# Interferometric Loop Method for Polarization Dispersion Measurements

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**Abstract:** A novel method for polarization dispersion measurements using an interferometric loop is presented. It can be achieved using a particularly simple setup and provides a representation of the probability distribution of the polarization dispersion.

## Introduction

A single-mode fiber is not truly single-mode since it can propagate two degenerate modes that are orthogonaly polarized. Weak residual birefringence together with environmental perturbations makes the polarization degeneracy to be actually removed leading to pulse broadening or Polarization Mode Dispersion (PMD). The combined effects of weak birefringence and mode coupling due to external perturbations result in a stochastic behavior of the polarization dispersion and consequently of the output polarization state. The so-called principal states, a particular set of orthogonal polarization states, experience the maximum propagation delay and are therefore very convenient for the description of PMD [1-5]. Dynamic equations show that polarization in fibers is a randomly varying quantity and its probability density function is a Maxwell distribution [2,4,5].

Several methods have been reported so far for the measurements of PMD in long single-mode fibers. A technique using a tunable laser source and analyzing paths over the Poincaré sphere provides a measurement of the instantaneous polarization dispersion [6,7]. This requires repeated measurements to obtain the delay statistical distribution. Another technique uses interferences produced by a low-coherence source to map the actual distribution of possible delays [8], so that a single measurement yields the delay statistical distribution and makes the determination of the PMD expectation value possible.

In this contribution we report a novel method that enables the measurement of PMD using a particularly simple setup, without polarizing elements or retardation plates. A single measurement also provides the PMD expectation value.

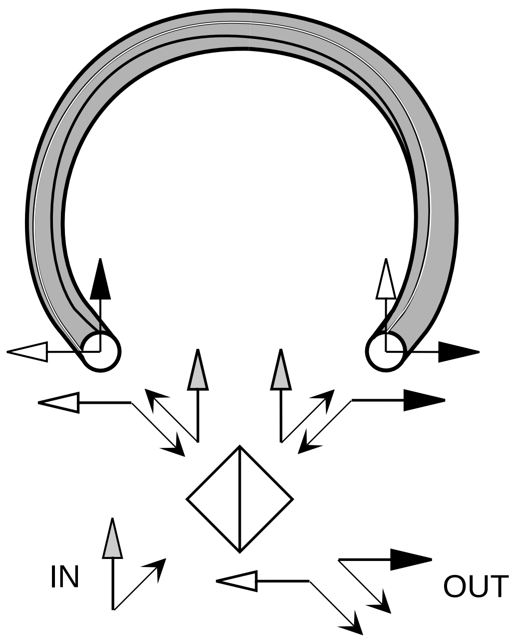


*Fig.1 Example of non-reciprocal propagation in an interferometric loop through a 90 deg twisted linearly birefringent fiber.*

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## Theoretical background

In an interferometric loop, counterpropagating lightwaves propagate along the same optical path, so that the propagation phase difference is zero at the recombination point for any optical path length, except when light experiences a non-reciprocal effect such as Sagnac effect (rotation) or Faraday effect (magnetic field).

A non-reciprocal propagation may also occur when the optical medium is birefringent. Our measurement method uses this property to evaluate the PMD.

For instance a linearly birefringent fiber experiencing a 90 deg twist in the loop gives rise to a complete non-reciprocal propagation, as shown in Fig.1. This way, light from the same input polarization state splits and propagates along two distinct polarization modes of the fiber. Their phase difference $\delta\phi$ is given by

$$\delta\phi = \frac{2\pi}{\lambda} \Delta n\, L$$

where $L$ is the fiber length and $\Delta n$ the birefringence. This phase difference may actually be changed by varying the wavelength $\lambda$, so that a succession of constructive and destructive interferences is observed when the wavelength is scanned, resulting in a periodic variation of the interferometer output intensity. For a given fiber length $L$, the higher the birefringence $\Delta n$, the faster the periodic variations, so that the period measurement straightforwardly yields the value of PMD. Actually this period is simply calculated by performing a Fourier transform.

For a long standard single mode fiber, the random nature of PMD makes the expression for interference intensity more difficult to be carried out. In addition, the set of principal states depends on the propagation direction. After some lengthy calculations using Jones calculus, the interferometer output intensity turns out to be for *any* input light polarization state:

$$I_{out} = I_o\left[1 + \cos^2\theta\, \cos 2\phi\ -\ \sin^2\theta\, \sin\left(\frac{2\pi}{\lambda}\Delta n\, L\right)\right]$$

where $\theta$ and $\phi$ are the angles defining the rotation on the Poincaré sphere to perform the vector base change from the principal states for one direction to the set of principal states for the other direction. When the wavelength is scanned, $\Delta n$ is expected to be constant only over a limited range, so that interference periodicity randomly varies over the spectrum. The wavelength scan makes the fiber experience a great number of polarization situations, so that it may be equivalent to an ensemble average, provided that the statistical distribution is unchanged over the spectrum. With this assumption the distribution obtained by performing the Fourier transform is a measure of the actual PMD statistical distribution. The angles $\theta$ and $\phi$ also vary when the wavelength is changed, but it was demonstrated elsewhere that they don't fluctuate at a higher rate than PMD[3,4], so that their fluctuations induce variations of the output intensity with longer periods. The resulting distribution function of delays has still to be determined, even though its asymptotic nature is expected to be Gaussian.

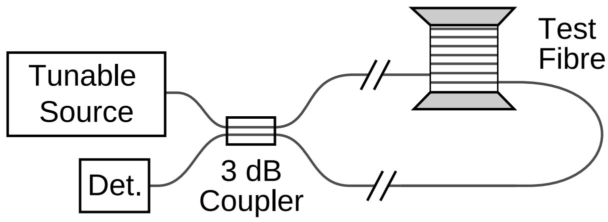


*Fig.2 Block diagram of the interferometric loop method.*

## Experimental results

The interferometer output intensity does not depend on the input light polarization as stated above, so that neither polarization preparation nor tuning is required using polarizing elements or retardation plates. Consequently, even unpolarized light may be used. The optical circuit is therefore particularly simple, as shown in Fig.2. The only needed optical component is a 3dB single mode coupler, that has to be preferably wavelength-independent.

The most critical element is the tunable source. Three configurations were actually tested:

- A white light halogen lamp, whereas detection is performed using an optical spectrum analyzer. This configuration provides the largest wavelength coverage, a very uniform and smooth spectrum, but has a poor dynamic range. It is also low-cost and quite suitable for the measurement of less than 10-km fibers [9].

- A set of LEDs, detection still performed using an optical spectrum analyzer. The dynamic range is larger, enabling the measurement of up to 30-km fibers. The drawback is a narrower and less uniform spectral coverage.

- A tunable external cavity laser diode. This advanced configuration enables the best performances, with an ideal dynamic range and a convenient spectral coverage. However it suffers from the drawback of the present high cost of such a source.

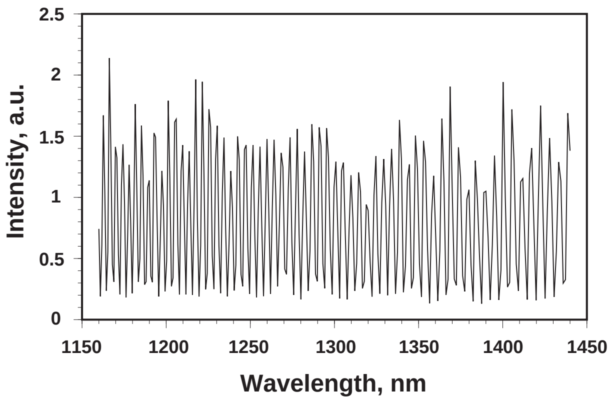


*Fig.3 Interferometric loop output intensity as a function of wavelength. The loop is a 0.5m highly birefringent fiber.*

The results obtained using any of these three configurations were identical. As a first test, a sample of 0.5 m highly birefringent fiber was measured, using a configuration equivalent to Fig.1. The output intensity periodically varies as the wavelength is scanned, as shown in Fig.3. The interference contrast was observed to change from a maximum to a minimum value when either fiber end was rotated. The period of the intensity spectral variations is obtained by performing a Fourier transform, so that the PMD corresponds to the peak position in the transformed distribution, as shown in Fig.4.

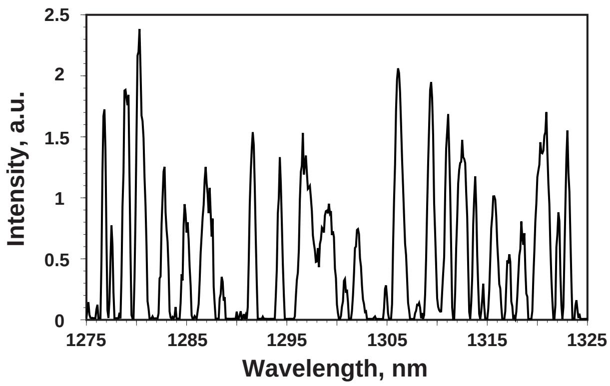


*Fig.5 Interferometric loop output intensity as a function of wavelength. The loop is a 3600m standard single mode fiber.*

The observed intensity variations are quite different when a several kilometers standard single-mode fiber is measured, as shown in Fig.5. The delay between polarization modes is wavelength-dependent making the

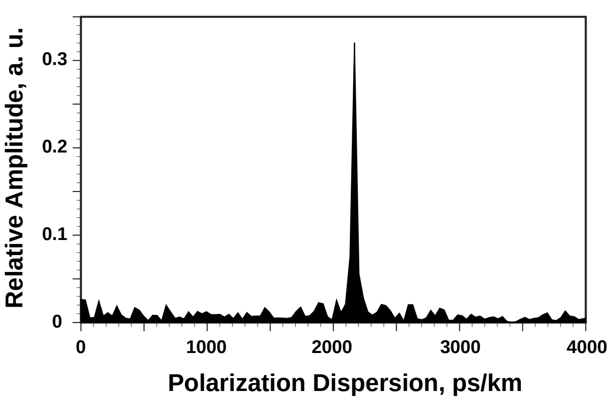


*Fig.4 Fourier transform of the measurements shown in Fig.3. One frequency is dominant, corresponding to the polarization dispersion value.*

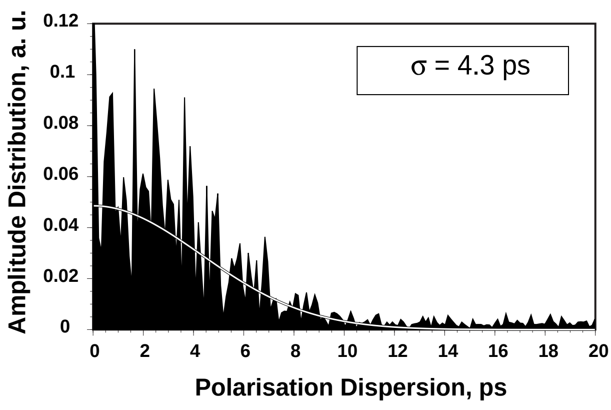


*Fig.6 Fourier transform of the measurements shown in Fig.5. The obtained Gaussian-like distribution is directly related to the statistical distribution of polarization dispersion.*

period of intensity variations to fluctuate over the spectrum. The Fourier transform of such a measurement is not just one peak, but a distribution of numerous peaks, as shown in Fig.6. With the "wavelength scan" = "ensemble average" assumption, this distribution is a close representation of the actual delay statistical distribution.

The minimum observable delay corresponds to an interference period equal to the spread of the measurement spectral range, so that the larger is this spread, the better is the resolution. Hence:

$$\delta\tau_{min} = \frac{\lambda_{max}\lambda_{min}}{c\,(\lambda_{max}-\lambda_{min})}$$

where $\lambda_{min}$, $\lambda_{max}$ are the lower and upper bounds of the measurement wavelength range, respectively.

On the other hand, the maximum observable delay is bounded by the source spectral width, because this delay must remain shorter than the coherence time in order to observe interferences. Hence

$$\delta\tau_{max} = \frac{\lambda^2}{c\,\Delta\lambda}$$

where $\Delta\lambda$ is the spectral width and $\lambda$ the center wavelength ($\Delta\lambda$ corresponds to the minimum wavelength step when using a tunable laser source). Actual obtained figures are shown in the table below:

| Source | $\delta\tau_{min}$ | $\delta\tau_{max}$ |
|---|---|---|
| White lamp | 0.008 ps | 1.4 ps |
| LEDs | 0.016 ps | 9.6 ps |
| Tunable laser | 0.075 ps | 375 ps |

## Conclusion

Reproducibility tests were successfully carried out using this method and the scattering of the obtained PMD expectation value was below 10%, even though the fiber was displaced between the measurements and the intensity versus wavelength curves look totally different. Results were also compared to those obtained using another measuring technique [10] and the agreement was excellent for expectation value below 1ps. For larger values, great differences are observed and are still unexplained. This method has the great advantage to be very easy to implement, because most of the setup elements are available in any optics lab, so that most of them can already afford the implementation of this technique.

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