Vol 13 No 8, August 2004
1009-1963/2004/13(08)/1291-05

Chinese Physics

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General demonstration of principal states of polarization and real-time monitoring of polarization mode dispersion in optical fibres*

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(Received 28 October 2003; revised manuscript received 12 April 2004)

We investigated the general properties of polarization effects in optical fibres and demonstrated the existence of so-called principal states of polarization (PSP), which mean the fixed points in mathematics, in different polarization effects, such as birefringence and polarization mode dispersion, by using fixed point theory. Furthermore, a time evolution vector is defined to describe the time evolution of polarization state in optical fibres, which is used to investigate the time evolution of polarization mode dispersion vector (PDV), including differential group delay and PSP. The experimental results of real-time monitoring of PDV by using this method are reported. To our knowledge, this is the first report on monitoring PSP evolution in optical fibres.

Keywords: birefringence, principal states of polarization, polarization mode dispersion, time evolution vector

PACC: 4280M, 4281C, 4281F

1. Introduction

In Stokes space, a state of polarization (SOP) is denoted as a point on the Poincaré sphere. Most polarization effects in optical fibres can be described as the motion of this point on the Poincaré sphere. We distinguish different polarization effects according to the cause of motion. For example, if the motion is caused by optical frequency, we call the effect polarization mode dispersion (PMD), and if it is caused by fibre length, we call the effect birefringence. In other words, if SOP in an optical fibre varies because of a physical parameter, some kind of polarization effect exists in this fibre. Generally, this motion will form a space curve on the Poincaré sphere. The properties of this curve can be analysed to study polarization effect. This paper does not consider the physical parameter in the first place, hence general properties of polarization effects can be obtained.

In this paper, firstly, we demonstrate that there always exist so-called principal states of polarization (PSP) in a polarization effect by using fixed point theory. Then we focus on studying three polarization effects in optical fibres: birefringence, PMD and polarization instability. In each of these effects, we can define a physical parameter-dependent vector if we assume there is no polarization-dependent loss (PDL).

PMD is an important limiting factor for high bit-rate optical fibre communication systems. According to principal state theory,[1,2] PMD is fully described by a frequency-dependent vector: the polarization mode dispersion vector (PDV), whose direction is parallel to PSP and whose amplitude is the differential group delay (DGD) between two PSPs. In our general demonstration, we know that the principal state theory is a special case of our result. In addition, during the demonstration of the existence of PSP in Ref.[1], the authors assumed that there is no PDL. This assumption is unnecessary in our demonstration. We only need to define the physical parameter-dependent vector.

Both DGD and PSP are sensitive to fibre environment and will fluctuate with time. Fluctuations of

*Project supported by the National Natural Science Foundation of China (Grant No 60272010) and by the High Technology Development Programme of China (Grant No 2003AA122510).

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PMD due to changes of fibre environment make PMD compensation very difficult. The compensation time of any technique must be short enough to overcome the fluctuations.

Fluctuations of PMD are caused by fluctuations of birefringence distribution in optical fibres, which also result in instability of the output SOP of this fibre. To characterize this instability, a time evolution vector (TEV) can be defined to describe the output SOP evolution with respect to time and the polarization instability of an optical fibre system. An equation can be derived to show the relationship between PDV and TEV.

In our work, time evolutions of both DGD and PSP are investigated. We monitor the time evolutions of DGD and PSP in a spooled single-mode fibre successfully.

2. General demonstration of PSP

We assume that the output SOP motion is caused by a physical parameter x, namely $\boldsymbol{S}(x)$. In a fibre, the output SOP is related to the input SOP by

$$\boldsymbol{S}(x) = M(x)\boldsymbol{S}_{\text{in}}, \tag{1}$$

where $M(x)$ is Müller matrix. If the initial value of x is x_0, then

$$\boldsymbol{S}(x_0) = M(x_0)\boldsymbol{S}_{\text{in}}. \tag{2}$$

From Eqs.(1) and (2), we obtain

$$\boldsymbol{S}(x) = M(x)M^{-1}(x_0)\boldsymbol{S}(x_0), \tag{3}$$

where M^{-1} is the inverse matrix of M. This equation determines the polarization effect of x process. The so-called PSPs are such SOPs which are not affected by parameter x. In mathematics, such special SOPs are called fixed points.

We have the fixed point theorem on sphere mapping:[3] if S^{2n} denotes a $2n$-dimensional sphere ($S^{2n} = \{(x_1, \ldots, x_{2n+1}) | x_1^2 + \cdots + x_{2n+1}^2 = \Gamma^2\}$) and mapping $\pi : S^{2n} \to S^{2n}$ is successive and homotopic to identical mapping, then mapping π has at least one fixed point. Homotopy is defined as two mappings $\pi : X \to X$ and $\pi 1 : X \to X$. If there is a set of mappings $f(t) : X \to X$ with parameter t, $f(0) = \pi 1$, and $f(1) = \pi$, then π and $\pi 1$ are homotopic.

Obviously, the Poincaré sphere is a two-dimensional (2D) sphere. $M(x)M^{-1}(x_0) : S^2 \to S^2$ and it is successive. We construct a new mapping: $M(x_0 + t(x - x_0))M^{-1}(x_0) : S^2 \to S^2$. When $t = 0$, we have $M(x_0 + t(x - x_0))M^{-1}(x_0) = M(x_0)M^{-1}(x_0) = I$, and I is a unit matrix which means identical mapping. When $t = 1$, we have $M(x_0 + t(x - x_0))M^{-1}(x_0) = M(x)M^{-1}(x_0)$. Then $M(x)M^{-1}(x_0)$ is homotopic to identical mapping which satisfies the conditions of the theorem. As a result, $M(x)M^{-1}(x_0)$ has at least one fixed point on the Poincaré sphere, which means there exists at least one special SOP. Note that this conclusion is suitable to all polarization effects and has no prerequisites assumed. On the other hand, we know that an arbitrary SOP can be decomposed into the linear combination of PSPs, and the Poincaré sphere is a 2D sphere, so it seems that two PSPs can exist, namely there are two fixed points. But it is not guaranteed that two PSPs are orthogonal as has been presented in Ref.[1].

3. Time evolution vector

Taking the derivative of Eq.(3) with respect to x and making a limitation $x \to x_0$, we obtain

$$\frac{\partial \boldsymbol{S}}{\partial x} = \frac{\partial M}{\partial x} M^{-1}\boldsymbol{S}. \tag{4}$$

If we want to define a vector $\boldsymbol{X}$, let $\boldsymbol{X}\times = \dfrac{\partial M}{\partial x}M^{-1}$, we have to use $|M| = 1$ and $M^{-1} = M^T$; M^T is the transpose matrix of M. So we have to assume there is no PDL in the fibre. On this assumption, two PSPs are orthogonal. Then

$$\frac{\partial \boldsymbol{S}}{\partial x} = \boldsymbol{X} \times \boldsymbol{S}. \tag{5}$$

To make $\dfrac{\partial \boldsymbol{S}}{\partial x} = 0$, we have $\boldsymbol{X} = 0$ or $\boldsymbol{X}$ is parallel to $\boldsymbol{S}$. If $\boldsymbol{X} = 0$, this kind of polarization effect will not exist. Hence $\boldsymbol{X}$ must be parallel to that special SOP which is a fixed point on the Poincaré sphere.

If parameter x is the fibre length z, then $\boldsymbol{X}$ is the local birefringent vector $\boldsymbol{\beta}$. If parameter x is the optical frequency ω, then the special SOP is PSP and $\boldsymbol{X}$ is just the PDV Ω.[1,4] Compared to the PSP demonstration in Ref.[1], our demonstration does not need to assume that there is no PDL in fibres. This means that the existence of the PSP does not depend on this condition.

As we know,[5–7] many ambient parameters, such as temperature and stress, will affect the birefringence distribution in optical fibres. The SOP at a fixed frequency and a fixed point in the fibre may change with time. Therefore, we define a vector $\boldsymbol{T}\times = \dfrac{\partial M}{\partial t}M^{-1}$ to describe this effect and call it the TEV.[8] Using

this vector, we can investigate the PMD time evolution with the following equation:

$$\frac{\partial \Omega}{\partial t} = \frac{\partial \boldsymbol{T}}{\partial \omega} + \boldsymbol{T} \times \Omega, \tag{6}$$

where ω is the optical frequency. The demonstration of Eq.(6) is the same as that of the PMD dynamic equation.[9] From Eq.(6), we know that $\partial \boldsymbol{T}/\partial \omega$ describes the time evolution of the DGD and $\boldsymbol{T} \times \Omega$ describes the time evolution of the PSP in a short time interval, so we can obtain the time evolution of the PDV.

To measure TEV, we observe the time-dependent SOP curve on the Poincaré sphere in Fig.1.

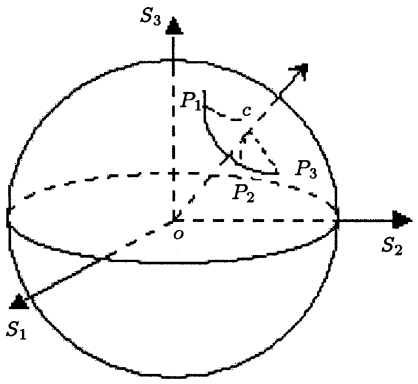


Fig.1. SOP evolution curve on the Poincaré sphere. P_1, P_2 and P_3 are three points on this curve, where c is the centre of the circle which is determined by P_1, P_2 and P_3.

In Fig.1, three points P_1, P_2 and P_3 denote three output SOPs at time t_1, t_2 and t_3 at a fixed wavelength respectively. They determine a circle; c is the centre of this circle. Then

$$|\boldsymbol{T}| = \Delta\phi/(t_3 - t_1), \tag{7}$$

where $\Delta\phi$ is the angle P_1–c–P_3 in radian and the direction of $\boldsymbol{T}$ is parallel to the vector $\boldsymbol{oc}$ as shown in the figure. This method is very similar to the PST method for DGD measurement.[10]

4. Experimental results

The time evolutions of SOP and PDV are measured in a 110km spooled single-mode fibre which is placed on a table in the laboratory. As the fibre is not covered with jacket, it is sensitive to fluctuations caused by temperature and all other mechanical vibrations. Such fluctuations can be considered as a fully stochastic process. Figure 2 shows our experimental setup.

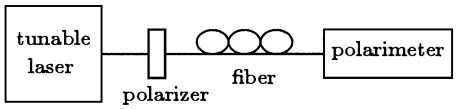
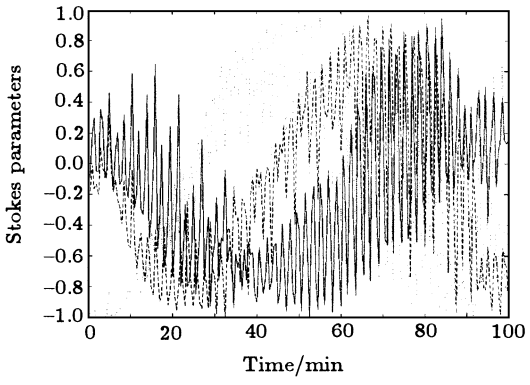
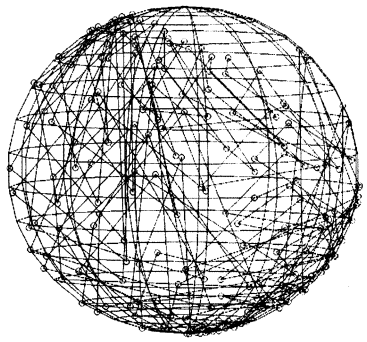


Fig.2. Experimental setup for TEV and PDV monitoring.

We use a tunable laser source to launch the light into the fibre at wavelengths of 1550nm and 1551nm. A polarizer is used to guarantee the stable input SOP. We take notes of SOP every 30s at two different wavelengths for 100min. The experimental results are shown in Figs.3 and 4. From Fig.3, we calculate the average amplitude of $\boldsymbol{T}$, which is $\langle|\boldsymbol{T}|\rangle = 1.77\,\mathrm{min}^{-1}$ at 1550nm.



(a)



(b)

Fig.3. Measured SOP evolution in a 110km spooled fibre at wavelength 1550nm. (a) Stokes parameters; (b) 3D notation on the Poincaré sphere. In Fig.3(a), the solid curve represents S_1, the dashed curve represents S_2, the dotted curve represents S_3.

After we measure the TEVs at two wavelengths, we obtain PDV evolution from Eq.(6). At the beginning, we have the initial PDV by using the MMM method.[11] The results are shown in Fig.4.

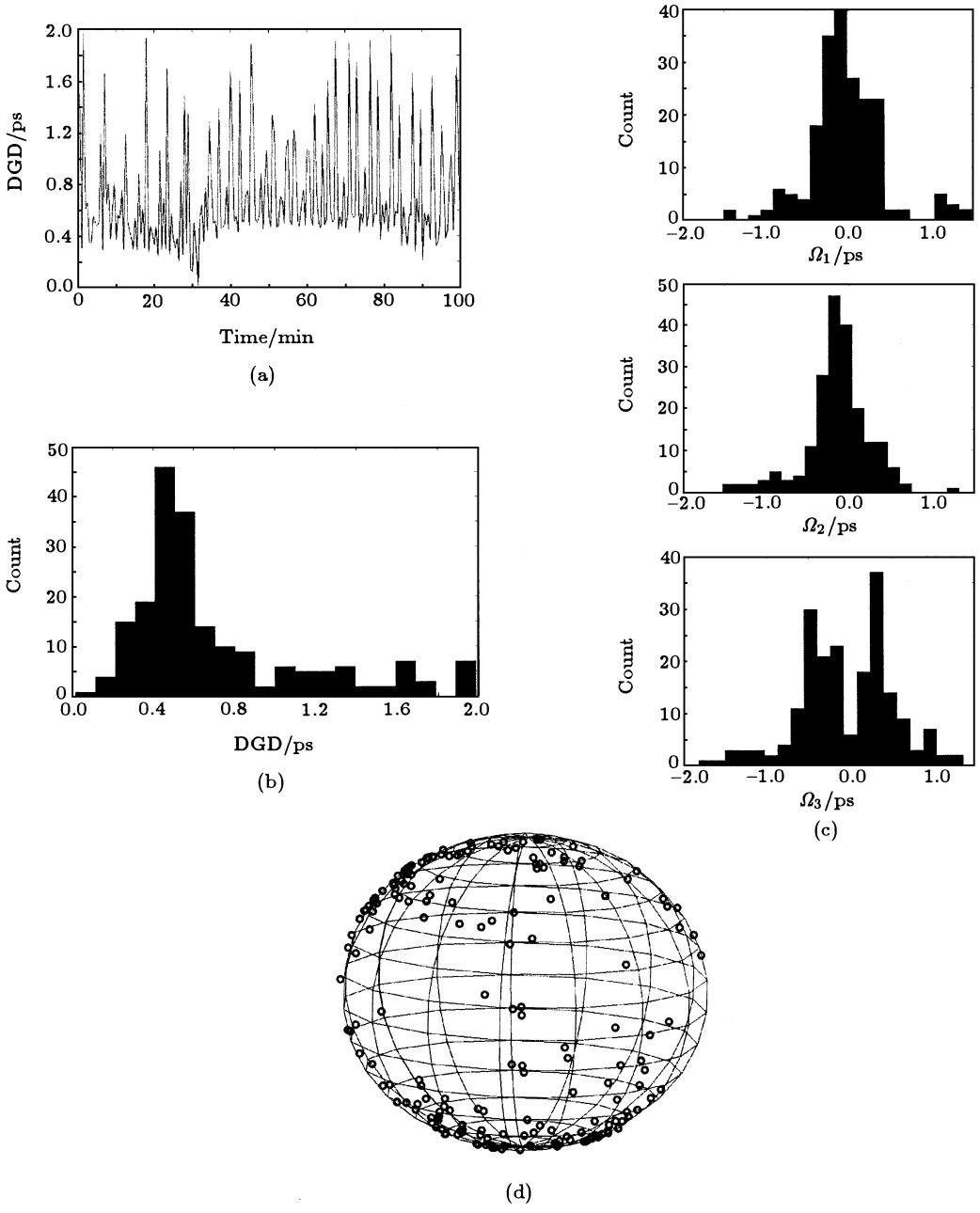


Fig.4. Measured PMD evolution in a 110km spooled fibre. (a) DGD time evolution; (b) histogram of DGD distribution; (c) histograms of Ω_1, Ω_2, Ω_3 distributions; (d) PSP time evolution on the Poincaré sphere.

Figure 4(a) shows the time evolution of DGD. The average DGD is 0.711ps which is almost the same as the result (0.713ps) obtained using the JME method.[12] Figure 4(b) shows the DGD distribution which satisfies the Maxwellian distribution very well.[13] Figure 4(c) shows the distributions of Ω_1, Ω_2, Ω_3 which are almost like Gaussian distributions.[13] In Fig.4(d), the dots on the Poincaré sphere denote PSP time evolution as a Brownian motion.[14]

5. Conclusion

We have demonstrated that there always exist so-called PSPs in a polarization effect by using fixed point theory. Then we investigate the polarization instability in optical fibres and define a TEV to describe this process. We present a time dynamic equation to connect PDV and TEV. Using this equation, we can monitor the time evolution of PDV by monitoring the time evolution of the output SOP. The experimental results show the time evolutions of both DGD and PSP, which are in agreement with the theoretical results.

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