National Institute of Standards & Technology

Certificate

Standard Reference Material® 2518

Polarization-Mode Dispersion (Mode-Coupled)

Serial No.: 032

This Standard Reference Material (SRM) is intended to calibrate only polarization-mode dispersion (PMD) measurement systems that use a polarimetric technique. Polarimetric techniques are those that directly measure differential group delay (DGD) as a function of wavelength and include Jones matrix eigenanalysis (JME) [1,2], Poincaré arc (or state of polarization - SOP) [3], and modulation phase shift [4] techniques. The certified value of $\langle DGD \rangle_{\lambda}$ for this SRM is not applicable to nonpolarimetric techniques such as fixed analyzer (wavelength scanning) or low coherence interferometry.

This limitation in scope arises because the SRM has fixed mode-coupling, rather than variable or no mode-coupling. A mode-coupled SRM is necessary in order to simulate conditions on measurements of typical fibers. The fixed mode-coupling geometry of the waveplate stack was chosen to eliminate the statistical uncertainties inherent in variably mode-coupled fibers and is not a judgement on the performance of any of the PMD measurement techniques. Simply stated, the polarimetric techniques are well suited to calibration by a fixed, mode-coupled device; the others are not. When nonpolarimetric techniques are used to measure this SRM, measurement-specific issues, such as source shape and the orientation of the fiber leads, will yield measured results that will not necessarily agree with the mean DGD value reported in this certificate. This limitation is discussed fully in reference 5.

Description: SRM 2518 consists of a stack of 33 to 35 quartz plates cemented together with their optic axes at quasi-random angles with respect to each other. The orientation angles of the plates were chosen to give a DGD versus wavelength signature that resembles a randomly mode-coupled fiber. The stack is pigtailed with single-mode fiber and connectorized with an FC/APC connector. Endcaps are furnished to protect the connectors when the unit is not in use.

Expiration of Certification: The certification of this SRM is valid indefinitely provided the SRM is stored, handled, and used in accordance with the instructions given in this certificate. However, certification will be nullified if the SRM is damaged or otherwise altered.

The research and development effort leading to certification were performed by D.L. Franzen and P.A. Williams of the NIST Optoelectronics Division and G.V. Sherwood of the NIST Radio-Frequency Technology Division.

Statistical consultation was supplied by C.M. Wang of the NIST Statistical Engineering Division.

The support aspects involved in the revision of this SRM were coordinated through the NIST Standard Reference Materials Program by C.S. Davis of the Measurement Services Division.

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See Certificate Revision History on Last Page

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Certified Values and Uncertainties: This SRM is certified for PMD, which is the wavelength averaged (arithmetic mean) DGD, denoted $<\mathrm{DGD}>_\lambda$. The certified values and their associated uncertainties appear in Table 1. Multiple wavelength ranges are reported to accommodate various spectral ranges of sources that may be available to the user. The SRM is calibrated at 23 °C and has a slight temperature dependence. This is accounted for as an uncertainty that increases with deviation of measurement temperature from the target 23 °C. The user should choose the uncertainty (23 ± 1 °C or 23 ± 3 °C) that corresponds to the temperature range experienced by the SRM during the measurement.

The measurements of $<\mathrm{DGD}>_\lambda$ were performed using the NIST JME system [6]. The uncertainties in Table 1 were calculated in accordance with NIST uncertainty policy [7], as

$$2\sigma_{Tot} = 2\cdot\sqrt{\sigma_{\mathrm{JME}}{}^2 + \left(\Delta T\cdot\frac{\mathrm{d}<\mathrm{DGD}>_\lambda}{\mathrm{d}T}\right)^2 + \left[\frac{\sigma_{\mathrm{S}}{}^2}{\mathrm{N_S}} + \frac{\sigma_\varepsilon{}^2}{\mathrm{N_{Tot}}}\right] + \left(\Delta\lambda\cdot\frac{\mathrm{d}<\mathrm{DGD}>_\lambda}{\mathrm{d}\lambda}\right)^2} \quad (1)$$

where σ_{JME} is the standard uncertainty of the NIST JME measurement system (1.6 fs), ΔT is the maximum allowed difference of the SRM temperature from the target 23 °C (either 1 °C or 3 °C in Table 1), and $\mathrm{d}<\mathrm{DGD}>_\lambda/\mathrm{d}T$ is the temperature dependence (ps/°C) of the wavelength-averaged DGD (as described below). The quantity in square brackets is the variance in the mean (variance-component model [8]) of the multiple measurements made on this SRM. Calibration data consisted of multiple scans where DGD(λ) was measured over the desired wavelength range. For each of these scans, $<\mathrm{DGD}>_\lambda$ was calculated. σ_ε is the weighted mean standard deviation of individual DGD(λ) values from the local mean and was calculated by locally detrending the data [9]. σ_{S} is the scan-to-scan standard deviation of $<\mathrm{DGD}>_\lambda$ for the given wavelength range. $\mathrm{N_S}$ is the number of scans, and $\mathrm{N_{Tot}}$ is the total number of data points measured. $\Delta\lambda$ is the uncertainty of the center wavelength of the scan range, and $\mathrm{d}<\mathrm{DGD}>_\lambda/\mathrm{d}\lambda$ is the change in the measured mean DGD for a given change in the measurement center wavelength. The overall factor of two yields a confidence interval of approximately 95 %.

Table 1. Certified Values and Uncertainties (Approximate 95 % Confidence Interval) of Wavelength-Averaged DGD ($\langle \mathrm{DGD} \rangle_{\lambda}$) Measured Over Various Wavelength Ranges

Vacuum Wavelength (nm)			$\langle \mathrm{DGD} \rangle_{\lambda}$ (ps)	Uncertainty $2\sigma_{\mathrm{Tot}}$ (ps)	
Start	Stop	Span		(23 °C ± 1 °C)	(23 °C ± 3 °C)
1480.5	1528.5	48	0.3811	0.0055	0.0116
1480.5	1538.5	58	0.4180	0.0044	0.0081
1480.5	1548.5	68	0.4282	0.0039	0.0061
1480.5	1558.5	78	0.4488	0.0043	0.0077
1481.5	1567.5	86	0.4609	0.0037	0.0056
1481.5	1529.5	48	0.3871	0.0056	0.0119
1485.5	1543.5	58	0.4364	0.0044	0.0080
1485.5	1553.5	68	0.4473	0.0053	0.0108
1485.5	1563.5	78	0.4664	0.0043	0.0076
1490.5	1538.5	48	0.4530	0.0064	0.0143
1490.5	1548.5	58	0.4589	0.0048	0.0095
1490.5	1558.5	68	0.4780	0.0056	0.0117
1490.5	1568.5	78	0.4868	0.0044	0.0082
1495.5	1543.5	48	0.4723	0.0035	0.0044
1495.5	1553.5	58	0.4789	0.0042	0.0073
1495.5	1563.5	68	0.4962	0.0036	0.0050
1500.5	1548.5	48	0.4733	0.0033	0.0034
1500.5	1558.5	58	0.4932	0.0038	0.0056
1500.5	1568.5	68	0.5010	0.0033	0.0035
1505.5	1553.5	48	0.4850	0.0050	0.0099
1505.5	1563.5	58	0.5043	0.0038	0.0059
1510.5	1558.5	48	0.5147	0.0058	0.0124
1510.5	1568.5	58	0.5202	0.0043	0.0077
1515.5	1558.5	43	0.5383	0.0060	0.0129
1520.5	1568.5	48	0.5542	0.0035	0.0041

NOTE: All wavelength values refer to vacuum wavelength. Measurement uncertainties on $\langle \mathrm{DGD} \rangle_{\lambda}$ are listed assuming a 0.2 nm wavelength uncertainty and either a 23 ± 1 °C or a 23 ± 3 °C temperature condition.

INSTRUCTIONS FOR USE

Make calibrating measurements at a nominal temperature of 23 °C. As discussed in the section on Temperature Dependence, the measurement uncertainty increases as the measurement temperature diverges from this 23 °C target. Two temperature tolerances are allowed in Table 1, 23 ± 1 °C and 23 ± 3 °C. For measurement stability, hold the SRM at the measurement temperature for at least one hour before making measurements. Make the measurements over one of the specified wavelength ranges (vacuum wavelength). The allowed uncertainty in wavelength of these ranges is 0.2 nm. As described in the Lead Birefringence Section, birefringence in the fiber leads of the measurement system can contribute to measurement error. Therefore, it is recommended that PMD be measured as the average of multiple measurements made with random orientations of the fiber leads.

Care should be taken in making connections to the SRM. The bulkhead connectors on the SRM unit are the FC/APC type. When making connections to the SRM, use high quality FC/APC connectors. The cleanliness of the connectors is important. Use a dust-free and residue-free air source and a commercial fiber endface cleaner before every connection. If such a cleaner is not available, then lens paper wetted with reagent grade alcohol can be used to wipe the ferrule endface and the air source used to dry the connector.

The SRM should not be subjected to temperatures outside of the range of 0 °C to 50 °C, and the unit should be stored in a dry environment with long-term temperatures in the range of 10 °C to 35 °C. The SRM should not be subjected to any sudden shocks or strong vibrations. The lid should not be removed.

Temperature Dependence: Temperature affects the quartz plates in the stack by changing their birefringence Δn and their physical length L. This effect can be expressed as the normalized quantity $\gamma = (1/\Delta nL)\mathrm{d}(\Delta nL)/\mathrm{d}T$. For quartz, $\gamma \approx -1.232 \times 10^{-4}$ /°C at 1536 nm [10]. For a waveplate stack with a given geometry of waveplate orientations, the shape of the DGD versus $\lambda/\Delta nL$ curve will be a constant. As the temperature changes, the amplitude of the DGD will change proportionally to ΔnL, but the curve's shape will remain the same. Therefore, if the average DGD were measured over a fixed range of $\lambda/(\Delta nL)$, there would be only a negligible temperature dependence proportional to γ (< 0.06 fs/°C for the nominally 0.5 ps SRM).

However, the temperature dependence of the SRM is complicated by the fact that the average DGD is measured over a fixed range of λ (not $\lambda/(\Delta nL)$). Two curves of DGD versus λ measured at different temperatures will have different values of ΔnL and will be shifted in wavelength with respect to each other. The strength of this shift is equal to $\mathrm{d}\lambda/\mathrm{d}T = \lambda\gamma$ = -0.19 nm/°C at 1536 nm. This temperature dependent wavelength shift can cause an error when the average DGD is measured over a fixed wavelength range. A further complication arises in the fact that the quartz is not the only component contributing a temperature dependence to the average DGD. Temperature-dependent wavelength shifts could come from birefringences in the graded-index lenses coupling light from the fibers into the quartz plates, the cement between the quartz plates or any stress birefringence in the plates themselves. While these factors do not contribute significantly to the average DGD of the device, they could easily contribute to the temperature-dependent wavelength shift of the DGD(λ) profile of the SRM. Since these secondary temperature dependences are not predictable, the temperature dependent wavelength shift is individually measured for each SRM.

The magnitude of the temperature dependence of $\langle DGD\rangle_\lambda$ also depends on the shape of the DGD versus λ curve at the measurement endpoints. For each SRM, the temperature dependent wavelength shift $\mathrm{d}\lambda/\mathrm{d}T$, as well as the wavelength dependence of the average DGD, $\mathrm{d}\langle DGD\rangle_\lambda/\mathrm{d}\lambda$, is measured for each of the wavelength ranges reported in Table 1. The temperature dependence is given by the product $(\mathrm{d}\langle DGD\rangle_\lambda/\mathrm{d}\lambda)(\mathrm{d}\lambda/\mathrm{d}T)$ and is generally different for each wavelength range of interest. This temperature dependence has been added in quadrature to the other uncertainties to give the final uncertainty listed in Table 1.

Lead Birefringence: Lead birefringence can impose an uncertainty on the measurement. NIST calibrations were performed with a short lead length (~80 cm total), and the PMD of the leads was measured and added to the uncertainty statement of Table 1. The orientation of the fiber leads was also randomized in between measurements in order to average away as much of the lead birefringence as possible. NIST recommends that the user of this SRM do the same. Note that the most complete randomization of the leads must include orientations where the fibers do not always lie in a single plane. Take care in reorienting the fiber leads so that significant bending, which increases the fiber birefringence, is not introduced. Bend birefringence B_b is calculated using

$$B_b = 0.093\left(\frac{A}{R}\right)^2 \qquad (2)$$

where R is the radius of the fiber bend, and A is the outside radius of the fiber itself [11]. NIST recommends that any bends in the fiber leads be restricted to a radius of 5 cm or greater. Some fraction of the lead birefringence might not average to zero due to inability to completely randomize the lead orientation. Therefore, the shortest possible leads for the measurement and orientational averaging is recommended. A measurement of the lead birefringence in the absence of the SRM gives an estimate of the uncertainty that could be expected due to lead birefringence.

Multiple Reflections: The most probable cause of multiple reflections is poor connections. Use only FC/APC type connectors cleaned as described in the Instructions for Use section. Dust or dirt in the bulkhead adapter or on the connector ferrule endface can cause multiple reflections across the specimen, which will add a random (with wavelength and temperature) noise to the measurement. Other sources of reflection in the measurement system are equally important. If the reflections cannot be reduced, multiple measurements can be made at slightly different wavelength sampling points or temperatures in order to average out the multiple reflection effects.

In the calibration of the SRM, this multiple sampling technique was used. Noise on the DGD versus λ curve indicated the presence of some multiple reflections. Consequently, DGD versus wavelength measurement scans were made with a 1 nm step, and each consecutive scan was made with a 0.2 nm offset from the previous scan. After five such sets were measured (on the same specimen), the average DGD was calculated as the average of all of the sets (445 points). The wavelength shift not only randomized the effects of the multiple reflections, but also gave a larger statistical base.

Wavelength Range: All wavelength values in this certificate are reported as vacuum wavelength. Since the average DGD of the SRM is a function of wavelength, Table 1 reports the mean DGD measured over each of 25 different wavelength ranges. These multiple ranges are included in order to provide calibrations that are within the 90-nm window accessible to the NIST laser source, but allow for SRM users who may have different wavelength coverage and are unable to make measurements over the NIST full wavelength window.

The average DGD values in Table 1 were calculated using the NIST rotating-waveplate Jones matrix eigenanalysis measurement system [6]. Measurements were made using a 1 nm step. Systematic errors were reduced by making multiple scans over the same nominal wavelength ranges, but with the input state of polarization randomized and the wavelength of the sampled points shifted by 0.2 nm for each scan. This was done in order to obtain multiple scans of a given wavelength range without sampling at the same wavelength points or at the same points on the Poincaré sphere. This interlaced technique randomizes errors due to multiple reflections and any errors that are a function of polarization state. This technique assures truly statistically independent averaging.

CAUTION: In a fixed, mode-coupled device such as this SRM, the DGD will depend strongly on wavelength. Therefore, correct wavelength setting is critical. The uncertainties of Table 1 are calculated assuming the endpoints of the scan to be accurate within 0.2 nm.

The start and stop wavelengths are defined as the wavelength locations associated with the first and last DGD measurements (with uniformly spaced samples in between). This is an important point and should be clearly understood. In the case of JME measurements, to measure the DGD at a given wavelength point requires the measurement of the Jones matrix of the device under test at two wavelengths on either side of the target wavelength. For example, a JME measurement of the DGD at 1480.5 nm might come as the result of measurements of the Jones transfer matrices at 1480 nm and 1481 nm. Following this example, measuring the DGD at 1480.5, 1481.5, ..., 1528.5 nm would require the Jones matrices to be measured from 1480.0 to 1529.0 nm. In this example, the start and stop wavelengths appropriate to Table 1 would be 1480.5 nm and 1528.5 nm (not 1480 nm and 1529 nm).

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Users of this SRM should ensure that the certificate in their possession is current. This can be accomplished by contacting the SRM Program at: telephone (301) 975-6776; fax (301) 926-4751; e-mail srminfo@nist.gov; or via the Internet http://www.nist.gov/srm.