A novel method to calibrate $LiNbO_3$-based polarization controllers

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A fast and reliable method to calibrate $LiNbO_3$-based polarization controllers (PCs) presented theoretically and experimentally. Particle swarm optimization (PSO) algorithm is used as an adaptive searching algorithm. Experimental results show that PSO algorithm is powerful in calibrating $LiNbO_3$-based multistage PCs. Only less than one minute is spent for all stages of the PC to be calibrated thoroughly.

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Polarization controllers (PCs) are vital elements in optical polarization mode dispersion compensators[1], polarization stabilizers[2], polarization multiplexed systems[3], coherent detection systems[4], etc. Lithium niobate ($LiNbO_3$) PC is widely used because of its high response speed (~100 ns). However, because of the characteristics of the waveguide (i.e., dichroism and birefringence) and its surroundings, remaining birefringence exists even if no voltage is applied on the electrodes. This affects the precision in controlling polarization behavior. To precisely control states of polarization (SOPs) in the fiber link and realize reset-free conditions, at least four parameters, namely, the voltage required to transform all power from TE to TM modes V_0, the voltage required to induce π phase shift between TE and TM modes V_π, and the bias voltages required to achieve zero birefringence between TE and TM modes $V_{\rm A,Bias}$, $V_{\rm C,Bias}$, have to be calibrated at each stage. The reference values provided by manufacturers are not trustworthy because these parameters vary with environment. Therefore, calibration must be conducted every time when the PC is switched on. The calibration of the $LiNbO_3$ PC is an important and complicated task. Therefore, a fast and reliable calibration method needs to be established.

In this letter, we present a smart calibration approach by using an adaptive algorithm referred to as the particle swarm optimization (PSO) algorithm. The time spent on calibration for all the stages of the PC is within one minute.

$LiNbO_3$ PC consists of a cascade of (3, 4, 6, or 8) integrated polarization transformer stages, each of which can be electro-optically adjusted at high speed to act as a wave plate with variable thickness and adjustable orientation[5,6]. Figure 1 illustrates the configuration of each of the stages of a $LiNbO_3$ PC. Three electrodes exist in the device.

Taking $V_{\rm B}$ as ground, the voltages applied to electrodes A and C are[7]

$$\begin{aligned} V_{\rm A} &= 2V_0\delta\sin 2\alpha - V_\pi\delta\cos 2\alpha + V_{\rm A,Bias}, \\ V_{\rm C} &= 2V_0\delta\sin 2\alpha + V_\pi\delta\cos 2\alpha + V_{\rm C,Bias}, \end{aligned} \qquad (1)$$

where δ is the desired wave plate retardation (in wavelength), for example, to generate a quarter-wave plate, $\delta = 1/4$; and α is the orientation of the wave plate (in radian). The reference values for the four parameters ($V_{\rm A,Bias}$, $V_{\rm C,Bias}$, V_0, and V_π) were presented by the manufacturer, but these are not accurate because the parameters change with the surrounding environment. Calibration is needed every time the PC is switched on. In turn, the right combination of the four parameters for each stage is difficult to obtain because these parameters do not undergo convergence monotonously. In this letter, we propose a fast and reliable calibration method.

The proposed calibration approach is based on the principle: when the orientation angle α of a perfectly separated half wave plate (HWP) changes from 0 to π, the trajectory of the output SOPs on the Poincaré sphere with any input fixed SOP is two horizontal coincident rings along the latitude[8]. We now consider what occurs when we use multi-stage $LiNbO_3$ PC instead of a single one.

By taking a four-stage PC as an example, and choosing one from all stages as a HWP (i.e., the other stages are without any actions), we let the orientation angle α of the chosen HWP vary from 0 to π. The trajectory of the output SOPs on the Poincaré sphere with any input fixed SOP was observed. Then, by taking any polarized light as the input SOP, we calculated the transmission matrix of the PC for different cases. Finally, the output results on the Poincaré sphere were simulated. Four cases were generated, as listed below.

1) Any of all stages of the PC was with exact calibration and without remaining birefringence. The output SOPs draw two horizontal coincident rings along the latitude on the Poincaré sphere (Fig. 2(a)). This is consistent with what was mentioned earlier for a perfectly separated HWP.

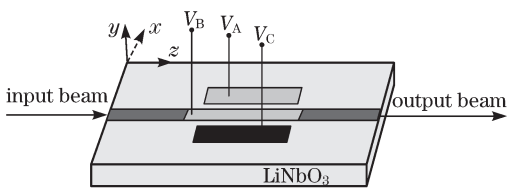

Fig. 1. Configuration of each stage of a $LiNbO_3$-based PC.

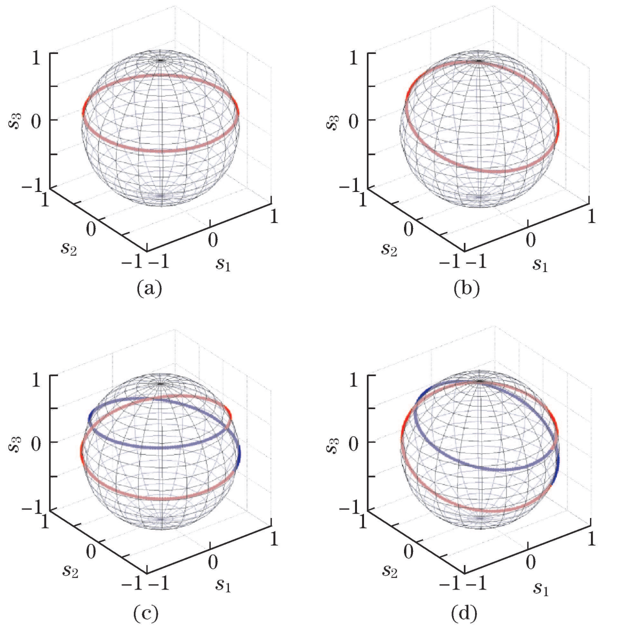

Fig. 2. Output SOPs by rotating α from 0 to π with different cases of remaining birefringence. (a) All stages without remaining birefringence; (b) only the chosen one wave plate without remaining birefringence; (c) only the chosen one wave plate with remaining birefringence; (d) all stages with remaining birefringence.

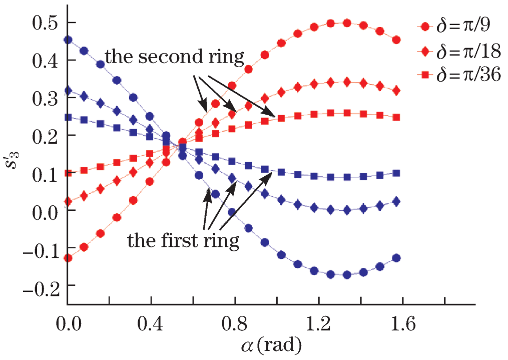

Fig. 3. Relationship between the output s_3' and orientation angle α for different remaining birefringence values.

2) The wave plate chosen as the HWP was calibrated exactly. However, one of the other wave plates was not calibrated and showed remaining birefringence. The output SOPs also draw two coincident rings (Fig. 2(b)). The only difference between cases 1) and 2) is whether the two coincident rings lay along the latitude. If birefringence remains in any of the other wave plates, the rings are inclined with the horizontal plane, and the inclined angle increases with the remaining birefringence δ.

3) The chosen wave plate was not calibrated and had remaining birefringence, whereas the other wave plates were exactly calibrated. Figure 2(c) shows that the output SOPs draw two separated rings.

4) All the wave plates were not calibrated exactly. The output SOPs draw two tilted and separated rings (Fig. 2(d)).

Figure 2 shows that if the chosen HWP is calibrated, the two output SOP rings become coincident with each other whether or not the other wave plates are calibrated; that is, the calibration of one wave plate is independent of that of the others. Thus, the wave plate can be calibrated separately from the first to the last.

The relationship between the separation distance of the two rings and the remaining birefringence were also simulated (Fig. 3). The separation distance between the two rings depends directly on the remaining birefringence. The less the remaining birefringence is, the closer the two rings are. If we label the SOP points of two rings on the Poincaré sphere as P_1, $\cdots$, P_N, P_{N+1}, $\cdots$, P_{2N}, the calibration problem can be summarized as a mathematic problem for finding the global minimum:

$$\underset{V_{\mathrm{A,Bias}},V_{\mathrm{C,Bias}},V_0,V_\pi}{\mathrm{MIN}} \sum_{i=1}^{N} (\text{distance between } P_{N+i} \text{ and } P_i)^2, \qquad (2)$$

indicating that the two rings are positioned as close as possible by adjusting $V_{\mathrm{A,Bias}}$, $V_{\mathrm{C,Bias}}$, V_0, and V_π. Therefore, the problem of calibration is transformed into the problem of searching for the global minimum of the function (2) in the four-dimensional space (by adjusting the parameters of $V_{\mathrm{A,Bias}}$, $V_{\mathrm{C,Bias}}$, V_0, and V_π).

PSO algorithm is very effective in solving global optimization for multi-dimensional problems[9], and is also reliable in polarization mode dispersion compensation[1] and polarization stabilization[2]. In this letter, we used PSO as the searching algorithm to realize the calibration of the $LiNbO_3$ PC.

The experimental setup is shown in Fig. 4. The light

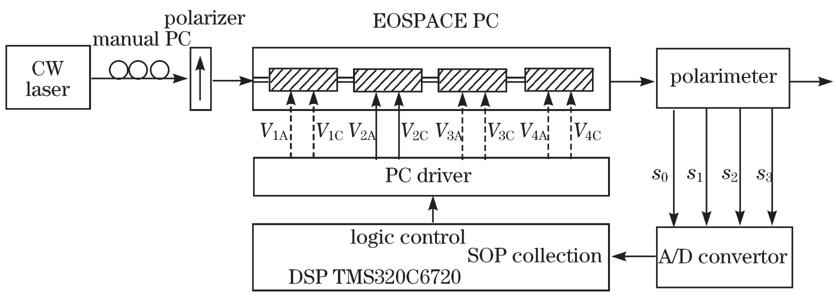

Fig. 4. Experimental setup.

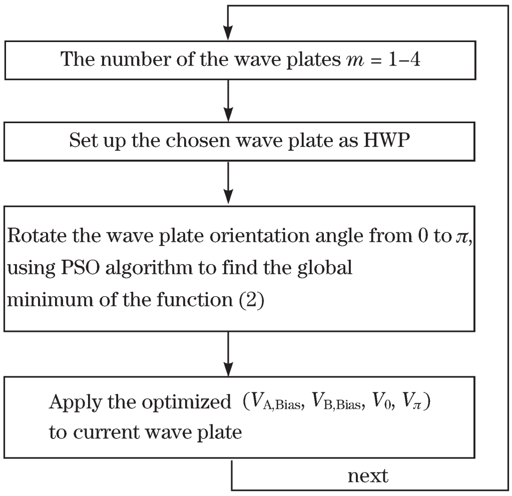

Fig. 5. Flow chart of the calibration.

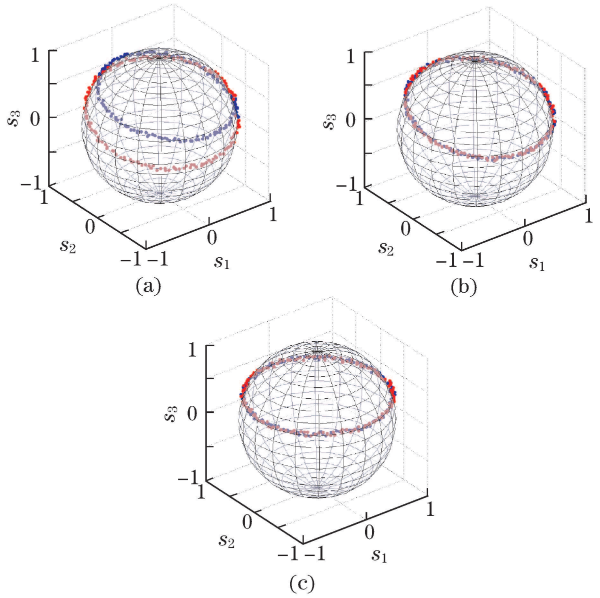

Fig. 6. Experimental output SOPs of PC by rotating α from 0 to π with different cases of remaining birefringence. (a) All wave plates are uncalibrated; (b) the first wave plate is calibrated; (c) all wave plates are calibrated.

from the continuous wave (CW) laser was polarized to generate a linearly polarized light and then fed into the EOSPACE $LiNbO_3$ PC (EOSPACE, USA) with four wave plates. An online polarimeter (PolaDetect^{TM}, General Photonics Co., USA) was used to measure the output SOPs. The digital signal processing (DSP) board (TMS320C6720) collected the output SOPs through an analog-to-digital (A/D) convertor, employed the PSO algorithm, and controlled the PC. This configuration formed a feedback loop that completed the calibration of the polarization controller based on the function (2).

The entire procedure on using the PSO algorithm for the calibration is shown in Fig. 5. The experimental results are shown in Fig. 6. The first wave plate was taken as a HWP, and α varied from 0 to π. Initially, not only the first wave plate was uncalibrated, but the other wave plates as well. The output SOPs form two separated and tilted rings on the Poincaré sphere (Fig. 6(a)). Results from using PSO as the searching algorithm to calibrate the first wave plate show that the two output rings nearly coincide with each other but remain tilted (Fig. 6(b)). This suggests that the first wave plate is already approximately calibrated, whereas the other wave plates still manifest remaining birefringence. In turn, by calibrating every wave plate, we finally obtained two nearly coinciding and horizontal rings (Fig. 6(c)), indicating that the calibration of all four wave plates within the range of deviation was completed. The entire process only requires less than one minute.

In conclusion, based on theoretical analysis and using the PSO algorithm, a fast and reliable calibration approach for $LiNbO_3$-based PCs is established. The entire calibrating process only takes less than one minute. Experimental results show that the PSO algorithm is powerful in calibrating multi-stage $LiNbO_3$ PCs.

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