Dispersion measurement in optical fibres over the entire spectral range from 1.1 µm to 1.7 µm

F. Koch *, S.V. Chernikov, J.R. Taylor
Femtosecond Optics Group, Physics Department, Imperial College, Prince Consort Road, London SW7 2BZ, UK
Received 19 October 1999; accepted 17 December 1999

Abstract

Using a super-continuum fibre laser we have measured the dispersion of optical fibre over the 1.1–1.7 µm spectral window in silica fibre. © 2000 Elsevier Science B.V. All rights reserved.

Dispersion is one of the key characteristics of optical fibre for telecommunication applications. Over recent years with increasing bit rates and transmission bandwidths, an accurate knowledge of the dispersion has been found to be an essential requirement. This applies not only to the so-called first order dispersion but to the higher order terms as well. In order to determine the higher order terms a precise measurement of the dispersion and higher order terms for one wavelength has to be carried out or a measurement of the dispersion curve has to be undertaken. With the rapid expansion of wavelength division multiplexing (WDM) systems in terms of number of channels, requirements for channel spacing and installed commercial systems, an accurate measurement of the dispersion curve becomes even more important.

Measurements of dispersion in optical fibres are based on two basic principles: (i) interferometric measurements in short samples of fibre and (ii) time of flight type measurements in long fibre spans. Both methods provide reliable and accurate measurement of dispersion in commercial and laboratory systems. Interferometric based measurements need a low coherence light source to form the interference pattern. The detection can take place in either the frequency or the time domain with differing requirements on the light source and the detection schemes. To measure low dispersion values in the frequency domain it is vital to use broadband sources because the interference pattern frequency is inversely proportional to the dispersion and therefore covers a wide wavelength range. In order to measure a delay time curve at several wavelengths the requirements for the light source are further extended. Intensity variations (noise) of the light source do not interfere with the measurement to some extent because only the positions of maxima and minima are necessary to determine the dispersion.

Time domain measurements depend on the envelope of the coherence function and to determine the dispersion a mechanically reliable and noiseless light source is required. All interferometric configurations need to be mechanically stable over the time to
acquire the data. For very weak signals, a long data acquisition or integration time is required placing addition demands on the stability of the system.

Time of flight time type measurements directly detect either the time of flight of a short pulse or the phase shift of a modulated wave packet. The resolution of direct time of flight measurements depends on the shortest resolvable differential time delay, which is limited by the resolution of the detection scheme and the rise time of the pulse. In order to determine the dispersion it is then necessary to differentiate the delay curve obtained and the accuracy depends on the number of data points collected. Therefore for time of flight type measurements a widely tunable short pulse laser is required.

Currently available commercial measurement systems use the phase shift technique to measure the dispersion in long samples of fibre. The resolution is determined by the bandwidth of the detection system and the noise. The availability of suitable light sources restrict these systems to measure only in the band of 1.31 µm and 1.55 µm using separate light sources for each band. A more detailed description of the different measurement methods can be found in [1] and references therein.

The requirements for light sources for both types of dispersion measurements such as pulse format, rise time, bandwidth, degree of coherence and high power levels are not readily fulfilled. In this letter we present the application of a super continuum fibre laser which covers the spectral range from 1.10 µm to 2.20 µm with a spectral brightness > 0.2 mW/nm. This is 5 orders of magnitude higher than other comparable sources. It is self-Q-switched with a rise time of less then 1 ns and the small diode pumping system employed makes it compact and easy to use. The unique features of the source make it an appropriate choice for the characterisation of optical telecommunication components [2].

The laser source generates Q-switched pulses of 3 ns duration at a repetition rate of 10–20 kHz and a rise time of less than 1 ns. The spectrum of the laser is Raman dominated and covers the range from 1.06 µm to 2.2 µm page (Fig. 1). The high spectral brightness enables continuous measurement over the wavelength range without the need of any signal enhancement. The average output power is ~300 mW at a repetition rate of 20 kHz and is fibre delivered from the laser which is housed in a compact 115×85×15 mm box. A more detailed description of the laser can be found in Ref. [3].

The interferometric measurement was based on a Mach–Zehnder-interferometer and broadband 3 dB fused fibre couplers were used instead of bulk beam-splitters simplifying the alignment as well as adding system stability [4–6]. The test fibre (60 cm) was spliced to the couplers for simplicity and the reference path consisted of collimating and focusing lenses mounted on a micron precision stepper as a adjustable delay line (Fig. 2).

The interference pattern in the frequency domain is characterised by the wavelength position for matched path lengths and the position of the maxima and minima. The rate of the interference pattern increases from the wavelength of matched path lengths with dispersion and the matching wavelength can be relatively easily determined. Fig. 3 shows three different delay settings for the reference path and the corresponding matching wavelengths are indicated.

![Fig. 2. Experimental configuration.](image)
A plot of delay time against wavelength (Fig. 4) was obtained by varying the delay in the reference path and monitoring the corresponding matching wavelength. Up to 70 data-points were collected over the spectral range and the acquired data points were fitted to a 5 term Sellmeier or a polynomial equation. From the delay the dispersion can be calculated by

\[ D = \frac{1}{L} \frac{\partial s}{\partial \lambda}, \]

where \( L \) is the length of the test fibre, \( c \) the speed of light, \( s \) the delay length of the reference path and the wavelength. The choice of the fitting curve was confirmed by comparison of the direct differentiation of the experimental data and the fitted curves. For standard and dispersion shifted fibres the Sellmeier equation gave a better agreement compared to dispersion compensating fibres with high dispersion, which were better fitted to polynomial expressions. The difference of the two fitting curves is only apparent at the extremities. The spectral range of the spectrum analysers limited the upper wavelength range to 1.7 \( \mu \)m. Because the spectrum of the source is continuous to 2.2 \( \mu \)m and above, more data points could be collected to enhance consistency in this wavelength range but an alternative detection system would be required.

For the determination of the zero dispersion wavelength it is important to equalise the path lengths leading to and from the couplers because any mismatch will contribute to the measured dispersion. The collimating and focusing lenses of the reference path have to been taken into account. This shows that the set-up is very sensitive to the measure of small values of dispersion and contributes to it.

Also based on the interferometric measurement it is possible to calculate the dispersion from a single spectrum for one setting of the reference path. From the wavelength at which the optical path lengths for reference and test path are equal the phase difference to the next maxima and minima is \( \pi \). The effect of dispersion can be described in the equation for the interference pattern as a Taylor expansion of the propagation constant around a wavelength \( \lambda \). The phase difference can therefore be written as a polynomial of the propagation constant and the wavelength/frequency difference \( \Delta \omega \) (Eq. (2))

\[
\Delta \phi(\Delta \omega) = \Delta \omega \left[ \frac{L_R}{c} - \beta_t^{(3)} + \frac{1}{2} \Delta \omega^2 L_{\gamma} \beta_t^{(5)} - \frac{3}{2} \Delta \omega^3 L_{\gamma} \beta_t^{(7)} \right] + \pi \cdot n,
\]

\( n = \ldots -3, -2, -1, 0, 1, 2, 3, \ldots \)
With $\beta_1^{(1)}$, $\beta_2^{(2)}$, $\beta_3^{(3)}$ as the propagation coefficients of the Taylor-expansion of the fibre and $L_R$, $L_T$ the length of the reference and test path. The integer number $n$ indicates the number of the maxima and minima and zero for the matched path lengths. From the spectrum the phase difference $\Delta \phi = n \cdot \pi$ can be plotted as function of wavelength difference. The coefficients from a polynomial fit to this graph give the propagation constant and therefore the value of dispersion for the particular wavelength $\lambda$. This method confirmed the measurements described earlier for any desired wavelength by varying the delay in the reference path. We used this method also to confirm the choice of fitting function because it does not rely on the fitting function but gives the dispersion for a single wavelength.

For measurements in long fibres we directly obtained the time of flight for pulses with a small bandwidth using a fast photodiode. A fraction of the laser spectrum was selected using a diffraction grating based monochromator with fibre input and output [Fig. 5]. For a bandwidth of $\sim 4$ nm average powers greater than 30 $\mu$W were achieved up to 1.65 $\mu$m. The detection scheme consisted of a biased photodiode and a sampling oscilloscope and the measured rise time was limited by the sampling oscilloscope and jitter in the signal (Fig. 6). Part of the power before entering the test fibre was used as a trigger for the delay measurement. By scanning the monochromator the delay times for several wavelengths were obtained and the dispersion was calculated, with relation to Eq. (1) and the associated description. It was possible to measure the delay time in various fibres for example 20 km of dispersion-shifted fiber or 110 m of dispersion compensating fiber which exhibited a dispersion of 130 ps/km nm. In the case of 20 km dispersion shifted fibre it was not possible within experimental error to observe any difference in the values measured using the interferometric method. However at the extremities of the measurement range, the slope of the curve differed slightly due to errors in the fitting. One limiting factor is that the pulses of the laser-source are unstable in repetition rate, peak power and pulse shape primarily as a result of the passive nature of the $Q$-switching process and therefore triggering and averaging over many pulses makes it difficult to determine accurately the delay time.

We have presented in this letter the application of a high brightness broadband self-$Q$-switch laser source for measuring the dispersion curve in short fibre samples using an interferometric technique and in long fibers by a time of flight technique. In both cases no additional signal enhancement was necessary and a standard spectrum analyser, photo-diodes and oscilloscopes were used. There is no limitation from the light source in the spectral resolution and it can be used for the characterisation of dispersion and other optical properties and components in the near infrared region.
References