2}/s_{\mathrm{in0}}$, Eq. (3) becomes

$$\mathrm{DOP}_{\mathrm{out}}=\sqrt{1-\sqrt{\det \mathbf{M}}(1-\mathrm{DOP}_{\mathrm{in}}^2)s_{\mathrm{in0}}^2/s_{\mathrm{out0}}^2}. \tag{4}$$

Here $s_{\mathrm{in0}}/s_{\mathrm{out0}}=s_{\mathrm{in0}}/(m_{11}s_{\mathrm{in0}}+m_{12}s_{\mathrm{in1}}+m_{13}s_{\mathrm{in2}}+m_{14}s_{\mathrm{in3}})$ and we already found[8]

$$\sqrt{\det \mathbf{M}}=m_{11}^2-m_{12}^2-m_{13}^2-m_{14}^2. \tag{5}$$

From Eqs. (4) and (5), we finally have

$$\mathrm{DOP}_{\mathrm{out}}=\sqrt{1-(1-D^2)(1-\mathrm{DOP}_{\mathrm{in}}^2)/(1+\vec{D}\cdot\vec{S}_{\mathrm{in}})^2}. \tag{6}$$

Here $\vec{D}=(m_{12}\,m_{13}\,m_{14})/m_{11}$ is defined as the PDL vector of an optical component, and we may easily find that $10\log[(1+D)/(1-D)]=\mathrm{PDL}$.[5] $\vec{S}_{\mathrm{in}}=(s_{\mathrm{in1}}\,s_{\mathrm{in2}}\,s_{\mathrm{in3}})/s_{\mathrm{in0}}$ is the input SOP. Further, we can rewrite $\vec{D}\cdot\vec{S}_{\mathrm{in}}=D\cdot\mathrm{DOP}_{\mathrm{in}}\cos\theta$, where θ is the angle between the PDL vector and the input SOP. Equation (6) is the governing equation describing the DOP variation through an optical device with PDL. In the following, we propose two applications of this equation.

The first application is a quasi-monochromatic depolarizer. Traditional Lyot-based or Mach–Zehnder-interferometer-based depolarizers cannot effectively depolarize quasi-monochromatic fully polarized light, but they can make it partially polarized.[2] From Eq. (6) we may find that the output DOP of a PDL device may be lower than the input DOP if the input DOP is less than 1. This suggests the possibility of depolarizing further a partially polarized quasi-monochromatic light, which can be obtained by using a traditional wideband depolarizer, with a variable PDL device. For completely depolarizing the input

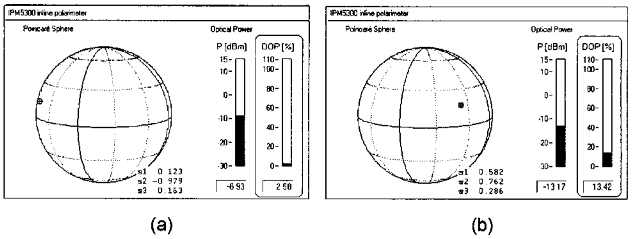

Fig. 5. Output DOPs for an unpolarized light through (a) an isolator and (b) a side-polished single-mode fiber.

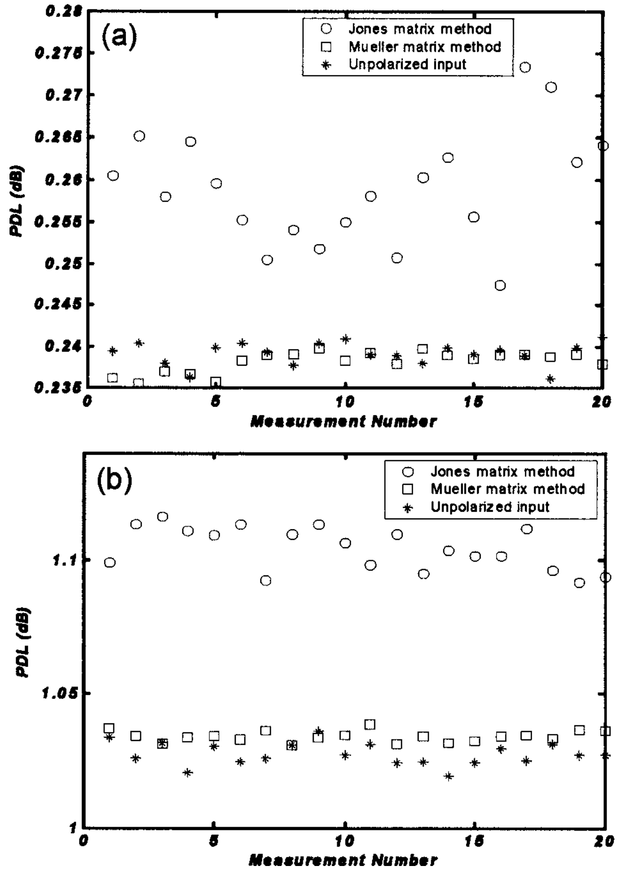

Fig. 6. PDL measurement results of (a) an optical isolator and (b) a side-polished single-mode fiber.

Table 1. PDL Measurement Results of Two Samples

Sample	Jones Matrix Method	Mueller Matrix Method	Unpolarized Input
Isolator (dB)	0.2590 ± 0.0068	0.2382 ± 0.0013	0.2392 ± 0.0014
Side-polished SMF (dB)	1.1046 ± 0.0080	1.0341 ± 0.0021	1.0276 ± 0.0042

light, namely, $\mathrm{DOP}_{\mathrm{out}}=0$, we may deduce from Eq. (6) that the conditions $D=\mathrm{DOP}_{\mathrm{in}}$ and $\theta=\pi$ must be fulfilled. We experimentally construct the following configuration to realize this function, as shown in Fig. 1.

The variable PDL component can be produced based on different principles and structures. For example, we can use bending-induced PDL in a Hi–Bi fiber section[9] or two polarization beam splitters plus a variable attenuator. For this setup we use the bending-induced PDL in a Hi–Bi fiber section. The PDL value is adjusted by changing the bent fiber length (or number of coils) of Hi–Bi fiber. The linewidth of the DFB LD is 50 MHz at 1550 nm. The DOP at the output port of a traditional depolarizer is about 30% measured using a polarimeter shown in Fig. 2(a). By tuning the polarization controller (PC) and variable PDL component, we can make the output DOP as small as 0.16% as shown in Fig. 2(b).

According to Eq. (6), for completely depolarizing the light with DOP 29.8%, the PDL value of the variable PDL component should be 2.6694 dB, which is very close to our measured value 2.6712 dB. Because some attenuation of optical power is induced in this technique, we have to consider the relation between the PDL value of the variable PDL component and the input DOP, as shown in Fig. 3. It can be observed that the PDL required at first increases linearly with input DOP, and it almost grows exponentially when input DOP is larger than 80%. If 10 dB attenuation is permitted, we can even fully depolarize the light with DOP up to 82%. In this way, we have realized a quasi-monochromatic depolarizer.

The second application is on a PDL measurement method using a quasi-monochromatic unpolarized light, which we have just produced using our quasi-monochromatic depolarizer. Also from Eq. (6), we can find that if $\mathrm{DOP}_{\mathrm{in}}=0$, then $\mathrm{DOP}_{\mathrm{out}}=D$. This means

$$\mathrm{PDL} = 10 \log\left(\frac{1+\mathrm{DOP}_{\mathrm{out}}}{1-\mathrm{DOP}_{\mathrm{out}}}\right). \qquad (7)$$

Namely, we may use the unpolarized light to measure the PDL of an optical device as shown in Fig. 4.

We use the quasi-monochromatic unpolarized light generated from the configuration in Fig. 1 to measure the PDL of two samples: one is an optical isolator, and the other is a section of side-polished single-mode fiber (SMF). Typical DOP values after two samples are shown in Fig. 5.

The 20-time measurement results of the two samples are plotted in Fig. 6. To verify the proposed method, the Jones matrix method,[4] and the Mueller matrix method[3] are also used to measure the same samples, whose results are also shown in Fig. 6. The mean values and standard deviations of measurement data of the three methods are summarized in Table 1. It is found that the result of our method agrees quite well with those of the other two methods.

Compared with the Jones matrix method, our method is insensitive to birefringence perturbation because birefringence perturbation does not affect DOP.[1] Compared with the Mueller matrix method, it can avoid the SOP-adjustment-induced error. And our proposed method apparently has the fastest measurement speed owing to its single input. It should be pointed out that Eq. (7) has been presented in some papers in a connotative mode[10] or in a simpler case.[11] But, to the best of our knowledge, no experimental work has been reported, which may be due to the difficulty in obtaining the high-quality unpolarized quasi-monochromatic light.

In conclusion, we have studied the DOP variation through an optical component with the PDL using the Lorentz group property of the Mueller matrix. Based on the theoretical relation, we proposed two novel technologies for depolarizing quasi-monochromatic light and measuring PDL using unpolarized light, respectively. Experimental results confirm the validity of these technologies.

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