Calibration system for polarization mode dispersion (PMD) of optical fibers

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Abstract. The *National Institute of Metrology, Quality and Technology* – Inmetro developed a measurement system for calibration of polarization mode dispersion (PMD) of optical fibers. Here we report the implementation of the measurement system, including its validation and uncertainty budget for a group of calibration artefacts. We also analyse the results of participation in an international intercomparison of PMD. Results indicate that this system can provide metrological traceability for this quantity.

1. Introduction

Fiber-optic technology is a core component for telecommunications and is largely used in many other applications as remote sensing, biomedical instrumentation, etc. Optical fibers are consolidated as a key element in the backbone of long-haul, high-speed communication links and also for the last-mile access with the popularization of the fiber-to-the-home (FTTH) technology [1,2].

Despite its high-rate capability, some features of optical fibers can impair the performance of the communication link. Polarization mode dispersion (PMD) is a phenomenon quantified as the statistics of the differential group delay (DGD) between the two degenerated modes with orthogonal polarization states propagating in a singlemode optical fiber [1]. DGD results from variation of the birefringence of the waveguide due to breaks in its cross-section symmetry (during fabrication and also due to mechanical stress in deployed cable). PMD causes pulse spreading during propagation and varies with wavelength and temperature. It may lead to increase in bit error rate or even outage of high-rate systems [2].

Some methods are available for determining the PMD of optical fibers, including the interferometry and the polarimetry-based approaches [3-5]. The former can be implemented based on optical low-coherence interferometry using a Michelson interferometer capable of performing the projection between the orthogonally-polarized signals of a broadband optical spectrum sent through the fiber. The interferogram results in a PMD value. On the other hand, *Jones matrix eigenanalisys* (JME) method [6] is based on polarimetry. It evaluates the changes in the Jones matrix of the fiber under test with wavelength. A series of known states of polarization (SoP) is launched into the fiber under test, followed by a polarimeter that determines the Stokes parameters. The procedure is performed at a series of neighbour wavelengths along a certain spectral range for determination of DGD values and then the PMD of the optical fiber.

Both methods were implemented at Inmetro over the last few years for measuring the PMD of optical fibers [7,8]. Here we report the JME approach, based on a Stokes polarimeter and a tunable laser source. The measurement system was recently used for measuring a series of calibration artefacts with different PMD values in the range from 0.3 ps to 5 ps and the measurement uncertainty budget was determined. Results were validated using the interferometry-based method. An intercomparison with other national institutes of metrology was carried out [9] and the results were evaluated. The results indicate good agreement with the pilot and assess the system for providing metrological traceability for the parameter.

2. Measurement method

The implemented methodology is based on the JME method. Three known SoP at a specific wavelength are consecutively sent through the device under test to a polarimeter. The evolved SoP is determined from the measured Stokes parameters and the Jones matrix of the device is then computed. The procedure is repeated with shifted wavelength and the DGD is calculated from the pair of matrices. A group of DGD values along the wavelength range of interest is considered for calculating the PMD.

2.1. Experimental setup

The experimental setup of the measurement facility is depicted in figure 1. The optical signal of a tunable laser source (Agilent 81940A/8163B) [10] passes through a 3-dB fiber beam splitter (BS) and is sent to a calibrated wavelength meter (Burleigh WA-1500). The second output branch passes through a SoP generator and is sent through the device under measurement, reaching polarimeter (HP 8509B). This comprises of four branches with optical polarizers and photodiodes for determination of the Stokes vector. The raw electrical signals from the four photodiodes are simultaneously measured with four calibrated digital voltmeters (Agilent 34401A). A personal computer controls the laser tuning wavelength, sets the SoP generator and acquires the voltage values through a GPIB interface using a customized Labview software.

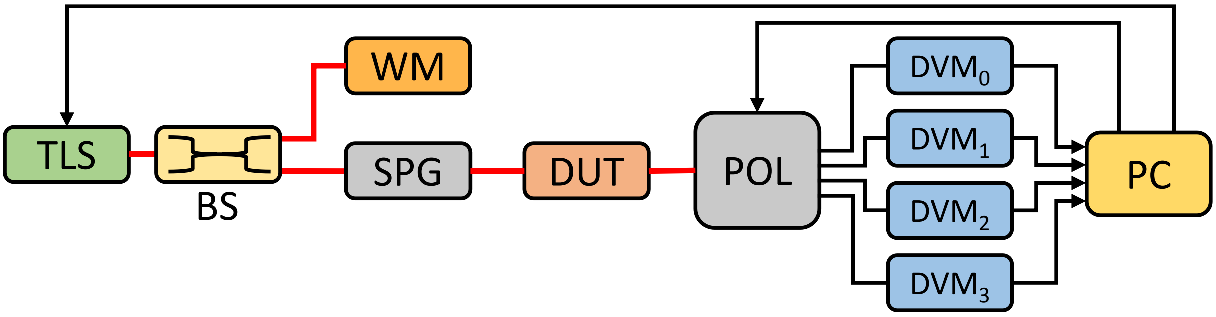

Figure 1. Experimental setup. TLS: tunable laser source; BS: beam splitter; WM: wavelength meter; SPG: SoP generator; DUT: device under test; POL: polarimeter; DVM: digital voltmeter; PC: personal computer. Red lines: fiber-optic connection; black lines: electrical connections.

The tunable laser source scans from 1520 nm to 1570 nm with a certain wavelength step $\delta\lambda$, so that $\delta\lambda \leq \lambda_0^2/(2c\Delta\tau_{max})$ [4], where λ_0 is the wavelength at the center of the spectral region, c is the speed of light, and $\Delta\tau_{max}$ is the maximum DGD value expected. The laser source is initially set to circular polarization and the SoP generator projects it sequentially to linear polarization at 0°, 60° and 120° using a rotatable linear polarizer. At each wavelength 60 voltage values are acquired simultaneously at the four outputs of the polarimeter by the voltmeters for composing each Stokes vector for each SoP. The set of SoP results in a Jones matrix. The device under test is measured 10 times consecutively along the whole spectral range, with at least 3 repetitions in different days. The average temperature nearby the artefact is measured as (23.5 ± 0.5)°C.

A picture of Inmetro's experimental facility is shown in figure 2. This setup was used in the international intercomparison of PMD.

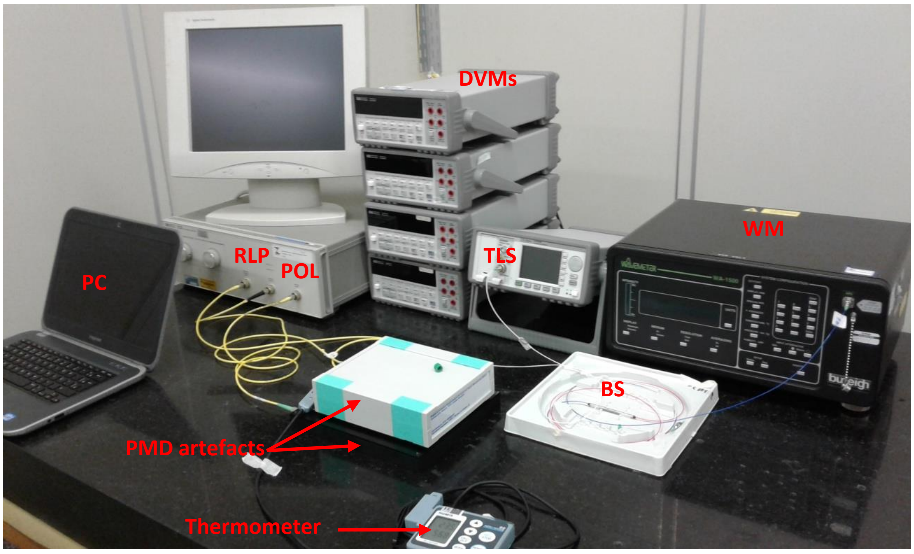

Figure 2. Picture of the experimental setup.

2.2. Traceability

Radiation from the tunable laser source was measured with a wavelength meter (Michelson interferometer with an internal HeNe laser reference), calibrated using a 1064-nm Nd:YAG laser with its frequency-doubled emission (532 nm) stabilized at the a_{10} component of the R(56)32-0 hyperfine transition of iodine [11]. The cold finger temperature at the iodine cell, the frequency modulation width and the saturating beam intensity were kept within the operational conditions required by the BIPM. The 1064 nm Nd:YAG laser was verified by frequency beating with Inmetro's optical frequency comb [12].

Traceability of digital voltmeters and thermometer were provided by Inmetro's national standards.

2.3. Data analysis

Each set of average voltage values simultaneously measured at the four output of the polarimeter's photodiodes with the digital voltmeters are converted into a normalized Stokes vector. Three vectors are computed by setting the SoP generator up, which then compose a Jones matrix. Each pair of Jones transfer matrices at adjacent wavelengths is used to obtain the frequency transfer matrix at their average wavelength. DGD value is then computed as the angle between the eigenvalues of the matrix divided by the angular frequency step of the radiation. PMD is obtained from the average DGD over the wavelength range. Consecutive spectral scans results in a group of PMD values, considered under repeatability condition. Reproducibility is evaluated from measurements performed on different days.

The uncertainty of the PMD measurement comprises the systematic component due to the measurement facility and method (u_{syst}), the repeatability (u_{repe}) and reproducibility (u_{repro}) of the measurements. The component u_{syst} originates from the analytical uncertainty analysis of the JME method, considering the statistics of the voltmeters collection (experimental standard deviation of the mean) and their calibration certificate, the wavelength uncertainty (worst-case value of 0.0025 nm), and the repeatability of the SoP generator angles (about 1°). The component u_{repe} is obtained from the statistics of the PMD values of the 10 consecutive scans of each group. The component u_{repro} is computed from the statistics of the PMD measured on at least three different days.

Uncertainty due to temperature (u_{temp}) is considered as the worst case drift in the PMD spectral shape (shifted towards blue [13]), with rectangular distribution.

2.4. *Measurement artefacts*

The analysis reported is based on the measurement of a set of PMD artefacts with different values used during an intercomparison [9]. Three PMD artefacts made of polarization maintaining (PM) fiber were measured. They were encapsulated into two boxes (A and C together), with the optical fibers accessible through FC-APC connectors:

- A: section of PM fiber in a plastic case with nominal PMD value of 0.3 ps;
- B: multiple sections of PM fiber at randomly oriented birefringence axis in a metal case with nominal PMD value of 0.6 ps.
- C: section of PM fiber in a plastic case with nominal PMD value 4.9 ps.

3. Results

3.1. *Uncertainty budget*

The measurement uncertainty analysis is performed following the ISO GUM [14]. The uncertainty budget evaluated for the measured artefacts is listed in table 1. Combined uncertainty, u_c, is expanded into U with a coverage factor k resulting from a t-Student distribution with ν degrees of freedom and coverage probability of 95%.

Table 1. Uncertainty budget for the measurement of the PMD artefacts.

Artefact	**Nominal PMD [ps]**	u_{syst} **[ps]**	u_{temp} **[ps]**	u_{repe} **[ps]**	u_{repro} **[ps]**	u_c **[ps]**	ν	**k (95%)**	**U [ps]**
A	0.3	0.0044	0.0002	0.0006	0.0013	0.0046	∞	1.97	0.009
B	0.6	0.0012	0.0011	0.0003	0.0011	0.0020	91	1.99	0.004
C	4.9	0.0026	0.0004	0.0003	0.0019	0.0033	80	1.99	0.006

Results indicate that uncertainty due to the system dominates. Temperature is a relevant parameter for artefact B due to its nature. In fact, this type of artefact emulates long optical fiber links which are usually very susceptible to temperature variation [8].

3.2. *Validation*

The system was validated using the interferometric method [7]. The method is based on optical low-coherence interferometry technique and uses a low coherence optical source and a Michelson interferometer. Light from a superluminescent diode emitting in C+L bands with bandwidth of 70 nm (FWHM) was launched into each artefact after passing through a manual polarization controller into a Michelson interferometer. The cross-correlation between the orthogonally-polarized versions of the beam results from their projection into a maximally non-orthogonal basis inside the interferometer. Evaluation of the envelope of the interferogram results in a PMD value. A series of measurements was performed with a group of random SoP settings distributed over the surface of the Poincaré sphere. The system was calibrated using a PMD calibration standard composed of a piece of thermally-stabilized high-birefringence (hi-bi) fiber with 0.903 ps.

Measurement uncertainty with the interferometric system comprises the statistical of the PMD values and the uncertainty of the calibration standard. Results are compared in table 2 using the criterion of normalized error (E_{norm}), computed as their absolute difference over their combined expanded uncertainty. Values smaller than unit indicate agreement of the results within their uncertainty.

Table 2. Validation of PMD results.

PMD artefact	JME		Interferometric		E_{norm}
	PMD [ps]	**U [ps]**	**PMD [ps]**	**U [ps]**	
A	0.309	0.009	0.309	0.013	0.02
B	0.654	0.004	0.687	0.067	0.49
C	4.903	0.006	4.913	0.017	0.57

Results indicate compatibility between the methods. This was possible due to the good match of the broadband optical source with the spectral span of the tunable laser source scan.

3.3. Intercomparison

The COOMET.PR-S9 intercomparison [9] aimed on the measurement of PMD over telecom C-band (1520 nm to 1570 nm). This took place from 2016 (technical protocol) to 2021 (technical report) [9]. Three PMD artefacts – see *section 2.4* – were measured in sequence by the pilot institute, by each participant institute, and then by the pilot again. Results are summarized in table 3. Pilot values are presented as the average between measurements and their RMS uncertainty.

Table 3. Measurement results of the PMD intercomparison [9].

PMD artefact	Inmetro		Lab A		Lab B		Pilot	
	PMD [ps]	U [ps]	PMD [ps]	U [ps]	PMD [ps]	U [ps]	PMD [ps]	U [ps]
A	0.3090	0.0090	0.3080	0.0050	0.3089	0.0021	0.3097	0.0038
B	0.6540	0.0040	0.6520	0.0090	0.6460	0.0118	0.6474	0.0076
C	4.9030	0.0060	4.9230	0.0050	4.9190	0.0384	4.9297	0.0410

Data in table 3 is also depicted in figure 3 with error bars representing expanded uncertainties. Results are exhibits in chronological order. Both pilot results are shown and no significant drift is observed. Shadowed areas represent average of pilot results, as in table 3.

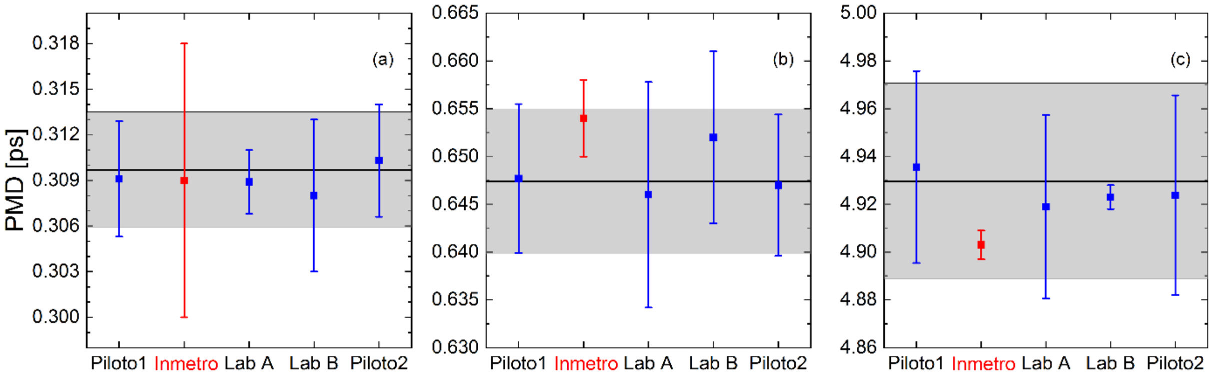

Figure 3. Measurement results of the PMD intercomparison [9], in chronological order. Shadowed areas represent average of the pilot.

Final results obtained by Inmetro are compared to the pilot average in table 4. Normalized error are below unit, indicating agreement of the results within the reported uncertainties. Relative differences are limited to 1.0 %.

Table 4. Comparison of results between Inmetro and the pilot.
Values within parentheses indicate expanded uncertainty.

PMD artefact	Δ_{PMD} [%]	Δ_{PMD} [ps]	E_{norm}
A	-0.2	-0.0007(98)	0.07
B	1.0	0.0066(86)	0.77
C	-0.5	-0.027(41)	0.64

The unilateral degree of equivalence (DoE) indicate the degree of agreement between measurements performed by both parties, the laboratory and the pilot. DoE is a metrics more robust than the straightforward relative difference between PMD values, as it takes into account other features of the intercomparison including the other participants. The parameter is taken not only from the difference to pilot but also from the CRV (comparison reference value) – see details in [9]. The results are summarized in table 5. Results indicate equivalence within 0.45 % as the worst case.

Table 5. Unilateral degree of equivalence between Inmetro and the pilot [9].
Values within parentheses indicate expanded uncertainty.

PMD artefact	Nominal PMD [ps]	DoE [ps]	DoE [%]
A	0.3	0.0002(91)	0.05
B	0.6	0.0029(37)	0.45
C	4.9	-0.0108(68)	-0.22

4. Conclusion

Inmetro developed and implemented a measurement system for calibration of polarization mode dispersion of optical fibers. The system was validated within the laboratory using another measurement method and also participated in an international intercomparison. Results indicate good agreement with other national institutes of metrology within the reported uncertainties and assess the system for providing metrological traceability for polarization mode dispersion of optical fibers.

References

[1] B. E. A. Saleh and M. C. Tech, “Fundamentals of Photonics,” *John Wiley & Sons* (2007).

[2] G. P. Agrawal, "Fiber-optic communication systems," *John Wiley & Sons* (2010).

[3] D. Derickson, “Fiber optic test and measurement,” *Prentice Hall PTR* (1998).

[4] *IEC 60793-1-48:2017*, "Optical fibres - Part 1-48: Measurement methods and test procedures - Polarization mode dispersion", 2017.

[5] *IEC TR 61282-9:2016*, "Fibre optic communication system design guides - Part 9: Guidance on polarization mode dispersion measurements and theory," 2016

[6] R. C. Jones, “A new calculus for the treatment of optical systems. VI. Experimental determination of the matrix,” *J. Opt. Soc. Am.* **37**, 110-112 (1947).

[7] T. Ferreira da Silva *et al.*, "Comparative analysis of interferometric measurements of PMD on optical fibers," in: *SPIE Optical Metrology* 2011, Munique/Alemanha, p. 80822U-1 - 80822U-9 (2011).

[8] J. Ferreira, G. Borghi, and T. Ferreira da Silva, "Evaluation of the relationship between DGD and

wavelength channels," in: *20th IMEKO TC2 Symposium on Photonics in Measurement*, Linz/Austria, p. 150-154 (2011).

[9] V. Kravtsov and A. Mitiurev, “COOMET Supplementary comparison on polarization mode dispersion in optical fiber,” *Metrologia* **58**, 02003 (2021).

[10] Equipment models are presented only as technical references and do not represent recommendation or endorssement by Inmetro.

[11] R. Felder, “Practical realization of the definition of the meter, including recommended radiation of other optical frequency standards (2003),” *Metrologia* **42**, 323-325 (2005).

[12] I. L. M. Silva et al., “Absolute frequency measurement at 563 THz with the Inmetro´s femtosecond laser comb,” in: *Congresso Brasileiro de Metrologia Óptica*, Fortaleza/Brazil (2017).

[13] S. K. Kim, S. C. Gil, B. W. Lee, and S. N. Park, “Development of certificated reference materials for polarization mode dispersion,” Proc. of SPIE Vol. 6351, 63510F-1 (2006).

[14] *JCGM 100:2008*, “Evaluation of measurement data — Guide to the expression of uncertainty in measurement,” 2010.