

An experiment for obtaining DOP ellipsoid using particle swarm optimization algorithm

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The degree of polarization (DOP) ellipsoid can be used as either feedback or feedforward signal for automatic polarization mode dispersion compensation. We have realized the experiment for obtaining DOP ellipsoid from 100 sampling data of output states of polarization using particle swarm optimization (PSO) as ellipsoid data fitting algorithm. It was shown that the PSO algorithm was powerful for ellipsoid data fitting with high precision within 250 ms.

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Polarization mode dispersion (PMD) limits the capacity of optical fiber communication. The PMD compensation has become one of hot topics for recent years^[1-8]. An ordinary automatic PMD compensator can be divided into three important subparts: PMD monitoring unit, compensation unit and control algorithm. An effective PMD monitoring system will enable its monitoring signal highly correlated to PMD. Two main kind of PMD monitoring techniques are usually adopted in various PMD compensation feedback schemes. One is called the electrical spectral hole burning^[1,2,5], in which the feedback signal is the power level of specific tones in the received radio-frequency spectrum of the base-band signal. The other is called degree of polarization (DOP)^[3,4,6], in which the feedback signal is evaluation for DOP of optical signal in the fiber link. The second one is widely used because of its advantages of bit-rate independent and not needs to use high speed devices.

An ideal PMD monitoring technique can reveal PMD vector as more information as possible, such as both differential group delay (DGD) and principal state of polarization (PSP). Because the DOP is affected by input state of polarization (SOP), it can not reflect the detailed information of PMD vector when the input SOP coincides with one of input PSP. DOP ellipsoid obtained by using a polarization scrambler can determine both DGD and PSP orientation^[9]. The polarization scrambler placed at the input fiber generates the random input SOP uniformly distributed over the whole Poincaré sphere. If there is no PMD in the transmission fiber link, the Stokes parameters of the output signals have the relation of $S_0^2 = S_1^2 + S_2^2 + S_3^2$, and DOP = 1. All the output SOPs form a perfect ball sphere in Stokes space with unity radius. For the first-order PMD in the fiber link, the Stokes parameters have the relation of $S_0^2 > S_1^2 + S_2^2 + S_3^2$, and DOP < 1, with the exception when the input SOP is aligned with one of the PSPs (in this point DOP = 1). So all the output SOPs form an ellipsoid whose longest radius has a length of unity and points to the direction of PSPs.

For the system with only first-order PMD, a DOP ellipsoid whose major axis is aligned with the PSP can be

described as^[9]

$$S_1^1 + \frac{S_2^2 + S_3^2}{R^2(\tau)} = 1, \quad (1)$$

where τ is the DGD and $R(\tau)$ is the normalized auto-correlation of the signal. And its longest axis points to S_1 axis. For first-order PMD whose PSP is point to arbitrary direction, a ellipsoid is with unity value for the longest radius ($r_{\max} = 1$) and same value of $R(\tau)$ for the shortest radius ($r_{\text{mid}} = r_{\min} = R(\tau)$), and its longest axis is oriented in the corresponding direction in Stokes space, as shown in Fig. 1.

For the system with second-order PMD, the longest radius of ellipsoid is shorter than unity depending on the amount of second-order PMD, which has analytically discussed in Ref. [9], and the ellipsoid is no longer in the symmetry of rotation ($r_{\text{mid}} \neq r_{\min}$).

From the discussion above, we can see that the DOP ellipsoid is a good PMD monitoring technique, from which we can read out detailed information of PMD. So it can be used in either feedback or feedforward PMD compensation systems^[9].

In order to obtain the information such as the three radii of ellipsoid r_{\max} , r_{mid} , r_{\min} and its orientation angles α , β , γ , it is important to find a good algorithm to

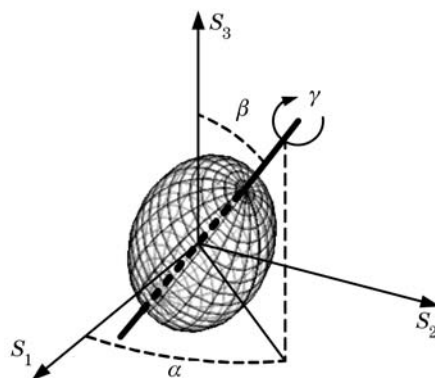


Fig. 1. The orientation of DOP ellipsoid in Stokes space.

get the analytical ellipsoid equation from measured output SOP data, as shown in Fig. 1. The angles α and β determine the direction of the longest axis, γ determines the rotation angle around ellipsoid axis itself. This algorithm is required to get right ellipsoid with high precision from as less numbers of data as possible for the speed request of PMD compensation.

We have introduced the particle swarm optimization (PSO) algorithm into automatic PMD compensation as a feedback control algorithm^[7,8]. The aim of PSO algorithm can be described as a procedure to find the global maximum or global minimum of a function in a multi-dimensional hyperspace by adjusting multi-control parameters, shown in mathematics as^[10]

$$\text{MAX}_{\text{parameters}} (\text{function}), \quad (2)$$

or

$$\text{MIN}_{\text{parameters}} (\text{function}), \quad (3)$$

where the number of parameters is the number of dimensions of hyperspace.

In automatic PMD compensation^[7,8], as an automatic control algorithm using Eq. (2), the PSO algorithm automatically searches the global maximum of feedback signal (function) through adjusting multi-voltages of polarization controllers (parameters).

In this paper, introducing PSO technique into PMD monitoring unit, we realized an experiment of getting DOP ellipsoid by using PSO algorithm in the form of Eq. (3). For getting a right DOP ellipsoid, we will first get a normal ellipsoid

$$\frac{S_1''''2}{r_1^2} + \frac{S_2''''2}{r_2^2} + \frac{S_3''''2}{r_3^2} = 1 \quad (4)$$

in the principal axis coordinate $S_1''''-S_2''''-S_3''''$ by three rotations of $-\alpha, -\beta, -\gamma$. Secondly, we will endlessly adjust six-dimensional parameters ($r_1, r_2, r_3, \alpha, \beta, \gamma$) until minimizing following function

$$\text{MIN}_{(r_1, r_2, r_3, \alpha, \beta, \gamma)} \left(\sum_{n=1}^N \left| \frac{S_{1n}''''2}{r_1^2} + \frac{S_{2n}''''2}{r_2^2} + \frac{S_{3n}''''2}{r_3^2} - 1 \right| \right), \quad (5)$$

where N is the number of sampling data used for ellipsoid data fitting.

Figure 2 shows the experimental setup for obtaining DOP ellipsoid. As the first step work, we only involve the experiment in the case of first-order PMD. The laser pulses with linear polarization state were generated by

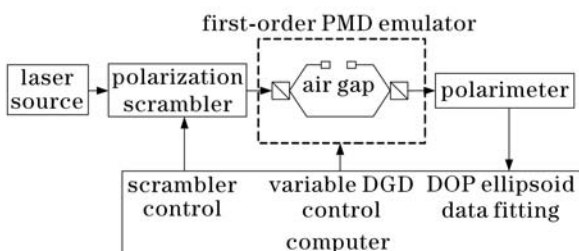


Fig. 2. Experimental scheme for DOP ellipsoid collection.

a fiber ring laser. The pulsewidth is 7 ps, and central wavelength is 1560.5 nm. A computer controlled polarization controller was used as a polarization scrambler to randomly transform the SOP of the laser signal to be uniformly distributed on entire Poincaré sphere, by randomly adjusting the three cells of polarization controller, with the speed of 59 kHz (the speed of SOP transformation). A computer controlled air gap time delay line was acted as the first-order PMD emulator. A polarimeter detected the SOPs of the output optical signals, and fed them into computer through 4-channel A/D, each channel has the bandwidth of 130 kHz. In the computer, the program with PSO algorithm made the data fitting from sampling data and obtaining the DOP ellipsoid and getting PMD information.

Figure 3 shows the 8000 sampling points of SOPs of the output optical signals with various DGD values in our experiment. It can be seen that, all the output SOPs form a ball sphere in Stokes space with zero DGD (Fig. 3(a)), and a needle-like spheroid is formed with larger DGD (Fig. 3(c)). The larger DGD is, the smaller value of minimum radius of ellipsoid is. Furthermore, the PSPs of PMD vector do not change for the first-order. Therefore we see that the longest radius of ellipsoid remains oriented in the same direction with various DGD (Figs. 3(b) and (c)).

Generally, the more numbers of the sampling data, the more accurate the ellipsoid is. But 8000 sampling data points will suffer from a long time. The whole procedure of getting 8000 sampling points combined with ellipsoid data fitting consumed the time of 3815 ms. It is important to obtain a precise analytical ellipsoid equation to get three radii $r_{\max}, r_{\text{mid}}, r_{\min}$ and its orientation angles α, β, γ through data fitting from limited sampling data. We made the data fitting from only 100 sampling data using PSO algorithm, and obtained the DOP ellipsoid shown in Fig. 4.

With the comparison between Figs. 3 and 4, we can see that, the data fitting ellipsoids of 100 samplings nearly fit close to the ellipsoids formed by 8000 sampling points with high precision. It can be conclude that the PSO

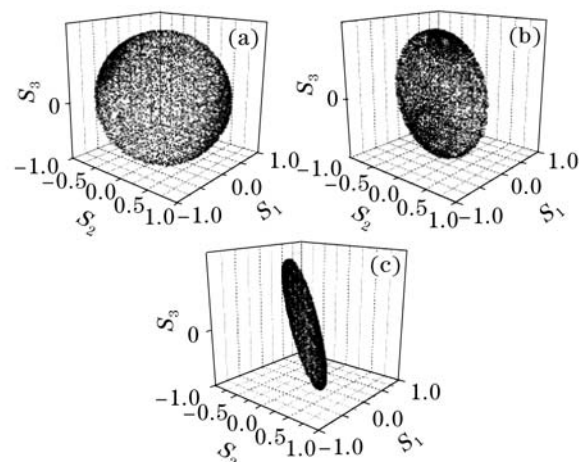


Fig. 3. 8000 sampling points of output SOPs with various DGD values. (a) DGD = 0 ps, (b) DGD = 4 ps, (c) DGD = 10 ps.

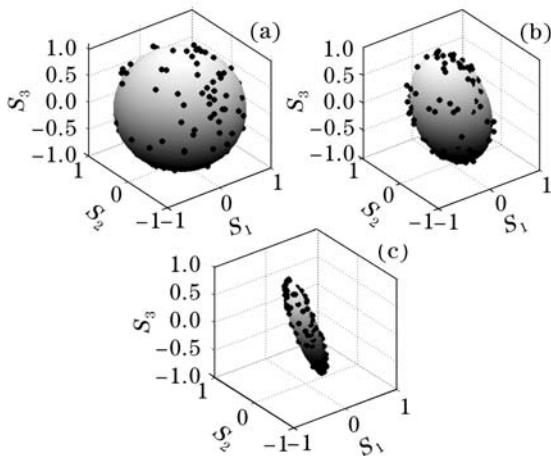


Fig. 4. Data fitting ellipsoid from 100 sampling SOP data using PSO algorithm. (a) DGD = 0 ps, (b) DGD = 4 ps, (c) DGD = 10 ps.

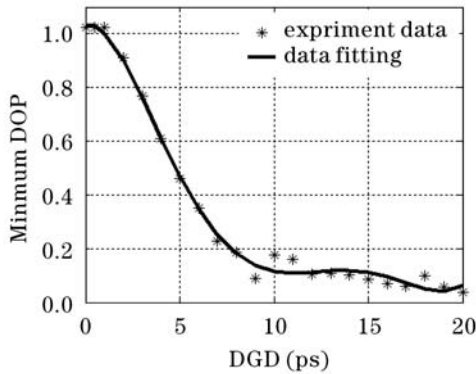


Fig. 5. The length of radius r_{\min} versus DGD.

algorithm is a powerful one to do the job of data fitting with multi adjusting parameters. The whole procedure of getting 100 sampling points and ellipsoid data fitting using PSO algorithm consumed the time within 250 ms.

We also recorded the relationship between the shortest radius of ellipsoid r_{\min} (minimum DOP) and DGD as shown in Fig. 5. It can be seen that, the r_{\min} decreases nearly monotonously with DGD increasing. So it can be used as the feedback or feedforward signal for PMD monitoring.

We have realized the experiment of obtaining DOP ellipsoid by data fitting from less number of sampling using PSO algorithm. By using PSO algorithm the DOP ellipsoid from only 100 samplings with high precision is got. The 100 data sampling and fitting were within 250 ms. The experiment showed that minimum DOP of ellipsoid decreased monotonously with DGD, and direction of ellipsoid orientation was unchanged for the first-order PMD in accordance with the fact that the PSPs of PMD vector kept unchanged.

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