Endless polarization stabilization control for optical communication systems

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An endless polarization stabilization control system is proposed in this letter. The system is independent of transmission data rate and modulation format, and it does not need high-speed circuit to track fast polarization change. Adaptive inertia weight particle swarm optimization algorithm is used and the effectiveness of polarization stabilization control is experimentally verified.

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High-speed optical fiber communication system is needed to keep up with the continuous increasing Internet traffic, which is growing at ~2 dB/year[1]. Digital coherent receiver, polarization division multiplexing (PDM), and high-order modulation formats are attractive choices to increase capacity[2–4]. State of polarization (SOP) of optical signal varies due to fiber asymmetry, distortion, and temperature drift. These factors are harmful to attempts to increase capacity. The digital coherent system can reduce polarization-related signal impairment by applying algorithm in electrical domain[5] and has broad business prospects, but it needs high-speed analog-to-digital converter (ADC). Most studies of it focus on off-line data processing and low-speed real-time implementation. Owing to random fluctuation of SOP, two orthogonally polarized channels in PDM system influence each other and polarization stabilization control is required before demultiplexing[6]. There are two popular schemes realizing polarization stabilization in optical fields. One scheme is based on direct tracking and detection of polarization and is mainly composed of polarization controller (PC), polarization beam splitter (PBS), photodiode (PD), ADC, digital-to-analog converter (DAC), and field programmable gate array (FPGA) based controller[7–9]. The application of this scheme is limited because it is sensitive to data rate and modulation formats of communication system. The other one is based on SOP detection and comprises PC, polarimeter, and digital signal processor (DSP)-based controller[10,11]; however, it cannot track fast polarization change limited by bandwidth of polarimeter.

A modified scheme based on direct tracking and detection of polarization is proposed in this letter. The scheme is independent of data rate and capable of tracking fast polarization change, most importantly, high-speed ADC is not required. Architecture and detailed theory, experimental configuration, and results of this scheme are given.

Figure 1 shows the design of polarization stabilization control system. In this scheme, we choose a commercially available lithium niobate PC to control the SOP of the
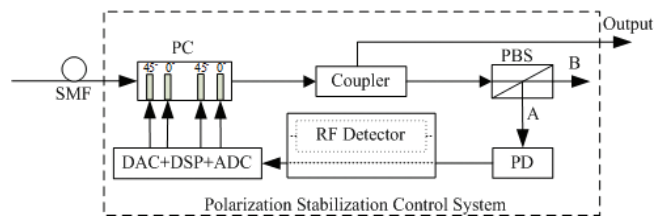

Fig. 1. Block diagram of polarization stabilization control system.

input optical signal. A PBS isolates two orthogonal polarizations, and the optical signal of port A is detected and used as feedback signal.

The optical fiber induces arbitrary, time-varying polarization rotations, and the effect of fiber on optical signal matrix can be expressed as Jones matrix[12]:

$$T = \begin{bmatrix} \cos\theta(t)\cos\varepsilon(t) - j\sin\theta(t)\sin\varepsilon(t) & -\sin\theta(t)\cos\varepsilon(t) + j\cos\theta(t)\sin\varepsilon(t) \\ \sin\theta(t)\cos\varepsilon(t) + j\cos\theta(t)\sin\varepsilon(t) & \cos\theta(t)\cos\varepsilon(t) + j\sin\theta(t)\sin\varepsilon(t) \end{bmatrix}, (1)$$

where $\theta(\tau)$ and $\varepsilon(\tau)$ are the angles corresponding to the s-SOP's azimuth and ellipticity, and they present random azimuth and ellipticity rotations of optical signal caused by optical fiber, respectively. They take values in the intervals $|\theta(t)| \leq \pi/2$　$|\varepsilon(t)| \leq \pi/4$.

The signal coming into PC is expressed as

$$E_{\text{out}} = T \cdot \begin{bmatrix} E_x e^{j[\omega_c t + \varphi_x(t)]} \\ E_y e^{j[\omega_c t + \varphi_y(t)]} \end{bmatrix}, \quad (2)$$

where E_x and E_y are the amplitudes of the optical field, ω_c is the angular frequency of continuous wave (CW) laser carrier, and $\varphi_x(t)$ and $\varphi_y(t)$ are the respective phases.

If laser source is linearly polarized, the optical signal is fed into a PBS and the signal of port A can be presented as

$$AE_x e^{j[\omega_c t + \varphi_x(t)]} + BE_y e^{j[\omega_c t + \varphi_y(t)]}, \quad (3)$$

$$\begin{cases} A = \cos\theta(t)\cos\varepsilon(t) + j\sin\theta(t)\sin\varepsilon(t) \\ B = -\sin\theta(t)\cos\varepsilon(t) + j\cos\theta(t)\sin\varepsilon(t) \end{cases}. \quad (4)$$

The power spectrum of the photocurrent obtained by PD can be defined as[7]

$$S(\omega) = \int_{-\infty}^{\infty} R(\tau)e^{-j\omega\tau}\,\mathrm{d}\tau \approx \int_{-\infty}^{\infty} \sigma^2 G_E^{(2)}(\tau)e^{-j\omega\tau}\,\mathrm{d}\tau$$

$$= \sigma^2 \left\{ \left[A^4 + B^4 + AB\cos(w_c\tau_0)e^{-\gamma\tau_0} \right] S_M(\omega) + \right.$$

$$\left. 2A^2B^2 e^{-2\gamma\tau_0} S_M(\omega) \otimes S_M(\omega) \otimes S_c(\omega) + A^2B^2\pi\delta(\omega) \right\}, \quad (5)$$

where $R(\tau)$ is the autocorrelation of photocurrent, $G_E^{(2)}(\tau)$ is the second-order correlation function, σ is the detector quantum sensitivity, τ_0 represents relative delay between two orthogonal polarizations, 2γ is the laser linewidth, $\otimes$ expresses convolution, $S_c(\omega)$ is the frequency component generated by mutual interference between X and Y polarization components, and $S_M(\omega)$ is the spectrum of the modulation envelop. For simplicity, we take non-return-to-zero on–off keying (NRZ-OOK) modulation as an example in the analysis, and the other modulation format has similar characteristics[13]. The spectrum $S_M(\omega)$ can be expressed as

$$S_M(\omega) = \frac{1}{2}\pi\delta(\omega) + \frac{1}{4}T\,\mathrm{sinc}^2\left(\frac{\omega T}{2\pi}\right), \quad (6)$$

and $S_c(\omega)$ is shorted for

$$S_c(\omega) = 4\pi\cos^2(\omega_0\tau_0)\delta(\omega) + \frac{8\gamma}{(2\gamma)^2 + \omega^2}\left\{ch(2\gamma\tau_0) - \cos(\omega\tau_0) + \right.$$

$$\left. \cos^2(\omega_0\tau_0)\left[\cos(\omega\tau_0) - e^{-2\gamma\tau_0} - \frac{\sin(\omega\tau_0)2\gamma}{\omega}\right]\right\}. \quad (7)$$

According to Eq. (5), the power spectrum of the photocurrent is closely related to $\theta(t)$ and $\varepsilon(t)$, in another words, it is connected with the SOP of input signal of the PBS.

In Fig. 2, θ and ε represent real-time azimuth and ellipticity of PBS's input signal, respectively, and they carry full polarization information. We can get fixed output polarization when θ and ε are stable[9]. From Fig. 2 the output power is minimum when $\theta = 0°$, $\varepsilon = 0°$ or $\theta = 90°$, $\varepsilon = 0°$, so we can control two degrees of freedom by continually adjusting the control voltages of PC to minimize the power and get stable output polarization.

According to the analysis, if the input signal of the polarization stabilization control system is NRZ phase shift keying (PSK) modulation format, the output of PD will have a constant value when the PBS's input SOP is stable. The output of PD changes with the PBS's input SOP, and it is a low-frequency signal. If the optical signal is OOK modulation format, the output of PD will be a high-frequency signal, and a radio frequency (RF) detector is needed to measure the RF power that changes with SOP of the optical signal. Different configurations of polarization stabilization control system can be selected easily according to application.
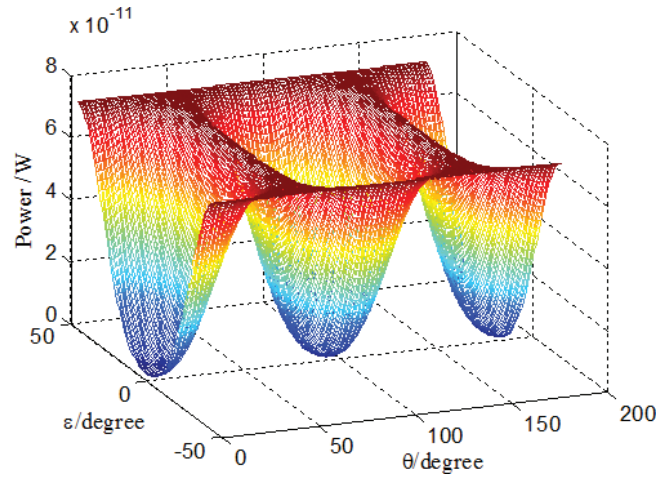

Fig. 2. Relationship between power spectrum on frequency and θ–ε.

Figure 3 shows the experimental setup for the polarization stabilization control system. The CW is modulated with 10 and 20 Gb/s pseudo random binary sequences (PRBS) to generate NRZ-OOK and NRZ-PSK signals respectively. A polarization scrambler is used here to generate polarization-scrambled signal of the modulated laser source, and the scan rate of scrambler is adjustable. Here we show polarization control for tracking polarization changes at up to 1 krad/s.

The PC is configured as two waveplates with 45° orientation angle and two waveplates with 0° orientation angle, and the driven voltages of each plate take values in the interval [−47,+47] V. The output signal of PC is split into two branches by a 3 dB coupler. The online polarimeter measures the SOPs of output optical signal and stores it in Stokes vectors as (s_1, s_2, s_3). The output optical signal of one PBS port is firstly converted to electrical signal by a 10 GHz PD. If the modulated signal is OOK format, the signal will be detected by a RF detector that has a wide input frequency range from dc to 6 GHz. The output of RF detector is a low-frequency signal, and it will be converted to digital signal. If the modulated signal is PSK format, the RF detector is not needed here and the output electrical signal of PD will be converted to digital signal directly. The digital signal is sent to DSP that executes search algorithm to control PC.

Search algorithm, which runs in the DSP-based controller, is a key factor to realize polarization stabilization control. In this letter, we proposed adaptive inertia weight particle swarm optimization (AIWPSO)
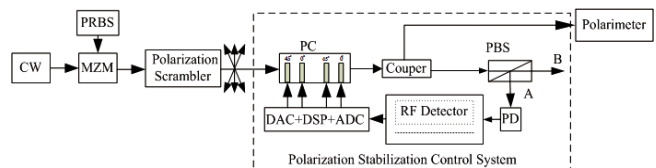

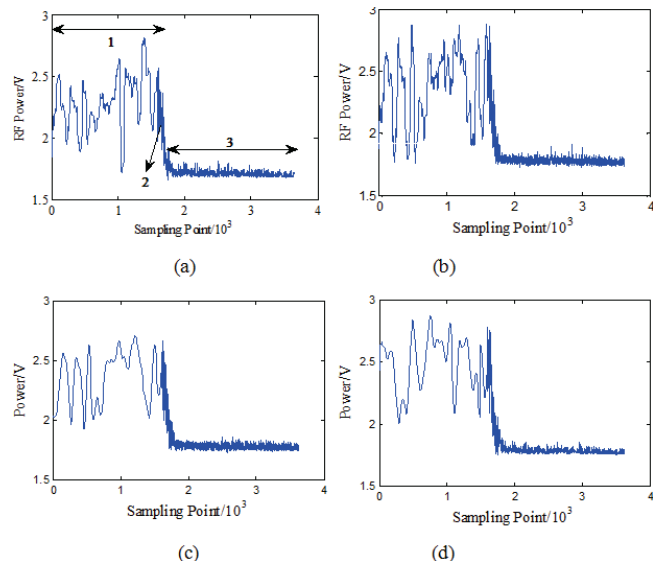Fig. 3. Experimental setup for the polarization stabilization system.

Fig. 4. Feedback signal real-time display when the input signal of polarization stabilization control system is (a) 10 and (b) 20 Gb/s NRZ-OOK format and (c) 10 and (d) 20 Gb/s NRZ-PSK format.

algorithm to polarization stabilization control system. It is a kind of modified particle swarm optimization (PSO) algorithm. Traditional PSO algorithm is few in parameters and easy in implementation, but has shortcomings of weak search ability and long convergence time. AIWPSO proposed in this letter can update search scope adaptively according to current feedback signal, which helps to reduce the average number of iterations and time cost compared with the traditional PSO algorithm.

Polarization scrambler is executed to generate random polarization state and run the AIWPSO algorithm; the feedback signal is stored in the DSP. When the algorithm achieves convergence, the DSP will export the feedback signal.

To verify the performance of polarization stabilization control system, we applied signals with different kinds of modulation formats and data rates. Figure 4 shows the real-time feedback signal. In the first stage, the detected feedback signal is arbitrary without feedback control. The search algorithm switched on in the second stage, and the feedback signal fully reaches the global minimum after several iterations.

Figure 5 shows the SOP tracking on Poincare ball. The SOPs are arbitrary corresponding to stage 1 in Fig. 4 before polarization stabilization control. AIWPSO algorithm adjusts the control voltages of PC according to current feedback signal, and the SOPs stabilize when the feedback signal reaches global minimum just as stage 3 in Fig. 4. Under the condition of our experiment, the polarization will be stable near the point of (1,0,0) after the algorithm reaches convergence; however, the precision of output SOP decreases because of system noise.

We have 50 tests using AIWPSO and traditional PSO algorithms, and Fig. 6 shows the number of iterations. From Fig.6 AIWPSO has less iterations to reach convergence than traditional PSO algorithm. The average number of iterations of AIWPSO is 87.8 and that of the traditional PSO algorithm is about 106.6. Thus, AIWPSO helps to reduce iterations and time cost in this polarization stabilization control system.

In conclusion, a polarization stabilization control system that can be applied to various modulation formats is presented. We test experimentally the real-time feed-
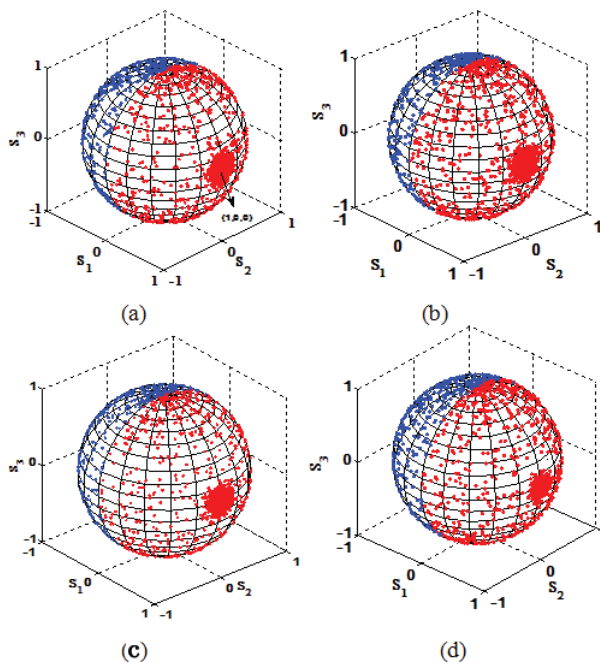

Fig. 5. SOPs tracking when the input signal of polarization stabilization control system is (a) 10 and (b) 20 Gb/s NRZ-OOK format and (c) 10 and (d) 20 Gb/s NRZ-PSK format.
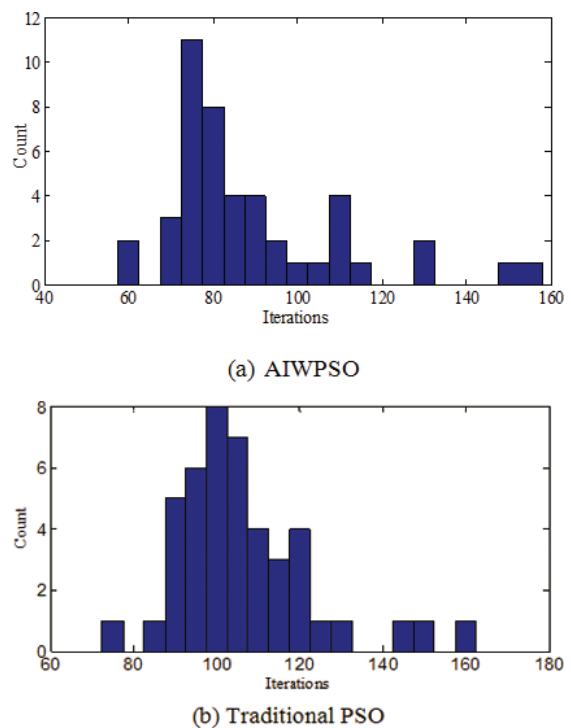

(a) AIWPSO

(b) Traditional PSO

Fig. 6. Number of iterations of AIWPSO and traditional PSO algorithms.

back signal and the tracking of SOPs on Poincare ball, under the existing conditions of our laboratory. The feedback signal maintains the minimum and the SOP of PBS's input is stable when the SOP of input optical signal is random. We apply modified AIWPSO algorithm in system, and it presents less iterations than the traditional one.

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