A polarization stabilizer up to 12.6 krad/s with an additional function of stable state of polarization transformation*

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(Received 23 April 2009; revised manuscript received 22 July 2009)

This paper reports on an experiment about a novel method of polarization stabilization. The polarization stabilizer proposed here has an additional function of polarization transformation from any state of polarization into any others. The particle swarm optimization is introduced as a control algorithm in the process of either searching or endless tracking. The tracking speed of the stabilizer is obtained up to 12.6 krad/s by using hardware we have in the laboratory, which means that we can achieve a higher speed practical polarization stabilizer if we have faster hardware.

Keywords: state of polarization, stabilization, optical fibre communications

PACC: 4281, 4225J, 4281F

1. Introduction

The state of polarization (SOP) of an optical signal in a fibre varies randomly (some time beyond 200 rad/s) due to the vibrations induced by passing trains (for buried fibres) or by strong wind (for aerial fibres),[1] or due to the change of polarization mode dispersion in fibres.[2−4] This phenomenon could be harmful to the coherent detection of multi-state per symbol optical modulation formats, the process of de-multiplexing in the optical polarization multiplexing system. The realization of adaptive SOP control and the stabilization of signals is an important and challenging issue in the field of optical fibre communications. SOP stabilization can be traced back to 1979,[5] and from then on lots of studies on it have been reported.[2−13] Reference [11] proposed an SOP stabilization approach, which can track up to 7 krad/s SOP change, by using a control system comprised of a Soleil–Babinet compensator. Reference [12] also proposed an FPGA-based SOP stabilizer with a speed of 9 krad/s. In the present paper, we propose a new endless SOP stabilization method based on a smart particle swarm optimization (PSO) control algorithm. The polarization fluctuations are produced by varying frequencies and phase amplitudes produced by a polarization scrambler. With the hardware in our laboratory, the SOP stabilizations can be realized up to 8 kHz $\pi/2$ scramble signals (equivalent to a 12.6-krad/s SOP change). Furthermore, using this approach we can choose any output stabilized SOP we want, such as (1,0,0), (0,1,0), or (0,0,1), etc., whatever the input SOP is. So a system based on this approach can play a role as a polarization stabilizer or a stable SOP transformer.

2. Experimental setup and principle

2.1. Experimental setup

Figure 1 illustrates the experimental setup of our SOP stabilizer. A laser diode (LD) generates a CW laser light beam, and the light is fed into a polarizer to output a linearly polarized light. A scrambler makes the light have a sinusoidal time-varying SOP. The polarization stabilizer in the dash frame has a polariza-

*Project supported by the National High Technology Research and Development Program of China (Grant No. 2009AA01Z224), and Huawei Technology Project, China (Grant No. YBON2008014).

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tion controller (PC), controlled via three voltages (V_1, V_2, V_3)[14] through a computer according to the information on the output lightwave collected by an in-line polarimeter.

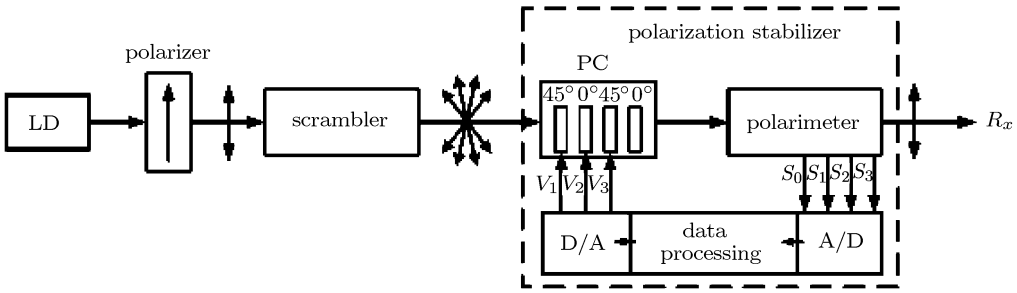


Fig. 1. Experimental setup for the polarization stabilizer.

2.2. Principle of the polarization stabilizer

The principle of the polarization stabilization and the stable SOP transformer are as follows. Let the stable output SOP we want be denoted by (S_1, S_2, S_3). We design a special objective function $F((S_1 - S_1')^2$, $(S_2 - S_2')^2$, $(S_3 - S_3')^2)$ with only a single maximum or minimum point in a region of any variable, where (S_1', S_2', S_3') is the SOP real-time detected by the polarimeter (PolaDetect™, General Photonics Co.). Through searching or adjusting (V_1, V_2, V_3) by a smart algorithm, we find the case where as $S_1' = S_1$, $S_2' = S_2$, and $S_3' = S_3$, the function reaches and keeps track at its maximum or minimum (in this experiment, we design a function which has a single maximum at $S_1' = S_1$, $S_2' = S_2$, $S_3' = S_3$). Therefore SOP stabilization is achieved. The procedure described above can be mathematically denoted as

$$\underset{V_1,V_2,V_3}{\text{MAX}} F\left((S_1 - S_1')^2, (S_2 - S_2')^2, (S_3 - S_3')^2\right). \quad (1)$$

In our previous work,[15−17] we introduced for the first time the particle swarm optimization (PSO) into PMD compensation, which showed the powerful ability to achieve PMD compensation.[18] In the present paper, we introduce again a PSO algorithm into SOP stabilization, which also shows its effectiveness.

The procedure of the polarization stabilization includes two stages. At the beginning the searching process searches for the desired (S_1, S_2, S_3) SOP from any input SOP in a short time. Then the tracking process will endlessly keep track in the searched SOP all the time afterwards. These two process steps of searching and tracking are both controlled by algorithms including different kinds of PSOs in the two stages of the whole control processing algorithm.

2.3. Selection of the objective function and the searching and tracking algorithms by using PSO

The objective function selected must have the following features. (i) The function has only one single maximum (or minimum) in the whole searching space, the maximum point locates in a relatively small region compared with the lower level values in other regions, for trapping the stabilized SOP point (S_1, S_2, S_3) in this region without escaping out of the region. (ii) The function is so designed that the searching algorithm can converge to the maximum (or minimum) quickly.

We select the objective function as follows:

$$y = \exp\left(\frac{1}{\alpha(S_1 - S_1')^2 + \beta(S_2 - S_2')^2 + \gamma(S_3 - S_3')^2 + \delta}\right), \quad (2)$$

where α, β, γ, and δ are adjustable parameters. The parameter δ determines the lower level value of the function y, and parameters α, β, γ adjust the shape of the convex shaped peak shown in Figs. 2 and 3, where $\Delta S_i = S_i - S_i'$. Because we can draw only three-dimensional (3D) figures, the surfaces of y only as a function of

ΔS_1 and ΔS_2 are shown in the following figures, with ΔS_3 omitted. We can see in Fig. 2 that, with parameter δ fixed, the larger the parameters α, β, γ are, the sharper the peak will be. With parameters α, β and γ fixed, the larger the parameter δ is, the broader the peak will be. For a broader shaped peak, it is easy to use an algorithm to find the maximum location accurately, but difficult to track the maximum location. For a sharper shaped peak, it is easy to track the maximum location, but difficult to find the exact maximum location (for the PSO algorithm used in this case, the particles will collide back and forth with the sharp wall of the peak, and so the top of the peak cannot be found). The two extreme cases of the objective functions are not suitable for polarization stabilization. With the comprehensive consideration according to the features mentioned above we choose the parameters $\alpha = \beta = \gamma = 5$, and $\delta = 1$, separately as shown in Fig. 4.

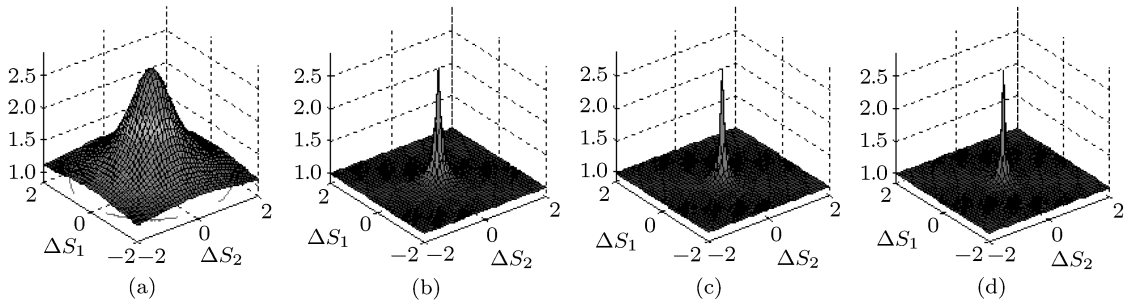


Fig. 2. Features of objective function y with $\delta = 1$, and $\alpha = \beta = 1$ (a), 51 (b), 101 (c), and 151 (d).

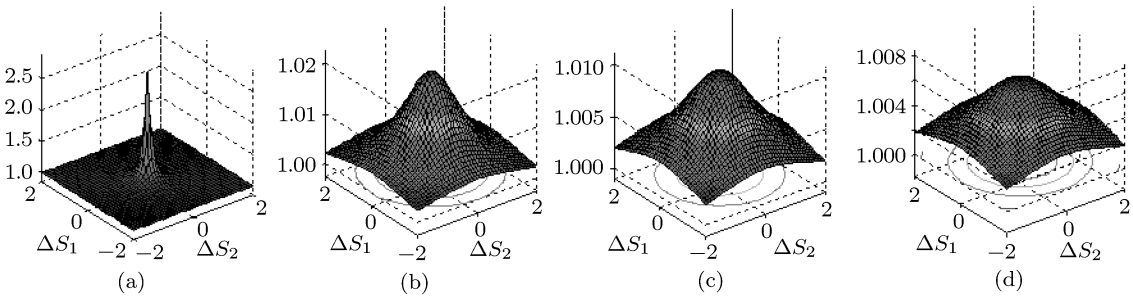


Fig. 3. Features of objective function y with $\alpha = \beta = 50$, and $\delta = 1$ (a), 51 (b), 101 (c), and 151 (d).

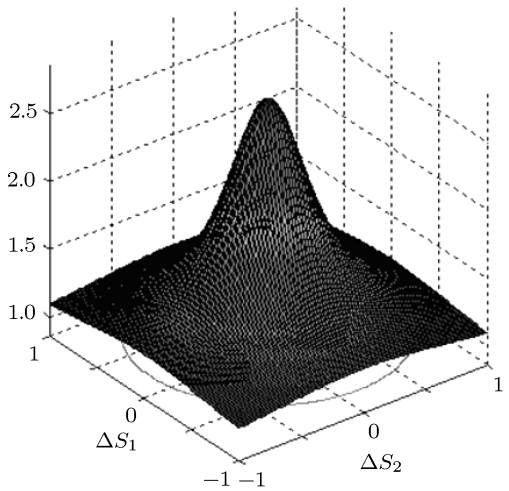


Fig. 4. Features of objective function y with optimum parameters $\alpha = \beta = 5$ and $\delta = 1$.

The PSO algorithm, proposed by Kennedy and Eberhart[19] has proved to be very effective in solving global optimization for multi-dimensional problems in static, noisy, and continuously changing environments.[20] At the beginning, the PSO algorithm randomly initializes a population (called a swarm) of individuals (called particles). Each particle represents a single intersection of D-dimensional hyperspace. The position of the i-th particle is represented by the position vector $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$. In the $3D$-DOF polarization stabilization scheme depicted in Fig. 1, the components of the i-th particle are represented by a combination of 3 voltages (V_1, V_2, V_3). The particles evaluate their position relative to a goal at every iteration. In each iteration every particle adjusts its trajectory by its velocity $V_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$ toward its own previous best

position denoted by *pbest*, and toward the previous best position attained by any member of its topological neighbourhood denoted by *gbest*. If any particle position is close enough to the objective function, it is considered that the global optimum has been found and the recurrence is ended, which means that the process of searching for the desired SOP (S_1, S_2, S_3) is completed.

The process for implementing the PSO is as follows.[21]

1) Initialize a population (array) of particles with random positions and velocities in D-dimensional space.

2) For each particle, evaluate the desired optimization fitness function in D variables.

3) Compare the particle's fitness evaluation with the particle's *pbest*. If the current value is better than *pbest*, then set the *pbest* value to be equal to the current value, and the *pbest* location is equal to the current location in D-dimensional space.

4) Compare the fitness evaluation with the population's overall previous best. If the current value is better than *gbest*, then reset *gbest* to be the current particle's array index and value.

5) Change the velocity and position of the i-th particle according to the following equations:

$$v_{id} = v_{id} + c_1 \times \text{rand}() \times (pbest_{id} - x_{id}) + c_2 \times \text{rand}() \times (gbest_d - x_{id}), \quad (3)$$

$$x_{id} = x_{id} + v_{id}. \quad (4)$$

6) Loop to step 2) and repeat until a criterion is met.

In expression (3), v_{id} and x_{id} are the velocity component and the current position component of the i-th particle respectively; $pbest_{id}$ and $gbest_{id}$ have been defined previously; constants c_1 and c_2, termed learning rates, determine the relative influence of *pbest* and *gbest*; the rand() generates pseudo random numbers that are uniformly distributed in an interval of [0, 1].

Generally, the larger the number of particles adopted in PSO is, the greater the opportunities to enter into the region where the peak locates will be, but the longer the time spent in searching for the global optimum will be. In our experiment 20 particles are used for searching for the optimum SOP process.

The algorithm for real-time adaptive SOP stabilization should include two stages. First, the searching algorithm finds the global optimum SOP from any initial SOP point. Then the tracking algorithm starts to track the optimum SOP, because the SOP in the real fibre link always randomly changes, due to changes in the environment such as temperature fluctuations, etc., and in our experiment due to the polarization scrambler.

Because of its good performance in the presence of noise, and its multi-dimensional searching capability, we used the PSO searching technique in a smaller $3D$ local space around the previous optimum SOP location to achieve the goal of tracking the changing SOP. After the global optimum search process is completed, the tracking algorithm starts to work according to the deviation of y values from the top value. When the deviation is less than 5% of that obtained for the previous optimum, the algorithm does nothing. Otherwise, as long as the deviation is larger than this criterion, local space searching is initiated. The size of the local searching space is adjusted with time according to the deviation from the criterion value, which is set to be 5%/95%=5.3% for the experiment. For the tracking algorithm, 5 particles were adopted for PSO because of the faster speed needed for tracking the changing SOP and the smaller space where global change takes place.

3. Experiment results

We used a voltage controlled PC as an SOP scrambler, controlled by a voltage of a sinusoidal wave with different frequencies and amplitudes, which made the scrambler generate time-varying SOPs with different phase amplitudes and frequencies. We made the scrambler generate the SOPs with phase amplitudes of $\pi/4$, $\pi/2$, π, and varying frequencies of 1 kHz, 2 kHz, 4 kHz, and 8 kHz, respectively. We aimed to stabilize the output SOP in (1,0,0) on a Poincaré sphere (which represents the horizontal linear polarization).

The procedure of the polarization stabilization includes two stages, i.e. the searching process at the beginning, which searches for the desired (1,0,0) SOP from any input SOP in a short time and the tracking process follows, which endlessly tracks the searched SOP all the time afterwards, as described in Subsection 2.3. Figure 5 shows this procedure. At the beginning, the start SOP output point happened to be located nearly above the S_2 axis. After the searching process, the ending SOP rapidly converged to the point (1,0,0), and kept tracking this SOP afterwards. The experiment also showed that with the hardware

we have, for a phase amplitude $\pi/4$ with varying frequency up to 8 kHz, the standard deviation σ from the stabilized (1,0,0) is less than 0.05, and for time-varying input up to 8 kHz with $\pi/2$ amplitude, σ is less than 0.1. But for a larger phase amplitude π, we cannot achieve SOP stabilization by using the experimental devices we have. The results are shown in Fig. 6.

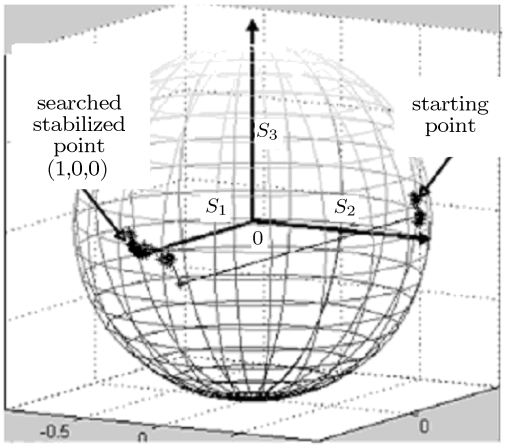


Fig. 5. Procedure of the convergence to (1,0,0) by the searching process.

Figure 7 shows the experimental tracking results of the stabilized SOP (1,0,0) for the input time-varying SOP with $\pi/2$ phase amplitude and varying frequencies 1 kHz, 2 kHz, 4 kHz, and 8 kHz, respectively. The diagrams in the left column of Fig. 7(a) to 7(d) are for the Stokes parameters after stabilization, and the diagram in the right column in Fig. 7(a) to 7(d) are for the corresponding SOP points on the Poincaré sphere. We can see that the effectiveness of SOP tracking stabilization is good enough by our polarization stabilizer.

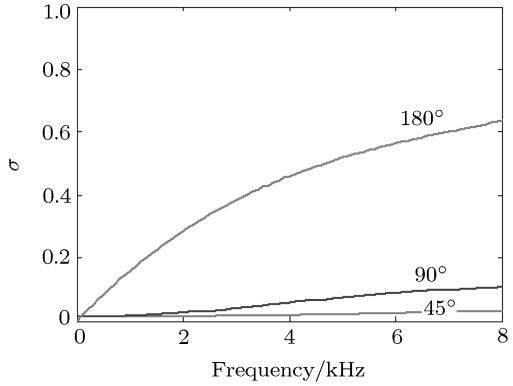
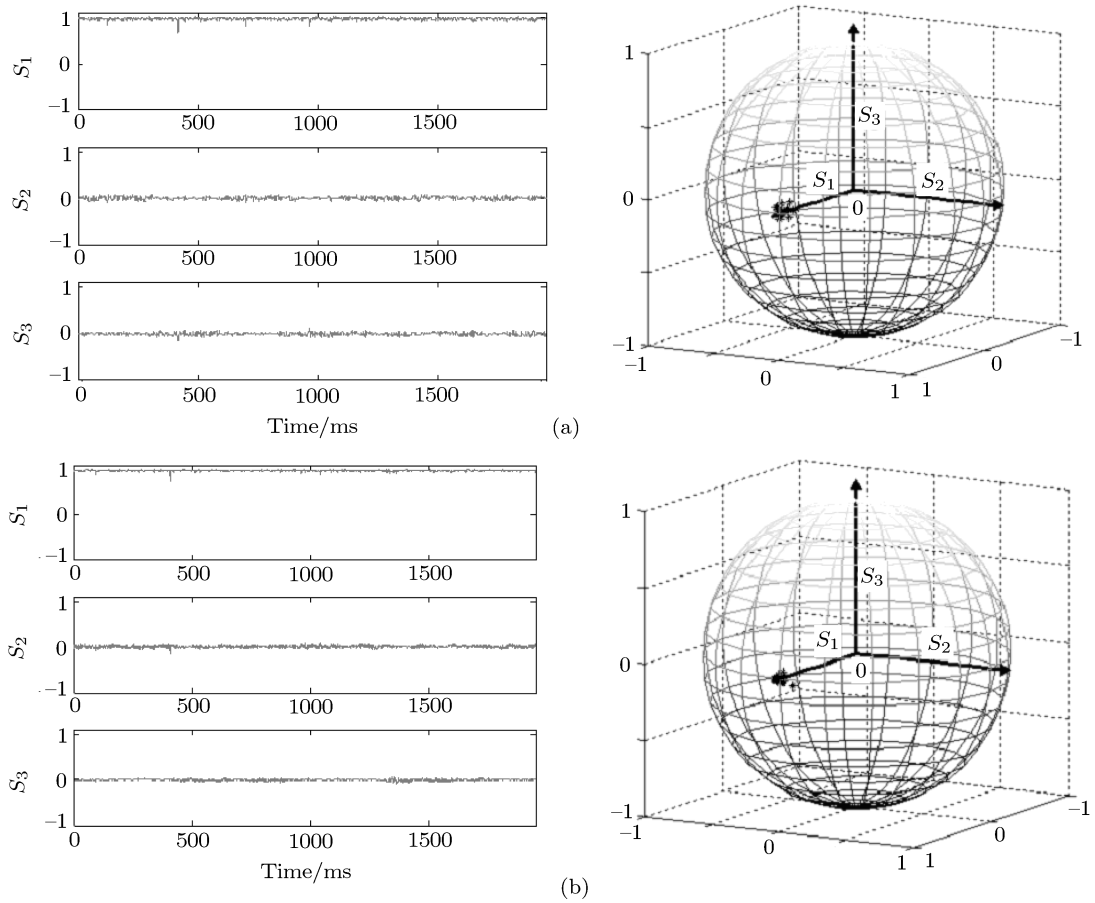


Fig. 6. Standard deviation σ of Stokes parameters, different from the designed output stabilized SOP (1,0,0) versus variation in frequency of input unstable SOPs.



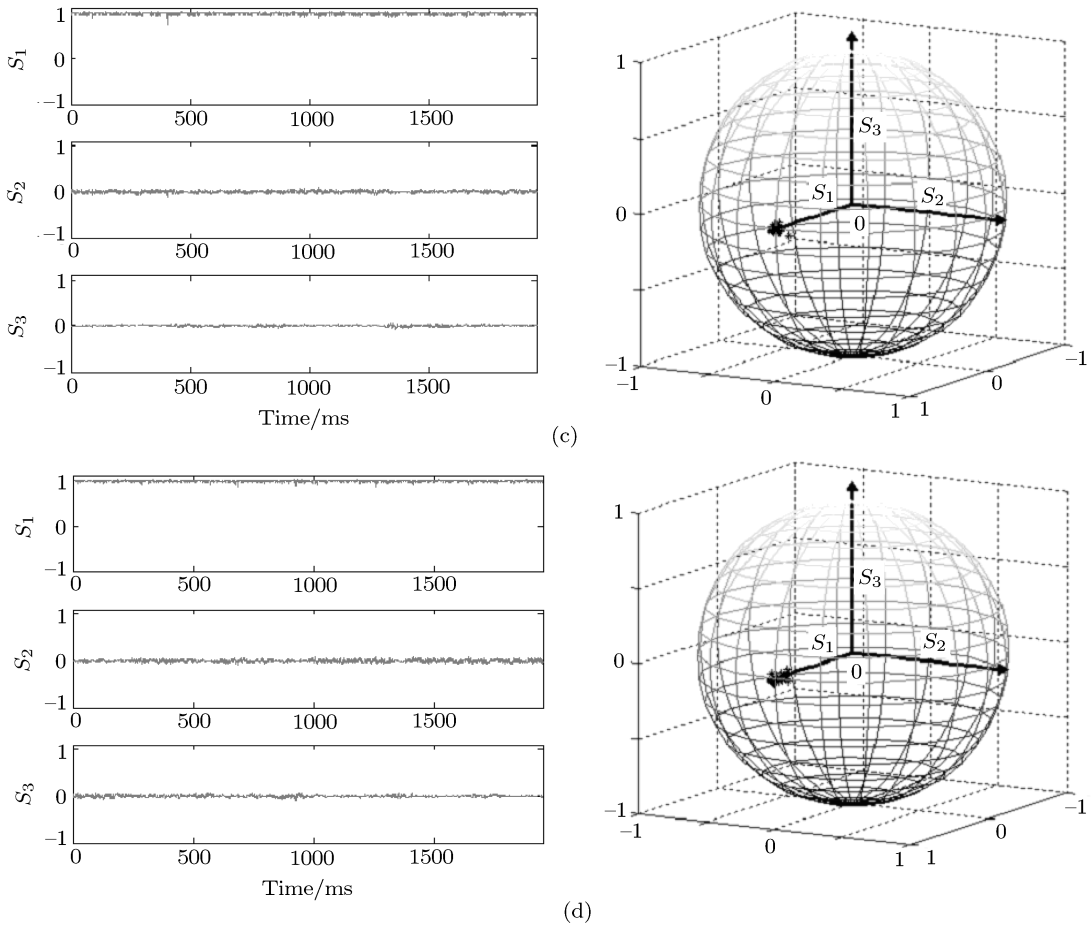


Fig. 7. Stabilized output SOP (1,0,0) shown in Stokes parameter diagrams and corresponding points on the Poincaré sphere when input SOPs have a phase amplitude of $\pi/2$, and variation frequencies of 1 (a), 2 (b), 4 (c), and 8 kHz (d).

If we want to obtain the other stabilized output SOP such as (0,0,1) (right-handed circular polarization), we can only change the parameter (S_1, S_2, S_3) in the objective function $F((S_1 - S_1')^2$, $(S_2 - S_2')^2$, $(S_3 - S_3')^2)$ into (0,0,1) as shown in Fig. 8. Therefore this SOP stabilizer can also act as a stabilized SOP transformer.

We also did an analysis of the time assignment among the processes of the software and the hardware of the polarization stabilizer, shown in Fig. 9. It is shown that the algorithm only occupies

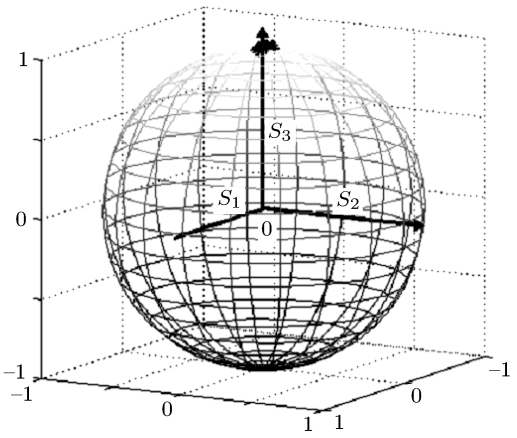


Fig. 8. The stabilized SOP at (0,0,1).

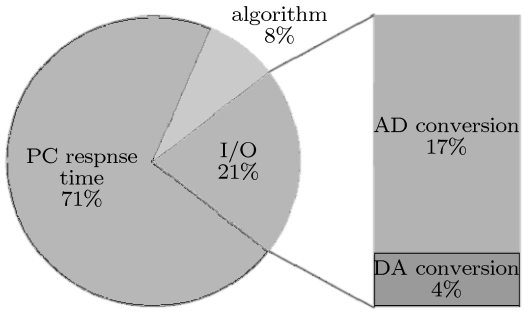


Fig. 9. Analysis of the time-consumming assignment among the processes of the soft- and hardware for the polarization stabilization system.

8% of the total time consumption. The I/O process

including AD/DA conversion and data recording in the computer occupies 21%, and the polarization controller responsible for the SOP transformation task occupies 72%. So the hardware in our experiment is a bottleneck of the speed and effectiveness of the stabilizer. In particular, our PC (PolaRITE™II, General Photonics Co.) has a slower response time, about 100 μs. If we have faster hardware like an EOSPACE PC with a lower response time of < 100 ns but larger insertion loss $\sim$3 dB and faster AD/DA, we can establish an SOP stabilizer capable of tracking more than 12.6 krad/s with the ability to solve larger polarization fluctuation amplitudes of more than π or up to 2π, and achieve a practical polarization stabilizer and transformer. That is our planned follow-up work.

4. Conclusion

A novel polarization stabilizer with an additional function of SOP transformation is established, which has the ability to stabilize up to 12.6 krad/s fast endless SOP changes together with SOP transformation, under the hardware we have. If our hardware was replaced by faster devices, we could achieve a practical polarization stabilizer/transformer.

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