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SIX BASIC STATES OF POLARIZATION EXPERIMENTAL ANALYSIS FOR MULTIPLE STAGE PASSIVE COMPENSATION ON SINGLE MODE OPTICAL FIBER

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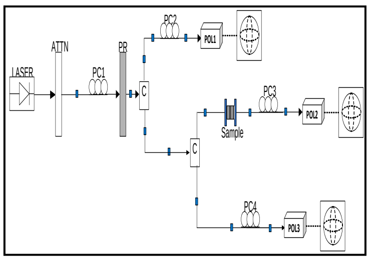
Graphical abstract



Abstract

We report a statistical approach of analyzing experimental data on three stages of passive compensations of light State of Polarization (SOP) in standard single mode optical fiber. Fidelity of every basic six SOPs which consist of two pairs of linear state of polarization and a pair of circular state of polarization were also analyzed by performing an experiment to measure the Stoke parameter of every state. Experimental results have shown that all six basic SOPs were maintained according to the state of the source at every stage of respective paths. These observations were regardless of different optical fiber length at the second stage of passive compensation. We achieved to ensure that the final destination of SOP will have similar state with its source at fidelity of above 96%.

Keywords: Optical fiber, passive compensation, State of Polarization(SOP), Stoke parameter

Abstrak

Kami melaporkan pendekatan statistik bagi menganalisis data eksperimen untuk tiga peringkat pampasan pasif keadaan polarisasi cahaya (SOP) di dalam gentian optik mod tunggal yang standard. Kesetiaan setiap enam SOP yang asas terdiri daripada dua pasangan keadaan polarisasi linear dan sepasang keadaan polarisasi membulat dianalisis dengan melakukan eksperimen untuk mengukur parameter Stoke di setiap keadaan polarisasi. Keputusan eksperimen telah menunjukkan bahawa kesemua enam keadaan polarisasi SOP asas dikekalkan mengikut keadaan polarisasi sumber di setiap peringkat laluan masing-masing. Cerapan ini adalah tanpa mengira panjang gentian optik yang berbeza pada peringkat kedua pampasan yang pasif. Eksperimen ini telah berjaya memastikan destinasi akhir SOP akan menpunyai keadaan polarisasi yang sama dengan sumber pada kesetiaan melebihi 96%.

Kata kunci: Gentian optik, pampasan pasif, Keadaan Polarisasi(SOP), parameter Stoke

1.0 INTRODUCTION

Light State of Polarization (SOP) can be used in many applications such as information coding in light based communication system [1]. For example, one famously known was it use in the implementation of Quantum Key Distribution communication [2, 3]. SOP of light is important to code information or as to code key for encryption. A major concern in the application of light SOP is on the maintaining and stabilizing the SOP along the communication channel.

There were several publications reported on polarization stabilization related to implementation of QKD communication whereby active polarization stabilization were implemented [2, 3], and claimed to be successful. It is recognized that the active compensation is more complicated and requires a realization of a feedback system that can transforms the excursion of the polarization inputs. The intention of stabilizing polarization of light normally aims for six main SOPs which include two pairs of linearly polarized and a pair of circularly polarized light.

Standard single mode optical fiber is a known low birefringence medium and the nature of its circular shape makes it not supportive to maintain the SOP of light propagation inside it [4-7]. The SOP will change along the way randomly and very difficult to retain the polarization at its original states. The issues of polarization control and stabilization in single mode optical fiber have been in research and discussed since three to four decades ago [4-6, 8, 9]. Earlier approach of passive compensation was on the preform and optical fiber construction itself. By increasing the birefringent and anisotropic properties of the optical fiber material, it is proven that the SOP can be controlled [8, 11-13]. This resulted in the implementation and usage of Polarization Maintaining (PM) fiber which is costly than the standard single mode fiber.

It is not known to us thus far that there were analysis on sustaining the six main SOP which one of its Stoke parameter value is at plus one (+1) or minus one (-1) and the other two are zeros using passive device compensation. The concerned six main states analysis in this paper were horizontal $|H\rangle$, vertical $|V\rangle$, diagonal left $|45°\rangle$, diagonal right $|135°\rangle$, circular left $|CIR^L\rangle$ and circular right $|CIR^R\rangle$. These polarization states can be observed and described by using Poincare sphere representation [10, 11].

Any points on the Poincare sphere will represent the SOP of the light. Each point on the sphere are related to Stoke parameter, S_i and it can be written as in equation (1) [10], where ω is the orientation angle and $\emptyset$ is the ellipticity angle of the polarization ellipsis.

$$\begin{cases} i = 0, 1, 2, 3 \\ s_1 = s_0 \cos 2\emptyset \cos 2\omega \\ s_2 = s_0 \cos 2\emptyset \sin 2\omega \\ s_3 = s_0 \sin 2\emptyset \end{cases} \quad (1)$$

Poincare Sphere is normally used to denote the SOP of light. In this experiment, we used polarimeter that have SOP representation depicted on a Poincare Sphere. It will also give Stoke value for each SOP measured. Stoke parameter measures can be represented as in equation (2).

$$S_0 = \sqrt{S_1^2 + S_2^2 + S_3^2} \quad (2)$$

Stabilizing the SOP by passive device compensations for longer distance and field deployment were not easy to achieve [14] but in this experiment, we analyze this potential method by expanding the path and inserted multiple lengths of fiber between the coupler and polarization compensator. We show how passive control will also play its roles in stabilizing the SOP in optical fiber link especially for information coding. We present an analysis where we introduced passive compensation devices and observed that six main SOPs at all the polarimeters used in the experiment were maintained.

2.0 EXPERIMENTAL

The design of multiple stages with multiple length passive SOP compensation experimental setups is depicted in Figure 1. Un-polarized tunable laser source was set at 1550nm with 11.5dBm power emitted and attenuated with 10dBm loss. The light source will experience first polarization effect via PC1. The PC1 was a manual polarizer where polarization state can be adjusted in order to get maximum power at the first polarimeter (POL1) where the original state of polarization (SOP) was set in order to ensure maximum polarized light going through it and at the same time reducing the polarization dependent loss (PDL).

Polarization Rotator (PR) was where light state of polarization is set in order to get certain target state from the original source that goes to the first polarimeter, POL1. It consists of three rotated wheels, which is marked as Polarizer Trans Axis, *V @ 0°*, Half Wave Plate Axis (HWP), *V @ 0°* and Quarter Wave Plate Axis (QWP), *V @ 0°*. Every wheel has a set of degree marking from 0 to 360.

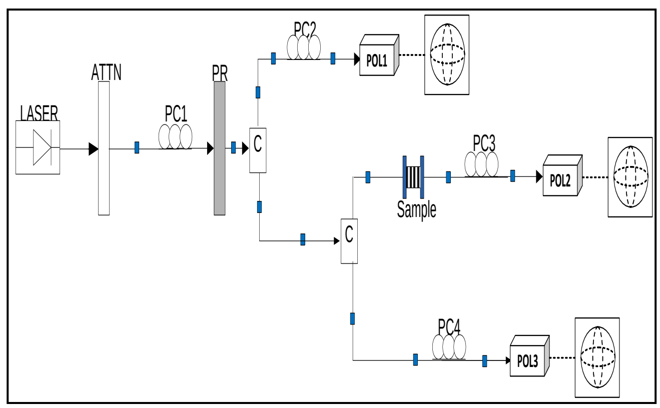


Figure 1 Multiple stages with multiple lengths experimental setup

All the polarized lights were then divided into two different paths via a normal first 50/50 polarization insensitive coupler. One path was connected directly to POL1 where it was to be treated as the first stage of passive compensation and the source of the six basic SOPs shall be set as reference. PC2 was used to compensate the target reference for original SOP. The Stoke parameters readings was visualized and observed from the Poincare Sphere displayed by the Agilent's polarimeter (POL 1).

The other path from the first coupler was divided again into two different paths. The first path from the second polarization insensitive coupler shall be treated as the second stage or stage 2 of passive compensation. Multiple lengths of single mode optical fiber were inserted in a sequence of every one meter up to twenty meters within this path. At each length, there will be new readings for the Stoke parameters. PC3 was used to compensate the original SOP at POL2. The second path shall be treated as the third stage of passive compensation and PC4 was used as polarization compensator where the SOPs of the light were to be observed at POL3. In this experiment PC2 and PC3 were acted as passive polarization controller and the target SOP measured shall be as closed as measured by POL1.

Major optical component and measurement equipment used in this experiment were off the shelf equipment, mainly from Agilent and Thorlabs. The main objective of this experiment was to analyze and find the best compensation setup at PC3 and PC4 so that the 6 main SOPs that normally used for information coding will be to the best similarity at POL1, POL2 and POL3. These 6 SOPs were measured by their related prevailing Stoke (S_1, S_2, S_3) value which S_1 was for the horizontal $|H\rangle$ and vertical $|V\rangle$, S_2 was for diagonal left $|45°\rangle$ and diagonal right $|135°\rangle$ and S_3 was for circular left $|CIR^L\rangle$ and circular right $|CIR^R\rangle$ SOP.

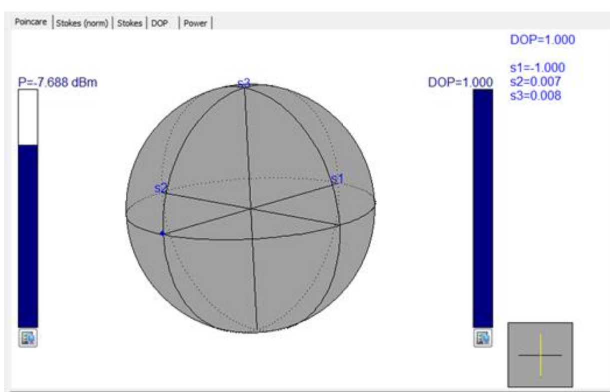


Figure 2 Results of polarimeter with summary of the SOP view

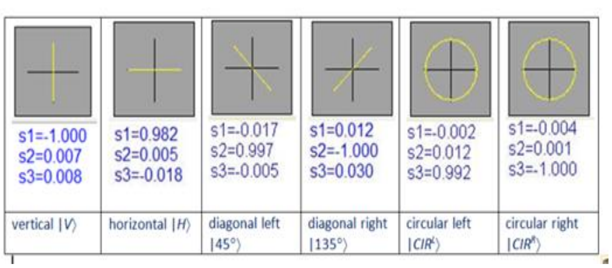


Figure 3 Polarimeter summaries and Stoke Parameter of SOP view to deduce SOP of each stage of passive compensation

Three sets of passive compensation based on three main bases of SOPs were performed and we report below results that were successful and promising. We consider the SOP will be at the said state if the prevailing Stoke value is within 0.965 +/- 0.035 and the other two values were less than 0.3 whereby at the polarimeter summary SOP view shown that the states was not elliptically obvious as shown in Figure 2 and Figure 3.

3.0 RESULTS AND DISCUSSION

We conducted two main areas of statistical analysis from this experimental data using Minitab software. The first analysis was on average value of Stoke parameters for each polarimeter. In this analysis, we included data for twenty different lengths of optical fiber at second stage of passive compensation, which was measured by POL2. The same analysis was also performed for readings from POL3 which measured the performance of the stage three of passive compensation.

From the multivariate chart plotted in Figure 4, it was observed that the trends of measurement at POL1 were followed closely by POL2 and POL3. The similarity of Stoke parameter value of the concern state was shown by the Stoke value at each state. The Stoke values plotted were the average reading for measurements that was based on the change of length at stage 2 passive compensation. Best compensation setup has been achieved from the first readings and has been maintained for PC2, PC3 and PC4 accordingly.

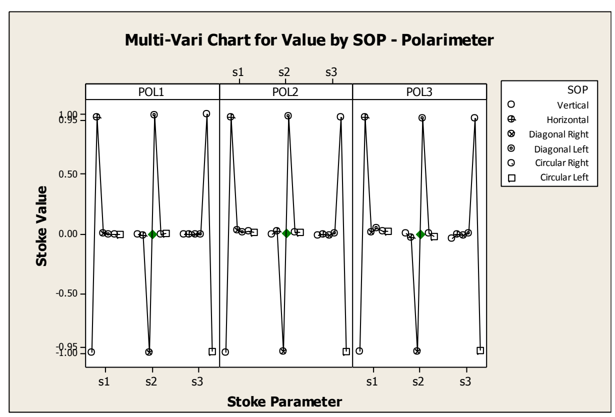


Figure 4 Multivariate chart summarizing 20 sample length optical fiber SOP properties at three different stages

Table 1 Average stoke value at each main six polarization states

SOP	Stage 1 POL 1	Stage 2 POL 2	Stage 2 SOP Fidelity	Stage 3 POL 3	Stage 3 SOP Fidelity
$\|H\rangle$, S_1	0.980	0.984	98.4%	0.978	97.8%
$\|V\rangle$, S_1	-0.997	-0.994	99.4%	-0.993	99.3%
$\|135°\rangle$, S_2	-0.996	-0.986	98.6%	-0.986	98.6%
$\|45°\rangle$, S_2	0.998	0.985	98.5%	0.972	97.2%
$\|CIR^R\rangle$, S_3	1.000	0.984	98.4%	0.968	96.8%
$\|CIR^L\rangle$, S_3	-0.990	-0.986	98.6%	-0.984	98.4%

As shown in Table 1, the highest Stoke parameter value fidelity was achieved at vertical $|V\rangle$ SOP, averaging at 99.3%. The lowest fidelity was at circular left $|CIR^L\rangle$, with average of 96.8%. We can state that the Stoke parameter value can be represented in the generic condition as in equation 3.

$$f(\text{SOP}) = -0.98 \pm 0.2,$$
$$\text{if } SOP = |V\rangle \text{ or } |135°\rangle \text{ or } |CIR^L\rangle \text{ for } S_1, S_2 \text{ and } S_3 \text{ respectively} \quad (3)$$

$$f(\text{SOP}) = 0.98 \pm 0.2,$$
$$\text{if } SOP = |H\rangle \text{ or } |45°\rangle \text{ or } |CIR^R\rangle \text{ for } S_1, S_2 \text{ and } S_3 \text{ respectively}$$

The Stoke parameter function in equations 3 applies to all polarimeters that are used to measure the six SOPs at stage 2 and stage 3 of passive compensation. Second analysis of data focus on the multiple lengths of optical fiber at the stage 2 of passive compensation as depicted in Figure 5. Stoke value trends were plotted in another multivariate chart based on four predictors namely length, state of polarization, polarimeter and Stoke parameter.

The chart shows pattern of every Stoke value at each polarimeter. It was observed that at every SOP, the Stoke value trend on each polarimeter will follow accordingly. This was regardless of optical fiber length inserted in between the coupler and the passive compensator, PC3 at the second stage of passive compensation.

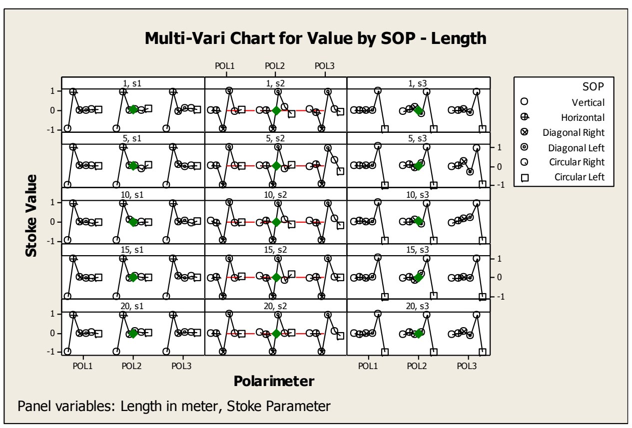


Figure 5 Multivariate chart shown pattern of passive compensation between five different lengths

In summary, for any length of optical fiber inserted in between the coupler and the PC3, the Stoke value can be written as prescript in equations (4),(5) and (6). The values for S_1 are described by f_1, S_2 in f_2 and S_3 in f_3.

$$f_1(\text{SOP}) = \begin{cases} +1 & , if\ SOP = |H\rangle \\ -1 & , if\ SOP = |V\rangle \\ 0 & , otherwise \end{cases} \quad (4)$$

$$f_2(\text{SOP}) = \begin{cases} +1 & , if\ SOP = |45°\rangle \\ -1 & , if\ SOP = |135°\rangle \\ 0 & , otherwise \end{cases} \quad (5)$$

$$f_3(\text{SOP}) = \begin{cases} +1 & , if\ SOP = |CIR^R\rangle \\ -1 & , if\ SOP = |CIR^L\rangle \\ 0 & , otherwise \end{cases} \quad (6)$$

The equations can be applied for expected value of SOP on all polarimeters which were placed at every stage of passive compensation in the experiment.

4.0 CONCLUSION

Analysis from this experiment has shown that passive compensation also plays a role in stabilizing the light State of Polarization (SOP) in standard single mode optical fiber that normally used in optical communication. We managed to demonstrate the six main light SOP changes based on one time passive device compensation at the beginning of each stage. This was regardless of any changes in optical fiber length in between the coupler and polarization compensator. SOP fidelity above 96% was achieved to ensure that the final destination of SOP will have similar state with its source.

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