Polarisation mode dispersion (PMD) is the temporal spreading of a light pulse, propagating along an optical fibre, caused by the different phase and group velocities of the different polarisation components of the signal. The pulse spreading limits the bandwidth of digital systems and causes distortions in analogue systems.

NPL has developed facilities to measure polarisation mode dispersion and other polarisation properties of optical fibres, optical fibre components and systems. To complement these facilities NPL has produced a calibration standard for polarisation mode dispersion measurement equipment.

Polarisation Mode Dispersion

The solution of the electromagnetic wave equation for single-spatial-mode optical fibre produces two guided polarisation modes. In ideal circularly symmetric optical fibre these modes are degenerate with identical propagation constants. In real fibres, asymmetry in the core geometry and internal stress removes the degeneracy leading to different propagation constants for the two modes. The fibre layout and external stress also destroy the degeneracy for ideal fibres. In general the fibre becomes locally birefringent with different refractive indices for the two modes, leading to different transmission times for the different polarisation modes. Globally this effect is combined with random polarisation mode coupling giving rise to a statistical phenomenon.

For a given arbitrarily deployed fibre at a given temperature and optical frequency, there always exist two polarisation states, the principle states of polarisation\(^1\) (PSP), such that the pulse spreading due to PMD vanishes if only one PSP is excited. There exists a differential group delay (DGD=\(\delta\tau\)) between signals propagating in the PSP. In low mode coupled fibre (eg. HiBi fibre) the DGD is constant over a large range of wavelengths. In high mode coupled fibres (eg. long spans) the DGD is a random effect, since it depends on the details of the birefringence and mode coupling along the entire fibre length, and is strongly dependant on wavelength, temperature and mechanical perturbations. In such a case the statistical population of DGDs follows a Maxwellian distribution\(^2\)\(^3\). The PMD (\(\Delta\tau\)) is characterised in terms of an average DGD between the PSP. This parameter is independent, to first order, of wavelength, temperature and mechanical perturbations.
**Definitions**

Principle States of Polarisation (PSP)
The two polarisation states that are independent of optical frequency to first order. In optical fibres where there is no polarisation dependent loss the two states are orthogonal. The two output PSP correspond to two input PSP.

Differential Group Delay (DGD, $\delta \tau$)
The difference in group delay between the light propagating in the PSP. For highly mode coupled fibres the DGD is a strong function of wavelength, temperature and mechanical perturbations.

Polarisation Mode Dispersion (PMD, $\Delta \tau$)
There are two definitions\(^4\) of PMD currently in use. The first is defined as:

Twice the root mean square deviation of the time dependent light intensity distribution $I(t)$ at the output of the fibre when a short pulse is launched into the fibre and chromatic dispersion can be neglected.

$$\Delta \tau_s = 2\left( \langle t^2 \rangle - \langle t \rangle^2 \right) = 2 \left( \frac{\int I(t) t^2 \, dt}{\int I(t) \, dt} - \left( \frac{\int I(t) t \, dt}{\int I(t) \, dt} \right)^2 \right)^{\frac{1}{2}}$$

This is equivalent to the root mean square (RMS) average of the DGD\(^5\), (averaged over frequency or temperature), ie.

$$\Delta \tau_r = \sqrt{\frac{\sum_{i=1}^{N} \delta \tau_i^2}{N}}$$

Alternatively PMD can be defined as the linear average of the DGD (averaged over frequency or temperature):

$$\Delta \tau_m = \frac{\sum_{i=1}^{N} \delta \tau_i}{N}$$

In the case of a highly mode-coupled fibre there is a simple factor linking these two definitions

$$\Delta \tau_s = \Delta \tau_r = \frac{3\pi}{8} \Delta \tau_m$$

These definitions are equivalent for low polarisation mode coupled devices and within the uncertainties of measurements for all practical cases of highly mode coupled fibres.

**Statistics**

The DGD for a high mode coupled fibre is a sample from a Maxwellian\(^{12,3}\) distribution. It can be shown that to first order samples taken at different frequencies, temperatures or times are taken from the same population. An effect of the Maxwellian distribution is that there is a good probability (in comparison to current bit error rates) that the instantaneous DGD may be five times the PMD. The PMD will have an uncertainty limited by Maxwellian statistics and the number of independent DGD measurements.

Typically measurements are made over a finite frequency interval that limits the number of independent measurements. This limits the uncertainty ($1\sigma$) to about 10% for PMD ~ 1 ps rising to 35% for PMD ~ 100 fs\(^6,7\). This is the uncertainty of the average DGD from the Maxwellian distribution given the limited number of independent measurements available from one frequency scan. The uncertainty applies to all methods; it could be reduced by using a larger wavelength scan (ultimately limited to the fibre transmission) or by repeating measurements at different temperatures (temperatures chosen such that the measurements are independent).
PMD Measurement

NPL has developed a facility to measure the PMD of optical fibre and optical fibre components based on the measurement of the output polarisation state for a number of defined input polarisation states as a function of wavelength. Initially the polarisation state analyser is connected to the point X and the programmable polarisation controller adjusted in order to set the desired input polarisation states for each input wavelength. The device under test is then connected between X and the polarisation state analyser and the output polarisation state for each input polarisation state and each wavelength recorded.

The data is analysed using the Stokes vector arc on the Poincaré sphere. As the wavelength is changed from $\lambda_1$ to $\lambda_2$ the output polarisation state describes an arc of angle $\Delta \theta$ about the principle state of polarisation. The differential group delay, $\delta \tau$, is given by,

$$\delta \tau = \Delta \theta \frac{\lambda_1 \lambda_2}{2 \pi c (\lambda_2 - \lambda_1)}$$

By using three input polarisation states, three arcs are described on the Poincaré sphere allowing the identification of the principle state of polarisation and a more accurate measure of the arc angle. This analysis leads to a measure of the full PMD vector and thus it is possible to calculate the change of this vector with wavelength and calculate the second order PMD.

PMD Calibration Artefact

NPL has developed PMD calibration artefacts as transfer standards for PMD measurements. These fall into two categories low mode coupled standards based on HiBi fibre and a high mode coupled artefact based on a multi-waveplate stack.

Low Mode Coupled Standard

These are suitable for the calibration of all types of PMD measurement equipment and give a single fixed DGD calibration point. Calibration artefacts with DGD in the range 0.3 ps to 15 ps can be produced with a calibrated measurement uncertainty of 2%.
High Mode Coupled Standard

These are only suitable for the calibration of PMD measurement equipment which measures DGD as a function of wavelength and can calculate PMD in a specific wavelength ranges. This applies to the polarimeter based PMD measurement methods (Jones Matrix, Muller Matrix and Poincaré Sphere Analysis). The artefact is based on a stack of 32 quartz waveplates with pseudo random orientations which provides a PMD of ~0.5 ps. It should be noted that this artefact is more specialised and may have long lead times.

References


Further Information

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