

REPORT

Dispersion Mapping of Optical Fibres

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Summary

This report looks at three ways of measuring the variation in dispersion along fibres and fibre links. The first uses OTDR derived mode field diameter data to do this. An accuracy of $0.2 \text{ ps.nm}^{-1}.\text{km}^{-1}$ appears possible using this technique and fibres up to at least 15 km long can be measured. The second, based on modulation instability, was briefly investigated but not pursued in any detail as it appears restricted to fibres with a zero dispersion wavelength in a rather narrow range. The third technique, four-wave mixing, follows on from NPL Report COEM 43. In contrast to the modulation instability approach, the four-wave mixing is applicable to most if not all single mode fibres. It is relatively quick (seconds to minutes depending on the length of the fibre) and is capable of measuring fibres up to at least 26 km long. From measurements on six different fibres, the accuracy of the measurements in the present study was $0.04 \text{ ps.nm}^{-1}.\text{km}^{-1} + 4\%$ of the dispersion value (correspondingly approximately to two standard deviations). In terms of dispersion fluctuation along fibres, fluctuation of 3% of the dispersion value are resolvable. With system improvements we would expect to be able to improve these accuracies by about a factor of two. Further, the technique looks capable of being developed into a system suitable for field use.

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1 Introduction

Fibre is now routinely manufactured in lengths greater than 25 km. However, when it is cabled section lengths are typically 2 to 5 km. Measuring fibre parameters in a non-destructive manner on the longer length offers the possibility of not having to repeat the measurement on each of the cable sections with a consequent saving in measurement time. Also, particularly in DWDM systems operating at high bit rates, it is important to know the dispersion distribution or map along fibres or in a link as well as the overall value. This report looks at ways of doing this.

Three techniques for doing this have been investigated. The first is a development of our earlier work using OTDRs to measure mode field diameter. The other techniques both use non-linear effects. Of the two investigated, modulation instability and four wave mixing, FWM, only the latter was investigated in any detail.

2 Dispersion from OTDR Mode Field Diameter Measurements

In a previous report, we reported mode field diameter, MFD, measurements on fibres by both conventional methods and from the analyses of OTDR traces. For the latter it can be shown [1] [2] that it is possible to separate the contributions due to the fibre absorption from those due to changes in other parameters such as MFD. Specifically, if $S_1(z)$ is the attenuation (in dB) measured by the OTDR from end 1 to the point z and $S_2(z)$ is the attenuation of the same section of fibre when measured from end 2 (ie. from z to 1) then it can be shown that the true fibre attenuation for this section is the average of these two values and further that the MFD at the point distance z from end 1, $d(\lambda, z)$, is related to that at end 1, $d(\lambda, 0)$ by

$$\begin{aligned} d(\lambda, z) &= d(\lambda, 0) 10^{-(S_1(z) - S_2(z))/20} \\ &= d(\lambda, 0) 10^{-\Delta S(z)/20} \end{aligned} \quad (1)$$

$$\text{where } \Delta S(z) = S_1(z) - S_2(z)$$

The measurement of the MFD at the end of the fibre plus analyses of the bi-directional OTDR trace can give the MFD at any point along the fibre. In the derivation of Eqn. (1) it is assumed that other parameters such as the scattering coefficient and the refractive index are constant along the fibre. This means that the method is only really applicable to a single unspliced fibre and fibres of the same type from the same manufacturer spliced together and is not likely to give the correct answer for fibre links made up of fibres of different types. It is thus probably most useful in fibre production control rather than installed links.

The dispersion is obtained from the variation of MFD with wavelength. The chromatic dispersion, D , is composed of two components, the material dispersion D_m and the waveguide dispersion D_w . The latter is given by

$$D_W(\lambda, z) = \frac{2\lambda}{cn} \cdot \frac{1}{(\pi d(\lambda, z))^2} \left\{ 1 - \frac{2\lambda}{d(\lambda, z)} \frac{\partial(d(\lambda, z))}{\partial \lambda} \right\} \quad (2)$$

where c is the velocity of light and n the refractive index. Assuming no change in material dispersion then

$$D(\lambda, z) = D(\lambda, 0) + D_W(\lambda, z) - D_W(\lambda, 0) \quad (3)$$

and

$$\lambda_0(z) - \lambda_0(0) = - \frac{D_W(\lambda, z) - D_W(\lambda, 0)}{S_0} \quad (4)$$

where S_0 is the dispersion slope at λ_0 and is assumed to be constant between λ and λ_0 .

At least two wavelengths are needed to obtain the change of MFD with wavelength. The wavelength dependence of the MFD was obtained by fitting the MFD to [3]

$$d(\lambda, z) = a + b\lambda^{2.5} \quad (5)$$

and hence

$$\frac{\partial(d(\lambda, z))}{\partial \lambda} = 2.5b\lambda^{1.5}. \quad (6)$$

To test this method the same fibres that were used in the MFD work were used. Two fibres were examined. The first was a 12.8 km matched clad fibre whose dispersion was measured by the phase shift method to obtain S_0 and λ_0 . The MFD at 1310 nm and 1550 nm at the ends of the fibre were measured and, in conjunction with the OTDR measurements at these wavelengths, used to calculate the MFD along the fibres. Equations 5, 6, 2 and 4 were then used to calculate the changes in λ_0 along the fibre relative to both ends. The fibre was subsequently cut up and S_0 , λ_0 measured for each section. Usually the value of λ_0 at the end of a fibre is not known but the average value for the whole fibre is easily measured using commercial test equipment. An iterative procedure was used in which a constant (started using the average value) was added to the changes in λ_0 at various points along the fibre and then adjusted so that the calculated average dispersion matched the measured value.

The results are shown in Figure 1. This shows the value of λ_0 along the fibre measured on each of the sections after cutting up the fibre together with λ_0 calculated from the OTDR MFD values and from the actual MFD for each section measured by the far field scan method. The general trend of both the OTDR MFD and actual MFD derived dispersions roughly follow that of the actual values. In the worst case, the agreement is better than 1.3 nm corresponding to a change in dispersion of $\sim 0.11 \text{ ps.nm}^{-1}.\text{km}^{-1}$, rather better than the accuracy of $0.2 \text{ ps.nm}^{-1}.\text{km}^{-1}$ claimed for the method by Rossaro et al. [4].

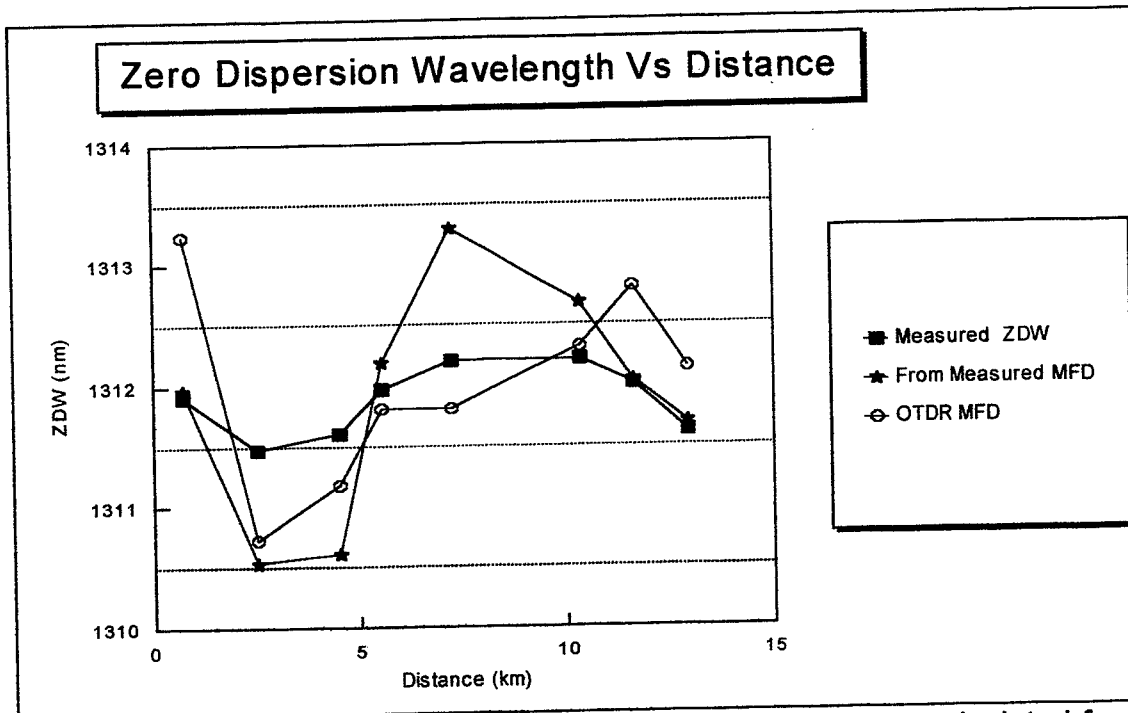


Figure 1. Measured zero dispersion wavelengths ■ and those calculated from measured MFDs ★ and from OTDR analysis ○ for the 12.8 km fibre.

In a second experiment, seven matched clad fibres each 2.2 km long were measured for λ_0 and MFD (at both ends and 1310/1550 nm). They were then fusion spliced together and a similar analysis to that above carried out to predict λ_0 using OTDR data. The results are shown in Figure 2 where the measured λ_0 values are again compared with those predicted from actual and OTDR predicted MFD values. The agreement with the measured MFD calculated λ_0 values is ~ 1 nm and with OTDR values ~ 2 nm, corresponding to $0.17 \text{ ps} \cdot \text{nm}^{-1} \cdot \text{km}^{-1}$ in dispersion.

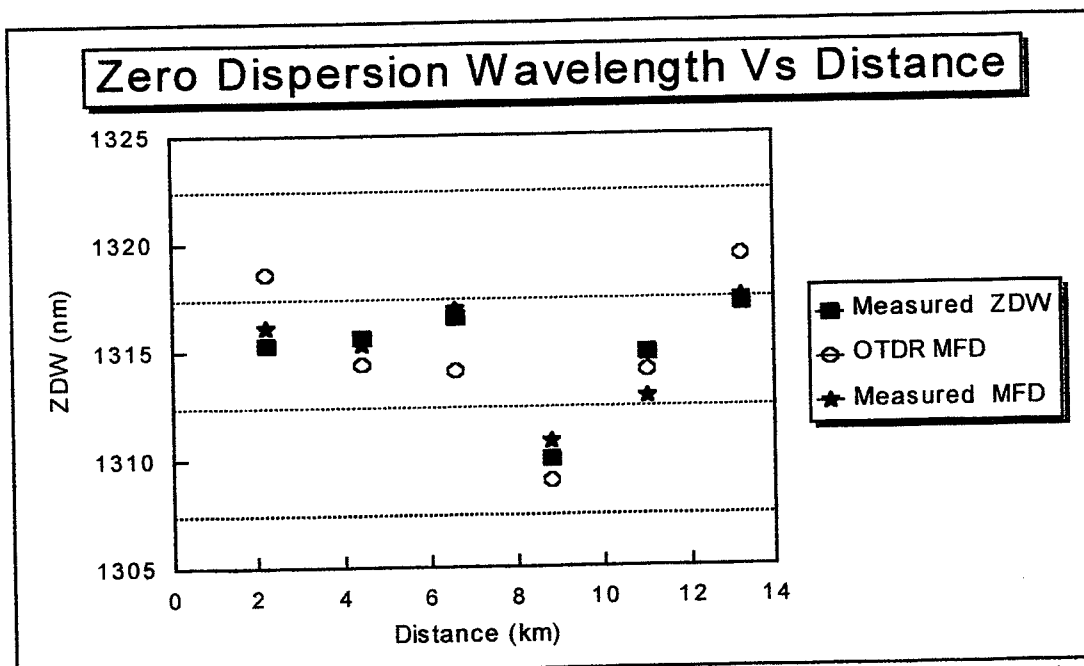


Figure 2 Measured zero dispersion wavelengths ■ and those calculated from measured MFDs ★ and from OTDR analysis ○ for the spliced fibres.

3 Dispersion from Modulation Instability

This technique relies on modulation instability which can be envisaged as a process where two pump and one OTDR photon produce two OTDR and one idler photon i.e.

$$2\omega_p + \omega_{\text{OTDR}} \rightarrow 2\omega_{\text{OTDR}} + \omega_i$$

As the number of photons at the OTDR wavelength is increased, this leads to increased backscatter and thus the OTDR trace can show gain rather than loss. For this process to occur $\lambda_p > \lambda_0 > \lambda_{\text{OTDR}}$ and also the efficiency of the process seems to fall off as the separation of the OTDR and pump wavelengths increases. In our work we did not observe any effects when the difference was greater than 20 nm. This essentially restricts the method to fibres with zero dispersion wavelengths within 20 nm of the OTDR wavelength.

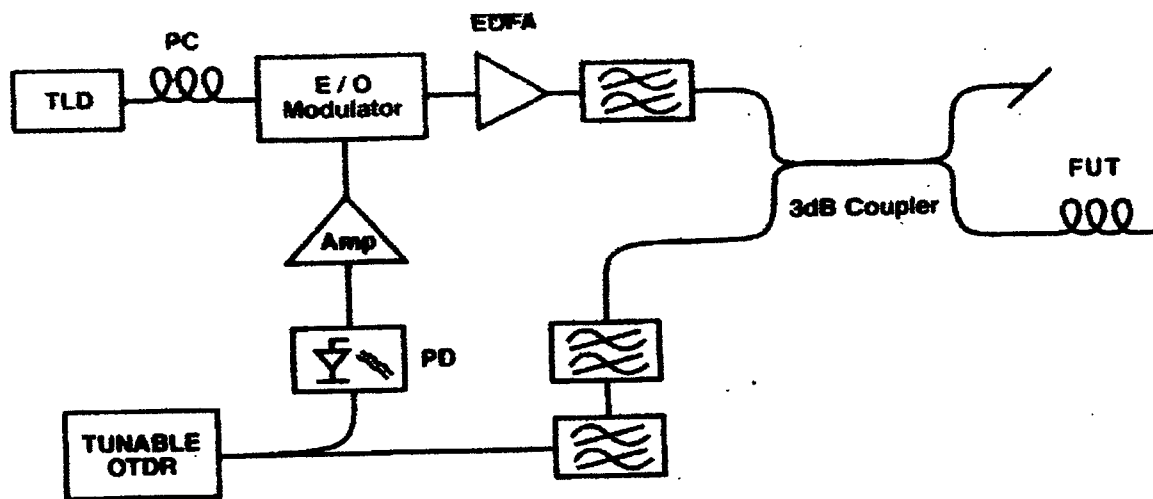


Figure 3. Set up for zero dispersion wavelength measurements using modulation instability.

The system used for making these measurements is shown in Figure 3. A fraction of the OTDR's output was tapped off and detected on a photodiode. The photodiode output was amplified and used to drive an electro-optic modulator which modulated the output of a turnable laser diode. The pulses were amplified in an erbium doped fibre amplifier, passed through an ASE filter and into the fibre under test, FUT, via a 3 dB coupler. Filters tuned to the OTDR wavelength prevented any backscatter from the pump wavelength returning to the OTDR. Ideally the wavelength of the OTDR should also be tuneable so that the pump-OTDR wavelength separation can be kept constant as the pump wavelength is tuned [5]. In our case we worked with a fixed OTDR wavelength. The OTDR trace produced by the system is shown in Figure 4, gain can clearly be seen at ~ 5.5 and 8.5 km. The pump laser was tuned to ~ 1546 nm and the OTDR wavelength was ~ 1535 nm. Whilst the method clearly works, the restrictions on the range of λ_0 values that can be measured limits its usefulness. In addition, for fibres where the zero dispersion wavelength goes up and down along a fibre the OTDR trace may not be easy to interpret. For these reasons we did no further work on this method and concentrated on the four wave mixing technique.

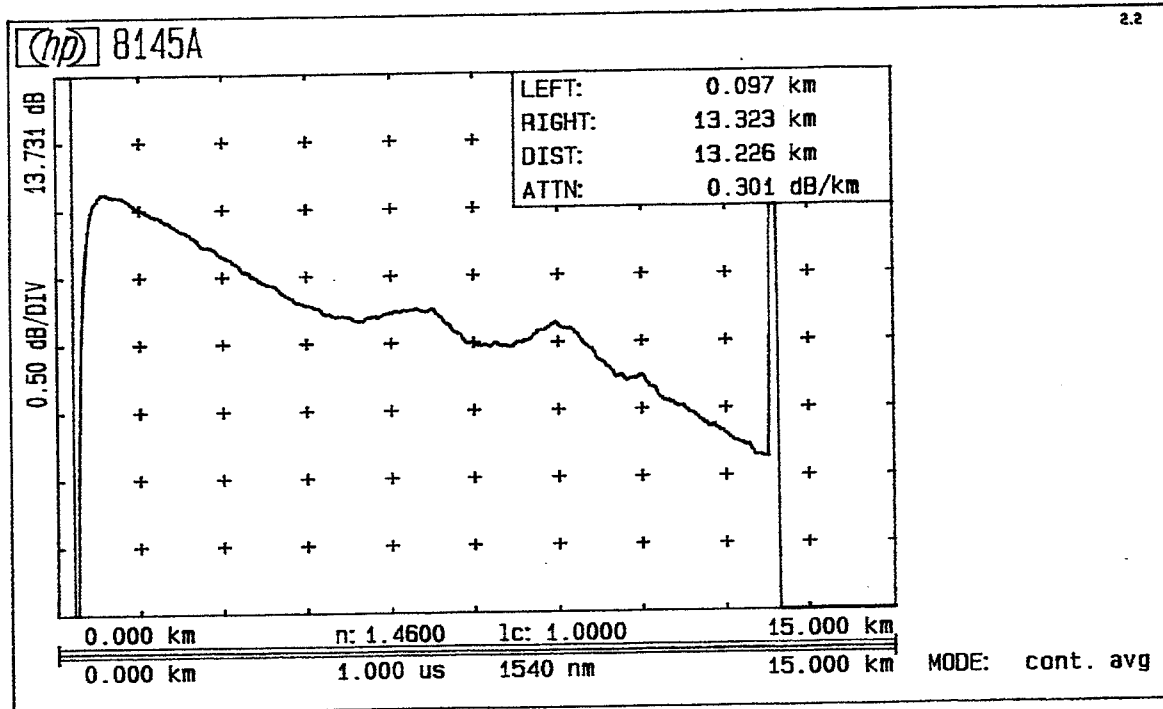


Figure 4. OTDR trace obtained using the set up of Figure 3 showing gain at ~ 5.5 and 8.5 km.

4 Dispersion from Four Wave Mixing

A drawback of the above method is that it requires a tuneable OTDR and also that the zero dispersion wavelength has to occur where a powerful pump source is available which essentially means in the EDFA gain band. This is not usually the case for some of the dispersion modified fibres used in WDM systems. The technique [6] based on four wave mixing measures dispersion rather than zero dispersion wavelength albeit only in the EDFA gain band.

4.1 Theory

The theory has been discussed in earlier reports and will only be briefly outlined here. More complete description can be found in refs. 6 - 9. In the partially degenerate FWM considered here, two pump photons at ω_1 interact with one probe photon at ω_2 to produce a new photon at ω_s where

$$\omega_s = 2\omega_1 - \omega_2 \quad (\omega_2 > \omega_1) \quad (7)$$

$$\text{and} \quad \omega_1 - \omega_s = \omega_2 - \omega_1 \quad (7a)$$

An analogue involving two photons at ω_2 yields

$$\omega_{as} = 2\omega_2 - \omega_1 \quad (8)$$

$$\text{with} \quad \omega_{as} - \omega_2 = \omega_2 - \omega_1 \quad (8a)$$

The process has maximum efficiency when the pump wavelength λ_1 equals the zero dispersion wavelength λ_0 . Other factors affecting the efficiency are the pump-probe wavelength separation and the degree of phase matching between the three wavelengths. For the first process, Eqn. 7 this is,

$$\delta k_1 = k_2 + k_s - 2k_1 \quad (9)$$

$$= -2\pi c \left| D_1 \right| \left(\frac{\lambda_1 - \lambda_s}{\lambda_1} \right)^2 \quad (10)$$

The method involves simultaneously launching two pulses at λ_1 and λ_2 into the fibre so that FWM generates the other wavelengths λ_s and λ_a . It can be shown [6] that because of the phase matching condition the power at λ_s oscillates at a spatial frequency F_s as the pulses propagate down the fibre with

$$F_s = \frac{\delta k_1}{2\pi} = c \left| D_1 \right| \left(\frac{\lambda_1 - \lambda_s}{\lambda_1} \right)^2 \quad (11)$$

and spatial resolution $1/F_s$. The generated power at λ_s produces backscatter which oscillates at the same frequency.

4.2 Results and Discussion

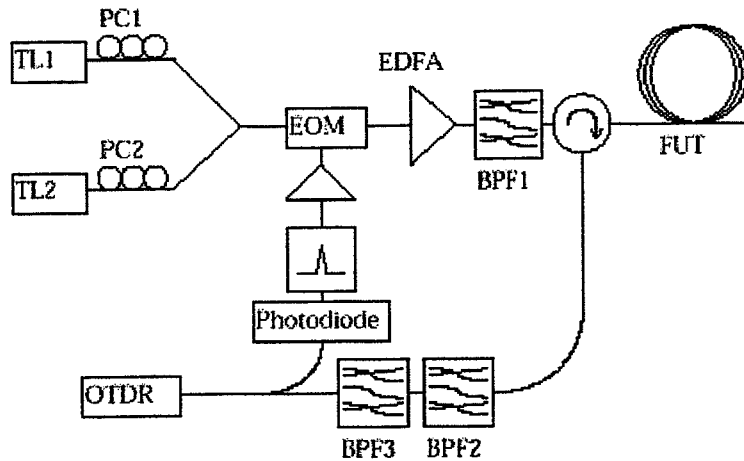


Figure 5. Experimental arrangement for zero dispersion wavelength measurement using four-wave mixing.

The set up used in the initial experiments is shown in Fig. 5. The output of two tuneable lasers were combined using a 50/50 splitter. Polarization state controllers were used after the lasers to align their polarization states parallel so as to maximise the FWM signal. The combined wavelengths were then passed through an electro-optic modulator with an extinction ratio of ~ 45 dB. The modulator drive signal was produced by tapping off 10% of the output of an OTDR, detecting it with a photodiode and then amplifying it to ~ 5 volt. The pulses produced by the modulator were amplified using an Er^{3+} amplifier (with a maximum cw output of

+ 27 dBm), filtered to remove ASE and fed to the fibre under test using a circulator. The backscatter signal at λ_s was filtered to remove any backscatter from ASE or the pump wavelengths. Two filters were typically used with 3 dB bandwidths of 0.5 and 1.5 nm. For the measurements on unshifted fibre, where a wavelength separation of 0.8 nm was used, additional Bragg grating filters were used, one after the amplifier to reject (~ 30 dB rejection) ASE at λ_s (or λ_A) and a second in the receiver chain to reject pump backscatter signal. Diagnostics (not shown in figure) consisted of an Optical Spectrum Analyser attached to the far end of the FUT for measurement of wavelength and a calibrated pin-fet receiver fed by a 5% tap coupler placed at the beginning of the FUT for measurement of the pulse power launched into the fibre.

The pulse width used was short compared with F_s . In practice the wavelength separation $\Delta\lambda$ was adjusted to give a suitable value for F_s and then the pulse width chosen accordingly. Typically $\Delta\lambda$ was chosen to give $F_s \approx 1$ km and the pulse width set to $\sim 1 \mu\text{s}$.

Whilst early experiments used the E/O modulator as described above, this was later replaced with a semi-conductor optical amplifier. This essentially acted as a loss-less switch with an extinction ratio of 50 dB. Most of the results reported here were obtained using the semi-conductor optical amplifier.

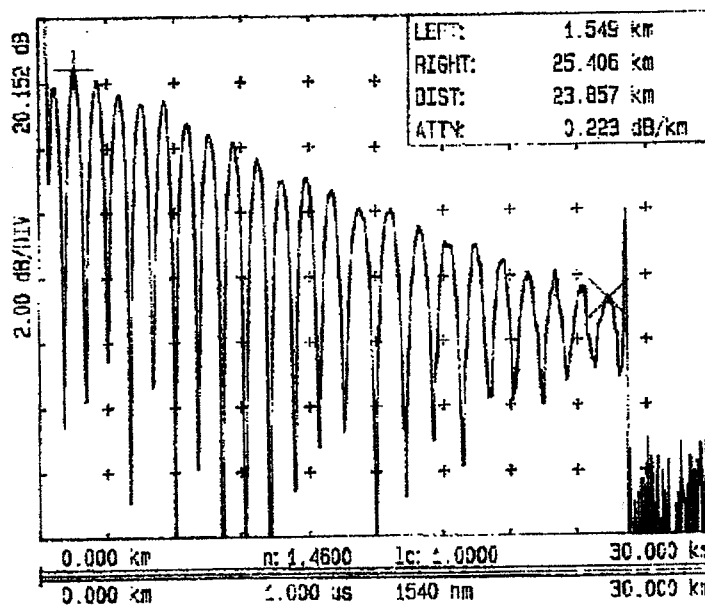


Figure 6 . OTDR trace obtained using four-wave mixing on two dispersion shifted fibres fusion spliced together.

Fig. 6 shows the trace obtained on two dispersion shifted fibres both ~ 13 km long fusion spliced together and Figure 7 the dispersion map obtained from it. Also shown is the total dispersion measurement for both fibres obtained using our phase shift system. The average values measured by the FWM technique were -0.824 and $-0.712 \text{ ps.nm}^{-1}.\text{km}^{-1}$ and by the phase shift -0.821 and $-0.704 \text{ ps.nm}^{-1}.\text{km}^{-1}$. The uncertainty in the phase shift measurement is $0.006 \text{ ps.nm}^{-1}.\text{km}^{-1}$ and in the FWM method $0.01 \text{ ps.nm}^{-1}.\text{km}^{-1}$. That the changes in dispersion were real was confirmed by measuring the fibres from both ends and comparing the dispersion maps. These two fibres were purchased at the same time and have probably been

drawn from the same preform. If we had fusion the other end of the second fibre to the first then there would have been a gradual change of dispersion from one end of the combined fibres to the other.

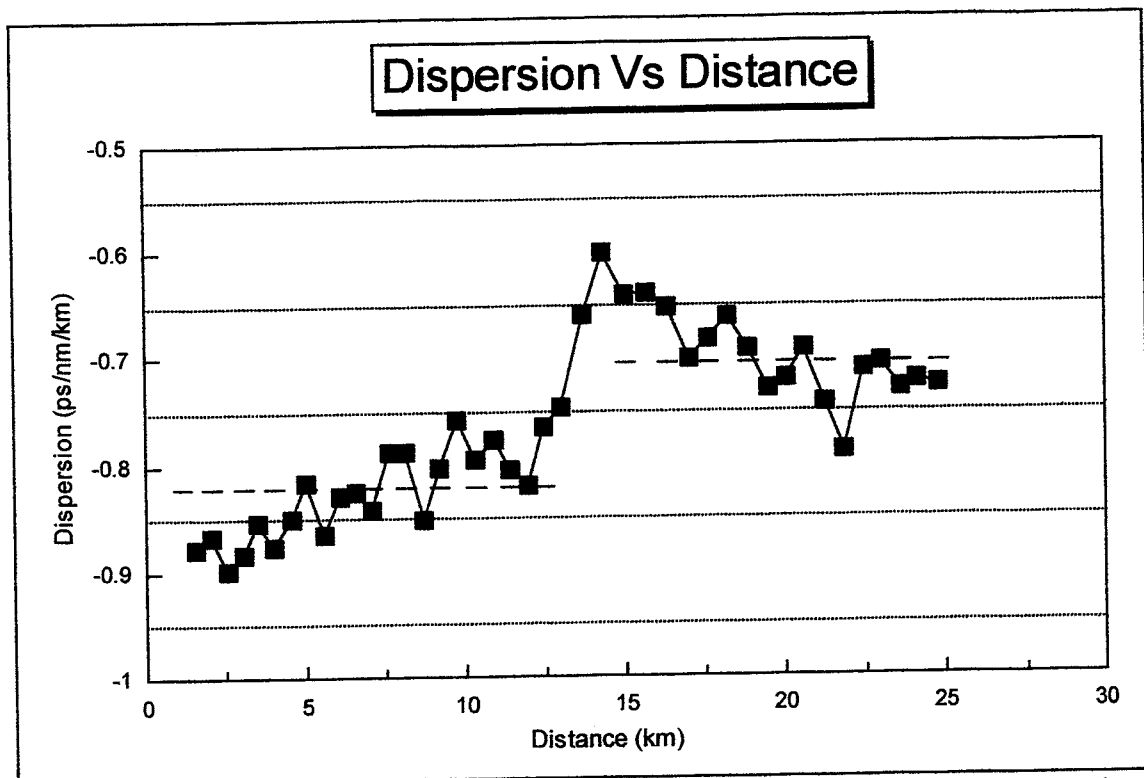


Figure 7. Dispersion map obtained by analysis of the trace of Figure 6 ■ and average values (-) obtained using a phase shift system.

Fig. 8 and Fig. 9 show the OTDR trace and dispersion map from a 12.8 km length of standard fibre.

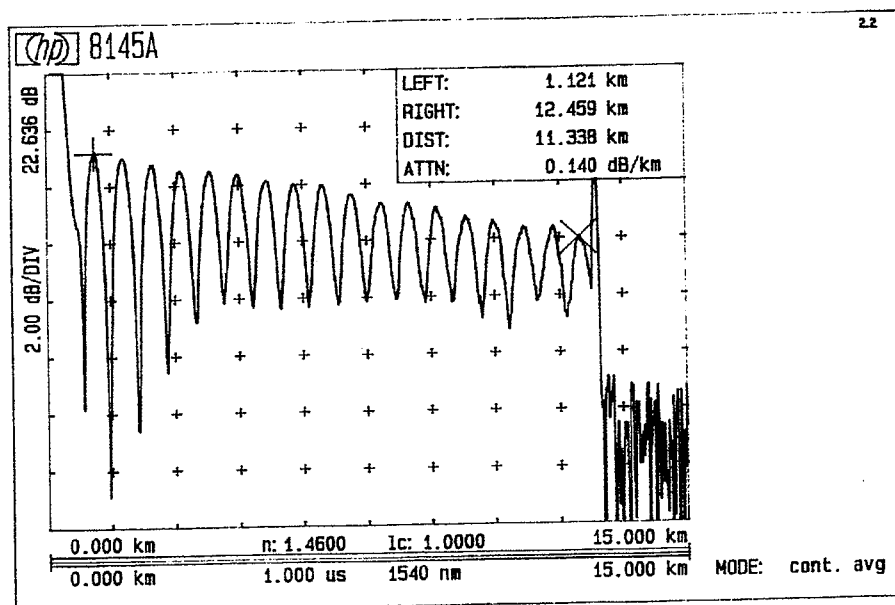


Figure 8 . OTDR trace obtained using four-wave mixing on a 12.8 km unshifted fibre.

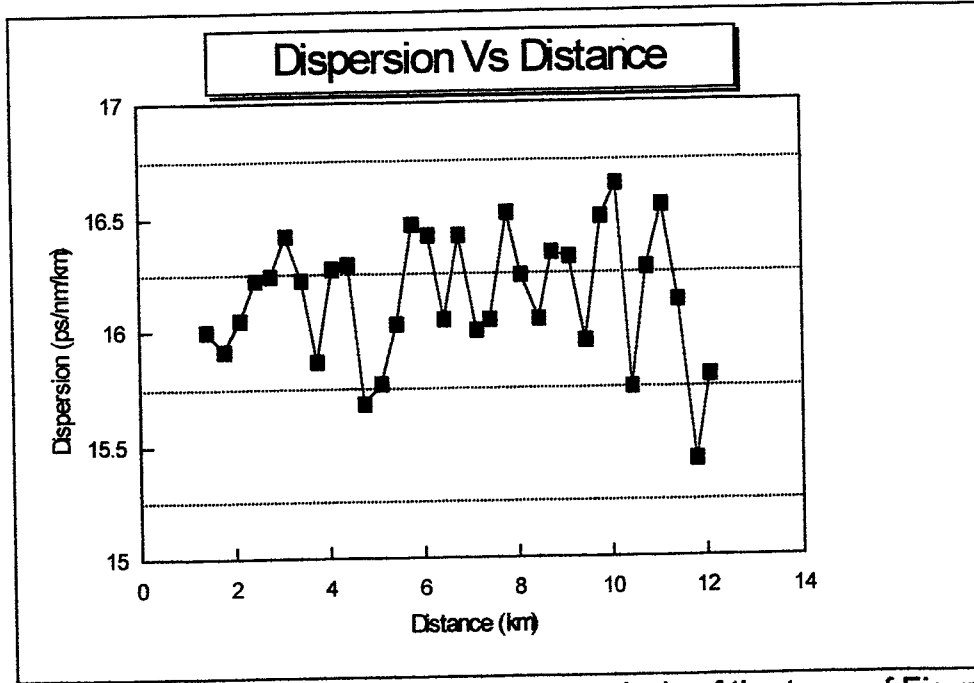


Figure 9. Dispersion map obtained by analysis of the trace of Figure 8.

The average dispersion measured by FWM was $16.14 \pm 0.6 \text{ ps.nm}^{-1}.\text{km}^{-1}$ and by phaseshift $16.6 \pm 0.12 \text{ ps.nm}^{-1}.\text{km}^{-1}$. The error in the FWM method arises primarily from the uncertainty in $\Delta\lambda$, the OSA only reading out to 0.01 nm which leads to around a 3.5% error in dispersion. Measuring the wavelength of the two lasers with a wavemeter would reduce this error by an order of magnitude. There is no obvious trend in dispersion along this fibre. However, by measuring it from both ends and comparing the traces showed that there were real fluctuations of $\sim 0.5 \text{ ps.nm}^{-1}.\text{km}^{-1}$, i.e. $\sim 3\%$, comparable to the 'noise' on the dispersion distribution. Measurements on other fibres suggested that 3% was a fairly typical figure for the resolution of changes in dispersion.

The results of the measurements of the average dispersion for 6 different fibres are given in Table 1 and are compared with the dispersion measured on our phase shift system. The difference in dispersion is given in absolute and percentage terms. The average difference is 5%. Further analysis shows that for all the results, except the LEAF - ve fibre at 1546 mm, the FWM and phase shift measurements agreed to within $0.04 \text{ ps.nm}^{-1}.\text{km}^{-1} + 4\%$ of the dispersion value.

The theory outlined above neglects any power level dependence of δk . If this is taken into account the new phase matching factor, $\delta k_1'$, is given by [6, 9]

$$\delta k_1' = \delta k_1 - \delta k(\lambda_1)_{NL} = \delta k_1 - \gamma(2P_1 - P_2) \quad (12)$$

$$\text{where } \gamma = \frac{2\pi}{\lambda} \cdot \frac{n_2}{A_{eff}}$$

and γ is the non-linear coefficient, A_{eff} the effective area, and P_1, P_2 the peak powers at λ_1 and λ_2 . For typical powers of less than one watt, the non-linear term is relatively small unless the dispersion is low. We investigated this effect by varying

FIBRE	WAVELENGTH (nm)	DISPERSION(FWM) ps.nm ⁻¹ .km ⁻¹	DISPERSION(PS) ps.nm ⁻¹ .km ⁻¹	D(FWM)-D(PS) ps.nm ⁻¹ .km ⁻¹	%
UNSHIFTED	1547.0	16.14	16.63	-0.49	3.0
DS	1550.0	0.336	0.31	0.026	8.4
	1553.0	0.527	0.54	-0.013	2.4
LEAF +	1547.5	3.30	3.25	0.05	1.5
	1549.5	3.35	3.45	-0.10	2.9
LEAF-	1546.0	-3.68	-3.46	-0.22	6.58
	1547.5	-3.39	-3.26	-0.13	4.0
	1549.5	-3.14	-3.02	-0.12	4.0
DS85	1545.0	-0.81	-0.74	-0.07	9.5
	1548.0	-0.49	-0.52	0.03	5.8
	1553.0	-0.175	-0.156	-0.019	12.2
TRUEWAVE RS	1547.5	4.24	4.14	0.1	2.4
	1549.5	4.11	4.22	-0.11	2.61

Table 1. Comparison of four-wave mixing(FWM) and Phase Shift (PS) dispersion Measurements. (LEAF and TrueWave or trademarks of Corning Inc. and Lucent Technology).

the relative powers of P_1 and P_2 and could find no obvious effect on the measured dispersion, although from the data of Table 1 there is perhaps a trend to a greater percentage error in dispersion when the dispersion is low. Any effect can be minimised by making $P_2 = 2P_1$, and choosing the measurement wavelengths such that the dispersion is greater than say 1 ps.nm⁻¹.km⁻¹.

The method give the modulus of the dispersion. The sign of the dispersion can be obtained by measuring at both λ_S and λ_{AS} . This is easiest when the dispersion is small since then the wavelength separation $\Delta\lambda$ used will be higher to give a suitable value for F_s and the fractional change in dispersion will also be higher. At higher dispersion values the change in dispersion may be small compared with uncertainty of the measurement. This can be seen for the measurement on the TrueWave RS fibre in Table 1 where the measured dispersion at 1549.5 nm was 0.13 ps.nm⁻¹.km⁻¹ less than at 1547.5 nm whereas in fact it is 0.08 ps.nm⁻¹.km⁻¹ higher. The solution is obviously to increase the range of wavelengths over which the measurements are made.

5 Conclusions

Three methods of measuring dispersion in fibre from measurements made only at the ends have been investigated. The first based on OTDR mode field diameter measurements has an accuracy of ~ 0.2 ps.nm⁻¹.km⁻¹. However, it is probably best suited to measurements on unspliced fibres or on spliced fibres of the same type from the same manufacturer. Long fibres should be measurable limited by the dynamic range and linearity of the OTDR.

The method based on modulation instability works but is rather complicated to implement and data interpretation may cause problems. It is also restricted to fibres with λ_0 in a limited wavelength range.

In contrast the method based on FWM is applicable to most if not all single mode fibres. It is relatively quick (seconds to minutes depending on the length of the fibre) and is capable of measuring fibres up to at least 26 km long. The accuracy of the measurements in the present study was $0.04 \text{ ps.nm}^{-1}.\text{km}^{-1} + 4\%$ of the dispersion value (correspondingly approximately to two standard deviations). In terms of dispersion fluctuation along fibres, fluctuation of 3% of the dispersion value are resolvable. With improvements in wavelength measurement accuracy, better control of the laser powers used, and improved data analysis, we would expect to be able to improve these accuracies by about a factor of two. Further, rather than using two external cavity tuneable lasers, several fixed wavelengths or two electronically tuneable lasers could be used, making a system for field use possible.

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