Polarization Dependent Loss Measurement Application Issues in Telecommunications

Purpose

The purpose of this bulletin is to provide a brief introduction to measurement issues associated with polarization dependent loss in telecommunications systems. This bulletin is intended for both users and designers of telecommunications networks. This version of the document is prepared on behalf of the TIA Working Group 6.1, Fiber Optic Test, Measurement and Inspection Instrumentation.

What is Polarization Dependent Loss

High capacity optical networks are generally based on four fundamental elements: a source laser that produces coherent, polarized light [1], single-mode optical fiber (SMF), interconnecting components that preferentially pass certain polarizations and a photodetector whose response depends, to some extent, on that polarization. The polarization of the source light is the key to understanding the problems that arise from it. Polarization implies a definite direction and phase relationship between electric fields of a propagating wave. It is generally absent from most multimode networks using broadband sources such as light-emitting diodes, super-luminescent devices and spontaneous emission sources unless externally imposed. As it turns out, once imposed, polarization is difficult to erase (depolarize) in single-mode fiber. Lasers impose polarization from the outset. Now, unlike polarization-maintaining fiber (PMF) [2], single-mode fiber has no preferred axis that maintains a given launched state of polarization. Consequently, the state is allowed to "wander" and take on different values because of an effect known as "birefringence." Birefringence in SMF derives from the uneven distribution of refractive index in deployed cable induced by real-world stresses and bends. Polarization dependent loss (PDL) is the variation of transmitted power in single-mode fiberoptic networks as the state of signal polarization takes on all values.

Where is PDL Typically Found

While PDL is present to a small extent in optical fiber, it is primarily associated with localized interconnecting components and is due to several factors. These include: media-media interfaces such as glass-air angled with respect to incident power, oblique incidence reflections inside components, offset fiber cores at both connector and fusion junctions, fiber bending, and dichroic media within components.

Component	PDL (dB)	Notes
Optical connector	0.005 - 0.02	Normal contact
	0.02 - 0.06	Angled contact
50/50 "3 dB" coupler	0.1 – 0.2	Single wavelength type
	0.15 – 0.3	1300/1500 nm type
90/10 "10 dB" coupler	0.02	Through path
	0.1	-10 dB path
Directional isolator	0.05 – 0.3	
Three port circulator	0.1 – 0.2	Any output port
DWDM multiplexer	0.05 – 0.1	Any output port

Table 1: Commonly observed PDL values in components

PDL is defined as $10\log(T_{max}/T_{min})$ (dB) where T is the optical transmittance (or power) taken over the entire polarization-state space. The impact of PDL on network performance is increased signal distortion, and consequently, higher bit-error-rate (BER).   Some typical values given in Table 1 are seen in network components. PDL is usually characterized as a localized component effect as opposed to the distributed nature of polarization mode dispersion (PMD). However it interacts with PMD in nonlinear ways to dramatically increase system BER.

Visualizing the Polarization of Light and Polarization Dependent Loss

Though a further discussion of optical polarization is beyond the scope of this bulletin, perhaps the best way to visualize it is through a useful aid known as a Poincaré sphere, cf. Fig. 1. The Poincaré sphere

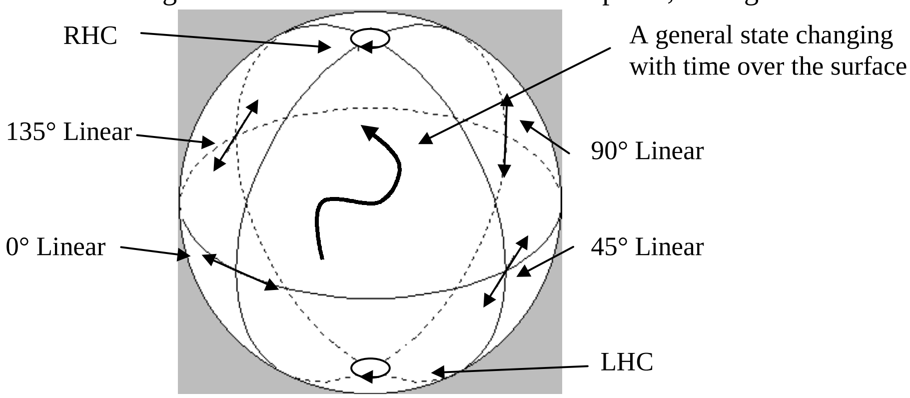

Figure 1: The Poincare sphere illistrated with key states

maps all states of polarization to the surface of a sphere wherein the north and south "poles" are mapped to right-hand circular (RHC) and left-hand circular (LHC) states respectively while the "equator" is

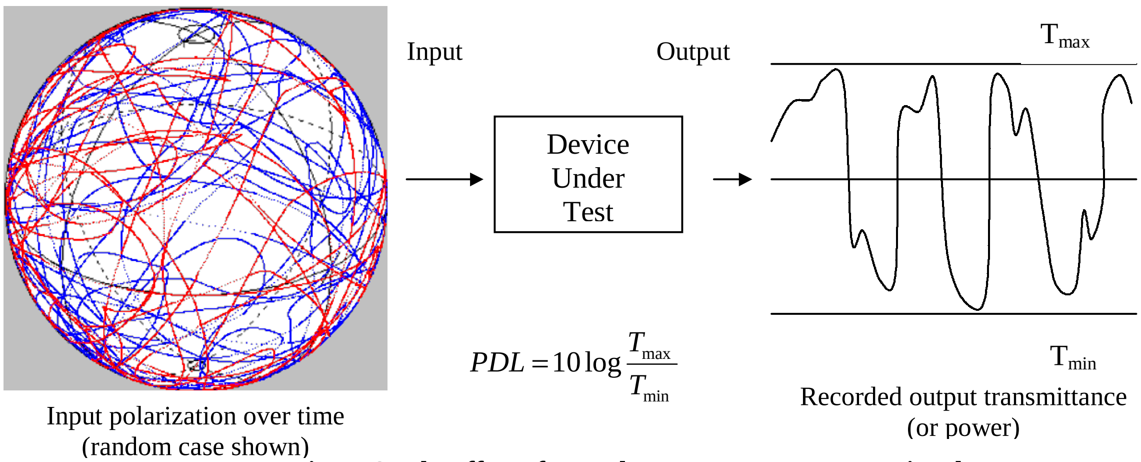

Figure 2: The effect of PDL due to a component on a signal

mapped to linear polarizations rotated through 360°, refer to reference [1] for more detail. We will use the Poincaré sphere to illustrate the differences between the various measurement methods.

The effect of PDL can be illustrated with the example of a "random walk" over the Poincaré surface and the subsequent effect on signal amplitude as in Fig. 2.

In fact, T_{max} and T_{min} represent opposite ends of an axis of the Poincaré sphere that passes through the origin. The goal then is to sample T_{min} and T_{max} as efficiently as possible by choosing a polarization modulation scheme that makes the best use of the equipment at hand.

PDL Measurement Methods

PDL measurement methods can be divided into two categories, both of which are represented by commercial instrumentation: all-states and fixed-states[1]. Both of these categories will be discussed first from the standpoint of single wavelength measurements and followed by disclaimers for swept wavelength measurements and measurements done in reflection. Optical source bandwidth should be appropriate for the component and wavelength range being tested. Fixed wavelength measurements of components with weak wavelength dependence can benefit from the low coherence of broad sources such as LED's while measurement of filter type devices and devices with strong wavelength dependence obvioulsly require (tunable) narrowband or laser sources.

<u>All-States Techniques</u>

Deterministic All-States

The term "deterministic all-states" refers to techniques that scan a large subset of the entire polarization-state space (as represented by the Poincaré sphere) in a repeatable way. This method scans the Poincaré sphere along predetermined trajectories to produce a good approximation of full sphere coverage as in Fig. 3. This may be done by continuously adjusting a quarter-wave /half-wave retarder pair in a well-defined phase relationship. An advantage of this approach is moderately high speed since the optics can be rapidly adjusted as long as the proper phase relationship is maintained. Accuracy, however, requires correction of wavelength dependence, and low internal PDL. Resolution is a function of the degree of sphere coverage and the signal-to-noise ratio. The polarization scanning method can be time consuming

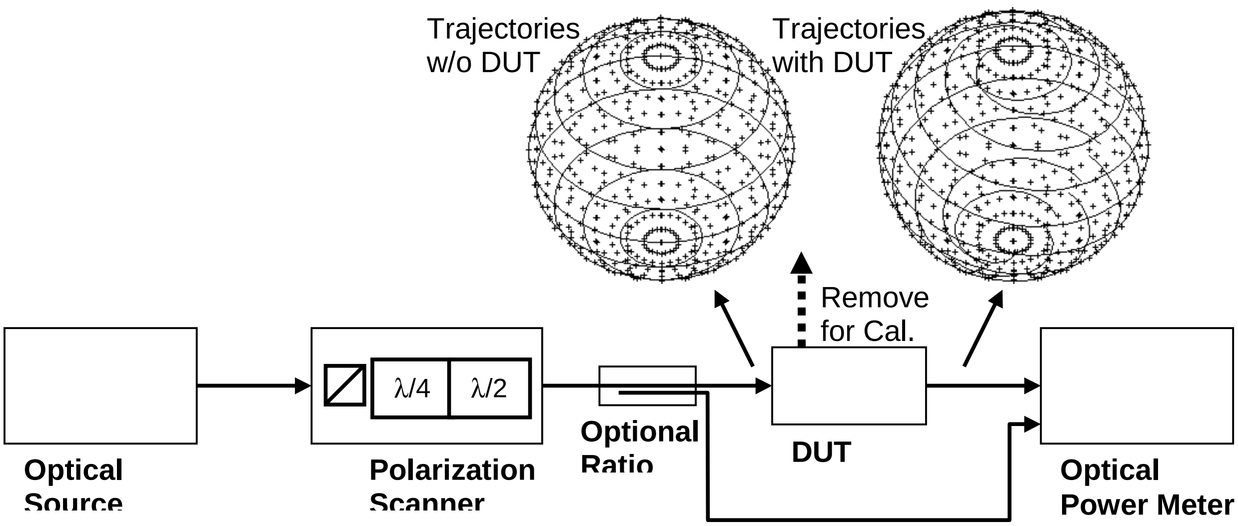

Figure 3:The polarization-scanning form of all-states measurement

even if an automated polarization controller and a fast power meter are used. This is especially true for wavelength dependent PDL measurements in broadband fiber optic components, since a large number of measurements must be obtained at each wavelength of interest to ensure measurement accuracy.

Calibration, Measurement and Calculation

Refer to Fig. 3 for the schematic of the deterministic all-states measurement. The polarization scanner used must be able to convert a fixed input polarization state from the optical source into all possible output polarization states that are sent through the DUT. The power meter and polarization controller as well must have low PDL contributions. A power calibration procedure is required to remove the PDL contributions of the polarization scanner and other optical components in the system. This is done by measuring the transmission variation through the whole system without the DUT versus polarization at each wavelength of interest. Next measure the transmission variation through the whole system with the DUT for the same polarization states at the same wavelengths. A polarization analyzer is helpful to monitor the input polarization states to ensure a pseudo-random rotation pattern to uniformly cover the whole Poincaré sphere after a certain scanning time. Subtracting the system transmission variations yields the wavelength dependent PDL of DUT using Equation (1).

$$PDL = \max\left[10\log\left(\frac{P_j^{DUT}}{P_j^{Cal}}\right)\right] - \min\left[10\log\left(\frac{P_j^{DUT}}{P_j^{Cal}}\right)\right](dB) \qquad (1)$$

Note that the optional ratio arm reduces the effect of source power variations and system wavelength dependence between the calibration and measurement runs so that the actual measured values are, in fact, ratios of the two power meter channels. The error dependence on run time is easily calculated and shown qualitatively below. It is important to realize that because of internal drift, extremely long scans may be counter-productive. For more information, refer to TIA FOTP-157

Pseudo-random All-States

The term "pseudo-random all-states" refers to techniques that span a large subset of the entire Poincaré sphere through a pseudo-random variation of retardance, usually the distributed retardance of optical fiber loops in motion [8], [10]. This method has the advantage of low system noise, weak wavelength dependence, and low internal PDL since the beam remains confined in a single-mode fiber. On the other hand, this is a statistical sampling technique with accuracy dependent on the sampling rate and sampling time. Resolution is fundamentally limited by both the signal-to-noise ratio and degree of Poincaré sphere coverage. Like the polarization scanning method, this approach too can be time consuming even if an

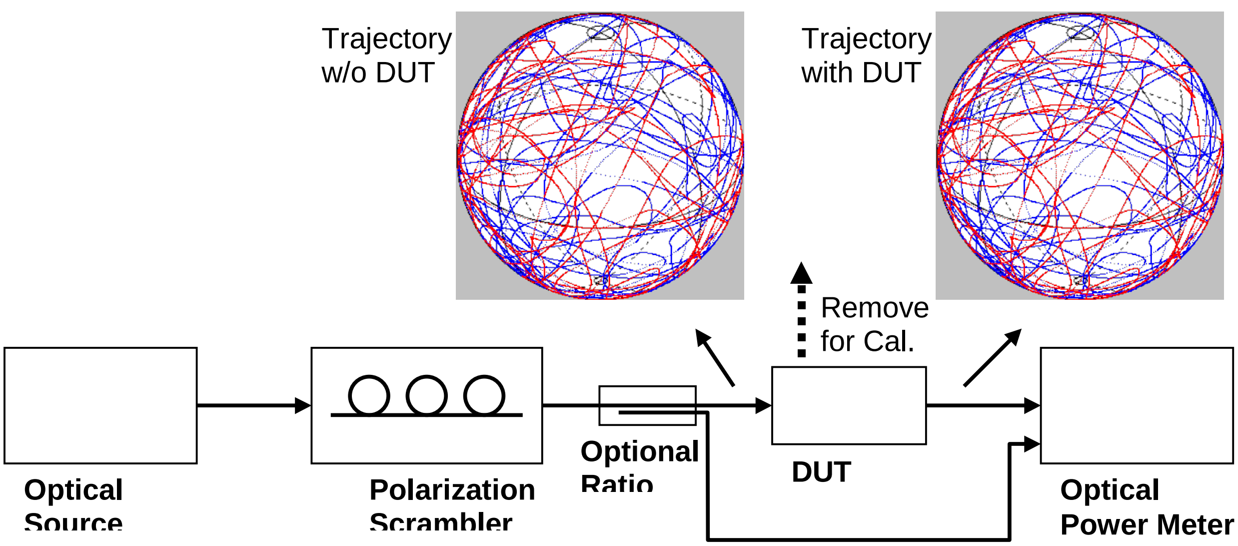

Figure 4:The polarization-scrambling form of all-states PDL measurement

automated polarization controller and a fast power meter are used. Again, this is especially true for wavelength dependent PDL measurements in broadband fiber optic components, since a large number of measurements must be obtained at each wavelength of interest to ensure measurement accuracy.

Calibration, Measurement and Calculation

Refer to Fig. 4 for the schematic of the pseudo-random all-states measurement. The polarization scrambler used must be able to convert a fixed input polarization state from the optical source into all possible output polarization states that are sent through the DUT. The power meter and polarization scrambler as well must have low PDL contributions. A power calibration procedure is required to remove the PDL contributions of the polarization controller and other optical components in the set-up. This is done by measuring the transmission variation through the whole system without the DUT versus polarization at each wavelength of interest. Next measure the transmission variation through the whole system with the DUT for the same polarization states at the same wavelengths. A polarization analyzer is helpful to monitor the input polarization states to ensure a pseudo-random rotation pattern to uniformly cover the whole Poincaré sphere after a certain scanning time. Subtracting the system transmission variations yields the wavelength dependent PDL of DUT using Equation (1). As before, the optional ratio arm reduces the effect of source power variations and system wavelength dependence between the calibration and measurement runs so that the actual measured values are, in fact, ratios of the two power meter channels. The error dependence on run time is easily calculated and an example is shown given Fig. 5 for the case of a commercial fiber-loop scrambler running at a rate that covers the sphere to 95% accuracy in 10 s. It is important to realize that because of internal drift, extremely long scans (minutes) may be counter-productive.

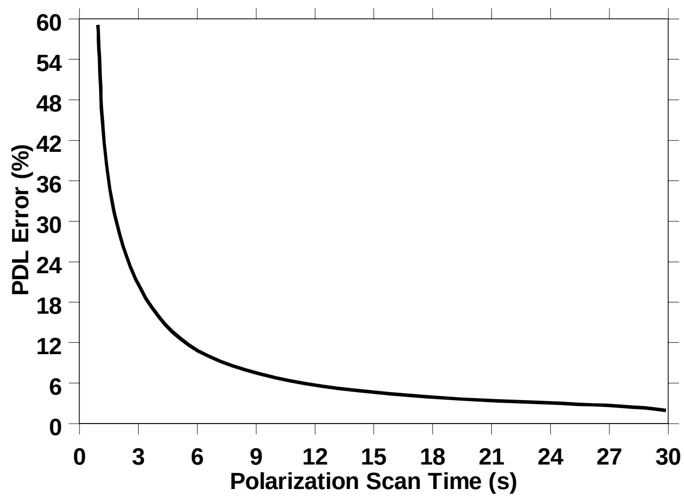

Figure 5:An example of PDL error as a function of scan time for an all-states measurement

Fixed-States Techniques

Mueller Matrix Method

The Mueller matrix method is a technique that employs only four orthogonal input states (fixed states) of polarization to derive global polarization dependence through matrix analysis. This technique typically employs bulk components in an open beam to set the states and measures power at each of the fixed input states. This method has the potential advantage of high speed and calibrated spectral dependence. Accuracy is subject to alignment precision as well as internal PDL. Resolution is not a function of sphere coverage but is fundamentally limited by the signal-to-noise ratio and drift in fiber birefringence.

Measurement and Calculation

Measurements using the Mueller matrix method require a two-step procedure consisting of a power calibration followed by a power measurement to obtain the PDL value of the DUT. First, the optical

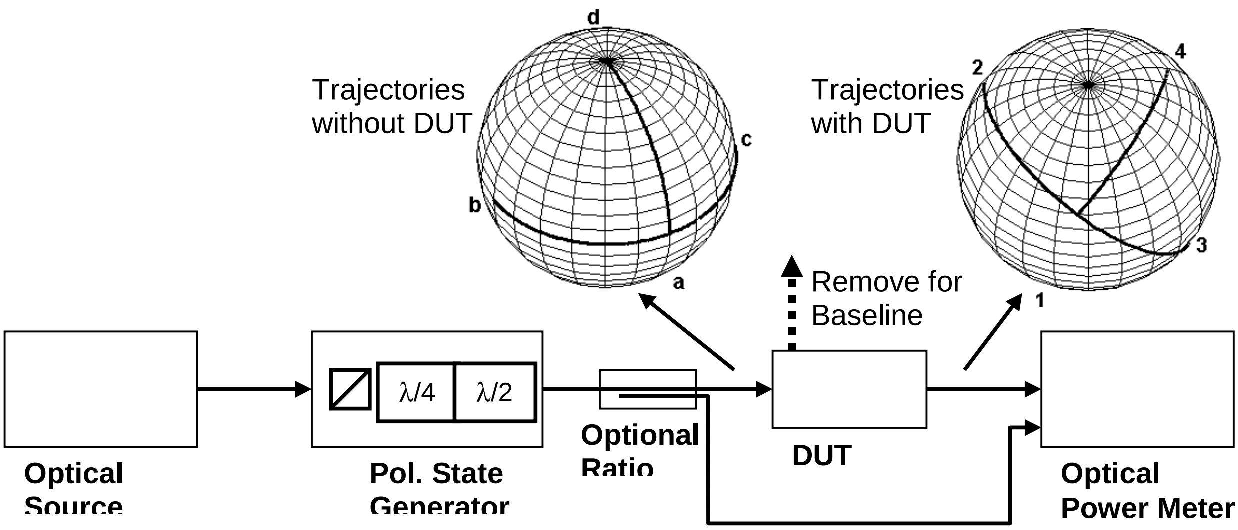

Figure 6:The Mueller matrix form of fixed-states PDL measurement

power is measured without the DUT, as in Fig. 6, at the four polarization states (a,b,c,d) to account for the power variations caused by the polarization controller (wave plates or variable retarders) from one state to another. Next, the optical power is measured with the DUT in place at states 1,2,3,4. A polarization analyzer can be used to verify the input polarization states to the DUT. The matrix elements of the DUT are then calculated using Table 2.

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

Once the matrix elements $m_{11}\ldots m_{14}$ are calculated, the maximum and minimum transmittances $T_{\max}$ and $T_{\min}$ as well as the PDL follow from Eq. 2. As before, an optional splitter can be inserted such that all power measurements are ratios with reduced source power and wavelength variation. It is very important

$$PDL = 10\log\frac{T_{\max}}{T_{\min}} = 10\log\frac{m_{11}+\sqrt{m_{12}^2+m_{13}^2+m_{14}^2}}{m_{11}-\sqrt{m_{12}^2+m_{13}^2+m_{14}^2}}\,(dB) \qquad (2)$$

in fixed states measurements to avoid disturbing any optical fiber during the measurement in order to prevent errors due to rotations of the PDL axis.

Jones Matrix Method

The Jones matrix method is a technique that employs only three orthogonal input states (fixed states on the sphere) of polarization to derive global polarization dependence through matrix analysis. This technique typically employs bulk components in an open beam to set the states and measures the polarization state at each of the fixed input states using a polarimeter. This method has the potential advantage of high speed and calibrated spectral dependence. Nonetheless, its accuracy is limited by the polarimeter as well as internal PDL. Resolution is not a function of sphere coverage but is fundamentally limited by the signal-to-noise ratio.

Calibration, Measurement and Calculation

The Jones matrix method measures the device's polarization response to three input states of polarization at a wavelength of interest. The PDL value of the DUT is then derived from these responses. The Jones matrix **A** represents the DUT. The Jones matrix of the fiber leads and DUT combined is **J = VAU**, which is obtained from the measured Stokes parameters for three linear input polarization states at 0°, 45°, and 90° as in Fig. 7. In the case of pigtails with a very low PDL used for the interconnection of the DUT in transmission, their PDL contributions can be neglected and their Jones matrices **V** and **U** can be assumed to be "unitary", i.e. they don't alter power levels. Consequently, the singular values, s, of the composite

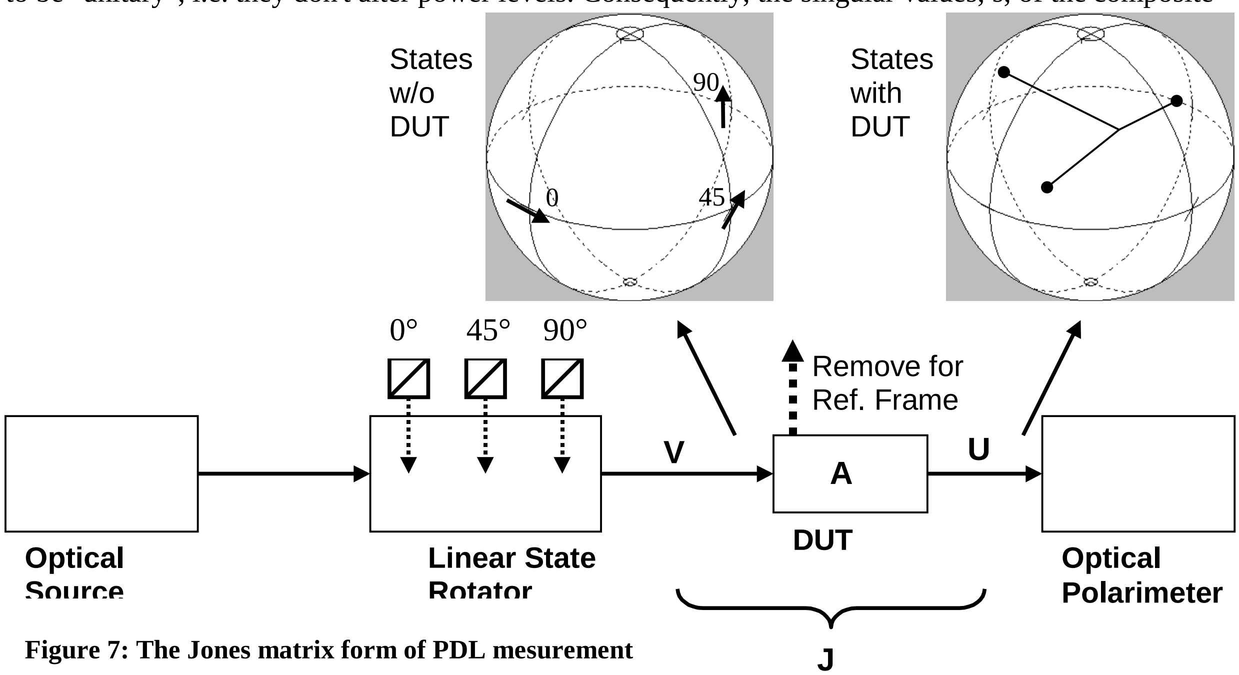

Figure 7: The Jones matrix form of PDL mesurement

Jones matrix **VAU** are the eigenvalues squared of a conjugate-transpose product and are equivalent those of the DUT matrix **A** under a unitary transformation as in Eq. 3. For this method, a power calibration is needed to account for the polarization sensitivity of the polarization analyzer. This can be accomplished

$$PDL = 10\log\frac{T_{\max}}{T_{\min}} = 10\log\frac{\lambda_2\left(\mathbf{J}^{*t}\mathbf{J}\right)}{\lambda_1\left(\mathbf{J}^{*t}\mathbf{J}\right)} = 10\log\frac{s_2^2\left(\mathbf{J}\right)}{s_1^2\left(\mathbf{J}\right)} = 10\log\frac{s_2^2\left(\mathbf{VAU}\right)}{s_1^2\left(\mathbf{VAU}\right)} = 10\log\frac{s_2^2\left(\mathbf{A}\right)}{s_1^2\left(\mathbf{A}\right)}\left(dB\right) \qquad (3)$$

by applying an internal calibration procedure that defines a "reference frame". First, the system transmission variation is measured with a short fiber-optic cable and a three-point reference frame is calculated. This is followed by the power transmission measurements with the DUT inserted. As with the Mueller matrix approach, care must be taken not to disturb the leads during a measurement to avoid altering the reference frame.

Wavelength Dependent Calibration

Due to the strong wavelength dependence of the polarization components in the instrumentation, a wavelength dependent calibration must be performed over the bandwidth of interest. The interval of wavelength calibration, typically a few nanometers, depends on the accuracy required. In the case of narrowband devices, such as single-channel dispersion compensation gratings or WDM grating filters (3-dB bandwidth of about 0.8 run), the wavelength dependence of the system components can be ignored. In the case of broadband devices, however, the strong wavelength dependence of the system components must be compensated.

Measurements in Reflection

To measure a device used in reflection, such as dispersion compensation gratings and WDM grating filters, a 3-dB coupler or a circulator must be added to the measurement setup, which increases the uncertainty of the measurements. The calibrations in reflection for the Mueller matrix method and polarization-scanning method are performed using an optical coupler and/or a gold-coated minor, as shown in Fig. 8. For the Jones matrix method in reflection, the same calibration schemes can be used whereby the power meter is replaced by a polarization analyzer

References

(To be filled in later)