*Indian J Phys*
https://doi.org/10.1007/s12648-024-03342-w

ORIGINAL PAPER

# Active polarization controlling in optical fiber links using optimization algorithms

**H Asgari, M Khodabandeh, S Hajibaba, A H Dadahkhani and S A Madani***

Quantum Communication Group, Iranian Center for Quantum Technologies (ICQTs), Tehran, Iran

Received: 15 April 2024 / Accepted: 05 July 2024

**Abstract:** Maintaining the state of polarization of a light beam in optical fiber links is a necessity for various applications. It is especially important for optical communication, polarization-based quantum key distribution, etc. There are several ways to compensate for polarization fluctuations, hence lowering the polarization drift error. In this paper, we have experimentally investigated the performance of two optimization algorithms for polarization compensation. We employed these algorithms to control an electrical polarization controller. Our results show that the particle swarm optimization and simulated annealing algorithms can efficiently compensate for polarization fluctuations and drifts. Thus, it is suitable for optical communication and quantum key distribution experiments.

**Keyword:** Polarization controlling; Polarization compensation; Optical fiber links; Optimization algorithms

## 1. Introduction

Maintaining the state of polarization (SOP) of a light beam along the optical fiber is one of the main challenges in polarization-dependent systems such as fiber-based polarization quantum key distribution (QKD) [1–9], fiber-based optical coherence tomography (OCT) [10–12], and optical communication [13–16]. This is important because as light travels through fiber, its SOP changes due to internal defects and birefringence. The ambient conditions, such as temperature, pressure, and vibrations, can also change the SOP [17–19].

These fluctuations and drifts play a vital role in optical communication. Therefore, one can decrease the polarization drift by controlling the polarization [20–22]. Various techniques are employed to maintain SOP to overcome this challenge, such as using polarization-maintaining fibers, polarization controllers, and feedback control systems [23–25]. Polarization-maintaining fibers are designed to maintain the certain SOP of light traveling through them. Polarization controllers are used to adjust the SOP of the light before it enters the fiber or at various points along the path. This helps to ensure that the SOP is maintained throughout the entire transmission. Feedback control systems use real-time monitoring of the SOP and adjust the polarization controller as needed to maintain the desired SOP. This technique is beneficial in long-distance QKD systems where the SOP can change significantly due to environmental fluctuations. A polarization controller instrument can be used to compensate for the polarization misalignment using passive or active elements [26–28]. The drift time and the compensation time are critical parameters in polarization compensation systems [29]. Drift time refers to the time when the amount of polarization drift is less than our desired threshold. If the polarization drift exceeds the threshold, the system starts to compensate for the polarization until it returns to an acceptable level. The drift time can be affected by various environmental factors such as temperature fluctuations, atmospheric conditions, and signal attenuation. The compensation time is also critical because it determines the efficiency of the compensation system. During the compensation time, the system must adjust for any polarization changes in the optical fiber. For example, in QKD systems, this adjustment process can take a significant amount of time, which can reduce the overall performance of the system. Therefore, it is essential to optimize compensation time to ensure the highest level of security and efficiency in QKD systems [30]. Researchers are continually developing new techniques and technologies to improve these parameters and overcome the limitations of interrupted systems. The polarization compensation can be regarded as an

*Corresponding author, E-mail: seyed.ahmad.madani@gmail.com

Published online: 24 July 2024

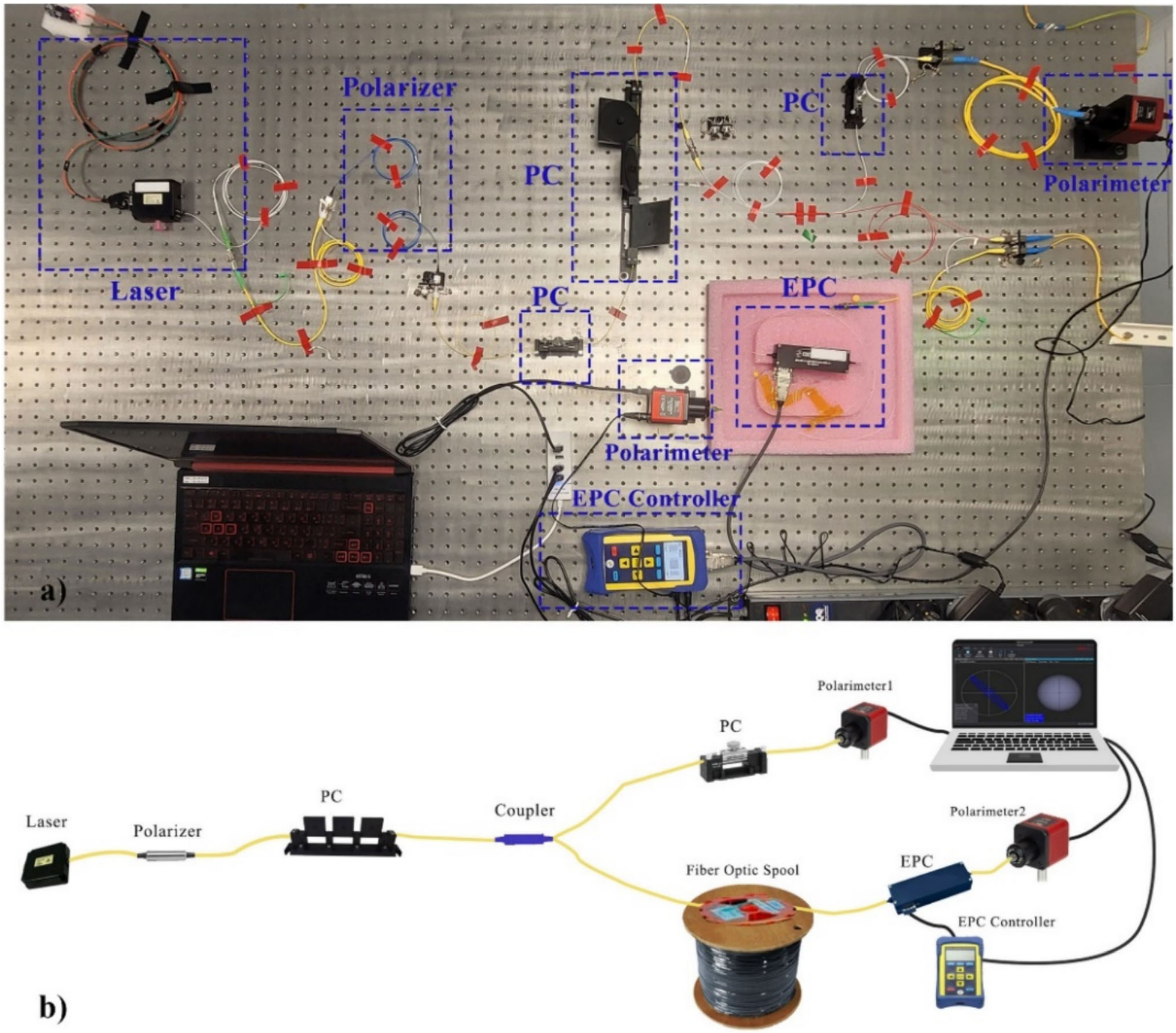


**Fig. 1** (**a**): Experimental and (**b**): schematic setup for polarization compensation in a 40 km long fiber link. A narrow-band 1550 nm diode laser with 4.75 mW output power is used as the source. A polarizer is used to create a linear polarized beam. A manual polarization controller (PC) is employed to create four orthogonal SOPs. An EPC is added to the end side of the 40 km long fiber. Two separate polarimeters are used to measure the polarization parameters before and after the 40 km long fiber

optimization problem. Thus, various optimization algorithms can be employed. Examples include the stochastic search algorithm [31] and the hill-climbing algorithm [32]. The choice of polarization controller instrument and corresponding optimization algorithm depends on the system and ambient conditions. In this paper, we have investigated the performance of two optimization algorithms for polarization controlling in a 40 km long fiber that will be used for optical communication. These two algorithms are particle swarm optimization (PSO) [33], and simulated annealing (SA) [34].

## 2. Experimental details

### 2.1. Theoretical Background

As already mentioned, the polarization of light is altered in the fiber due to birefringence and ambient conditions. That will lead to a basis mismatch between the transmitter and receiver. With these considerations, the polarization drift error ($e_{Pd}$) can be described [20].

Under weak depolarization, one can assume that photons remain polarized after a long distance. Therefore, the normalized Stokes vector of received photons by receiver

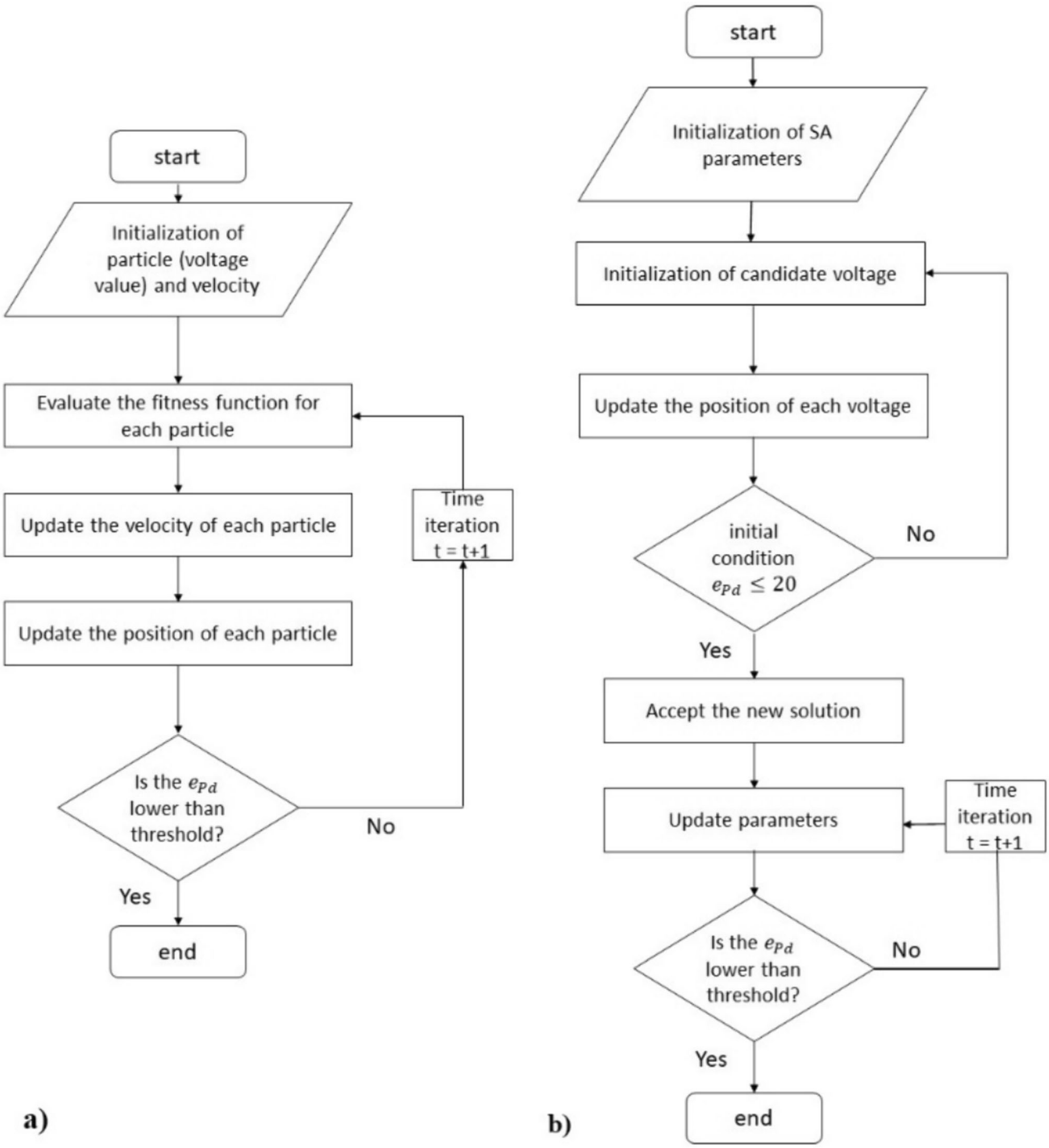


**Fig. 2** The flowchart diagram of the (**a**) PSO (**b**) SA algorithm

$S_{receiver} = (S_0, S_1, S_2, S_3)^T$ will have the following conditions:

$$S_0 = 1, \quad S_1^2 + S_2^2 + S_3^2 = 1, \quad -1 \leq S_1, S_2, S_3 \leq 1 \tag{1}$$

One can obtain the $e_{Pd}$ for the H/V basis in terms of $S_1$ as:

$$e_{Pd_{H/V}} = \frac{1 - S_1}{2} \tag{2}$$

And the $e_{Pd}$ for the ± basis can be described by the equation:

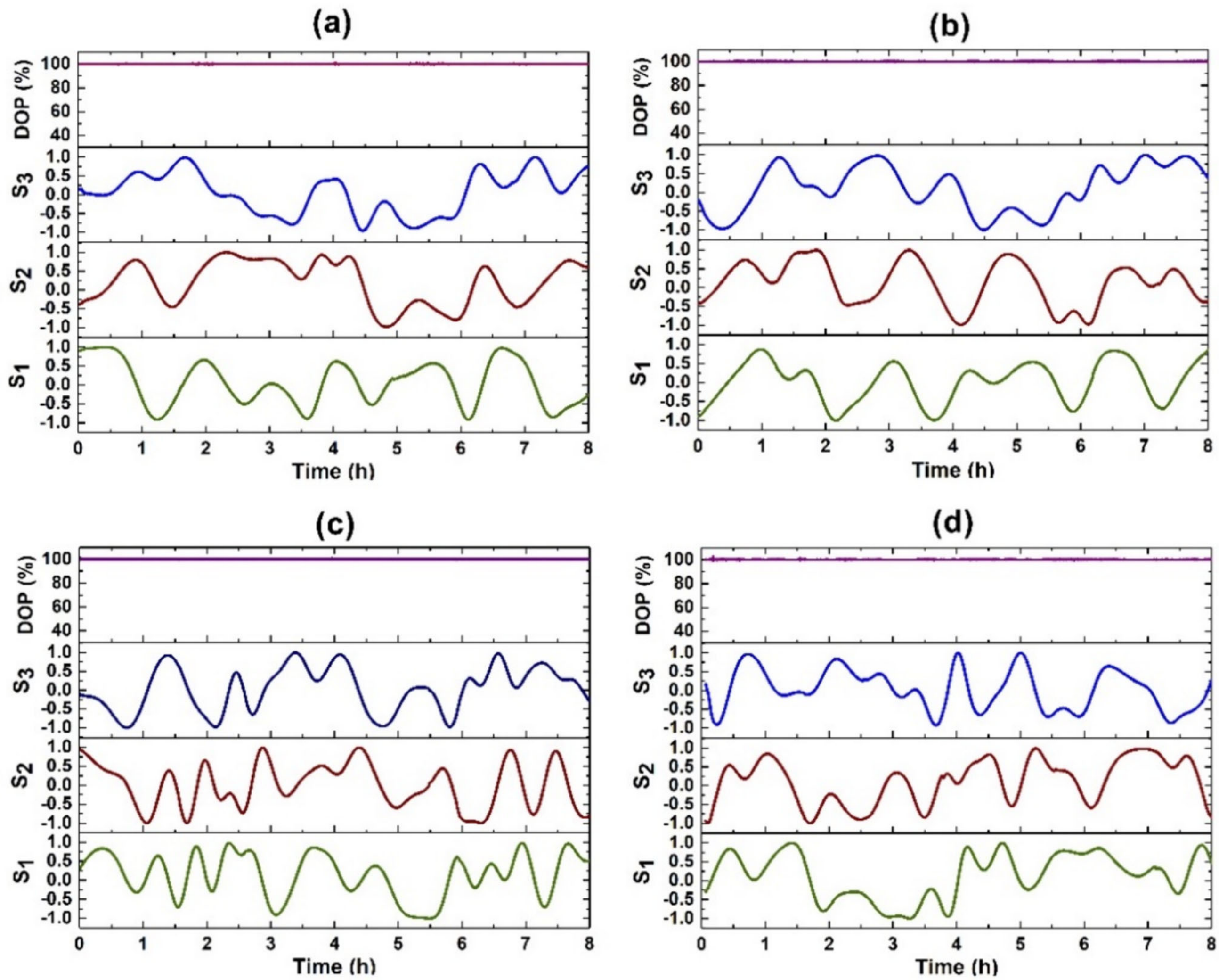


**Fig. 3** Variations of normalized stokes parameters ($s_1$,$s_2$,$s_3$) and DOP of the output beam after 40 km optical fiber link as a function of time for 8 h. The initial SOPs are (**a**) H, (**b**) V, (**c**) +, and (**d**) −

$$e_{Pd_{+/-}} = \frac{1 - S_2}{2} \tag{3}$$

Consequently, the $e_{Pd}$ for each of these basis sets can be calculated using only $S_1$ and $S_2$ [21].

## 2.2. Experimental Methods

### *2.2.1. Polarization fluctuation measurements*

In order to measure the polarization fluctuations, we used a 40 km long fiber (0.32 dB/km) and recorded the stokes parameters for 8 h. In this work, we employed four states of polarization (i.e. H/V and ±) and recorded the output SOP after a 40 km fiber link. For this purpose, we used a narrow-band continuous wave (CW) laser in telecommunication wavelength (1550 nm) manufactured by G&H as the light source. We employed an inline polarizer (Thorlabs) to make linear polarized beams and used manual polarization controllers to create the mentioned SOPs. We tuned the SOPs and measured the polarization parameters of both input and output beams using a fiber beam splitter and two polarimeters (Thorlabs) at the beginning and end of the 40 km long fiber.

### *2.2.2. Polarization controlling and optimization algorithms*

After observing the fluctuations, it is obvious that we need a method to compensate for the state of polarization quickly. If we can compensate for all the polarization states using a polarization controller, we will take a step toward creating an effective polarization system. For this purpose, we added an electrical polarization controller (EPC) manufactured by OZ Optics to the previous setup. The final experimental setup is shown in Fig. 1. We set the threshold

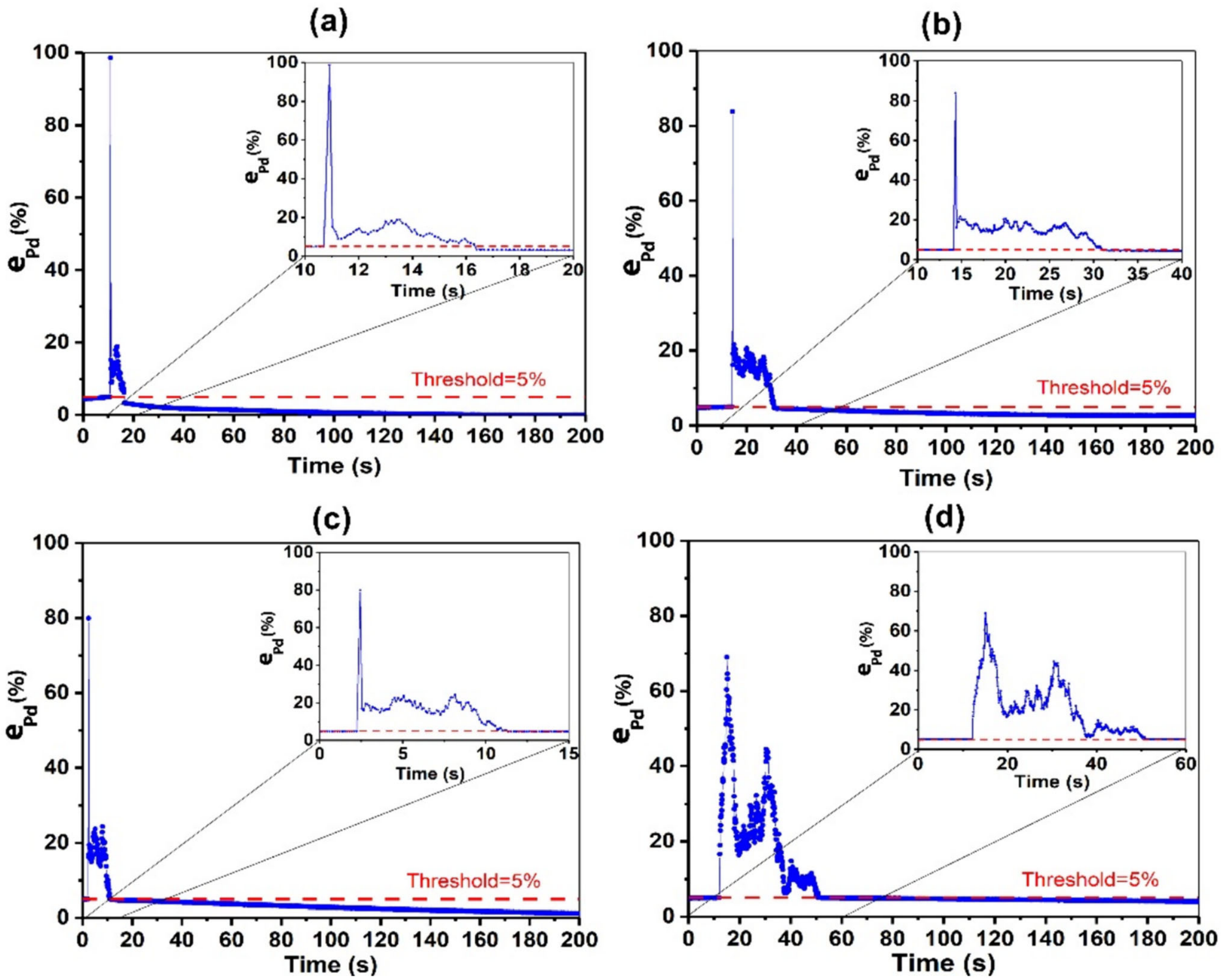


**Fig. 4** Reduction of the $e_{Pd}$ to below the threshold value using the SA algorithm after 40 km optical fiber link over a certain time (200 s) for different input SOPs: (**a**): H, (**b**): V, (**c**): + , (**d**): −

$e_{Pd}$ to 5% and automatically compensated the SOP whenever the $e_{Pd}$ exceeds this threshold. This EPC has four input channels that accept voltages in the range of − 5000 to 5000 mV. Therefore, the main challenge is to find the optimal values for these channels in a short time. The maximum speed of this EPC is 100 Hz. The $e_{Pd}$ is a function of these four voltages, i.e. $e_{Pd} = f(V_1, V_2, V_3, V_4)$. In an effective system, the compensation process time should be less than 10 percent of the mean drift time.

As this is an optimization problem, we chose two famous optimization algorithms for operating the EPC. The first algorithm is PSO, which is inspired by a flock of birds searching for food. In this algorithm, the position and velocity of a bunch of particles are initiated randomly. The position of each particle is a point in the multidimensional space of states. In each iteration, the particles change their velocity and position toward the local minimum of a cost function. In our case, each point in the 4-dimensional space of voltages corresponds to an $e_{Pd.}$

Figure 2.a shows the flowchart diagram of the PSO algorithm, which is explained step by step below.

i. Initialize the parameters:

- particle (voltage value) and velocity

ii. Perform initialization of particles:

- Generate random positions and velocities for each particle within a specified range.
- Set the initial best $e_{Pd}$ values for each particle.

iii. Perform the optimization loop:

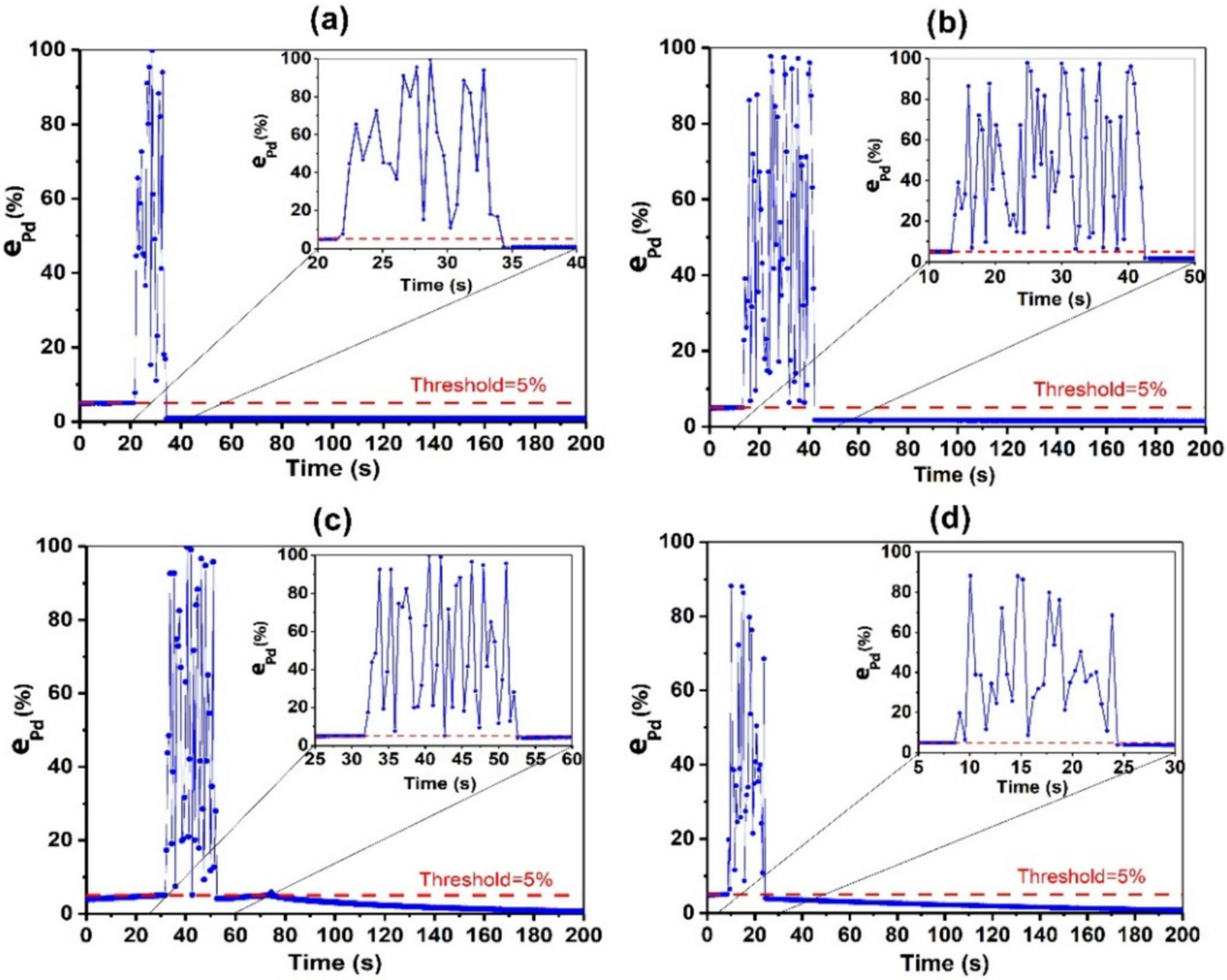


**Fig. 5** Reduction of the $e_{Pd}$ to below the threshold value using the PSO algorithm after 40 km optical fiber link over a certain time (200 s) for different input SOPs: (**a**): H, (**b**): V, (**c**): + , (**d**): −

**Table 1** Statistical results of polarization compensation process time

| Algorithm | SOP | Number of runs | Min time (s) | Max time (s) | Mean time (s) | Std (s) |
|---|---|---|---|---|---|---|
| SA | H | 136 | 0.1 | 48 | 8.9 | 11.7 |
| | V | 203 | 0.1 | 110.3 | 11 | 16.72 |
| | + | 229 | 0.1 | 53.2 | 9.3 | 12.4 |
| | − | 163 | 0.1 | 60.6 | 9.2 | 14.4 |
| PSO | H | 106 | 0.1 | 82.1 | 9.2 | 12.4 |
| | V | 126 | 0.1 | 67.8 | 9.9 | 13.2 |
| | + | 130 | 0.1 | 205 | 11.4 | 20.7 |
| | − | 90 | 0.1 | 202.7 | 11.9 | 26.1 |

- While the iteration is less than the maximum number of iterations:

Evaluate the cost function ($e_{Pd}$) for each particle:

Apply voltage values to the EPC.

- Update the best $e_{pd}$ values and corresponding voltage values for each particle and overall:

If the current $e_{pd}$ value is lower than the particle's best $e_{pd}$ value, update the best $e_{pd}$ and voltage values for that particle.

If the current $e_{pd}$ value is lower than the overall best $e_{pd}$ value, update the overall best $e_{pd}$ and voltage values.

- Check if the overall best $e_{pd}$ value is below a specified threshold:

Apply the voltage values corresponding to the overall best $e_{pd}$ value to the EPC.

Print the iteration number, total time, voltage point, and minimum $e_{pd}$.

Break out of the loop.

This algorithm aims to find the best voltages which lead to an $e_{Pd}$ lower than the threshold. The second algorithm is SA, which is inspired by the annealing process in crystals. SA can be summarized as a metaheuristic optimization technique inspired by the metallurgical annealing process. It's an effective method for finding the global optimum, especially in the presence of multiple local optima. This algorithm is useful for solving unconstrained and bound-constrained optimization problems. Figure 2.b shows the flowchart diagram of the SA algorithm, which is explained step by step below.

i. Initialize the parameters:
- Bounds for each dimension of the search space.
- Maximum number of iterations.
- Size of the step taken during each iteration.
- Initial temperature for the SA algorithm.

ii. Generate an initial point best within the specified bounds.
- Apply the voltage values of best to the EPC.
- Calculate the $e_{pd}$
- Repeat this step until the $e_{pd}$ is below 20%.

iii. Run the algorithm for a certain number of iterations:
- Accept the new solution.
- generate the candidate's best point around the initial best point.
- Apply the voltage values of candidate to the EPC.
- Calculate the $e_{pd}$.
- the best $e_{pd}$ value is below the threshold, terminate the loop.

SA also aims to find the best point in the 4-dimensional space corresponding to an $e_{Pd}$ lower than the threshold.

To statistically investigate these algorithms, we let the compensation system work for 8 h per each SOP. During this time, the compensation process was repeated several times to keep the $e_{Pd}$ below the threshold. Therefore, we can calculate the mean drift time and mean compensation time.

## 3. Results and Discussion

### 3.1. Polarization fluctuations

The variations of normalized Stokes parameters and degree of polarization (DOP) of the output beam as a function of time for 8 h are depicted in Fig. 3 for H/V and ± SOPs.

As shown in Fig. 3, the Stokes vector changes randomly as time passes. Thus, in order to have a stable polarization system, it is necessary to compensate for changes in polarization. We used standard single mode (SM) fibers, and the measured DOP was always near 100%. Thus, we can safely calculate the ePd using Eqs. 2 and 3.

### 3.2. *Polarization compensation*

Figures 4 and 5 show a small portion of the compensation process for SA and PSO algorithms respectively.

As shown in Fig. 4, the SA algorithm reduces the $e_{Pd}$ in steps toward the threshold value. On the other hand, it can be seen in Fig. 5, the PSO algorithm changes the $e_{Pd}$ randomly until it reaches the threshold. This is because some particles in the PSO algorithm are trapped inside local minimums. The statistical results are summarized in Table 1.

The number of runs shows how many times the $e_{Pd}$ rose above the threshold and the algorithm executed. According to Table 1, the compensation time of SA and PSO are very close and do not show a statistically significant difference.

## 4. Conclusions

Changes and fluctuations in polarization leads to the $e_{Pd}$ which plays a critical role in fiber-based polarization-dependent systems. The main challenge of these systems is to maintain the SOP fast and efficiently. In this work, we employed two different optimization algorithms to run an electrical polarization controller and compensate for the changes in polarization. Our setup continuously compensated for all SOPs for an 8-h interval and 40 km long fiber. The results show that despite fundamental differences in PSO and SA algorithms, there are no statistically significant differences in their compensation times. Therefore, both algorithms can be employed efficiently to compensate for the polarization fluctuations in fiber-based systems.

This method can be extended with a bit of modification for use in fiber-based polarization QKD systems.

**Acknowledgements** We thank the Iranian Center for Quantum Technologies (ICQTs) and all our colleagues who helped us in this work.

## References

[1] S Pirandola, U L Andersen, L Banchi, M Berta, D Bunandar, R Colbeck, D Englund, T Gehring, C Lupo and C Ottaviani *Adv Opt Photonics* **12** 1012 (2020)
[2] J Yin, Y-H Li, S-K Liao, M Yang, Y Cao, L Zhang, J-G Ren, W-Q Cai, W-Y Liu and S-L Li *Nature* **582** 501 (2020)
[3] T Kupko, M von Helversen, L Rickert, J-H Schulze, A Strittmatter and M Gschrey *Quantum Inf* **6** 29 (2020)
[4] S Hajibaba, A H Dadahkhani and S A Madani *Opt. Continuum* **1** 1572 (2022)
[5] S Hajibaba, A Dadahkhani, H Asgari, M Khodabandeh and S A Madani *Eng. Sci. Technol.* **5** 374 (2024)
[6] Y Du, X Zhu, X Hua, Z Zhao, X Hu, Y Qian, X Xiao and K Wei *Chip* **2** 100039 (2023)
[7] Z Tang, Z Liao, F Xu, B Qi, L Qian and H-K Lo *Phys. Rev. Lett.* **112** 190503 (2014)
[8] T-Y Ye, H-K Li and J-L Hu *Int. J. Theor. Phys.* **59** 2807 (2020)
[9] W Li, L Wang and S Zhao *Sci. Rep.* **9** 15466 (2019)
[10] S Jiao and M Ruggeri *J. Biomed. Opt.* **13** 60503 (2008)
[11] N Wang, X Liu, Q Xiong, J Xie, S Chen and L Liu *Opt. Lett.* **42** 2996 (2017)
[12] B Baumann and A Wohrer *Opt. Lett.* **48** 3499 (2023)
[13] G P Agrawal *Lightwave Technology: Telecommunication Systems* (Hoboken: Wiley) (2005)
[14] G Soliman Temporal Ph.D. Thesis (University of Waterloo, Canada) (2013)
[15] H A Yasser and N S Shnan *Int. J. Opt.* **2013** 1 (2013)
[16] G Xu and M Skorobogatiy *Opt. Express* **31** 12894 (2023)
[17] M Ahmadian, M Ruiz, J Comellas and L Velasco *Lightwave Technol.* **40** 4119 (2022)
[18] M Karlsson, J Brentel and P A Andrekson *Lightwave Technol.* **18** 941 (2000)
[19] Krzysztof Perlicki and M Yasin Polarization effects in optical fiber links (Intech) 125 (2015)
[20] N J Muga, M F S Ferreira and A N Pinto *Lightwave Technol.* **29** 355 (2010)
[21] R Liu, Y Hao, J Zan, S Gao, L Wang, X Mulan and J Tao *Opt. Fiber Technol.* **48** 28 (2019)
[22] D Huang, P Huang, D Lin and G Zeng *Sci. Rep* **6** 119201 (2016)
[23] X J Chen and X S Yao *Polarization Measurement and Control in Optical Fiber Communication and Sensor Systems* (Hoboken: Wiley) (2022)
[24] S Wengerowsky et al *Proc. Natl. Acad. Sci.* **116** 6684 (2019)
[25] S Wengerowsky, S K Joshi, F Steinlechner, J R Zichi, B Liu, T Scheidl, S M Dobrovolskiy, R van der Molen, J W N Los, V Zwiller et al *Quantum Inf.* **6** 5 (2020)
[26] P Huang, T Wang and R Chen *New J. Phys.* **23** 113028 (2021)
[27] J Chen, G Wu, L Xu, X Gu, E Wu and H Zeng *New J. Phys.* **11** 065004 (2009)
[28] J Chen, G Wu, Y Li, E Wu and H Zeng *Opt. Express* **15** 17928 (2007)
[29] Y-Y Ding, H Chen, S Wang, D-Y He, Z-Q Yin, W Chen, Z Zhou, G-C Guo and Z-F Han *Opt. Express* **25** 27923 (2017)
[30] M F Ramos, N A Silva, N J Muga and A N Pinto *Opt. Express* **28** 5035 (2020)
[31] Y Shi, H S Poh, A Ling and K Kurtsiefer *Opt. Express* **29** 37075 (2021)
[32] D-D Li, S Gao, G-C Li, L Xue, L-W Wang, C-B Lu, Y Xiang, Z-Y Zhao, L-C Yan, Z-Y Chen et al *Opt. Express* **26** 22793 (2018).
[33] J Kennedy and R Eberhart *Particle Swarm Optimization* International Conference on Neural Networks **4** 1942 (1995)
[34] P J M van Laarhoven and Emile HL Aarts *Simulated annealing*, (Heidelberg: Springer Netherlands) p 7 (1987)