

## Scrambling to Minimize Polarization Related Impairments

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### Polarization Fundamentals

Polarization is a fundamental property of light. In classical physics, light is modeled as a sinusoidal electromagnetic wave in which an oscillating electric field and an oscillating magnetic field propagate through space. Polarization is defined in terms of the pattern traced out in the transverse plane by the electric field vector as a function of time.

For unpolarized light, the plane of polarization fluctuates randomly around the direction of light beam propagation. Therefore, on average, no direction is favored. The rate of the fluctuation is so fast that an "observer" or a detector cannot tell the state of polarization (SOP) at any instant in time. For example, natural light (sunlight, firelight, etc.) is unpolarized. In any other case, the light beam can be considered to consist of partially polarized or fully polarized light. Degree of Polarization (DOP) is used to describe how much of the total light intensity is polarized. For totally polarized light, the DOP is one. For completely unpolarized light, the DOP is zero. Most high performance lasers used in long-haul communication systems are polarized light sources.

The polarization of light beams is an important factor in high-speed optical communication network system design. As the bit rate increases, fiber optic communication systems become increasingly sensitive to polarization related impairments. Such impairments include polarization mode dispersion (PMD) in optical fibers, polarization dependent loss (PDL) in passive optical components, polarization dependent modulation (PDM) in electro-optic modulators, polarization dependent gain (PDG) in optical amplifiers, polarization dependent center wavelength (PDW) in WDM filters, polarization dependent response (PDR) in receivers, and polarization dependent sensitivity (PDS) in sensors and coherent communication systems.

Polarization scrambling can be used to mitigate many polarization related impairments. Light is called "scrambled" if the SOP of totally polarized light is made to vary randomly at a relatively low rate. At any instant of time, the SOP is well defined, and DOP is close to 1. However, on a time average, DOP is close to zero. Therefore, the DOP of scrambled light depends on the averaging time or the detection bandwidth of the observer.

### Principles of Polarization Scrambling

A polarization scrambler actively changes the SOP using polarization modulation methods. Several polarization scramblers based on different technologies are available today, including LiNbO<sub>3</sub> based scramblers, resonant fiber coil based scramblers, and fiber squeezer based scramblers.

LiNbO<sub>3</sub> scramblers use the electro-optic effect to modulate the state of polarization. For example, a LiNbO<sub>3</sub> phase modulator can be used as a scrambler when the input SOP is linearly polarized at 45 degrees with respect to the applied modulation electric field. Such a scrambler is high speed, but it suffers from high insertion loss, high PDL, high residual amplitude modulation (activation loss), high sensitivity to input polarization state, and high cost due to insertion of a waveguide in the fiber line. Multiple modulation sections with different electric

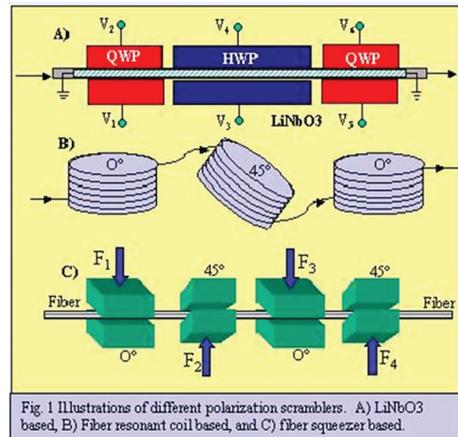


Fig. 1 Illustrations of different polarization scramblers. A) LiNbO<sub>3</sub> based, B) Fiber resonant coil based, and C) fiber squeezer based.

field directions, as shown in Fig. 1A, may be used to make the device less polarization sensitive but at the expense of increased complexity and additional cost.

A resonant fiber coil based scrambler is constructed by winding fiber around an expandable piezo-electric cylinder. Applying an electric field to the cylinder causes it to expand, which in turn induces a birefringence in the fiber via the photoelastic effect. If the frequency of the electric field is in resonance with the piezo-electric cylinder, the induced birefringence will be large enough to cause sufficient polarization modulation with a relatively low applied voltage. In practice, multiple fiber cylinders with different orientations may be cascaded to make the scrambler less polarization sensitive, as shown in Fig. 1B. Compared with LiNbO<sub>3</sub> scramblers, the expanding fiber coil based scramblers have the advantages of low insertion loss, low PDL, and low cost. On the other hand, they suffer from large size, low scrambling speed, and large residual phase modulation resulting from the significant amount of fiber stretching when the fiber coil expands.

Squeezing fiber can induce large birefringence in the fiber via the photo-elastic effect, and can cause large polarization modulation if the input polarization is 45 degrees from the squeezing axis. A polarization insensitive scrambler can be constructed by cascading multiple fiber squeezers oriented 45 degrees from each other, as shown in Fig. 1C. The device can be operated either resonantly at higher scrambling frequencies or non-resonantly at lower scrambling frequencies. Compared with the LiNbO<sub>3</sub> scrambler, this device has the benefit of low insertion loss, low PDL, and low cost. Compared with the fiber coil scrambler, it has the advantages of small size, low residual phase modulation, and scrambling flexibility. In addition, it has the advantages of low residual phase modulation and residual amplitude modulation (activation loss) over both the LiNbO<sub>3</sub> and fiber coil scramblers. 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. Fig. 2A illustrates a fiber squeezer polarization scrambler board for OEM applications.

The performance of the scrambler is generally measured by the degree of polarization of the scrambled light over a certain period of time, and by the uniformity of the 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.



Fig. 2 A polarization scrambler board made with fiber squeezers

Fig. 3A shows the excellent scrambling uniformity on the Poincaré Sphere of the scrambler board in Fig. 2, while Fig. 3B shows its DOP as a function of detector bandwidth. The wavelength sensitivity is illustrated in Fig. 3B. As can be seen in Fig. 3C, a multi-stage fiber squeezer scrambler is much less sensitive to wavelength changes than other types of scramblers. Experimental results also indicate that the fiber squeezer scrambler is less sensitive to temperature change, as shown in Fig. 3D.

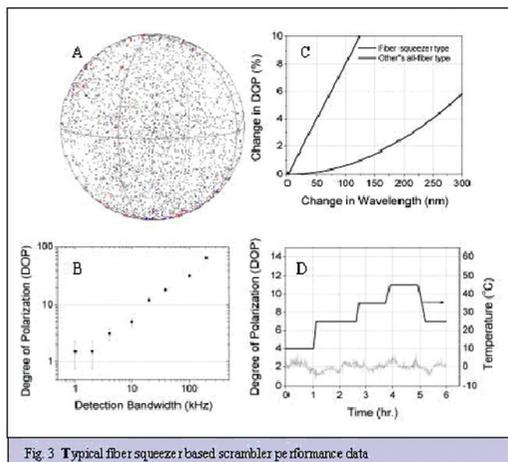


Fig. 3 Typical fiber squeezer based scrambler performance data

Operation lifetime is always an important parameter to consider for system and industrial applications. Some users may question the lifetime of the fiber under stress in the fiber squeezers. Indeed, without proper treatment and protection, the fiber may break in a short period of time. General Photonics has spent a great deal of effort in finding fiber failure mechanisms under stress and corresponding methods for protection since 1996. With our proprietary and patented fiber protection methods, the fiber in our squeezer under maximum operation stress has an estimated mean time to failure (MTTF) of 2 billion years. Such a result is not surprising, considering that the stress in a PM fiber induced by the two stress rods is on the same order of magnitude as the stress applied to the fiber by the fiber squeezer. In our continued endurance test, the fiber squeezers have passed one trillion ( $10^{12}$ ) activation cycles, and the number is expected to rise as the test continues.

There are a number of companies that manufacture different types of polarization scramblers, including a stand-alone desktop instrument type made by ILX Lightwave (Model PSC 8420), a plug-in module type by EXFO (model IQS-5100B) as a part of a main-frame test instrument, and finally, board level scramblers designed for low cost system & OEM applications by General Photonics (model PCD-003/004). These scramblers have their own intended markets and their own advantages. What type is best suited for a particular user depends on the application, user preference, and budget.

Scramblers can also be classified by driving frequency. For fiber squeezer based scramblers, the driving frequencies of the different squeezers are different. To obtain the best results, they should not be harmonics or sub-harmonics of each other. The driving frequencies of some scramblers are factory-set and cannot be changed. Therefore, the scrambling rate for such scramblers is fixed. Such scramblers are generally designed for the highest possible scrambling rate by using the resonant nature of the piezo-electric transducers. In addition to such resonant-frequency scramblers, General Photonics has also designed a miniature scrambler for hand-held and field instruments. The scrambling rate of the miniature scrambler can be easily changed in steps from a few hertz to a few tens of kilohertz either by a push-button switch or via a computer command.

Polarization scramblers have numerous applications in optical communication networks, fiber sensor systems, and test and measurement systems. As shown in Fig. 4A, a polarization scrambler can be used at the transmitter side to minimize PDG or polarization hole burning of Erbium doped fiber amplifiers (EDFA) in ultra-long haul systems. For this application, the scrambling rate should be significantly faster than the inverse of the gain recovery time constant of the fiber amplifiers (on the order of 10 kHz).

Scramblers can also be used to assist in the monitoring of PMD in a WDM system, as illustrated in Fig. 4B. Generally speaking, PMD can be monitored by measuring the degree of polarization

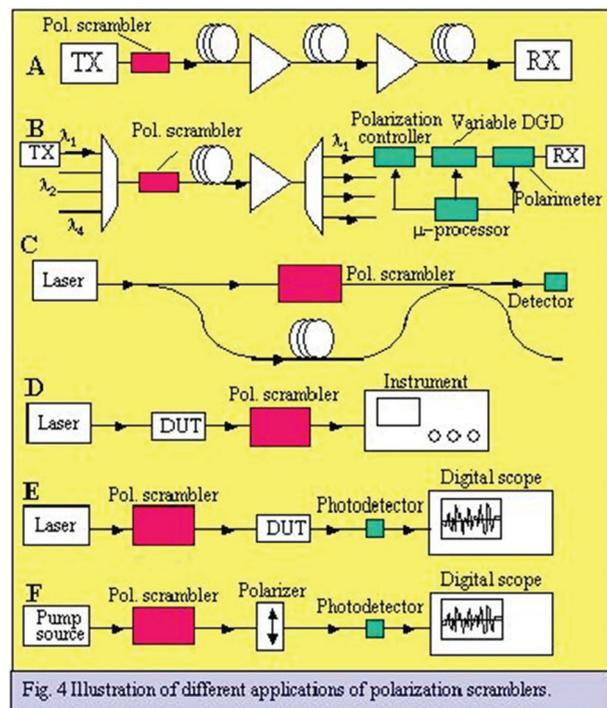


Fig. 4 Illustration of different applications of polarization scramblers.

INSTRUMENTS	<p>(DOP) of the optical data stream propagated through the fiber. Low DOP usually indicates a large PMD effect. However, such a measurement may be erroneous if the input SOP to the transmission fiber is substantially aligned with the principal state of polarization (PSP) of the fiber. In such a situation, the measured DOP is always large no matter how large the differential group delay (DGD) between the two principal states of polarization. A scrambler at the transmitter side can be used to effectively eliminate such an anomaly. Furthermore, it enables a polarimeter in the PMD compensator at the receiver side to identify the PSP, which in turn speeds up PMD compensation. Other optical network applications include signal to noise ratio monitoring of WDM channels with a polarizer placed after the scrambler.</p>	<p>polarimeter-based polarization analyzing instruments; however, such instruments are not accurate for low DOP (&lt;5%) sources. Polarization scramblers, again, can be used to accurately measure the DOP with a digital scope, as illustrated in Fig. 4F. Assuming that the maximum and minimum voltages measured with the digital scope are <math>V_{max}</math> and <math>V_{min}</math>, respectively, the DOP of the light source can be calculated using the following formula:</p>
MODULES	<p>Polarization scramblers can also be used to eliminate the polarization fading of a fiber sensor, as shown in Fig. 4C. In such a system, the envelope of the response curve is independent of the polarization fluctuation.</p>	$DOP = (V_{max} - V_{min}) / (V_{max} + V_{min})$ <p>In summary, a polarization scrambler is an important device for fiber optic communications, fiber sensors, and fiber optic test and measurement applications. With low insertion loss, low back reflection, low residual amplitude and phase modulation, low wavelength and temperature sensitivity, low cost, and small form factor, fiber squeezer based scrambler modules are especially well suited for OEM applications, where they can be readily integrated into various network equipment, fiber sensor systems, and test and measurement instruments.</p>
OCT PRODUCTS	<p>Placing a scrambler in front of a polarization-sensitive instrument, such as a diffraction grating based optical spectrum analyzer, can effectively eliminate its polarization dependence, as shown in Fig. 4D, if the scrambling rate is sufficiently faster than the detector speed in the instrument. In addition, as illustrated in Fig. 4E, polarization scramblers can be used to measure the PDL of a device under test (DUT) with the help of a digital scope. The resulting PDL of the device can be calculated as:</p>	<p>Suggested Readings:</p> <ol style="list-style-type: none"> <li>1. F. Heismann, S. Korotky, and J. Veselka, "Lithium Niobate integrated optics: selected contemporary devices and system applications", Ch. 9, Optical Fiber Telecommunications, IIIB, edited by I. Kaminow and T. Koch, Academic Press, 1977</li> <li>2. Steve Yao, "Have you hugged your fiber today?" Photonics Spectra, February 2001.</li> <li>3. L. S. Yan, et al, "Differential Group Delay Monitoring used as feedforward information for polarization mode dispersion compensation," Photonics Technology Letters, Vol. 14 (10) (2002)</li> <li>4. H. Rosenfeldt, Ch. Knothe, R. Ulrich, E. Brinkenmeyer, "Automatic PMD compensation at 40 Gbits/s and 80 gbits/s using a 3 dimensional DOP evaluation for the feedback", OFC 2001, Technical Digest Postconference Edition, March 2001.</li> </ol>
SPECIAL POLARIZATION COMPONENTS	$PDL = 10 \log (V_{max} / V_{min}),$ <p>where <math>V_{max}</math> and <math>V_{min}</math> are the maximum and minimum signal displayed by the digital scope.</p> <p>Raman amplifiers generally exhibit strong PDG if the pump laser is highly polarized. To minimize the PDG, a depolarized pump source must be used. The DOP of the pump source directly relates to the PDG of the amplifier, and therefore, must be carefully characterized. DOP can be measured using expensive</p>	
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