TIA round robin for the measurement of PMD

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From 1994 to 1996, the National Institute of Standards and Technology (NIST) conducted a round robin for the measurement of polarization mode dispersion (PMD). This comparison was coordinated through the Telecommunications Industry Association (TIA) and involved participants from the United States as well as Europe and Japan measuring three PMD specimens. This paper will report the results of that round robin.

Three specimens were circulated to test various aspects of the measurement. These specimens were: Specimen 1, a pigtailed quartz waveplate with no polarization mode coupling; Specimen 2, a mode-coupled artifact composed of a stack of 12 quartz waveplates cemented together and pigtailed; and finally, Specimen 3, a 15 cm diameter spool of 25 km of typical communication fiber. All three specimens had a nominal PMD of a few tenths of one picosecond. This round robin included 16 participants from the United States, Europe, and Japan, and used up to four different measurement techniques: Jones matrix eigenanalysis (JME) – or equivalently the Stokes method, interferometry, and wavelength scanning, also known as fixed analyzer, with either extremum counting (WSEC) or Fourier transform analysis (WSFT) [1].

Specimen 1 (Stable, non-mode-coupled)
The single quartz waveplate has a theoretically predictable PMD which was calculated from the thickness of the waveplate and its wavelength dependent birefringence. However, the 2-3 m long fiber pigtails of the specimen have a non-negligible PMD which dominates the uncertainty of the device PMD. It is therefore possible to predict the measured PMD as the wavelength-averaged differential group delay DGD of the single waveplate device only to within ±2.5%, where the uncertainty is the maximum PMD variation seen experimentally when the fiber leads are arranged in various orientations.

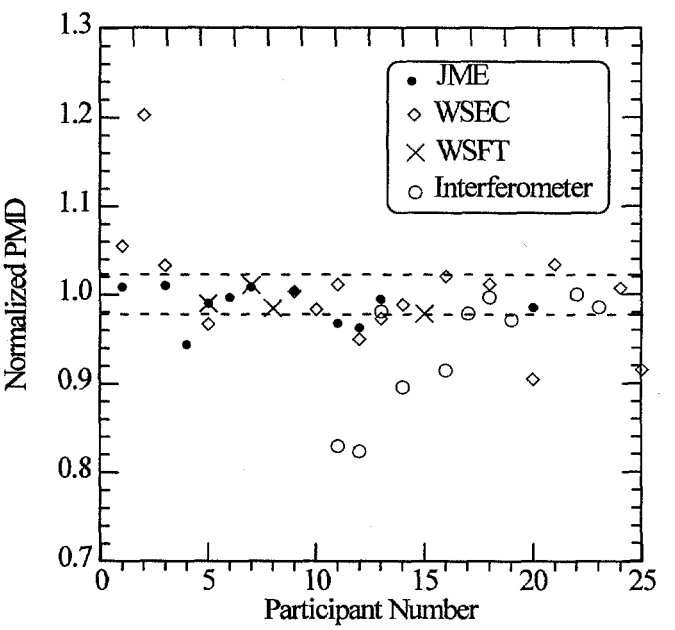

Figure 1 Single waveplate (Specimen 1).

Figure 1 shows the variation among participants' measurements of Specimen 1. The x-axis represents the participants, and the y-axis is their measured PMD normalized to the theoretically predicted value for the wavelength

at which the measurement was made. There are more participant numbers on the x-axis than participants because some participants made measurements on more than one similar system and consequently were assigned two participant numbers. Table I shows the measurement statistics. The agreement among participants is good, with most of the variation explainable by the PMD uncertainty due to the fiber leads (dashed lines of Figure 1). A few significant disagreements with theory can be seen. Some of these disagreements are explained by improper measurement techniques. One such disagreement is apparent in some of the interferometric results, where measurements were made by calculating the second moment of the double-peaked interferogram rather than measuring the time delay between the peaks. The existence of the autocorrelation peak in the interferogram might have led to incorrect results (yielding the smaller than theoretical values).

Table I Average / standard deviation of normalized measurements for each specimen. *One extreme data point was removed for interferometry (Int) statistics.

	Specimen 1	Specimen 2	Specimen 3
WSEC	1.00 / 0.067	1.02 / 0.119	1.08 / 0.28
WSFT	0.99 / 0.014	1.00 / 0.038	1.014 / 0.13
Int	0.94 / 0.068	0.99 / 0.051	0.96 / 0.21 *
JME	0.99 / 0.022	1.00 / 0.010	0.92 / 0.22
Total	0.98 / 0.060	1.00 / 0.076	n.a. / 0.24

Specimen 2 (Stable, mode-coupled)

The second specimen also has a theoretically predictable PMD. However, its application is not as straightforward. The DGD of the waveplate stack is derived from the measured thickness and known birefringence of each plate along with the known orientation angles of their optic axes with respect to each other. From this information, a Jones matrix for the 12-plate stack was calculated and DGD as a function of wavelength was derived. This information allows a theoretical prediction of PMD (as the average DGD over wavelength) with an accuracy similar to that of the single waveplate where the limit is a ± 2% uncertainty due to PMD of the fiber leads. This evaluation method allows accurate theoretical prediction of JME measurement results.

There is, however, a complication for other measurement techniques. A theoretical prediction of PMD is more difficult for techniques which do not measure DGD directly but rather measure PMD through some statistical parameter. Such techniques as interferometry and wavelength scanning with either extremum counting or Fourier analysis are subject to the fact that an exact theoretical prediction of the PMD of the mode-coupled artifact is possible only if the orientations of the measuring polarizer and analyzer are known with respect to the axes of the waveplate stack. This is not possible since the fiber pigtails randomly alter the polarization state before it impinges on the waveplate stack. In order to establish a theoretical prediction, participants made between 3 and 6

measurements with the polarizer and analyzer randomly rotated (or alternatively with the lay of the fiber leads randomized) between each measurement. The average of these measurements was normalized to a theoretical average derived from a computer simulation of 100 measurements over the same wavelength range using random polarizer and analyzer orientations.

Results are shown in Figure 2 and Table I. As expected, the best agreement came from the JME measurements where all of the data points fell within the uncertainty due to the PMD of the fiber leads (dashed lines). For the rest of the measurement techniques, most of the disagreements between experiment and theory are within the $2\sigma/N^{1/2}$ error bars, where σ is the standard deviation of the theoretical prediction and N is the number of measurements made by the participant. Uncertainties of the participant's measurement system are not included.

Specimen 3 (Spooled fiber)

Finally, for comparison Figure 3 and Table I show the results of measurements made on the spool of 25 km of single-mode fiber. Participants' results are plotted as the measured value divided by the average measured value of all the participants. There is no theoretical prediction with which to compare, but the standard deviation among participants gives an indication of the repeatability which can be expected on such a spooled fiber.

Conclusion

For measurements on the fiber spool (Specimen 3), the standard deviation σ was 24% with no statistically significant disagreements between measurement techniques.

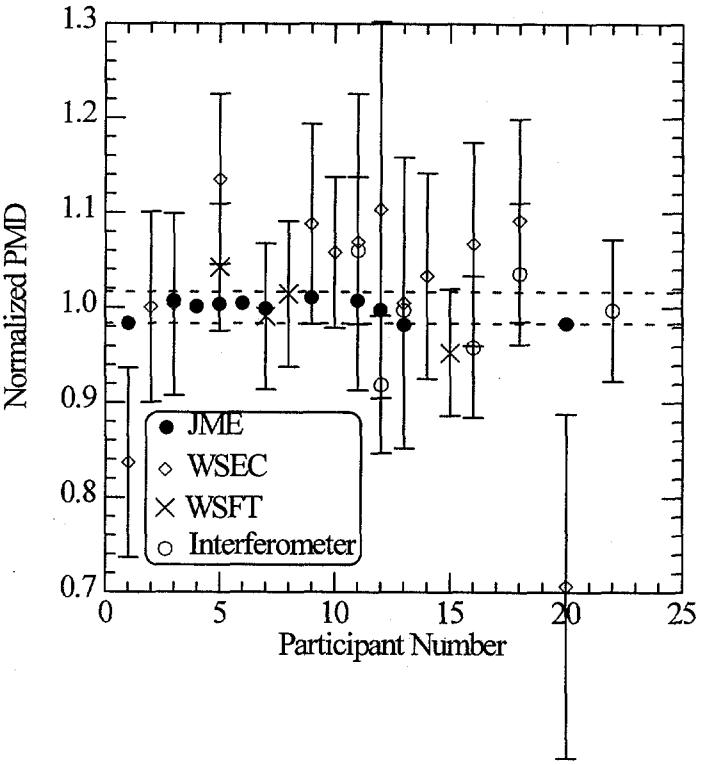

Figure 2 Waveplate stack (Specimen 2).

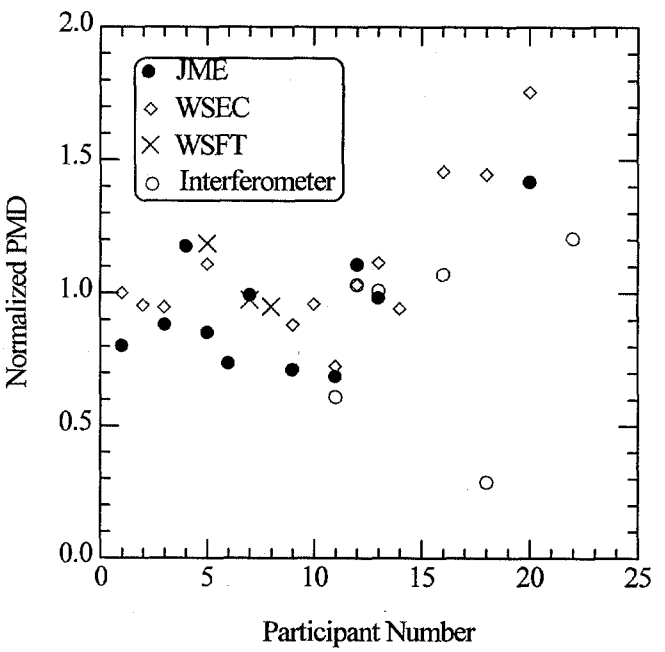

Figure 3 Spooled 25 km fiber (Specimen 3).

The non-mode-coupled Specimen 1 shows significant improvement over the fiber spool. With the

exception of interferometry, all of the measurement techniques yielded averages among the participants which were within 1% of theory. The overall uncertainty of specimen 1 is only 6%. The WSFT and JME techniques performed best with sigmas of only 1.4% and 2.2%, respectively (the WSFT result represents only 4 measurements). The poorer repeatability of WSEC and interferometry might be due to applying mode coupled measuring techniques to measuring the non-mode-coupled device.

For mode-coupled Specimen 2, each measurement technique's average value agrees within 2% of theory. The theory predicts only what the participant will measure using a given technique. It makes no statement as to whether different techniques should measure the same value. Indeed for this moderately mode-coupled 12-waveplate stack, all the techniques are not expected to measure the same value, but the normalized data does not illustrate these systematic measurement differences. With regard to standard deviation, the overall σ of 7.6% is only slightly higher than for Specimen 1 and is significantly lower than for the fiber spool. The JME technique shows the best stability among participants, with a σ of only 1%. This is as expected, since the JME technique is only weakly affected by birefringence in the fiber leads. Based on the results of this round robin, NIST is constructing a stack of 35 waveplates to increase mode-coupling and PMD. We anticipate that this new artifact will reduce the uncertainty due to PMD of fiber leads for all of the measurement techniques.

The author expresses thanks to the members of the TIA who helped in the organization of this round robin and also to all the participants from the United States, Japan, Switzerland, and the United Kingdom for taking part.

[1] For measurement methods using these techniques, see Fiber Optic Test Procedure (FOTP) 113, 122, and 124, Telecommunications Industry Association.