A novel method of polarization state control for polarization division multiplexing system

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We describe a new algorithm in a cost effective polarization division multiplexing (PDM) system. Without modifying the existing transmitter, receiver electronics, or softwares, we use a special optical scheme to demultiplex the signal multiplexed and improve it with a conjugated gradient algorithm. We experimentally resume the polarization state with a deviation under 5% and the power loss less than 20 dB which proves the feasibility of the polarization control algorithm in the new polarization multiplexing system.

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Utilizing the polarization parameter[1], polarization division multiplexing (PDM) is different from the previous multiplexing technologies. The problem in signals demultiplexing, which is the key section of PDM, is blocking the actual application of PDM system[2]. And after a long distance of independent transmission, the polarization of the combined signal will be changed due to some factors such as stress on fiber at the receiver ends. Therefore, it demands that the states of polarization of the system should be self-calibrated in order to keep orthogonal at the receiver ends, so that the system needs to be complexly structured[3].

In this letter, we describe a novel and simple all optical demultiplexing scheme for automatically separating the two orthogonal polarization channels in a PDM system[4], which is slightly changed to produce doubled capacity of communication.

As shown in Fig. 1, the system requires low-speed control circuits, a polarization beam combiner, a polarization beam splitter, and a polarization controller as the key components to automatically multiplexing and demultiplexing[5]. Signal beams at the same wavelength are transmitted by transmitters TX1 and TX2 and then multiplexed through a polarization beam combiner (PBC). Described by Stokes vectors, the arbitrary polarization state is $\vec{S}$ before entering a polarization beam splitter (PBS). At the receiver ends, PBS is used to demultiplex the two orthogonal polarization optical beams. And there are two orthogonal transmission axes chosen as reference coordinates x and y in PBS[6], and their corresponding Mueller matrix can be obtained. According to the structural form of Stokes vector, we can acquire the optical power of each component.

Without regarding to the bandwidth of light source or a selected wavelength, the following function is hold. In this condition, these two optical beams can be considered orthogonal all the time

$$\varepsilon_1 = -\varepsilon_2, \quad \begin{cases} \theta_2 = \theta_1 + \frac{1}{2}\pi, & 0 \le \theta_1 \le \frac{1}{2}\pi \\ \theta_2 = \theta_1 - \frac{1}{2}\pi, & \frac{1}{2}\pi \le \theta_1 \le \pi \end{cases}, \tag{1}$$

where ε_1 and ε_2 are elliptical angles of the input light, θ_1 and θ_2 are the orientation angles.

In signal processing, we use the same response coefficient α of the two low-speed photo-detectors for the sake of simplification. So the voltage difference ΔV can be expressed as

$$\begin{aligned} \Delta V &= V_1 - V_2 = \alpha P_x - \alpha P_y \\ &= \alpha\,(P_1 - P_2)\cos 2\varepsilon_1 \cos 2\theta_1. \end{aligned} \tag{2}$$

The equations above show the reason why we set the optical power difference of these two signal channels intentionally. Actually, at a low speed, this difference can be regarded as a constant. For the target polarization state, $(1,0,0)$ or $(-1,0,0)$, θ_1 and ε_1 are set as $(\theta_1 = 0°, \varepsilon = 0°)$, $(\theta_1 = \pm 90°, \varepsilon = 0°)$, $(\theta_1 = 0°, \varepsilon = \pm 90°)$, or $(\theta_1 = \pm 90°, \varepsilon = \pm 90°)$, where ΔV reaches positive or negative maximum[1]. Naturally,

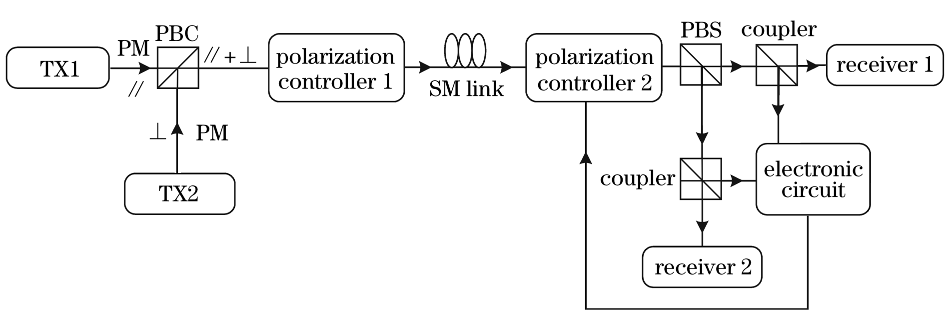

Fig. 1. Conceptual illustration of PDM using automated feedback controlment. PM: polarization modulation; SM: single mode.

we choose ΔV as the final feedback signal and by maximizing it, we minimize the damages of crosstalk and effects of randomly-changing coupling angles.

Compared with the polarization state controller based on multiple wave plates, the controller we use is based on the fiber squeezers and driven by piezoelectric actuator for high speed. It has extremely low insertion and polarization-dependent loss because of its all-fiber construction. The response time is 30 μs. It is fast enough to track the fastest polarization fluctuation in field-installed fiber links. As shown in Fig. 2, the controller consists of four 'individual' fiber squeezers and the fast axes of the second and the fourth squeezer are rotated to 45°. And briefly, in the Stokes space, the retardation caused by squeezers is expressed as δ.

When feedback signal is received, polarization controller is used to adjust the polarization state and hence an effective algorithm is necessary. Among so many optimization methods, conjugate-gradient method is fast-convergent, simple, and effective, proved by our experiments. As to conjugate-gradient method, it is known that when $\vec{A}$ is an $n \times n$ symmetric positive definite matrix and n-dimensional vectors $\vec{r}^{(1)}, \vec{r}^{(2)}, \cdots, \vec{r}^{(n)}$ are non-vanishing, mutual $\vec{A}$-conjugate, the minimum of quadratic function (3) can be searched along $\vec{r}^{(k)}$ ($k = 1, 2, \cdots$) by dimensional one-wave

$$f(x) = \frac{1}{2}\vec{X}^{\mathrm{T}}\vec{A}\vec{X} + \vec{B}^{\mathrm{T}}\vec{X} + \vec{C},$$
$$f\left(x^{(n)}\right) = \min f\left(x_{\lambda_1}^{(n-1)} + \lambda_1 \vec{r}^{(n)}\right). \quad (3)$$

From the above equations, we deduce that the extremum of quadratic function is reached just through a one-dimensional search along n conjugate directions. However, the search order can be arbitrary. Namely, the extremum is reached through several different paths. If $\lambda^{(k)}$ is defined as the search step at the $x^{(k)}$ along $\vec{r}^{(k)}$ direction, we can get $x^{(k+1)} = x^{(k)} + \lambda\vec{r}^{(k)}$. $F(\lambda)$ is reached to the minimum at the point $\lambda = \lambda^{(k)}$. Namely,

$$\frac{\partial F}{\partial \lambda} = -\nabla F(x^{(k)} + \lambda^{(k)}\vec{r}^{(k)}) \cdot \vec{r}^{(k)} = -g^{(k+1)} \cdot \vec{r}^{(k)} = 0. \quad (4)$$

From the beginning point $x^{(0)}$, its gradient $g^{(0)}$ is defined as the first conjugate direction $\left(g^{(0)} \neq 0\right)$, and $r^{(1)} = -g^{(0)}$. Then we get

$$\vec{r}^{(k+1)} = -g^{(k)} + \alpha_{k+1}\vec{r}^{(k)}, \quad k = 1, 2, \cdots, n-1, \quad (5)$$

In this letter, we adopt the function of algorithm proposed by Fletcher-Reece[7]

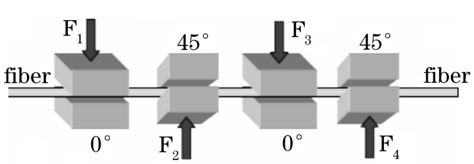

Fig. 2. Theoretical scheme of polarization state controller based on four fiber squeezers. The angles among squeezers are stable and the presses are variable. The retardation between fast and slow axes is dependent on the variation of voltages applied on the squeezers.

$$\alpha_{k+1} = g^{(k)^T}\left(g^{(k)} - g^{(k-1)}\right) / \left|g^{(k-1)}\right|^2. \quad (6)$$

It is known that phase delay is in the direct ratio to refractive index in the polarization state controller based on fiber squeezers and the difference of refractive index is controlled by control voltage. Let δ be the phase difference, θ be the oriental angle between fast axis and x axis, and $\vec{S}_{\mathrm{in}}$ be the Stokes vector of input optical beam. Naturally, the output $\vec{S}_{\mathrm{out}}$ can be expressed as

$$\vec{S}_{\mathrm{out}} = \mathbf{M}\vec{S}_{\mathrm{in}}. \quad (7)$$

As the relationship of squeezer angles shown in the Fig. 2, Stokes vector $\mathbf{M}$ is

$$\mathbf{M} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\Delta\delta & \sin\Delta\delta\cdot\sin\delta1 & -\sin\Delta\delta\cdot\cos\delta1 \\ 0 & \sin\Delta\delta\cdot\sin\delta4 & M_{22} & M_{23} \\ 0 & \sin\Delta\delta\cdot\cos\delta4 & M_{32} & M_{33} \end{bmatrix}, \quad (8)$$

$$\Delta\delta = \delta3 - \delta2. \quad (9)$$

We get another form of Eq. (4)

$$f(\cos\delta1, \cos\delta2, \cos\delta3, \cos\delta4) = \frac{1}{2}\vec{S}_{\mathrm{in}}^{\mathrm{T}}\mathbf{M}\vec{S}_{\mathrm{in}} - \vec{S}_{\mathrm{out}}^{\mathrm{T}}\vec{X}, \quad (10)$$

where $\vec{S}_{\mathrm{in}}$ and $\vec{S}_{\mathrm{out}}$ are known quantities. Utilizing Eq. (10), we can obtain the minimum value by conjugate-gradient method. Finally, we can gain the solution $(\cos\delta1, \cos\delta2, \cos\delta3, \cos\delta4)$ of the equation above and then transform them to the different voltages to control the four fiber squeezers in the polarization state controller. The flow chart of arithmetic method is shown in Fig. 3.

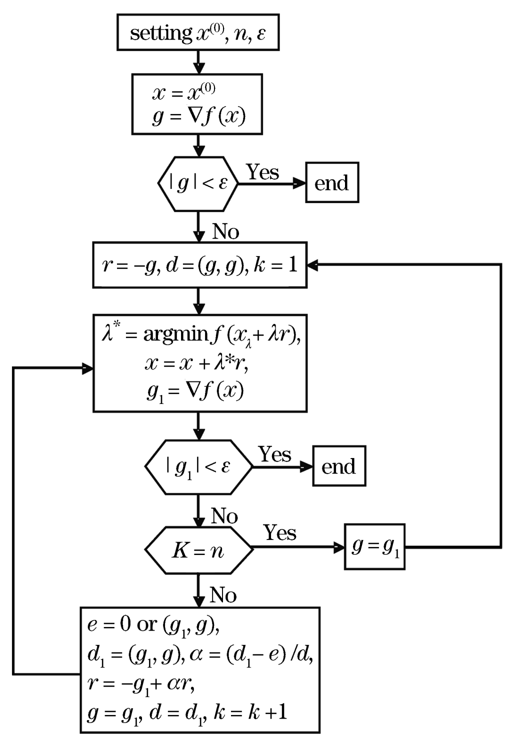

Fig. 3. Flow chart of arithmetic method.

During the experiments, we put a PBS in front of the photodiodes as a polarization analyzer and the optical power difference between the two separated beams is used as feedback signal. In the process of tests, we manually control the rotatable fiber squeezer as a scrambler, adjusting its rotation direction and pressure randomly, and so is the polarization state which can reach a stochastic point in the Poincare sphere[8]. And then, we set up our program to track the target point. To simplify the experimental process, we use photodiodes as sensor of feedback system to omit the signal receiving links. The experimental scheme is shown in Fig. 4.

From the result shown in Fig. 5(a), we adjust an arbitrary oriented polarization state to the target state manually and automatically, respectively. At last, we compare the results of these two methods. Five independent tests are included and because the low optical power is in microwatt magnitude, it is common that there are some slight fluctuations in normal range; however, we successfully constrain the power difference of these two control ways to an extent of no more than 20 dB. In Fig. 5(b), we verify the proportion of match between the state of polarization before and after control, then we get that under the algorithm and the deviation can be limited less than 5%.

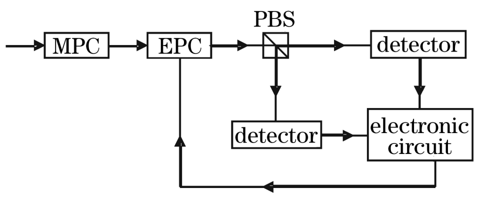

Fig. 4. Simplified experimental scheme. MPC: manual polarization state controller. EPC: electric polarization state controller adjusted by feedback signals.

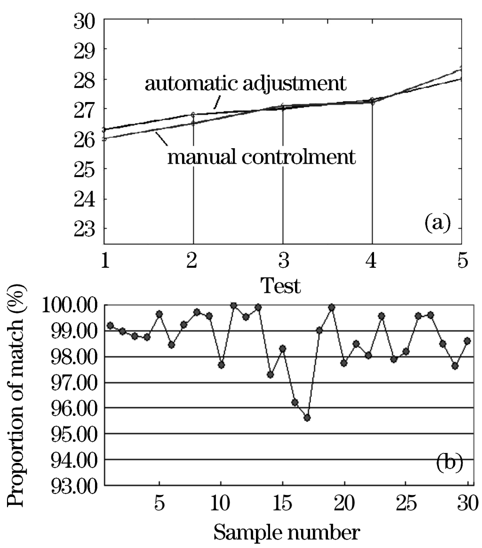

Fig. 5. Result of five experiments. (a) One line stands for the results of manual controlment, the other means automatic adjustment; (b) proportion of match between the state of polarization before and after control.

In summary, to meet the increasing requirements of bandwidth in communication, we show and demonstrate a novel all-fiber scheme used in the ultra high-speed optical fiber communication system, especially the dense wavelength division multiplexer (DWDM) system[9]. We also obtain the functions and theoretical models in details. Two orthogonal optical beams are combined into PBC. Through a polarization controller and a PBS, the beams with changing polarization states are received by a photodiode. As the feedback is variable, the detected optical power controls the voltages on the fiber squeezers to adjust the polarization state for tracking the target point in Poincare sphere. From the comparison between manually and automatically arithmetic adjustments and the match proportions before and after control, we can conclude that this optimum arithmetic method is effective for this scheme.

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