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WAVELENGTH DEPENDENCE OF LIGHT PROPAGATION IN LONG FIBRE LINKS

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Abstract

A model for the analysis of the bandwidth along an optical fibre route has been extended to include the variations of the bandwidth with wavelength. It is concluded that alternately jointing under and over compensated fibres has the advantage not only of producing high bandwidth but also stabilizing it with wavelength.

Introduction

Over the past three years a number of optical fibre links have been described and their overall performance assessed. [1-6]. The routes were relatively short owing to fairly high loss fibres but since then, fibre standards have improved and a 140 Mbit/s system for example can now operate with distances as long as 15 km at 850 nm [7] and at least 30 km at 1.3 μm when sufficient bandwidth is available. Such systems would require exceptionally well graded fibres if the pulse broadening was linear with length; fortunately measurements along a link reported so far [1-6] show that this assumption is pessimistic. The $\sqrt{L}$ model was first suggested for heavily mode mixed fibres [1] and later the L^{γ} with $0.5 < \gamma < 1$ [2,3,6] for fibres which are similar and/or for final bandwidths dominated by material dispersion (which has the effect of smoothing the multipath bandwidth variations). A general theory which could be applied to any graded fibres, with any degree of mode mixing or material dispersion was finally presented in [8] together with a great deal of experimental evidence. This theory was recently extended to include wavelength dependence of bandwidth [9] and this paper outlines that work and its experimental testing.

Wavelength effects on a jointed link

The theory of the propagation of light in single fibres [10] predicts that the optimum profile for time dispersion is a function of wavelength and that, as a consequence, large variations in the fibre time dispersion are expected with relatively small changes of λ. This has actually been checked, first at three wavelengths [11,12] and then over a restricted range [13]. This is worrying since fibre systems might have to support different light wavelengths during their lifetime (for instance 0.8 μm then 1.3 μm) or even support them simultaneously in a colour multiplexing system. Reductions of the variations of bandwidth with wavelength are therefore highly desirable. Ternary system fibres have been suggested to achieve this [14] since, at least in theory, suitable double doping can reduce considerably profile dispersion around a chosen wavelength. Measurement of such fibres has not appeared in the literature yet and this might well be due to fabrication difficulties.

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Before tackling the problem of stabilizing the bandwidth with wavelength, its effect on a link must first be assessed. To do this we recall the basic formula giving the rms pulse broadening σ of a jointed pair as a function of the individual σ_1 and σ_2

$$\sigma^2 = \sigma_1^2 + \sigma_2^2 + 2\sigma_1 \sigma_2 r_{12} \qquad (1)$$

r_{12} is here the correlation coefficient between times of flight in fibres 1 and 2. Its most important property lies in its sign: it is positive if both fibres are on the same side of the optimum and negative otherwise [8]. Since this optimum for time dispersion is a function of λ any fibre with a well behaved profile will move from one side of the optimum to the other at some wavelength. This implies that the sign of r_{12} must change with λ. To check this, we were able to select a pair of fibres which were both undercompensated at 902 nm, on different sides at 835 nm and both overcompensated at 647 nm. These wavelengths correspond to three sources used at the British Post Office for bandwidth measurements. The bandwidths (3 db optical) of fibres A, B, A + B at the three wavelengths are displayed in the table below. r_{AB} calculated from formula 1 is also presented.

λ	647 nm	835 nm	902 nm
A	873 Mhz	569 Mhz	512 Mhz
B	495 Mhz	749 Mhz	822 Mhz
A + B	361 Mhz	524 Mhz	382 Mhz
r_{AB}	+ 0.49	-0.26	+ 0.33

As can be seen, the correlation coefficient changes sign at 835 nm. This happens because the optimum for fibre A lies between 647 nm and 835 nm and the optimum for fibre B lies between 835 nm and 902 nm.

This makes the point that the variation of bandwidth of A + B results not only from the separate variations of A and B but from the change of sign of r_{AB} as well.

To show the complexity of this situation we now turn our attention to a longer link and we recall the general formula giving the final bandwidth of slightly mode mixed fibre links:

$$\sigma^2 = \sum_1^N \sigma_k^2 + 2 \sum_1^{N-1} \sigma_k \sigma_{k-1} r_{kk-1} \qquad (2)$$

A well planned link is a link where all the coefficients r_{kk-1} are negative which is achieved by jointing alternately under and over compensated fibres. We did just this with four fibres A, B, C and D which formed an optimized link in that order at 835 nm. We measured the cumulative bandwidth for this link at 835 nm as well as at 647 nm and 902 nm. This is plotted in figure 1. It is clear from this figure that the cumulative bandwidth of this link is strongly dependent on the wavelength at which it has been measured. This is due to the fact that individual fibre bandwidths are wavelength dependent and that profiles move from one side of the optimum to the other so that what was the ideal configuration at 835 nm might not stay so at 902 nm and 647 nm. These competing effects seem extremely difficult to control, however a simple theoretical treatment was first presented in [9] and is now outlined in the next paragraph as well as its experimental testing.

Wavelength stabilization of a fibre link

Let us consider first a jointed pair in a qualitative manner. As a stable resonator is made of two slightly detuned circuits or an achromatic lens is formed by two elements which have opposite wavelength dispersion, in the same way a stable fibre pair can be made of two fibres placed on different sides of the optimum. Any change of wavelength will produce an increase in bandwidth for one fibre and a decrease for the other. If the change of wavelength is restricted to the window formed by the two wavelengths at which each fibre is optimum, then the correlation coefficient does not change sign and the opposite variations in bandwidth results in a stable combined bandwidth.

More precisely differentiation of Formula 1 leads to:

$$\sigma \frac{d\sigma}{d\lambda} = [\sigma_1 + r_{12}\,\sigma_2]\,\frac{d\sigma_1}{d\lambda} + [\sigma_2 + r_{12}\,\sigma_1]\,\frac{d\sigma_2}{d\lambda} \qquad (3)$$

Careful examination of Formula 3 shows that there is a wavelength in the above defined window for which $\frac{d\sigma}{d\lambda}$ vanishes. Furthermore it can be proved for alpha type fibres for instance [9] that $\frac{d\sigma}{d\lambda}$ varies very slowly in this window. This property is very attractive because it guarantees a stable and high bandwidth at the same time due to equalisation.

In order to check this theoretical prediction we selected three fibres labelled 180, 181 and 182 with respective alpha values 1.9, 1.8 and 1.97. The dye laser facility of Southampton University which is able to deliver short pulses (1 ns at the 1/e point) anywhere in the range 0.4 µm-1.6 µm was then used for the bandwidth measurements. The three single fibres were first measured and after numerical processing plots were made of the 3 db optical point versus wavelength (figures 2, 3 and 4). Examination of these plots reveals that all fibres possess a sharp optimum and that changes in bandwidth are large in the vicinity of these optima. A great deal more could be said about these measurements but only the two above observations are essential to our experiment. These three fibres were then used to form two pairs 182 + 181 and 181 + 180. The corresponding measurements are displayed in figure 5 and 6. The vertical broken lines indicate the wavelengths at which the two fibres seem to be optimum for time dispersion. Two remarkable features are obvious. One is that the bandwidth of the pair is highest in the window defined by the two optima, a phenomenon that we would expect since the two fibres should show some equalisation in this region; the other is that the variations of bandwidth with wavelength are much reduced in the same region which confirms our prediction. A striking example is the pair 180 + 181 which exhibits a stable bandwidth of 1.8 Ghz.Km over more than 100 nm.

The same phenomenon should also take place on long links and should produce extremely stable bandwidth in the minimum window which contains the optimum at the chosen wavelength and which is bounded by the two closest fibre optima.

Conclusion

We have presented an extension of the theory of the time dispersion in a fibre links which predicts that alternatively jointing under and over compensated fibres in a route produces a high and stable bandwidth around a chosen wavelength. This has been checked experimentally. This procedure optimizes the performance of a custom made link and guarantees a 'safety' margin for the planning of complete networks. The same principle could also be used for the design of achromatic analog picture transmission systems.

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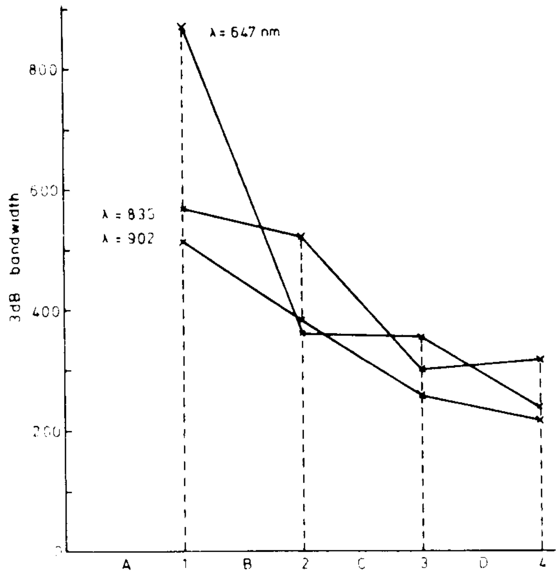
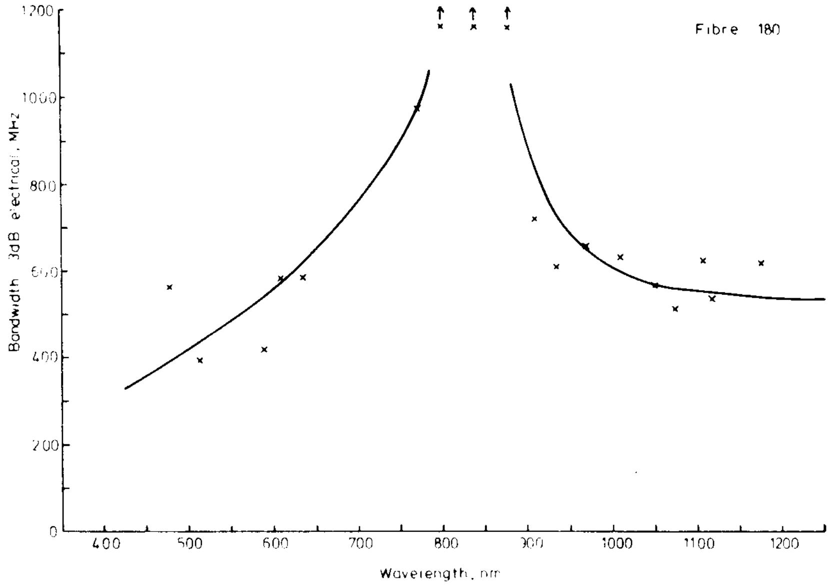


Figure 1

Cumulative bandwidth of the 4 km link at three wavelengths

Figure 2

3 db electrical bandwidth versus wavelength of fibre 180



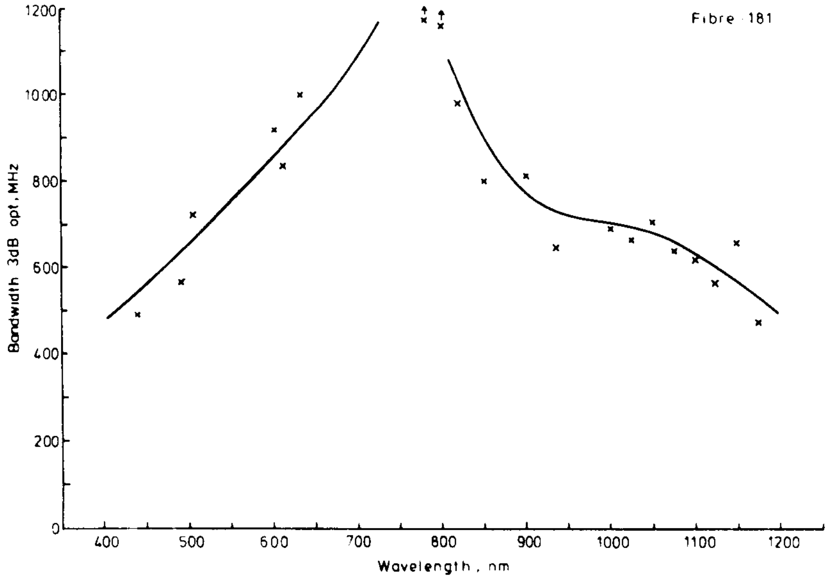


Figure 3

3 db optical bandwidth versus wavelength of fibre 181

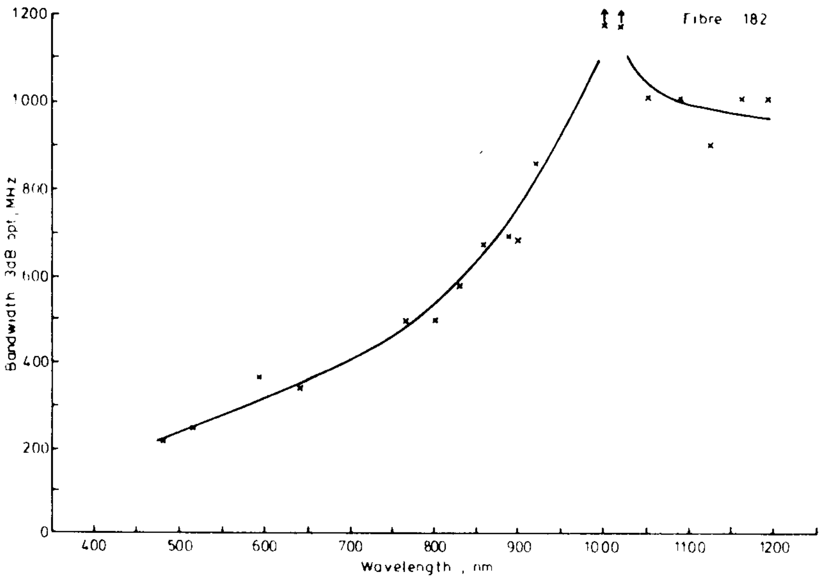


Figure 4

3 db optical bandwidth versus wavelength of fibre 182

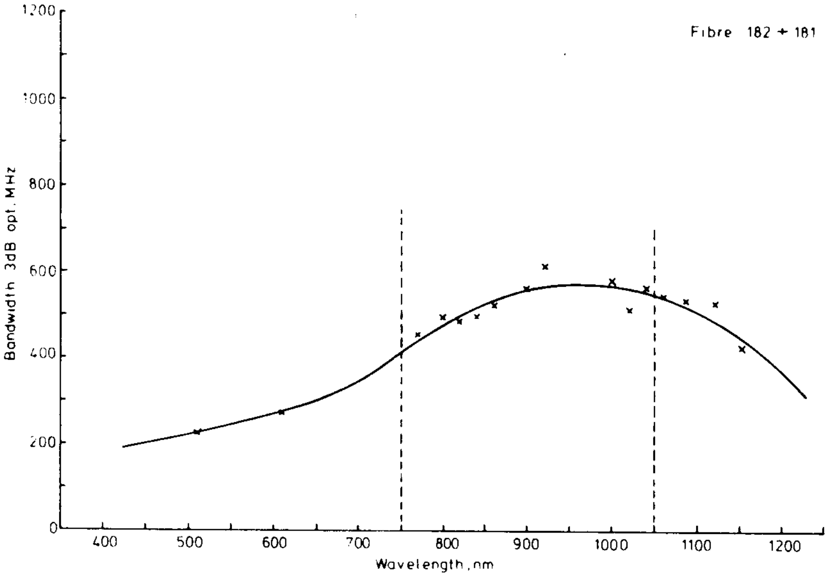


Figure 5

3 db optical bandwidth versus wavelength of the jointed pair 182 + 181

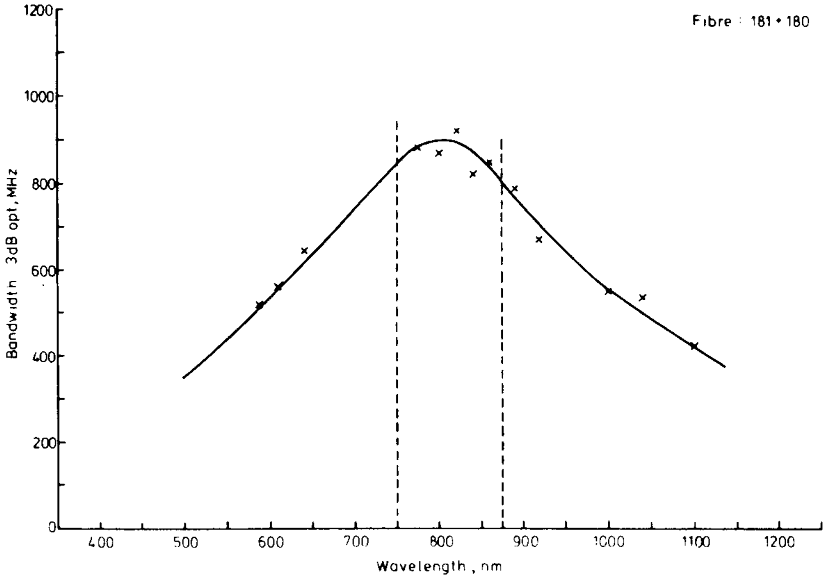


Figure 6

3 db optical bandwidth versus wavelength of the jointed pair 180 + 181