Introduction

The determination of polarization dependent loss has become a standard measurement when characterizing passive optical components. In optical networks, where polarization is not constrained and changes randomly, the PDL of components can accumulate in an uncontrolled manner. This effect can degrade the network transmission quality and even lead to network failure.

Two methods are widely used for testing passive components for polarization dependent loss: the Polarization Scanning Technique and the four-state method, usually referred to as the Mueller method. The Polarization Scanning Technique is an easy-to-implement measurement method providing high accuracy, and is fairly insensitive to operating conditions. However, it can allow measurement speed to become too slow if testing passive components for DWDM applications. In this case swept-wavelength PDL measurements based on the four-state or Mueller method result in much faster PDL measurements. On the other hand, the Mueller method demands greater care in order to achieve high accuracy and its implementation requires a greater effort than the scanning technique.

The present article explains and compares both measurement techniques, uncovers challenges and sources of uncertainties, and illustrates means to improve the measurement accuracy and their practical employment in today’s component test.
Polarization Dependent Loss

Polarization dependent loss (PDL) is a measure of the peak-to-peak difference in transmission of an optical component or system across all possible states of polarization. It is the ratio of the maximum and minimum transmission of an optical device with respect to all polarization states. The PDL is defined as:

$$PDL_{\text{db}} = 10 \log \left( \frac{T_{\text{max}}}{T_{\text{min}}} \right)$$

where $T_{\text{max}}$ and $T_{\text{min}}$ denote the maximum and minimum transmission through the device under test (DUT), respectively.

PDL has become critically important for the characterization of optical components. Practically every component exhibits a polarization dependent transmission. As polarization of the transmission signal is not constrained in fiber optic networks, the insertion loss of a component varies over polarization. The effect can grow in an uncontrollable manner along a transmission link with severe consequences for the transmission quality because the polarization changes randomly along a fiber. The PDL of individual components can cause large power fluctuations in the system which can increase the bit error rate of the system. It may even lead to a failure of the network. In combination with PMD, PDL can be a major source of pulse distortion and spreading.

Generally, the PDL of several concatenated components cannot be determined by adding the PDL of all individual components. The sum of the component’s PDL yields only the worst case PDL of the system. The actual overall PDL depends on the geometrical alignment of the individual components to each other, and the polarization transformation of the fibers between the components.

With wavelength-selective components for WDM networks, the PDL varies over wavelength, corresponding to the spectral transmission characteristics of the component. Also, some filter properties such as ripple or passband width can be polarization dependent. Hence, it is more and more required to determine the PDL over wavelength.

There exist two different classes of PDL measurement principles, deterministic and non-deterministic. The deterministic techniques derive the DUT’s PDL from its Mueller or Jones matrices, which are obtained by measuring the transmission properties of the DUT over a set of defined input polarization states, like for example in the Mueller method. The nondeterministic techniques measures the minimum and maximum transmission through the DUT over a large number of input polarization states.
Polarization Scanning Method

The polarization-scanning method is a non-deterministic method that is based on the actual measurement of the minimum and maximum transmission. The DUT is exposed to a large number of polarization states, which are generated either deterministically or pseudo-randomly. In the first case, the polarization states are deterministically generated along defined trajectories of the Poincare sphere. The latter technique covers pseudo-randomly a large part of the Poincare sphere.

The polarization-scanning technique is fairly easy to implement. A typical measurement setup uses a source, a polarization controller that generates different states of polarization deterministically or pseudo-randomly, and a power meter, as shown in Figure 1.

![Figure 1. Polarization Scanning technique using pseudo-random scanning of the Poincare Sphere.](image)

The polarization-scanning technique is a relative measurement, where the actual measurement captures the variations in optical power over time, while the polarization state of the incident light is changed. From the measured power values, the difference of maximum to minimum measured power determines the PDL. However, power measurement and polarization transformation are decoupled. It cannot be determined from the measured power values whether a change in power was caused by the DUT’s PDL or by a fluctuation in source output power.
Therefore, a high level of power stability is mandatory to obtain accurate measurement results. The PDL uncertainty is basically influenced by the following factors: The polarization sensitive response of the detector, the source power stability and degree of polarization, and the transmission variation over polarization of the polarization controller.

A detector with low polarization dependent responsivity must be used in order to keep its influence on the measurement small enough. A source with high degree of polarization is mandatory for PDL measurements. The polarization controller changes the state of polarization of the polarized fraction of the light, but does not affect the unpolarized part. Therefore, any unpolarized fraction of the light is transmitted independent of the DUT’s PDL. The optical power meter cannot detect the PDL if the DUT is exposed to unpolarized light.

Finally, the polarization controller exhibits some polarization dependent loss variation over polarization. In case of deterministic scanning of the Poincare sphere, the transmission variation through the polarization controller could be captured and calibrated. In case of pseudo-random generation, the accuracy of the measurement relies on low loss variation of the polarization controller across all states of polarization.

The PDL uncertainty is therefore mainly influenced by the source power stability, the PDL of the receiver and the insertion loss variation of the polarization controller. The total uncertainty can be estimated as the root sum squared of the individual contributed uncertainties. Assuming a source power stability of 0.006 dB, an insertion loss variation of 0.004 dB and 0.004 dB PDL of the detector, the total uncertainty is then given with 0.008 dB.
The major source of systematic error comes from the fact that the scanning time, or measurement time, is finite. Therefore, the DUT is only exposed to a finite number of polarization states. The scanning time that is required to obtain a certain systematic error is related to the rate of change in polarization that the polarization controller can perform. The minimum angular step in scanning the Poincare sphere, which is correlated to the minimum achievable systematic error $\varepsilon_{\text{min}}$, is given by the product of the polarization controllers angular velocity of rotation $v$ and the averaging time $\Delta t$ of the power meter:

$$
\varepsilon_{\text{min}} = \frac{(v \Delta t)^2}{4\pi}
$$

The total measurement time, which depends on the power meter averaging time $\Delta t$ and the desired systematic error $\varepsilon$, is given by:

$$
T_{\text{total}} = \frac{\pi \Delta t}{2\varepsilon}
$$

As an example, assume that the desired systematic error is 0.1%, with a power meter averaging time of 1ms. Then, the total scanning time is $T_{\text{total}} = 1.5s$.

If the PDL of a DUT is measured over wavelength, the estimated scanning time goes linear with the number of wavelength points. Clearly, a spectral PDL measurement can easily become very time consuming for a large number of wavelength points. For example, performing a PDL measurement with the polarization-scanning technique over a wavelength range of 20nm with a step size of 10pm, i.e. 2000 datapoints, the time for the entire measurement is around 50min, given that the total scanning time per wavelength is 1.5s.

It is not unusual that the PDL must be obtained over a wavelength range with small resolution. For this case, the polarization scanning technique is inefficient. However, if for example the PDL is only desired at three wavelength points within the passband of a filter, such as the center and 3 dB bandwidth wavelengths, the polarization scanning method is attractive because of its simple implementation and small uncertainties.
The Mueller method is a deterministic method that derives the PDL of a DUT from its Mueller matrix. The Mueller method obtains the Mueller matrix through the measurement of the DUT’s transmission at only four well-defined states of polarization, for example at linear horizontal (LHP), linear vertical (LVP), linear +45 (L+45) and right-hand circular (RHC) polarized light.

The calculation of the PDL is based on Mueller-Stokes calculus, a means to analytically obtain the polarization transformation of a component or system. An incident lightwave, characterized by the Stokes vector $S_{in}$, interacts with the component. The output lightwave can be described by a second Stokes vector, $S_{out}$. The polarization transformation and loss properties of the component are denoted by the Mueller matrix, a 4x4 matrix:

$$S_{out} = M \times S_{in}$$

The above equation represents a set of four linear equations. To determine the PDL, only the first row coefficients $m_{11}, m_{12}$ of the Mueller matrix are required because $S_{out0}$ represents the total optical power. Any variations in optical power of the emerging light depending on the polarization of the incident light are apparent in the $S_{0out}$ coefficient:

$$S = m_{11}S_{0in} + m_{12}S_{1in} + m_{13}S_{2in} + m_{14}S_{3in}$$

One of the advantages of the Mueller–Stokes calculus is that the coefficients of the Stokes vector are measurable in terms of optical power. The optical input powers are denoted with $P_a, P_b, P_c,$ and $P_d$. The optical output powers are described as $P_1, P_2, P_3,$ and $P_4$. For simplicity, the wavelength dependence of all power values is omitted here. The above equation can be rewritten for all four polarization states as:

$$P_1 = m_{11}P_a + m_{12}P_b$$
$$P_2 = m_{13}P_c + m_{14}P_d$$
$$P_3 = m_{11}P_a + m_{12}P_b$$
$$P_4 = m_{13}P_c + m_{14}P_d$$
Determining all power values requires two steps:

1. Four reference measurements must be performed, one at each of the four polarization states. The reference measurements yield the optical input power $P_a$, $P_b$, $P_c$, and $P_d$.

2. Then, the DUT is inserted and the transmitted power $P_1$, $P_2$, $P_3$, and $P_4$ corresponding to the four polarization states is recorded.

Note that the reference and DUT measurement must be performed at the same conditions, such as wavelength and power, to ensure validity of the PDL calculation.

Solving this linear equation system for the first row coefficients of the Mueller matrix yields:

$$
\begin{bmatrix}
m_{11} \\
m_{12} \\
m_{13} \\
m_{14}
\end{bmatrix} = \begin{bmatrix}
\frac{1}{2} \left( \frac{P_1}{P_a} + \frac{P_2}{P_b} \right) \\
\frac{1}{2} \left( \frac{P_1}{P_a} - \frac{P_3}{P_b} \right) \\
\frac{P_3}{P_b} - m_{11} \\
\frac{P_4}{P_d} - m_{11}
\end{bmatrix}
$$

Rewriting the relationship between an arbitrary input Stokes vector and the total output power in terms of transmission then yields:

$$
T = \frac{S_{0\text{out}}}{S_{0\text{in}}} = \frac{m_{11}S_{0\text{in}} + m_{12}S_{1\text{in}} + m_{13}S_{2\text{in}} + m_{14}S_{3\text{in}}}{S_{0\text{in}}}
$$

The extreme of the above equation can be derived as:

$$
T_{\text{max}} = m_{11} + \sqrt{m^2_{12} + m^2_{13} + m^2_{14}} \\
T_{\text{min}} = m_{11} - \sqrt{m^2_{12} - m^2_{13} - m^2_{14}}
$$

Inserting $T_{\text{max}}$ and $T_{\text{min}}$ in the equation for PDL yields the desired result.

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1. For convenience, a vertical representation of the equation was chosen.
A typical measurement setup for PDL measurements using the Mueller method is shown in Figure 2.

The polarization controller consists of a polarizer, a quarter- and a half-wave retarder. The polarizer generates a linear polarization state. The retardation plates transform the linear input state into any other state of polarization, depending on their angular rotation relative to each other and to the input polarization set by the polarizer. The polarizer – retarder arrangement allows setting any polarization state deterministically.

Because the PDL is obtained by measuring the transmission at only four states of polarization, a tunable laser source capable of continuously tuning could be used to perform the wavelength dependent measurements in a swept manner. At each state of polarization, the transmission over wavelength is recorded. From the transmission data, the PDL over wavelength can be calculated following the above algorithm.

Before the measurements, the polarizer is aligned to the input polarization to reduce transmission loss through the polarization controller. The reference measurement records any wavelength and polarization dependence of the measurement setup, excluding the polarization dependent responsivity of the detector, which cannot be calibrated.
The polarization controller especially exhibits a varying transmission over wavelength and polarization. As the wavelength is changed, the polarization on the polarizer is changing periodically, resulting in an oscillating transmission over wavelength. Re-orienting the polarizer at each wavelength point to achieve maximum transmission would counteract the advantage of using swept wavelength measurement systems. Thus, the wavelength dependent transmission is captured in the reference measurement. Furthermore, the power variations that occur from one polarization state to another caused by the polarization controller are captured in the reference measurement.

Figure 3. Insertion Loss of one AWG-type filter channel, shown for the four states of polarization. The polarization dependent wavelength shift of the filter curves is clearly visible.
Clearly, the measurement principle of the Mueller Method posts several stringent requirements on the measurement setup to reduce the uncertainty in the measurement:

(1) The angular uncertainty of the polarization controller affects the measurement uncertainty.

(2) The tunable laser source must provide a high degree of wavelength accuracy and repeatability. The latter is especially important in two aspects: First, the wavelength dependent power variations through the polarization controller must be repeatable between reference and DUT measurements to completely eliminate it in the Mueller Stokes calculus. Second, a wavelength shift of the measured slope of a filter response between the four polarization states because of insufficient wavelength repeatability by the source induces PDL caused by the setup, not the device. As some devices such as AWG-type multiplexers/demultiplexers truly exhibit a polarization dependent wavelength shift of their filter curves as shown in Figure 3, the influence of the measurement setup can yield misleading results.

(3) The PDL of an AWG filter channel is shown in Figure 4. The PDL is correlated to the four loss measurement curves shown in Figure 3. The polarization dependent wavelength shift of the filter slope is strongly reflected in the PDL of the filter. At the wavelengths where all four curves cross each other, the minima in PDL are obtained. In this particular case, the shift in wavelength is exhibited by the DUT itself. However, similar PDL results are obtained if the measurements are not repeatable over wavelength even if the DUT does not exhibit any polarization dependence.

(4) Another crucial point for accurate PDL measurements is the fiber link between the source and the polarization controller. If the fiber is exposed to any environmental changes during a measurement, such as vibration, temperature change or movement, the state of polarization incident on the polarizer changes, resulting in a different spectral transmission pattern of the polarization controller. Consequently, the reference and DUT measurement show different influences of the setup, which can then not be eliminated in the calculation.

Figure 4. PDL of an AWG-type filter channel.
Single Scan Mueller Method

The aforementioned shortcomings are overcome by a newly introduced single scan Mueller Method. This method is based on a single-scan technique in which all measurement data are collected in a single wavelength sweep of the tunable laser. The measurement setup is shown in Figure 5.

Compared to the traditional Mueller Method setup shown in Figure 2 there are two important changes:

1. The polarization controller has been replaced by a polarization synthesizer which includes a polarization controller consisting of various waveplates and an in-line polarimeter which allows measuring the actual state of polarization of the optical signal. This polarization synthesizer is capable of switching the setting of the waveplates within few microseconds.

2. The power meter has been replaced by a high-speed power meter allowing fast sampling rates.
While the laser is sweeping, the polarization is switched with high speed to a set of four or six polarization states. High speed sampling ensures that the measurement data is collected accurately for every polarization state. Using six polarization states instead of four allows additional averaging and increases the accuracy of the measurement. The exact set of Stokes parameters for each polarization state is determined by the polarimeter which is integrated in the Polarization Synthesizer. The benefits of this technique include:

- High measurement speed – only one wavelength sweep required.
- Increased PDL measurement accuracy because there is only minimum uncertainty of the polarization states as these are measured during the sweep.
- Increased Loss measurement accuracy, because there is no polarizer in the polarization synthesizer causing a ripple of the power during the wavelength sweep.
- Insufficient wavelength accuracy does not contribute anymore to PDL uncertainty as all data are taken in a single sweep and therefore issues with mapping different sweeps are cancelled out.
- Minimized sensitivity to movements and drift of DUT during the measurement: As all measurement data are taken in a single sweep, drift and movement between multiple sweeps do not contribute to the measurement uncertainty anymore.

![Figure 6. Measurement taken on a multichannel device (Mux/DeMux) using the single scan Mueller method:](image)

*Top: loss characteristics  
Bottom: PDL (here shown as example for one selected channel)*
PDL measurements can be performed with deterministic and non-deterministic methods. The Mueller Method as well as the Single Scan Mueller Method belong to the class of deterministic measurement techniques, where the PDL of a component is determined from its Mueller or Jones matrices.

The polarization scanning method is a non-deterministic measurement technique, where the PDL is obtained by recording the power transmission variation of the DUT over polarization. From the power measurements, the minimum and maximum power yields the PDL.

Figure 7. PDL measurement of a WDM filter passband, comparing Polarization Scrambling and Mueller Method.

Despite using different approaches to determine PDL, all measurement techniques should yield similar, ideally equal measurement results. For comparison, a sample PDL measurement of a grating-based WDM filter using the polarization scanning and the Mueller method is shown in Figure 7.
The measurement time is very different for all techniques.

The polarization scanning time determines the PDL for each wavelength, thus the measurement time is linearly related to the number of wavelength points.

The Mueller Method, combined with a swept wavelength measurement setup, yields the PDL for all wavelengths simultaneously by taking a complete loss measurement over wavelength at each polarization state, thus requiring four wavelength scans to complete a PDL measurement.

The Single Scan Mueller Method uses only a single scan to complete a full PDL measurement and therefore shows the highest measurement speed.

In conclusion, if the PDL should be obtained for a large number of wavelengths, the Single Scan Mueller Method is preferred, because it is fast, combined with a largely reduced sensitivity to drift and movements. In contrast, the polarization scanning method is typically preferred if the PDL is required only at a few wavelength points.
References


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