Accurate DOP Characterization With Less Effort

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Degree of Polarization (DOP) is an important property of light sources. It directly relates to the accuracy of optical component characterization, the sensitivity of sensor systems, and the quality of optical signals in optical communication systems. Therefore, the accurate and fast characterization of DOP is increasingly important. This article first reviews the fundamentals of DOP and summarizes the DOP properties of various light sources. It then describes different methods of DOP measurement, and compares their pros and cons. Finally, it describes some unique applications that an accurate DOP meter can offer for light source production, system monitoring, and quality assurance.

DOP describes how much of the total light power is polarized. Mathematically, it is defined as the power of the total polarized portion of a light beam divided by the total optical power (sum of the total polarized portion and the total unpolarized portion):

$$DOP = \frac{P_{polarized}}{P_{total}} = \frac{P_{polarized}}{P_{polarized} + P_{unpolarized}} \qquad (1)$$

The DOP of totally polarized light is unity, while the DOP of completely unpolarized light is zero.

Classification of Light Sources:

The DOP of different light sources ranges from 0 to 1. High DOP sources include DFB lasers and external cavity lasers. They are generally incorporated in laser transmitters in telecommunication systems, and are used as light sources in interferometers.

At the other end of the spectrum, amplified spontaneous emission (ASE) sources, light emitting diodes (LED), and super-luminescence light emitting diodes (SLED) represent sources with low DOP. Such low DOP sources are important to minimize polarization sensitivity in sensor applications. For example, SLED and ASE sources are ideal for the fiber gyro, a rotation sensor for measuring the rate and degree of rotation of an object. Low DOP sources are also attractive for accurate characterization of optical components, because they can remove PDL effects in the measurement system, including the polarization sensitivity of photodetectors. Therefore, accurate characterization of the DOP of these light sources is extremely important for both optical component manufacturers and users.

Optical amplifiers are critical devices in fiber optic communication and sensing systems. One of the important parameters of the amplifiers is low polarization sensitivity. Unfortunately, both Er^{3+} doped amplifiers and Raman amplifiers have polarization dependent gain (PDG). In particular, the PDG of Raman amplifiers can be much stronger than that of Er^{3+} amplifiers.

Raman amplifiers are based on stimulated Raman scattering of optical signals by optical phonons excited by a pump laser in an optical fiber. A weak optical signal is amplified by stimulating the excited phonons to release energy into the signal. This process is called stimulated Raman scattering. PDG is particularly strong for Raman amplifiers because in stimulated Raman scattering, an incident photon can only stimulate a phonon contributed by a pump photon of the same polarization. Raman gain is the strongest when the polarization of the signal is aligned with that of the pump, but is negligible if the polarization of the signal is orthogonal to that of the pump.

One effective method to minimize the PDG or polarization sensitivity of a Raman amplifier is to pump it with depolarized laser sources. A depolarizer may be used to convert a polarized pump laser into a depolarized source with DOP close to zero, as shown in Fig. 1. Such a depolarizer can be made with birefringent crystals, PM fibers, or other methods. Alternatively, a polarization beam combiner can be used to obtain a nearly unpolarized light beam by combining two laser sources of similar frequency but orthogonal polarization, as illustrated in Fig. 1.

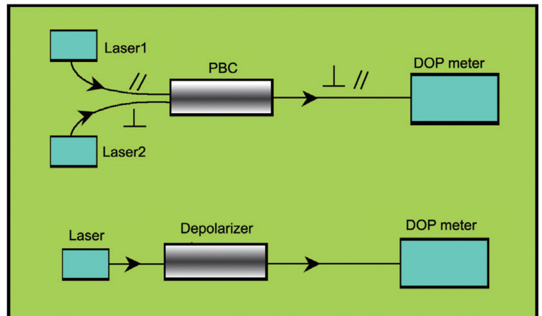

Fig.1. Monitoring DOP of depolarized pump sources for Raman amplifiers. Upper: Depolarization by polarization combining. Bottom: Depolarization with a depolarizer.

Because the DOP of pump sources directly relates to the polarization sensitivity of the amplifier, accurate characterization of their DOP is of paramount importance for Raman amplifier manufacturers. For example, the DOP of the combined pump source critically depends on the power balance between the two orthogonally polarized pump lasers, so a fast, inexpensive DOP meter is desirable for the live adjustment of the pump lasers on the manufacturing floor.

DOP Measurement Methods

Polarimeter method

DOP may be measured with a traditional polarimeter, an instrument that fully characterizes the polarization properties of light sources, using the four Stokes parameters S_0, S_1, S_2, and S_3. Fig. 2 illustrates two polarimeter configurations. The first is based on a rotating waveplate and a polarizer, while the second is based on separating the incoming light beam into four beams so that each beam is analyzed with an analyzer of a different orientation.

Fundamentally, the Stokes parameters fully define the polarization characteristics from power measurements only:

$$S_0 = P_o \ (polarized + unpolarized) \qquad (2a)$$

$$S_1 = P_x - P_y \qquad (2b)$$

$$S_2 = P_{45} - P_{-45} \qquad (2c)$$

$$S_3 = P_L - P_R \qquad (2d)$$

where P_0 is the total power, and P_x, P_y, P_{+45}, P_{-45}, P_R, P_L are the powers along the x-axis, y-axis, +45˚ axis, -45˚ axis, right hand circular axis, and left hand circular axis, respectively.

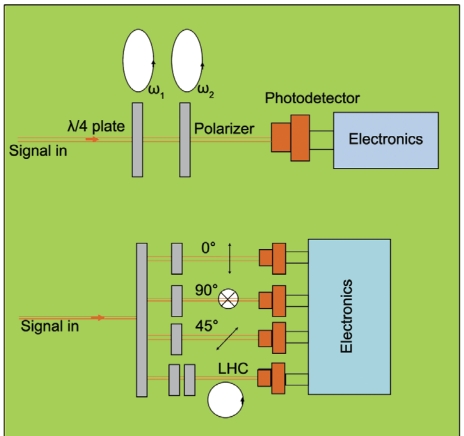

Fig. 2. Polarimeter constructions. Upper: Rotating waveplate polarimeter. Bottom: space division polarimeter.

The DOP of the light beam is related to the Stokes parameters by the following formula:

$$DOP = \sqrt{S_1^2 + S_2^2 + S_3^2} \Big/ S_o \qquad (3)$$

For completely unpolarized light, all SOP states exist, so that $P_x = P_y = P_{45} = P_{-45} = P_L = P_R$. Consequently, S1, S2, and S3 are all theoretically zero. However, in reality, uncertainties due to detector noise, digital noise, signal power fluctuation, rotating optics' repeatability, gain balances between analyzing channels, imperfections of the optical elements inside the polarimeter, and wavelength dependence of the elements all cause measurement errors for each Stokes parameter. From Eq. 2, the DOP is just the root-mean–square of the last three Stokes parameters, normalized by the total optical power S_0. Therefore, errors in Stokes parameters add up to signify the error in DOP measurement. As a rule of thumb, the polarimeter is less accurate in measuring low DOP light sources. Other disadvantages of the polarimeter method include high cost, wavelength sensitivity, cumbersome calibration requirements, and complexity of operation.

Polarization scrambling method

Another commonly used method is the scrambling method, in which a polarization scrambler is placed in front of a polarizer and a photodetector, as illustrated in Fig. 3.

Ideally, at some points during the scrambling cycle, the polarized portion of the signal will either be aligned or orthogonal to the polarizer's passing axis. When aligned, all of the polarized portion passes through the polarizer, corresponding to a maximum power level at the photodetector. When orthogonal, the polarized portion is blocked by the polarizer, assuming that the extinction ratio of the polarizer is sufficiently high, corresponding to a minimum power level at the photodetector. Therefore, the difference P_{max}-P_{min} equals $P_{polarized}$ in Eq. (1).

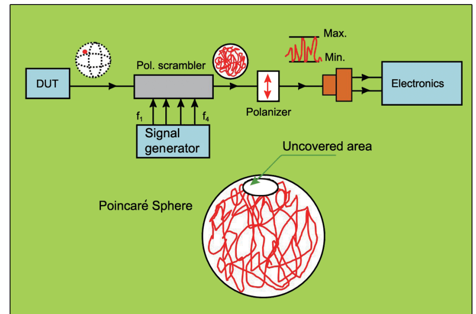

Fig. 3. Upper: DOP meter based on the polarization scrambling method. Bottom: SOP Poincare Sphere traces showing uncovered area of SOP.

The unpolarized portion, on the other hand, is not affected by the scrambler. Its contribution to the total detected power is constant, but reduced by half by the polarizer. Because the contribution of the polarized portion is zero at P_{min}, $P_{min} = P_{unpolarized}/2$. The DOP from Eq. (1) then can be calculated as:

$$DOP = (P_{max} - P_{min})/(P_{max} + P_{min}) \qquad (4)$$

Therefore, the DOP of the signal can be easily determined by measuring the maximum and minimum power levels at the detector while scrambling the incoming signal.

However, in order for the method to be practical, the scrambler must first be sufficiently fast to cover the whole Poincaré Sphere in a short period of time. Second, the scrambler itself must have negligible activation loss (the maximum insertion loss variation during scrambling). Finally, the detection electronics must be fast and accurate enough to correctly detect the maximum and minimum power levels.

Scramblers with activation loss less than 0.01 dB are available off the shelf from General Photonics. The 0.01 dB activation loss contributes to a negligible DOP error of 0.12%. Electronics can also be made to satisfy the speed and accuracy requirements. However, no matter how fast and uniform the scrambler is, the Poincaré Sphere cannot be completely covered in a finite time. There will always be uncovered areas (as shown in the bottom portion of Fig. 3), which contribute to the DOP measurement uncertainty. The faster the measurement requirements, the larger the uncertainty. Such uncertainty makes the scrambling method less accurate, especially for measuring light sources with high DOP. However, for low DOP values, the requirements for coverage of the Poincaré Sphere are less stringent, and therefore the scrambling method is more accurate and faster than the polarimeter. In addition, compared with the polarimeter method, it has the advantage of wavelength insensitivity, calibration free operation, high power capability, simplicity, and low cost.

Maximum/minimum search method

To remove the measurement uncertainty in the polarization scrambling method, General Photonics invented and implemented a deterministic maximum and minimum search method. As illustrated in Fig. 4, a feedback circuit is used to direct the polarization controller to adjust for the maximum and minimum power levels in the detector. Instead of trying to hit the right polarization states by luck, as in the scrambling method, the maximum/minimum search method assures that the instrument unmistakably finds P_{max} and P_{min}, and then uses them in the final DOP calculation in Eq. 4.

Because only two points on the Poincaré Sphere are required, and can be found deterministically and precisely, measurement speed

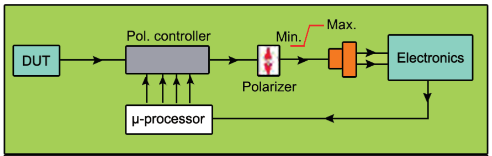

Fig. 4. DOP meter based on the active maximum and minimum search method.

and accuracy are guaranteed for both low and high DOP sources. 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). Fig. 5 is a photo of General Photoncs' DOP meter.

Fig. 5. Photo of a max/min search method based DOP meter by General Photonics.

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 method, including wavelength insensitivity, calibration free operation, high power capability, easy operation, simple construction, and low cost. In addition, it also enjoys the edge of high measurement speed (less than 0.2 seconds).

High-power handling approaches

The optical powers of different light sources vary dramatically, ranging from microwatts for LEDs to watts for pump lasers. However, typical DOP meters have a dynamic range on the order of 30 dB. Users may specify their intended power range, e.g., from –30dBm to 0 dBm, or from –10 dBm to 20 dBm. For high power light sources, such as Raman pump lasers with powers up to 500 mW, fixed attenuators may be used. To preserve the DOP accuracy, these attenuators must have low PDL, because PDL generally repolarizes the light source. As a good estimation, the DOP error introduced by a PDL source when measuring an unpolarized source is

$$DOP\,(\%) = 12 \cdot PDL\,(dB) \qquad (5)$$

For example, the DOP error introduced by an attenuator with a PDL of 0.1 dB is 1.2%.

Other applications

In addition to being able to simply determine the DOP value, an accurate and fast DOP meter is also important on the manufacturing floor for tuning the DOP values of light sources. For example, by monitoring DOP in real time while adjusting the power balance of the two pump lasers in Fig. 1, an extremely low DOP value for the Raman pump can be achieved. Polarimeters are generally too expensive to be used in production stations, too complicated to operate for less sophisticated production personnel, and not accurate enough for so demanding an application. By contrast, due to its low cost, simplicity to operate, and high accuracy, the DOP meter based on the max/min. search by General Photonics is ideal for such applications.

Besides measuring the DOP of light sources, a high-speed DOP meter can also be used in optical networks to monitor PMD or optical signal to noise ratio (OSNR), as illustrated in Fig. 6. Because PMD in an optical system degrades the DOP of the optical signal, monitoring the DOP directly reveals the influence of PMD on optical signals.

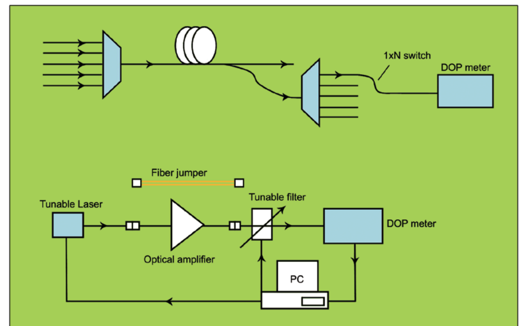

Fig. 6. Additional applications of DOP meters. Upper: PMD or OSNR monitoring in networks. Bottom: Noise figure measurement of amplifiers.

In the absence of PMD influence, OSNR can also be obtained from DOP measurement by (assuming signal is totally polarized and noise is totally unpolarized):

$$\begin{aligned} OSNR &= 10\ \mathrm{Log}\ [(P_{max} - P_{min})/(2P_{min})] \\ &= 10\ \mathrm{Log}\ [DOP/(1-DOP)] \end{aligned} \qquad (6)$$

An accurate DOP meter can also be used to measure the noise figure of an amplifier, as shown in Fig. 6. One may first measure the OSNR of the signal source without the amplifier ($OSNR_0$) by inserting a jumper in the place of the amplifier, and then measure the OSNR of the signal after the amplifier ($OSNR_{amplifier}$). The noise figure of the amplifier is simply the difference between the two OSNR measurements, in dB. In practice, noise figure is generally given within a 0.1 nm bandwidth; therefore, the effects of the bandwidth and shape of the filter need to be taken into account in determining the final OSNR value. With the aid of a computer, the wavelength dependence and power dependence of the noise figure can also be determined.

In summary, the DOP meter is an important instrument for accurate characterization of the DOP values of different light sources for communication, manufacturing, testing and sensing applications. The newly developed DOP meter based on the maximum and minimum power search method has the advantages of low cost, simple operation, high speed, and low wavelength sensitivity, and does not need calibration. It offers high accuracy for both high and low DOP values with less cost, less effort, and less measurement time.

The author would like to thank Drs. Y. Shi and J. Ma for helpful suggestions.