

Comparative Study: Polarization Scrambling vs. Mueller Matrix Method in PDL Measurement

White Paper WP-101

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Introduction

In the dynamic field of photonics, the quest for precision and accuracy underscores the importance of robust testing systems. Among the myriad of parameters that these systems evaluate, Polarization Dependent Loss (PDL) stands out as a critical factor that significantly impacts the performance of optical components. PDL, a measure of the maximum change in loss that a component can exhibit for variations in the state of polarization, is an essential aspect to assess in order to maintain the quality and reliability of photonic systems.

This white paper aims to serve as a comprehensive guide to the PDL measurement process. Our aim is to deepen your understanding of PDL through a close examination of two prominent measurement methods - the Polarization Scrambling method and the Mueller Matrix method.

We will delve into the Mueller Matrix method, the preferred approach implemented in our PDL measurement device, unpacking the mathematical principles that underpin it. Our exploration will demystify the intricate calculations and equations integral to this method, providing a clear explanation of why it is widely recognized for its accuracy in PDL measurements.

Additionally, we will provide a brief overview of the key components in our system - the tunable laser source and power meter. Although we will not delve into technical specifics, this section will offer a clear understanding of how these essential components contribute to the overall measurement process.

Upon concluding this white paper, you will have a thorough understanding of PDL measurements, the methodology, and the technology behind it. Our comparative analysis will grant you a greater appreciation for the intricacies involved in measuring PDL, equipping you to make informed decisions for your photonics testing needs. Welcome to a comprehensive journey through the world of PDL measurement.

Background

At the core of efficient and precise photonic testing stands the Swept Test System (STS), a system meticulously crafted to meet the high-speed analysis, superior resolution, and precision requirements of photonic components testing. The STS, comprised of key elements including a tunable laser, an optical power meter, a polarization control unit, and custom software, provides a holistic solution suitable for a broad range of environments, from sophisticated research and development labs to demanding production settings.

One of the standout features of the STS is its real-time referencing capability. By synchronously measuring the tunable laser's output power and the power transmitted through the PD device Under Test (DUT), the STS ensures an unwavering accuracy of measurements.

Further enhancing its efficiency, the STS uses a blend of over-sampling and rescaling algorithms to speed up testing processes, all while maintaining the reliability and integrity of measurements. This intricate balance between speed and accuracy is a testimony to the thoughtful design and functionality of the system.

Unpacking the components of the STS, the tunable laser functions as an adaptable light source, crucial for testing photonic devices over a range of wavelengths. This flexibility enables thorough and versatile measurements. Paired with the tunable laser, the optical power meter is responsible for measuring the output from the laser and the power transmitted through the DUT. In some configurations, the power meter can team up with a 4-channel current meter module to evaluate the performance of various fiber optic components, adding another layer of versatility to the STS.

Understanding the mechanics and the individual components of the STS sets the foundation for appreciating the complex yet accurate process of PDL measurement using the Mueller Matrix method, the primary focus of this white paper. By the end of this paper, you will not only have a grasp of the STS but also a deeper understanding of why this system is crucial in the efficient and accurate measurement of PDL.

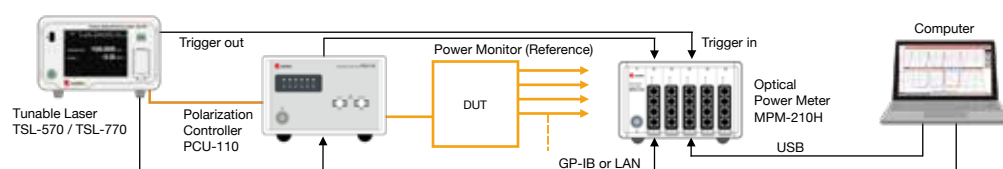


Figure 1: Santec Swept Test System with Polarization Controller (PCU-110)

Understanding Polarization Dependent Loss (PDL)

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Exploring PDL Measurement Techniques: Polarization Scrambling and Mueller Methods

Navigating the complex realm of Polarization Dependent Loss (PDL) measurement, we encounter two primary techniques: the Polarization Scrambling method and the Mueller method. Each approach possesses unique characteristics, offering advantages and posing challenges.

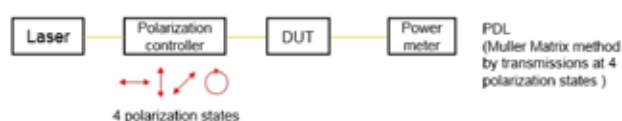
Polarization Scrambling Method

The Polarization Scrambling method, as its name suggests, works by randomizing the input signal to span the full range of polarization states. This wide-ranging scan ensures comprehensive coverage, capturing the nuances of various polarization states. It's especially known for its high accuracy, making it highly reliable for PDL measurement. However, a downside to this comprehensive technique is that it's somewhat time-consuming, which can be a significant consideration in high-output settings. It is particularly suitable for measurements at a single wavelength.



Mueller Method

The Mueller method, on the other hand, strikes a balance between speed, precision, and efficiency. This method measures the insertion loss using four well-defined input polarized waves—linear horizontal (LHP), linear vertical (LVP), linear +45 (L+45), and right-hand circular (RHC) polarized light—controlled by a polarization controller. The average insertion loss and PDL are then computed based on these measurements, utilizing the Mueller Matrix method.



What sets the Mueller method apart is its capacity to maintain high wavelength accuracy akin to the polarization scrambling method, while significantly reducing the measurement time. This is made possible by performing sweep measurements, which maintain high wavelength resolution. However, the catch lies in the necessity to adjust the setting of the polarization controller for each wavelength during wavelength sweep measurement.

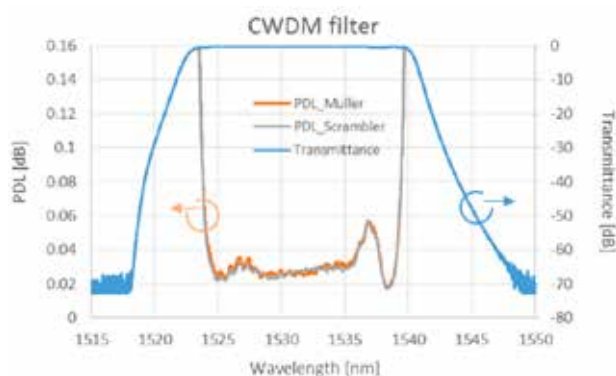
In the next chapter, we'll delve deeper into the mathematical principles underpinning the Mueller Matrix method. This detailed exploration will provide a more comprehensive understanding of the method's technical aspects and how it enables high-speed, precise PDL measurement.

Let's compare these methods side-by-side:

Method	Content	PDL accuracy	Measurement time	Wavelength
Polarization scrambling	Measurement power variation at all polarization state	Highest	Slow	Suitable for one wavelength
Mueller	Calculates at four polarization state's insertion loss	High	Fast	Suitable for sweep measurement

This chart gives a clear comparison between the Polarization Scrambling and Mueller methods in terms of their content, PDL accuracy, measurement time, and wavelength suitability.

To further illustrate these methods' performance, consider the following graph representing the PDL measurement result using a CWDM filter. The blue line represents the filter transmittance data (left y-axis), while the orange and gray lines represent the PDL for the Mueller and Scrambler methods, respectively (right y-axis). The x-axis represents the wavelength in nm.



As can be seen in this graph, the Mueller and Scrambler methods' outcomes (orange and gray lines) are almost identical, indicating comparable levels of accuracy. This visual representation emphasizes the efficacy of the Mueller method, suggesting that it can fulfill the required accuracy standards while offering faster results and being more suitable for sweep measurements. This data further illustrates how both methods interact with the filter transmittance (blue line) across various wavelengths, reinforcing the merits of each method in practical PDL measurement scenarios.

The complexity of these methods underscores the importance of a finely tuned system to perform these measurements. Specialized correction methods, such as those employed by Santec, can ensure high-accuracy PDL measurements even during wavelength sweep measurements, providing a reliable solution to this challenging task.

Math Behind PDL Measurement

In the realm of Polarization Dependent Loss (PDL) measurement, the Mueller method is not just about the steps taken but also the intricate calculations performed behind the scenes. Let's unravel this complex mathematics together.

The procedure starts by capturing reference measurements of optical input powers, denoted as P_a , P_b , P_c , and P_d , each associated with a different polarization state. The Device Under Test (DUT) is then introduced, and the transmitted powers, labeled as P_1 , P_2 , P_3 , and P_4 , are recorded for the corresponding polarization states.

The next stage involves a series of calculations to determine the Mueller matrix elements [m_{11} , m_{12} , m_{13} , m_{14}]. These elements, which form the basis for subsequent calculations, are derived from the transmitted powers and reference input powers, using the following equations:

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

With the Mueller matrix elements in hand, we can calculate the system transmission coefficient (T), a key step in understanding how light transmits through the device. This is calculated using the input and output Stokes vector (S_{0out} and S_{0in}) as follows:

$$T = \frac{S_{0out}}{S_{0in}}$$

This equation can be expanded to show T as a function of the input Stokes vector and Mueller matrix elements:

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

Once we have the system transmission coefficient, we can compute the maximum (T_{max}) and minimum (T_{min}) transmission coefficients. These are derived from the Mueller matrix elements using the following equations:

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

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

The final step in the calculations is to determine the PDL value in decibels (PDL_{dB}). This is achieved by comparing T_{max} and T_{min}, with the equation:

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

This calculation gives us the PDL value in decibels, which quantifies the polarization-dependent-loss of the DUT. By dissecting these mathematical operations, we get a glimpse into the underlying framework that powers the Mueller method for PDL measurement, providing a comprehensive understanding of the device's polarization-dependent characteristics.

Conclusion

Throughout this white paper, we've explored the technicalities and practicalities of Polarization Dependent Loss (PDL) measurement – a critical factor in the performance of optical components. We focused on comparing two prevalent techniques for this task: the Polarization Scrambling method and the Mueller method, each offering its unique strengths.

The Polarization Scrambling method, although time-consuming, offers the highest accuracy in PDL measurement by covering a wide spectrum of polarization states. On the other hand, the Mueller method strikes a balance between accuracy and speed, proving itself as a robust method for sweep measurements and ideal for high-output environments.

By integrating a comprehensive Swept Test System (STS) - inclusive of a tunable laser, optical power meter, polarization control unit, and custom software - we demonstrated how we can effectively employ the Mueller method for PDL measurements. The graphing example with a CWDM filter further illustrated that our Mueller matrix-based PDL measurement system stands at par with the Scrambler method while offering more efficiency and versatility.

In sum, this white paper not only aimed to provide a deeper understanding of PDL measurement but also endeavored to validate our commitment to delivering efficient, reliable, and high-quality solutions. We trust that this comparative exploration will serve as a valuable guide for your decision-making process and contribute to advancing your optical testing efforts.