Dispersion measurement of single-mode optical fibre using intensity modulator

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Abstract
We propose a technique for dispersion measurement of single mode optical fibre, using a variation of interferometric method with intensity modulators that realize an interferometer structure. We have measured group delay spectrum of standard single mode optical fibre of lengths up to 25 km. The results are in agreement with the previously reported values. The dispersion coefficient at 1555 nm was found to be 20.1 ps/nm-km which differs only by 0.5 percent from the standard value of 20 ps/nm-km. We have used LabView to automate the measurement process to ensure good repeatability.

1. Introduction
Dispersion causes the transmitted pulses to broaden beyond their initial time slot into the neighboring slots. Such inter symbol interference (ISI) limits the maximum data rate of transmission [1],[2]. Dispersion arises due to the fact that the group velocity (and group delay) of the optical signal propagating in a fibre depends on the refractive index, n(λ), of the doped silica, which is a nonlinear function of wavelength λ [2],

\[
d^2n \neq 0. \quad (1)
\]

Thus, simultaneously launched wavelengths propagate with different group velocities and cause pulse broadening. It is customary to specify the dispersion characteristic of a fibre by the quantity, dispersion coefficient, expressed in ps/nm-km. Dispersion coefficient, \(D_\lambda\), is the first derivative of group delay with respect to wavelength:

\[
D_\lambda = \frac{1}{L} \frac{d\tau_\lambda(\lambda)}{d\lambda} \quad (2)
\]

where \(\tau_\lambda(\lambda)\) is the group delay spectrum and \(L\) is the length of the test fibre.

A number of techniques have been used to measure the dispersion characteristic of single mode optical fibres [3], [4], [5]. The conventional time of flight measurement works by measuring the time of arrival (TOA) of a short pulse as a function of the wavelength. By measuring TOA over a given range of wavelength, the group delay of the fibre is estimated [6], [7]. The interferometric method, by Stone and Cohen [8], provides a high accuracy of dispersion measurement. The method uses either a Michelson or Mach-Zehnder interferometer and measures the interference pattern between the two arms of the interferometer. The pattern provides a direct way of estimating the group delay spectrum from which the dispersion coefficient is obtained.

This paper presents a modification of the interference technique to measure the dispersion of single mode optical fibre. These methods usually require a calibrated reference fibre and an optical delay element to achieve high degree of precision. Measurements which use air-reference, instead of reference fibre, are more difficult to align and generally do not guarantee good repeatability [3], [9]. Moreover, these methods are limited to short fibre lengths (< 1 m). We overcome the above mentioned problems by utilizing optical intensity modulators to realize the interferometer. The method achieves simplicity by eliminating the requirement for a reference fibre. This allows characterization of dispersion over long fibre lengths (> 10 km) which is not possible by using air-reference methods [3], [9]. The entire set-up is automated using LabView [10] to ensure repeatability of experiment.

Intensity modulator based dispersion measurement has been used earlier [11]. In that arrangement, dispersion of fiber was measured by modulating a bidirectional Mach-Zehnder modulator. The time delay was estimated and dispersion coefficient calculated by obtaining the optical transfer function [6]. However, in this method, interference was measured in the RF domain using a NA. The NA clearly limits the maximum resolution achievable and distance with this set-up [11]. Our method achieves higher resolution since we measure the average voltage of the interference signal. Also our method is applicable for measuring dispersion of long fiber lengths. Finally, we point out that automation of experiment allows repeatability of measurements.
The principle of Mach-Zehnder interferometer (MZI) based dispersion measurement is shown in Fig. 1. In-put light is divided into two beams by an input beam splitter (BS). One beam is launched into a reference fibre, whose group delay spectrum is carefully calibrated. The second beam is launched into the test fibre of approximately same length as the reference fibre. At the output, the two beams are combined into a single beam, which is fed through a detector. The detector cross-correlates the test beam relative to the reference beam. By carefully adjusting the length of the interferometer arms the optical path lengths can be equalized. The cross-correlation produces an interference pattern between the test and reference beams, which is measured to determine the group delay spectrum of the test fibre relative to reference fibre.

We realize the MZI structure by the set-up shown in Fig. 2. The tunable laser source produces light over the desired wavelength range. A sinusoidal signal, of frequency $\Omega$ rad/s, is used to amplitude modulate the light beam by an external travelling wave intensity modulator, MOD-1. The intensity of the light beam at the output of MOD-1 is

$$I_1 = I_i [1 + m_1 \cos(\Omega t)]$$

where, $I_i$ is the intensity of the laser, which is constant for all wavelengths, and $m_1$ is the modulation index of MOD-1 [13]. The modulated light beam is launched into the test fibre of length $L$. The optical fibre introduces a wavelength dependent group delay, $\tau_g(\lambda)$ so that different wavelength components of the modulated light beam travel at different velocities. At the output of the fibre, the intensity of light beam becomes

$$I_2(\lambda) = I'_1 [1 + m_1 \cos(\Omega(t - \tau_g))]$$

The light beam from the fibre is amplitude modulated by a local oscillator of frequency $\Omega$ rad/s and synchronized to the transmitter. The output of the second modulator, MOD-2 is given by

$$I_2 = I'_1 [1 + m_1 \cos(\Omega(t - \tau_g))] \times [1 + m_2 \cos(\Omega t)]$$

$$= I'_1 [1 + \frac{m_1 m_2}{2} \cos(\Omega \tau_g) + \frac{m_1 m_2}{2} \cos(2\Omega t - \Omega \tau_g)]$$

$$+ m_1 \cos(\Omega t) + m_2 \cos(\Omega t)$$

We see from (5) that the combination of MOD-1, fibre and MOD-2 acts as an MZI with the second modulator cross-correlating the light beam from the first modulator to produce an interference pattern. The output of MOD-2 is applied to the detector and the average term $I'_1 [1 + \frac{m_1 m_2}{2} \cos(\Omega \tau_g/2)]$ is extracted. The unmodulated power at the output of MOD-2 is proportional to $I'_1$. By measuring the intensity of the modulator output with and without modulation, we estimate the group delay $\tau_g(\lambda)$ by solving the average term

$$\Omega \tau_g(\lambda) = \cos^{-1} \left[ \frac{2}{m_1 m_2} \left( \frac{I_2(\lambda)}{I'_1} - 1 \right) \right]$$

3. Experimental results

The complete experimental setup is shown in Fig 3. We used the Agilent 8164 lightwave measurement system, which incorporates a tunable laser source (TLS)-Agilent 81689A, and a power sensor, capable of measuring extremely low optical powers (up to -100dBm) [12]. The wavelength tuning range of TLS is [1524, 1576] nm with minimum step size of 0.01 nm. We confined ourselves to the wavelength range [1545, 1555] nm so as to characterize dispersion around 1550 nm. This is important in applications such as quantum key distribution, where the two wavelengths 1546 and 1552 nm are used to transmit quantum information and phase reference [14]. The modulators MOD-1 and MOD-2 were Mach-Zehnder based intensity modulators from JDSU, with LiNbO3 crystal as the birefringent medium. The half wave voltage $V_{na}$ of the modulators were 3.6 V. The modulators were biased at $\frac{1}{2} V_{na}$ to ensure better linearity of the modulation. We used the standard SMF-28 fibre spool of length 25 km from Corning. The frequency of the sinusoidal modulating signal was 2 MHz. As the group delay measurement is sensitive to changes in temperature, mechanical stress, and drift the set-up was automated using LabView.
was calculated by measuring the average term and solving for total group delay, \( \tau_t(\lambda) \) from which the calibrated group delay, \( \tau_c(\lambda) \) is subtracted.

\[
\Omega \tau_t(\lambda) = \cos^{-1}\left( \frac{2}{m_1 m_2} \left( \frac{I_2(\lambda)}{I_1} - 1 \right) \right)
\]

\[
\Omega \tau_c(\lambda) = \cos^{-1}\left( \frac{2}{m_1 m_2} \left( \frac{I_2(\lambda)}{I_1 e^{-\alpha L}} - 1 \right) \right)
\]

\[
\tau_g(\lambda) = \tau_t(\lambda) - \tau_c(\lambda)
\] (8)

The results of the experiment are plotted in Fig. 4. The top half of Fig. 4 shows the plot of total and correction group delay spectrum. The bottom half of Fig. 4 shows the group delay spectrum of the fibre per unit length, \( \tau_g / L \), measured in ns/km.

4. Conclusions

We have demonstrated a technique for measuring dispersion in single mode optical fibres using intensity modulators. The method is simple and accurate, requiring...
no reference fibre for calibration. The automation of the measurements ensure good repeatability and ease of operation. Finally, our method can be used to measure dispersion over long fibre lengths (> 25 km).

5. References


