DEGREE OF POLARIZATION VS. POINCARÉ SPHERE COVERAGE - WHICH IS NECESSARY TO MEASURE PDL ACCURATELY?

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Introduction

High speed and low degree of polarization (DOP) are frequently considered critical specifications when choosing a polarization scrambler. High-speed scramblers allow faster measurement and higher throughput; low DOP minimizes effects of polarization dependent loss (PDL). It is also thought that low DOP is equivalent to good Poincaré sphere coverage and will enable accurate PDL measurements. This white paper will show that good sphere coverage is essential for accurate PDL measurements and that good sphere coverage ensures low DOP, but low DOP does not guarantee good sphere coverage.

The favored PDL measurement method described in the TIA/EIA Standard FOTP-157 is the polarization scanning method. The basic idea of this method is that an instrument is used to scan the polarization state of light through all possible states before the device under test (DUT). The maximum and minimum powers are measured after the DUT. The difference in these powers is the PDL, since the changes in polarization cause the changes in power.

Polarization Dependent Loss of a Simple Component

Consider a simple case where the DUT is merely a piece of glass tilted 8° from normal to the incident beam*. Figure 1 shows a schematic of this situation. There are two axes of interest for the polarization: the ones parallel and perpendicular to the plane of incidence**. Indeed, the amount of reflection for these two axes is not the same.

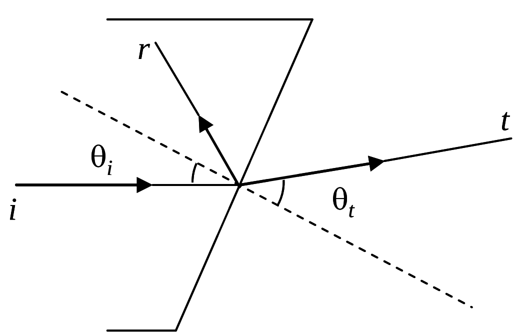

Figure 1. Angles and rays for an angled interface.

As described in most elementary texts on optics, the reflection coefficient for the polarization parallel to the plane of incidence is:

$$R_{\parallel} = \tan^2(\theta_i - \theta_t) / \tan^2(\theta_i + \theta_t),$$

and the reflection coefficient for the polarization perpendicular to the plane of incidence is:

$$R_{\perp} = \sin^2(\theta_i - \theta_t) / \sin^2(\theta_i + \theta_t),$$

The angles θ_i and θ_t are related by Snell's law: $n_i \sin \theta_i = n_t \sin \theta_t$. Figure 2 shows a plot of these two reflection coefficients for the case where $n_i = 1.5$ and $n_t = 1.0$. It can be seen that $R_{\perp}$ is never zero, but when $\theta_i + \theta_t = 90°$, $R_{\parallel}$ vanishes. This incident angle is the well-known Brewster's Angle. Note that the fraction of transmitted light is $T = 1 - R$.

The PDL of this DUT can be calculated by determining $R_{\parallel}$ and $R_{\perp}$, $T_{\parallel}$ and $T_{\perp}$, using $\theta_i = 8^{\circ}$, Snell's Law, $n_i = 1.5$, $n_t = 1.0$, and finally

$$PDL = 10 \log (T_{\parallel} / T_{\perp}).$$

For a standard APC connector, the PDL going from single mode fiber into air is 0.022 dB.

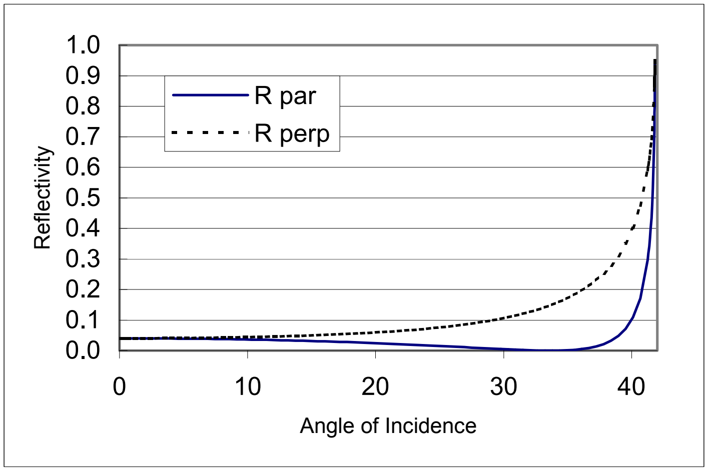

Figure 2. Reflection coefficients of light parallel and perpendicular to the plane of incidence.

Measuring Polarization Dependent Loss

In our example, measuring the PDL of the DUT only requires two linear, orthogonal states of polarization. To measure the PDL, the transmitted power is measured when the light is purely polarized parallel to the plane of incidence and compared to the transmitted power measured when the light is purely polarized perpendicular to the plane of incidence. The result, 0.022 dB, should be easily calculated.

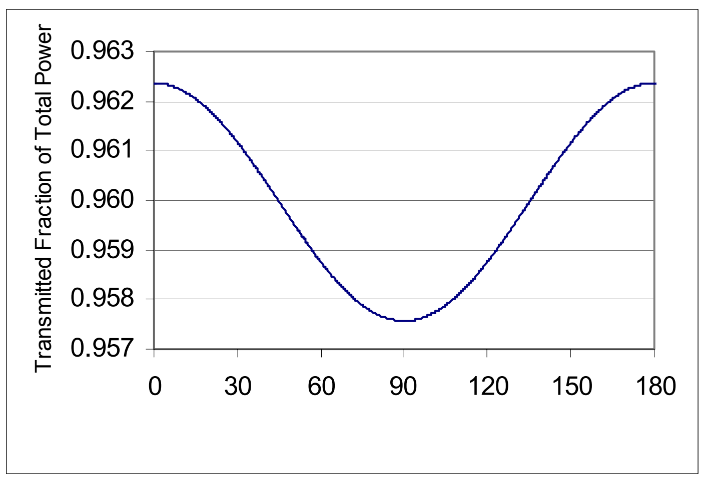

Figure 3. Power transmitted through the DUTs when rotating linearly polarized light with respect to the plane of incidence perpendicular to the plane of incidence.

However, this is only possible if the orientation of the plane of incidence is known. In a general case the orientation is not known. In order to measure the PDL of the component with an unknown orientation of the plane of incidence, one must cover all linear states of polarization. If the polarization of the light is described using a Poincaré sphere representation, all linear states are covered if the polarization vector sweeps around the equator. Figure 3 shows the transmitted power as a function of angle from plane of incidence. It is clear that the PDL measured by rotating the polarization is the same as when it is measured using just two polarization states that are parallel and perpendicular to the plane of incidence because the maximum transmission occurs at 0° and the minimum transmission occurs at 90°.

Extension to a Realistic Optical Component

The PDL of an APC connector is not often measured. Usually we are interested in the PDL of a complicated optical component that consists of many different interfaces. Generally, the PDL in passive components arises from differences in reflection, just as with the APC connector. We will ignore the effects of active elements such as erbium-doped fiber because that would unnecessarily complicate the discussion and the conclusion of the paper would be the same.

In a realistic situation, each interface is oriented differently than the last. If we were to extend our example of a single APC connector to model a real component, we would have two or three or more connectors - all with different planes of incidence - linked by fiber optic cable. In addition to the complication of randomly oriented planes of incidence, each section of fiber adds birefringence to the optical path. The practical effect of birefringence is simply to rotate a polarization vector on the Poincaré sphere. Therefore, if we are sweeping the equator in an attempt to measure the PDL of the component, the birefringence from the fiber rotates the circle on the sphere that we trace out. The polarization vector will still trace out a great circle, but it will not be on the equator. This rotation is illustrated in Figure 4.

With birefringence present we change the polarization state at each interface from linear polarization into elliptical polarization and back again rather than rotating linearly polarized light. This means that we cannot guarantee coverage of the situations where linear light enters the interface parallel and perpendicular to the plane of incidence. The consequence is that we will not measure the true PDL of the component. In order to measure the PDL of a real component accurately, we must cover the entire Poincaré sphere.

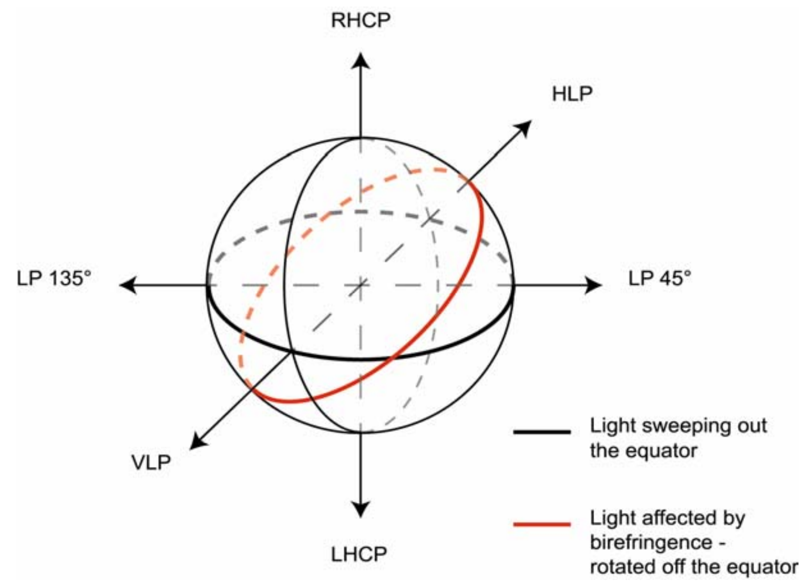

Figure 4. The effect of birefringence is to rotate the Poincaré sphere - perhaps from an equatorial circle to another great circle, as shown here in the thick black and red paths.

DOP vs. Poincaré Sphere Coverage

In the previous section it was shown that in order to get accurate measurements of PDL, the polarization entering the component must cover the entire Poincaré sphere. In other words, a polarization scrambler must be capable of generating all states of polarization. It may be obvious to the reader that if all states of polarization are generated - that is the entire sphere is covered - then the average DOP of the light will be zero. However, it may not be obvious that zero DOP does not guarantee complete sphere coverage of good PDL measurements.

We have considered four cases above:

- First, only two states of polarization were used. These were the states parallel and perpendicular to the plane of incidence. If those axes were also used as the basis for describing the Stokes vector for the polarization, the two Stokes vectors would be (1,1,0,0) and (1,-1, 0,0). The average of these is (1,0,0,0), which is completely unpolarized light whose DOP is zero.

- Second, all linear states of polarization were considered, and the polarization vector traced out the equator of the sphere. In this case, the Stokes vector was (1, cos θ, 0,0), where θ ranged from 0° to 360°. The average vector then is again (1,0,0,0), with zero DOP.

- Third, a birefringence was introduced that rotated the polarization off the equator of the sphere. The path traced was still a great circle, the polarization vector averaged to (1,0,0,0) giving zero DOP.

- Fourth, a scrambler was used to cover all points on the Poincaré sphere. The average polarization vector for this situation is (1,0,0,0), which has zero DOP.

In the first three of these cases, the DOP is zero, but we found that none was sufficient for ensuring an accurate measurement of PDL. It is only the fourth case where the sphere was completely covered - and we had zero DOP - that produced the acceptable PDL result.

Conclusion

This white paper has discussed measuring the PDL of a simple component and extended that discussion to a realistic component. The conclusion from the discussion is that complete sphere coverage - not zero DOP - is essential for effective PDL measurements.

The implication is that, while DOP is often the scrutinized specification when evaluating polarization scramblers, it is sphere coverage that is the critical specification for PDL measurement. The DOP specification is only useful in identifying scramblers that cannot be used to measure PDL accurately, not in identifying ones that can.

* A practical example of this situation is when light emerges from a fiber that has an angle polished finish.

** The plane of incidence contains the incident, reflected and transmitted rays of light.

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