APPLICATION NOTE

Fiber Optic Polarization

20

Polarization Control and Measurement for Optical Fibers

Spectra-Physics
A Division of Newport Corporation

Newport®
Experience | Solutions

Polarization Control and Measurements for Optical Fibers

Jay Jeong, Ph.D.

Sr. Photonics Application Engineer

Introduction

A beam of light can be thought of as being composed of two orthogonal electrical vector field components that may vary in amplitude and frequency. Polarized light occurs when these two components differ in phase or amplitude. Polarization in optical fiber has been extensively studied and a variety of methods are available to either minimize or exploit the phenomenon. In this tutorial, basic principles and technical background are introduced to help explain how polarization in fiber optics works and how its control and measurement can be done.

Polarization Manifestation in Optical Fibers

Birefringence in Optical Fibers

Birefringence is a term used to describe a phenomenon that occurs in certain types of materials, in which light is split into two different paths. This phenomenon occurs because these materials have different indices of refraction, depending on the polarization direction of light.

Birefringence is also observed in an optical fiber, due to the slight asymmetry in the fiber core cross-section along the length and due to external stresses applied on the fiber such as bending. If the fiber geometry is perfectly symmetric, there would not be birefringence. In general, the stress-induced birefringence dominates the geometry-induced one.

Polarization Maintaining (PM) Fiber

A specialty fiber called the Polarization Maintaining (PM) Fiber intentionally creates consistent birefringence pattern along its length, prohibiting coupling between the two orthogonal polarization directions. In any design, the geometry of the fiber and the materials used create a large amount of stress in one direction, and thus create high birefringence compared to that generated by the random birefringence. There are a number of designs available commercially, using various stress inducing architectures, such as Panda and Bow Tie PM Fibers available with various cut-off wavelengths.

The potential killer application for the PM fiber is their deployment for high speed telecom/datacom network, where polarization mode dispersion (PMD) can become a problem. If one can launch polarized light and maintain its polarization state throughout the transmission fiber, PMD can be avoid and thus signal degrading pulse spreading.

There are other, small volume applications where the PM fibers are desirable, such as fiber sensing and imaging. Please see Newport's other application notes for detailed accounts on various applications.

Stokes Vectors

There are a number of different methods of describing the polarization state of the electric fields. One of them is the Stokes vector method, and is obtained by the following measurements.

$$\vec{S} = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} E_H + E_V \\ E_H - E_V \\ E_{45} - E_{135} \\ E_R + E_L \end{bmatrix}$$

where E_x is the horizontal linear polarization field,
E_y is the vertical linear field,
E_{45} is the 45 linear field,
E_{135} is the 135 linear field,
E_R is the right-hand circular field, and
E_L is the left-hand circular field.

By using the Stokes vectors, it is possible to describe any arbitrary polarization state.

Poincaré Sphere

The Poincaré sphere is another method of describing the polarization state, and it is closely related to the Stokes parameters. Since it is very easy to visualize the polarization state changes on the sphere, it is often used to follow the dynamic changes in polarization state. It provides a convenient way of predicting how any given retarder will change the polarization form. Any given polarization state corresponds to a unique point on the sphere. The center of the sphere indicates that the electric field is unpolarized. The north and the south pole of the sphere represent right-hand and left-hand circularly polarized light, respectively. Points on the equator indicate various linear polarization states: (1, 0, 0) for the horizontal polarization, (-1, 0, 0) for vertical, (0, 1, 0) for 45 degree angled linear polarization, and (0, -1, 0) for the 135 degree of –45 degree linear polarization. All other points on the sphere represent elliptical polarization states. An arbitrarily chosen point H on the equator designates horizontal linear polarization, and the diametrically opposite point V designates vertical linear polarization. Therefore, any two orthogonal polarization states are positioned on the opposite points of the sphere.

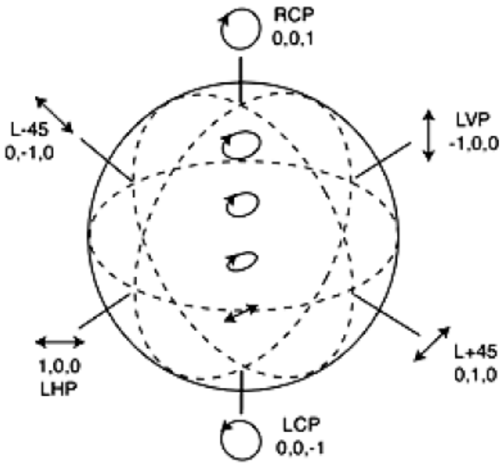

Figure 1. Poincaré sphere representation of polarization states. [Courtesy of Ref. [i]]

Measurable Polarization Properties

DOP

Degree of Polarization (DOP) is defined as

$$DOP = I_{pol} / (I_{pol} + I_{unp})$$

Where I_{pol} and I_{unp} are the intensity of polarized light and unpolarized light, respectively. When DOP = 0, light is said to be unpolarized, and when DOP = 1, it is totally polarized. Intermediate cases correspond to partially polarized light. This value is typically specified in an optical component to often demonstrate the polarization independency of it.

The DOP is also related to the Stokes vectors by the following relationship:

$$DOP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}.$$

Likewise, the Degree of Circular Polarization (DOCP) can be obtained from

$$DOCP = \frac{S_3}{S_0}$$

and the Degree of Linear Polarization (DOLP) can be obtained from

$$DOLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}.$$

PER

Polarization Extinction Ratio (PER) is the ratio of the minimum polarized power and the maximum polarized power, expressed in dB. Any polarization-exploiting optical component will specify this value as a specification.

PDL

Polarization Dependent Loss (PDL) is the maximum (peak to peak) variation in insertion loss as the input polarization varies over all its states, expressed in dB. This is a one of the fundamental specifications provided for any optical component.

PMD

Polarization Mode Dispersion (PMD) is a form of material dispersion, whose properties are of interest in the telecommunication sector, for high band, high speed applications. Single-mode fiber supports a mode, which in fact consists of two orthogonal polarization modes. Ideally, the core of an optical fiber is perfectly circular. However, in reality, the core is not perfectly circular, and mechanical stresses such as bending, introduce birefringence in the fiber. This causes one of the orthogonal polarization modes to travel faster than the other, hence causing dispersion of the optical pulse.

The maximum difference in the mode propagation times due to this dispersion is called Differential Group Delay (DGD), whose unit is typically given in picoseconds. Because of its dynamic properties, PMD has a distribution of DGD values over time. The probability of a DGD with a certain value at any particular time follows the Maxwellian distribution shown in Figure 2. As an approximation, the maximum instantaneous DGD is about 3.2 times the average DGD of a fiber.

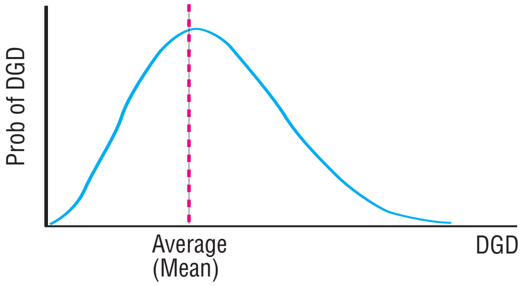

Figure 2. Maxwellian distribution of DGD. [Courtesy of Ref. [1]]

Measuring Various Polarization Properties in Optical Fiber

There are several standardized methods of measuring polarization. The easiest method that is typically employed in a simple experimental setup is to simply compare the power between two igen-states of polarization. The standardized methods approved by TIA/EIA or IEC are the “Pseudo-random All State Method” and the “Deterministic Mueller Matrix Method”.

The Pseudo-random All State method uses a polarization scrambler to randomly scan all possible polarization state while measuring the maximum and the minimum power.

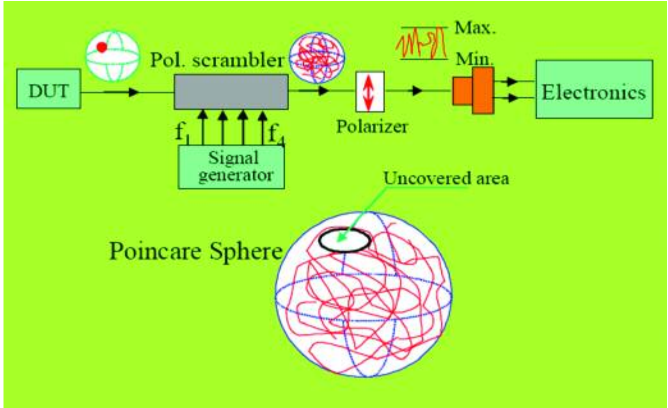

Figure 3. Measurement layout of the Pseudo-random All State Method. [Courtesy of Ref. [ii]] Since it is impossible to cover all possible SOP in each scan, this method is always associated with an error, being larger as the scanning time is getting shorter. In any realistic measurement setup, each scan can take even more than 10 seconds.

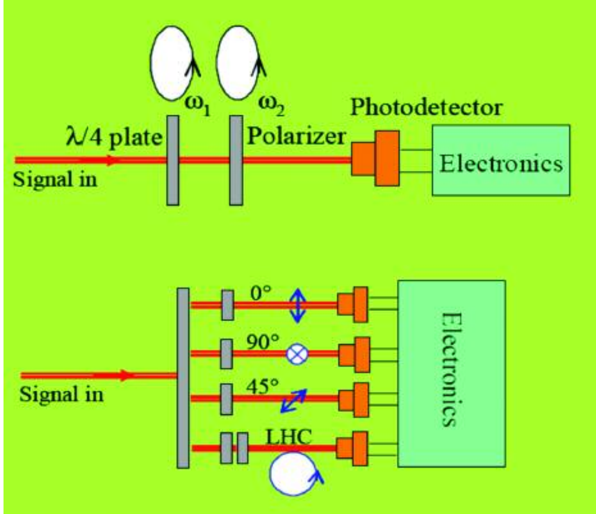

Figure 4. Measurement schematics for Mueller Matrix method. [Courtesy of Ref. [2]]

The Mueller Matrix method relies on the Stokes parameter measurements with the background measurements without the DUT (device under test). The Muller matrix is a 4¥4 matrix, which describes the transformation of the Stokes parameters. The power values measured Stokes parameters before and after inserting the DUT are related by the following equation:

$$\vec{s}_{out} = \begin{pmatrix} S_1' \\ S_2' \\ S_3' \\ S_4' \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{pmatrix}$$

PDL is calculated by

$$PDL = -10 \log\left(\frac{T_{\min}}{T_{\max}}\right)$$

where

$$T_{\max} = m_{11} + \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}$$

$$T_{\min} = m_{11} - \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}.$$

This method requires the internal PLD measurement proceeding the DUT measurements. This method also requires a very accurate measurement setup in order to assure accurate measurements of the orthogonal states. In any case the orthogonality is disturbed, an error in the measurement is introduced. Thus an experienced technician is necessary to perform the test.

In contrast to the two methods mentioned earlier, **Newport’s 25xx Series Polarization Measurement Instruments** use a different deterministic approach. As illustrated in Fig. 5, a feedback circuit equipped with a microprocessor is used to direct the polarization controller to adjust for the maximum and minimum power levels in the detector. As opposed to the random scrambling method, the maximum/minimum search method assures the instrument to unmistakably find the Pmax and Pmin. Because only two points on the Poincaré Sphere are required and can be found deterministically and precisely, high measurement speed and accuracy are guaranteed. Consequently, such an approach overcomes the shortcomings of both the polarimeter method (less accurate for low DOP values) and the polarization scrambling method (less accurate for high DOP values). The maximum/minimum search method is essentially a closed loop polarization scrambling method.   It eliminates the inaccuracies, but inherits all the advantages of the scrambling methods, including wavelength insensitivity, calibration free operation, high power capability, easy operation, simple construction, and low cost.

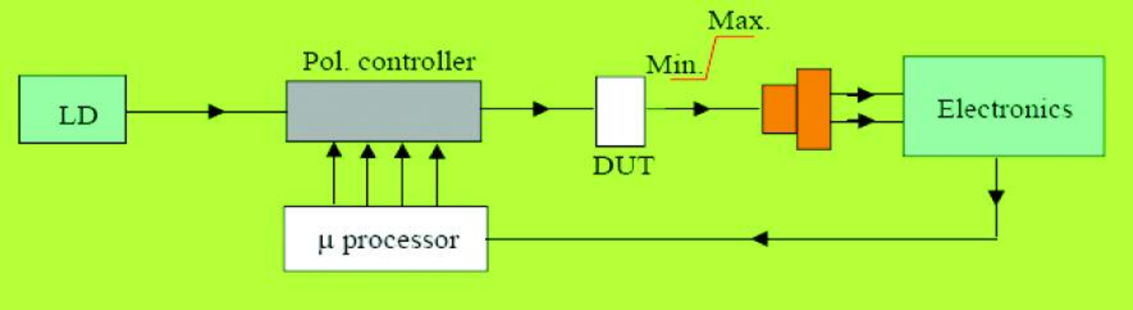

Figure 5. The min/max approach used by Newport Polarization Instruments. [Courtesy of Ref. [2]]

Controlling Polarization in Optical Fiber **(Excerpt from Ref. [iii])**

Methods of Controlling Polarization

Controlling the polarization state in optical fiber is similar to the free space control using wave plates via phase changes in the two orthogonal states of polarization. In general, three configurations are commonly used.

In the first configuration, a Half-Wave Plate (HWP) is sandwiched between two Quarter-Wave Plates (QWPs) and the retardation plates are free to rotate around the optical beam with respect to each other. The first QWP converts any arbitrary input polarization into a linear polarization. The HWP then rotates the linear polarization to a desired angle so that the second QWP can translate the linear polarization to any desired polarization state.

This method can be employed either by free space wave plates or by coiling fiber. An all-fiber controller based on this mechanism can be constructed, with several desirable properties such as the low insertion loss and cost, as shown in Figure 6. In this device, three fiber coils replace the three free-space retardation plates. Coiling the fiber induces stress, producing birefringence inversely proportional to the square of the coils' diameters. Adjusting the diameters and number of turns can create any desired fiber wave plate. Because bending the fiber generally induces insertion loss, the fiber coils must remain relatively large.

Drawbacks of this approach include wavelength sensitive characteristic, and slow control due to either rotating the wave plates or the fiber coils. The free space configuration also comes with a high cost, due to the use of lenses and wave plates with antireflection coating at the operating wavelength range. Insertion loss can be high due to the fact that the light must exit the fiber and then be coupled back into another fiber. The all-fiber approach is typically bulky, because the insertion loss increases with the decreased fiber loop diameter.

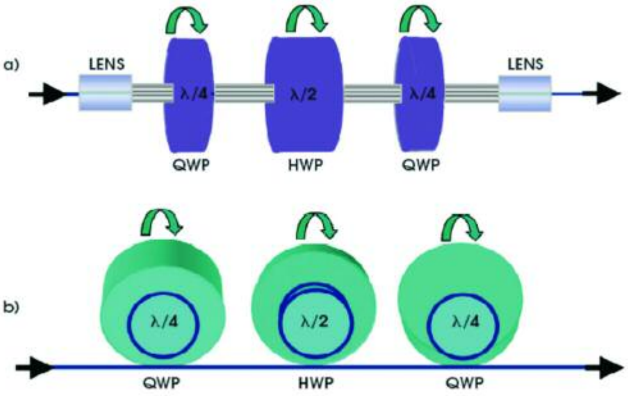

Figure 6. Polarization control using, a) multiple wave plates and, b) using multiple coiled fiber.

The second approach is based on the Babinet-Soleil Compensator. A free space configuration and an all-fiber polarization controller based on this technique are shown in Figure 7. The free space approach utilizes a composite wave plate which consists of two pieces of birefringent crystal wedges. A complete control of polarization becomes possible as the wave plate is moved in position and is rotated.

The all-fiber version is a fiber squeezer that rotates around the optical fiber. Applying a pressure to the fiber produces a linear birefringence, effectively creating a fiber wave plate whose retardation varies with the pressure. Simple squeeze-and-turn operations can generate any desired polarization state from any arbitrary input polarization.

This method reduces the wavelength dependency of the device, however, the free-space device still bears the high cost and high insertion loss drawbacks due to the multiple lenses and composite wave plate. The all-fiber device is low cost and has low insertion loss. However, the speed is still slow, as the fiber must be strained and rotated using a mechanical method.

Finally, polarization controllers also can be made with multiple fixed wave plates oriented 45° from each other. Elimination of moving parts makes devices operate in high speed. The free-space approach requires a high cost, high insertion loss and limited wavelength range due to the use of anti-reflection coating on the components.

An all-fiber device based on the same operation principle would reduce the insertion loss and cost. The retardation of each wave plate components varies with the pressure of each fiber squeezer. The challenge is making the device reliable, compact and cost-effective.

Piezoelectric actuators drive the fiber squeezers for high speed. Because it is an all-fiber device, it has no back reflection and has extremely low insertion loss and polarization-dependent loss. All new **25xxP Series Polarization Control instruments** employ the fiber squeeze technique.

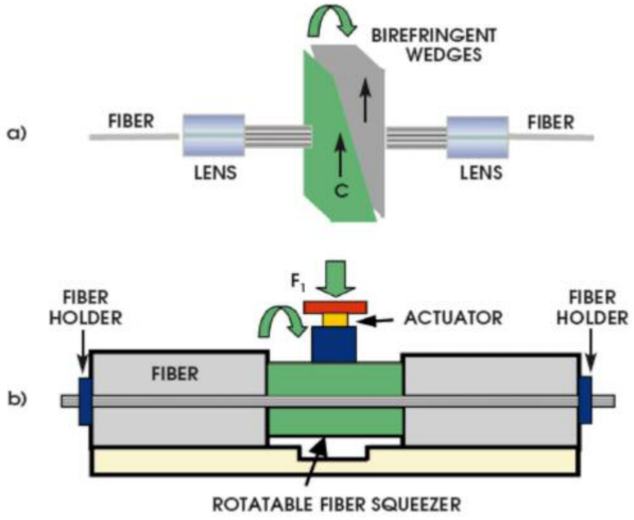

Figure 7. Polarization control using Babinet-Soleil compensator principle, a) with two birefringent wedges, and b) with a rotatable fiber squeezer.

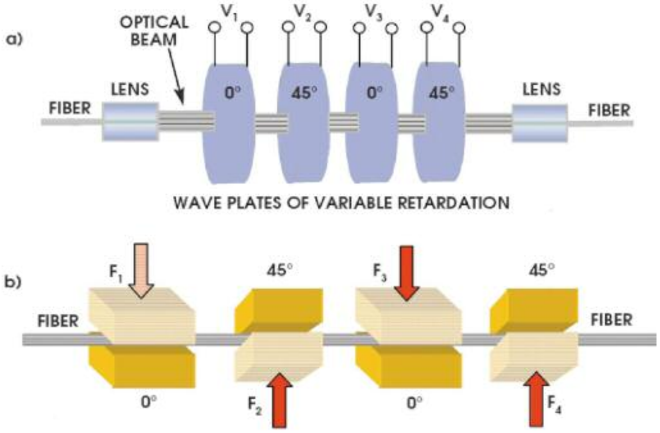

Figure 8. Polarization control by a) varying the retardation of multiple fixed wave plates, and b) squeezing fiber from various directions.

Scrambling of Polarization Modes

A polarization scrambler actively changes the State of Polarization (SOP) by modulating or randomizing polarization. The device can be operated either resonantly at higher scrambling frequencies or non-resonantly at lower scrambling frequencies. Using the fiber squeezing method, low residual phase modulation and residual amplitude modulation can be achieved. Low residual phase modulation is important for avoiding interference related noise in optical systems and low residual amplitude modulation is critical for using the scrambler for PDL and DOP measurement of optical devices.

The performance of the scrambler is generally measured by the degree of polarization of the scrambled light over a certain period of time and the uniformity of Poincaré Sphere coverage of the SOP. In practice, the wavelength sensitivity and temperature sensitivity of the performance of the scrambler are also important for real world applications.

Conclusion

In this application note, we briefly discussed fundamentals of fiber optic polarization, followed by an account of measurable properties and three methods with which to make such polarization measurement. For each method, advantages and disadvantages are discussed. Finally, we described three different methods of how to control polarization in fiber and their pros and cons.

References

[i] "What is Polarization?", 2005/06 General Photonics Catalog.

[ii] S. Yao, "Accurate DOP Characterization with Less Effort", 2005/06 General Photonics Catalog.

[iii] S. Yao, "Polarization in Fiber Systems: Squeezing out More Bandwidth", The Photonics Handbook, 2003, Laurin Publishing, 2003.

Newport Corporation
Worldwide Headquarters

1791 Deere Avenue
Irvine, CA 92606

(In U.S.): 800-222-6440
Tel: 949-863-3144
Fax: 949-253-1680

Internet: sales@newport.com

Newport
Experience | Solutions

Visit Newport Online at: **www.newport.com**

ISO 9001
FM 27207

Newport Corporation, Irvine, California, has been certified compliant with ISO 9001 by the British Standards Institution.

Spectra-Physics
A Division of Newport Corporation

In 2004 Spectra-Physics including Oriel Instruments, Richardson Gratings, Corion Filters, and Hilger Crystals was acquired by Newport.