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Distributed dispersion measurements and control within continuously varying dispersion tapered fibres

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Abstract

We report the first continuous non-destructive measurement of dispersion along a fibre designed to have a continuously varying dispersion profile. This measurement highlights the flexibility of the measurement technique and illustrates the levels of accuracy [$\approx 0.05\,\mathrm{ps/(nm.km)}$] that can be achieved when pulling long fibres with arbitrary dispersion profiles.

Keywords

I. INTRODUCTION

Dispersion Varying optical Fibres (DVFs) i.e. fibres with continuously varying axial dispersion profiles have been demonstrated to have a wide range of applications in high bit-rate communications and short pulse laser systems [1], [2], [3], [4], [5]. Techniques for the fabrication of ≈ km lengths of such fibre were first demonstrated in 1989 and early experimental work work focused on their use for high bit-rate bright[2] and dark soliton generation[5] and adiabatic pulse compression [6]. More recently interest has centered on the use of such fibres in high capacity soliton transmission systems[7]. Using such fibres between amplifiers permits one to reduce the deleterious effects of loss and four wave mixing allowing for considerably enhanced soliton transmission for both single channel [8] and WDM systems [4]. To date most experimental work has used compromise dispersion maps which are stepwise constant approximations to the ideal continuously varying profiles which are generally considered to be impractical to fabricate and are not currently available in long lengths. However a number of groups have now reported the fabrication of fibre with dispersion profiling over lengths of several 10's of km's and the issue of how reliably and with what dispersion accuracy such fibre can be fabricated becomes a key issue as to their practical implementation in any future high speed communication system.

Clearly the essential feature of a DVF is the dispersion map $D(\lambda, x)$ along its length. Yet until recently conventional non-destructive dispersion measurements only provided the average dispersion and it was not possible to directly measure $D(\lambda, x)$ along a DVF span. The only non-destructive way of assessing the quality of the dispersion profile was to take sample measurements at the beginning and end of the fibre, to measure the average dispersion along the fibre span and/or to try and infer the fibre's quality from the performance of the system under test. However, recently a number of techniques for distributed dispersion measurement [9], [10], [11] have appeared in the literature with km resolution and sufficient dispersion accuracy to allow for a direct assessment of dispersion control within DVFs of amplifier span length scales. In this paper we report the first direct measurements of dispersion profiles in DVFs based on a distributed dispersion measurement technique developed by Mollenauer and coworkers [9], illustrating the accuracy of both the fabrication technology and the measurement technique when applied to dispersion tapered fibres with large scale dispersion variation. Such measurement capability is crucial to improving the fabrication quality of DVF.

The technique of Mollenauer *et al.* is based on the four wave mixing of two pump beams at frequencies ω_1 and ω_2. Due to the fibre nonlinearity the pump beams mix to generate both a Stokes (ω_s) and an anti-Stokes (ω_a) wave at frequencies given by

$$\omega_s = 2\omega_1 - \omega_2, \tag{1}$$

$$\omega_a = 2\omega_2 - \omega_1. \tag{2}$$

At any position x down the fibre the phase mismatch between the Stokes wave and the pump beam at ω_1 is proportional to both $D(\lambda_1, x)$ and the frequency separation $\omega_1 - \omega_2$. This phase mismatch manifests itself as intensity oscillations in both the Stokes and anti-Stokes waves, which can be observed as temporal oscillations in the intensity of the the Rayleigh backscattered light at the front end of the fibre and whose frequency at a time t is proportional to the $D(\lambda, x = c/(2n)t)$.

By launching strong microsecond pump pulses into the fibre and observing the intensity oscillations of the Rayleigh backscattered light we thus get a direct measurement of $D(\lambda, x)$ along the entire fibre length. The experimental setup to do this is shown in Fig. 1. The acousto-optic modulator (AOM) produces one microsecond square pulses at a repetition rate of 1 kHz. These pulses are then amplified to a peak power of ≈ 1 W before entering the fibre. The backscattered light is optically amplified before passing through a tunable narrow band optical band pass filter allowing observation of either the Stokes or the anti-Stokes signal. The repetition rate of the AOM allows averaging over many repetitions to be made in a few seconds, resulting in unambiguous results.

This method is ideal for measuring distributed dispersion values below ≈ 1 ps/(nm.km) around 1550 nm however our fibre's dispersion is considerable higher, varying from 6 ps/(nm.km) down to 0.5 ps/(nm.km). This large dispersion variation meant that the pump frequencies $\omega_{1,2}$ were within the anomalous dispersion regime and not in the normal dispersion regime as advised by Mollenauer. Hence to avoid the effects of modulational instability we had to run with reduced peak power resulting in a reduction in interrogation length (≈ 20 km). Also the factor of 10 variation in dispersion resulted in the measurement resolution varied correspondingly along the fibre length for a given measurement setting. In order to get the most accurate measurement of the dispersion profile we therefore needed to make a significant number of independent measurements for different wavelength spacings and settings from both ends of the DVF.

II. RESULTS

The dispersion measurements presented here were made on a 38km long loss compensating soliton transmission fibre whose dispersion profile was designed to decrease exponentially from 6 ps/(nm.km) to 0.55 ps/(nm.km) at 1550 nm [3]. The fibre was fabricated from a commercial grade preform of step index refractive index profile and NA=0.175 by appropriate tapering of the fibre external (core) diameter. from 105 μm at the high dispersion end to 92 μm at the low dispersion end. The fibre was designed to have a 1300nm single mode cut-off wavelength at a diameter of 125 μm. The RMS external diameter deviation from design was measured to be less than 0.2 μm along the entire fibre length resulting in local dispersion fluctuations < 0.1 ps/(nm.km) [12].Such rapidly varying , local fluctuations are relatively unimportant in this fibre with its high average dispersion but could be of more significant in low dispersion DVFs, however before these measurements it was not clear at what level preform inhomogeneity, which we were unable to quantify, had effected the longer scale dispersion profile accuracy. This fibre was pulled in two sections of lengths 20km and 18km respectively[3]. Previously the only dispersion measurements made on the fibre were average measurements along the individual fibre spans plus measurements made on short lengths of constant dispersion fibre drawn immediately before and after the DVFs to allow a determination of the input and output dispersions. The measured values were within 0.15 ps/(nm.km) of the design values in each instance. The third order dispersion D_3 was measured to be 0.053 ps/nm^2/km [3]. In addition to these direct, but sampled measurements, ps pulse propagation experiments demonstrating high quality loss compensation over as many as 40 soliton periods indicated that the actual dispersion profile follows the desired profile very closely[12].

As discussed previously the relatively high dispersion of these fibres meant that we needed to make a number of measurements with different conditions to obtain the most accurate information as to the fibre dispersion profile along the entire fibre length. We varied the wavelength of the pump beams between 1545 nm to 1550 nm and the wavelength separation between the pump beams from one to four nanometres. Measurements were made for both forward and backward directions in each fibre and along the entire 38 km span. A typical experimental backscattered Stokes trace is shown in fig2. Note that the oscillations can be well resolved along the entire 18 km length of the fibre and that the period can be seen to be decreasing as expected for a fibre with steadily increasing dispersion. The period was determined by the peak to trough distance, giving the average dispersion over that length. In Fig. 2 22 maxima or minima can be distinguished indicating a spatial resolution of less than one kilometer was achieved. The amplitude of the signal is determined by both the loss in the fibre and the nonlinearity[9] and although irrelevant for measuring the dispersion does contain useful information that could, for example, be used to investigate mode field variations.

Using the measured third order dispersion[3] we extrapolated the results of our individual measurements at different wavelengths to the fibre design wavelength of 1550 nm. The average of these measurements, for each kilometer section, is shown in Fig. 3 along with the desired profile (solid line). The error-bars shown correspond to the standard deviation of our measurements. Over the first 18 km low dispersion section the absolute error in our measurements is < 0.05 ps/(nm.km) while over the high dispersion length the error is < 0.5 ps/(nm.km). The larger error in the high dispersion section results from the fact that as the dispersion increases the period of the signal decreases and thus any absolute errors in estimating the period are magnified.

The average deviation between the measured and the desired profile is less than 8% for the whole length indicating that an excellent degree of control over dispersion is possible over significant fibre lengths. Of particular note is the control achieved at the low dispersion end of the fibre. In this regime an average error of $< 0.05\,\text{ps}/(\text{nm.km})$ is obtained over the 18 km of fibre comparable with the measurement uncertainty and is of the same magnitude as deviations from nominal uniform dispersion observed over $\approx 10\,\text{km}$ length scales in commercial dispersion shifted fibre [10]. The absolute deviation for the higher dispersion 20 km section appears slightly higher $\approx 0.1\,\text{ps}/(\text{nm.km})$ and systematically slightly low, but is still well within the bounds of measurement error.

III. CONCLUSIONS

We have presented here the first direct measurements of $D(\lambda, x)$ for a DVF with a spatial resolution of less than one kilometer and a typical error of $\pm 0.05\,\text{ps}/(\text{nm.km})$. The results show that the dispersion measurement technique can readily be applied to fibre with considerable average dispersions and dispersion tapers. More importantly the measurements demonstrate that excellent dispersion control with an absolute accuracy of order $0.05 - 0.1\,\text{ps}/(\text{nm.km})$ can be achieved in fibres over 10's kms length scales using the core diameter tapering technique, providing that sufficient attention is paid to diameter control and preform homogeneity. However, it should be stated that such a dispersion accuracy is still significant for the development of tapered fibres for soliton transmission application where relatively low average dispersions will be required with accurate profiling close to zero dispersion. Considerable effort will be required in preform design, fabrication and/or real time active control during the pulling process to gain significant improvements in the fabrication of such fibre.

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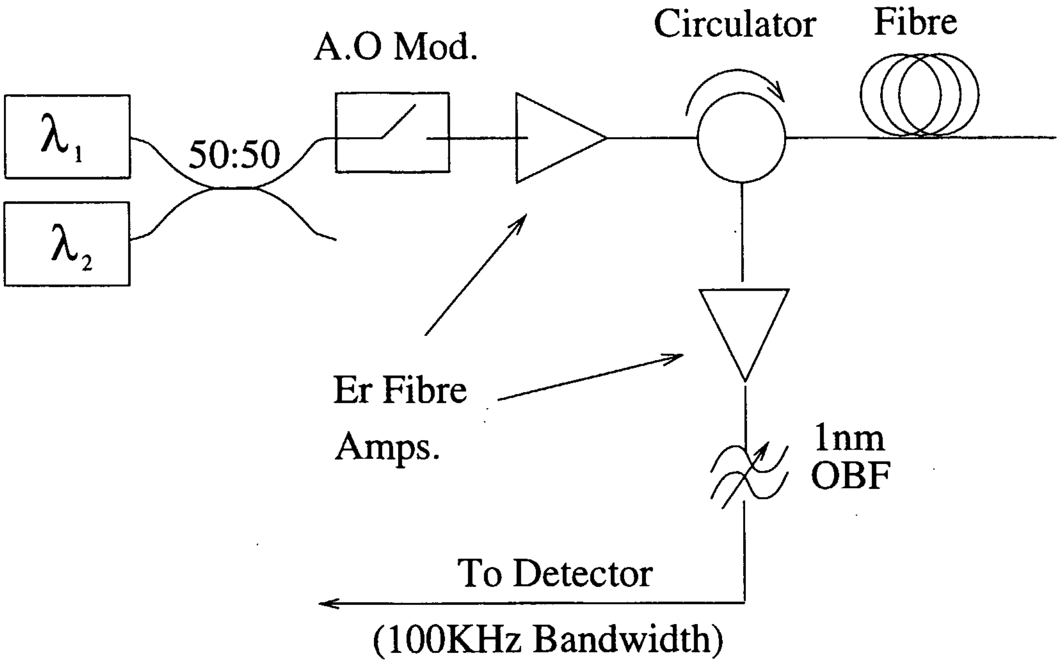
Fig. 1. Schematic of the dispersion measuring rig.

Fig. 2. Typical trace of the backscattered light from the fibre. The sudden drop in the signal near the end of the trace corresponds to end of the fibre and allows an accurate measurement of the length to be made. The amplitude variation is due to the loss in the fibre.

Fig. 3. Measured dispersion along the fibre. The solid line is the designed profile. The dashed vertical line indicates the position of the splice in the fibre.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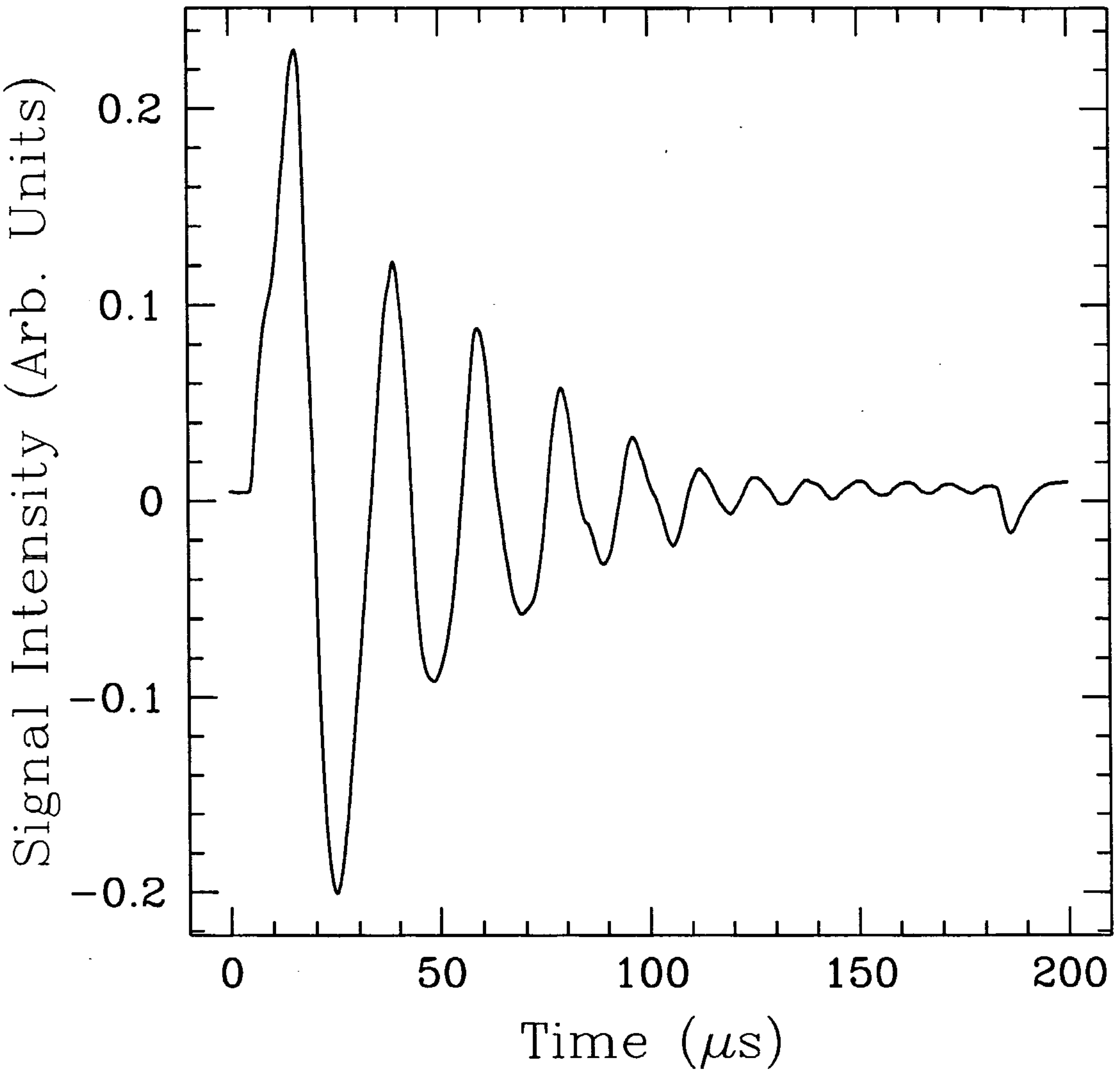
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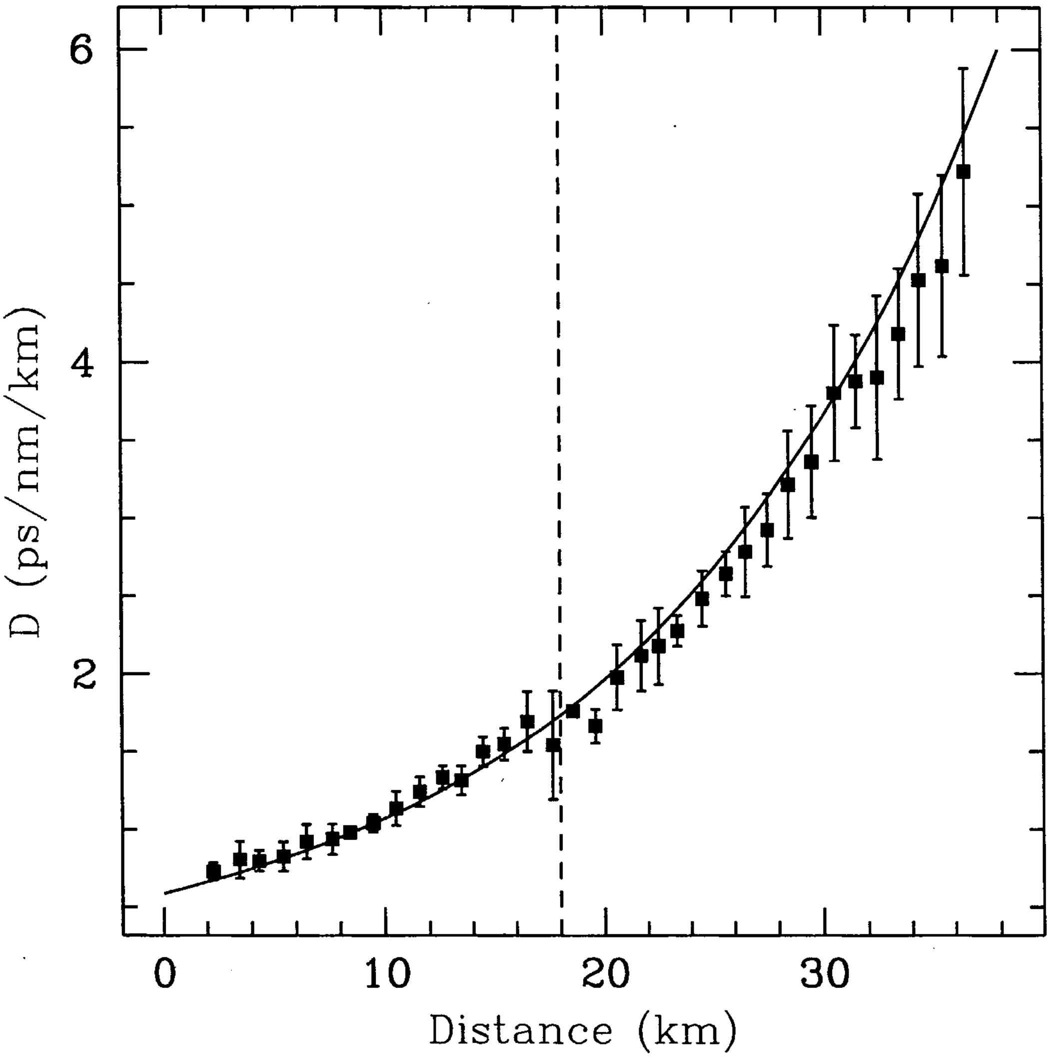
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