

Group Index Variations in Single-mode Optical Fibres

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ABSTRACT

This report examines the variation in group index along fibres and between fibres of the same type from the same manufacturer. It is shown that changes in group index can be related to changes in MAC^{-2} multiplied by a constant, the MAC value being the ratio of the mode field diameter to the cut-off wavelength. The constant was found to be 0.275 for a set of six matched clad fibres close to a theoretically predicted value of ~ 0.3 . For a highly non-uniform fibre the constant was 0.42. Assuming that a value of 0.42 for the constant represents a worst case, it is possible to set limits on group index variations along fibres using variations in the MAC number.

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1 Introduction

In previous reports the potential of OTDRs for the measurement of mode field diameter, MFD, cut-off wavelength, λ_c , dispersion and PMD along the length of a single-mode fibre from measurements of the parameter at one end of the fibre plus OTDR measurements have been explored. (1-4). These studies showed that this could be done with varying degrees of accuracy for all these parameters. This report examines the possibility of extending this work to the fibre group index, N_{eff} , defined as the ratio of the velocity of light in vacuum to that in the fibre.

2 Theoretical background

Previous work on MFD, λ_c , and dispersion was based on the assumption that there were no changes in the refractive index along the fibre. The fact that these parameters could be predicted under this assumption implies that either there were no changes in refractive index or if there were, they had little effect on these parameters. Saunders and Gardner (5) quoting Anderson and Glodis (6) give the following empirical relation between the zero dispersion wavelength λ_o , the core diameter, d , and relative refractive index difference Δ , ($\Delta = 1 - n_2 / n_1$) between the core index n_1 and cladding index n_2 as

$$\lambda_o = C_o + \frac{C_1}{d} + C_2 \sqrt{100\Delta} \quad (1)$$

with $C_o=1.207$, $C_1=1.933$ and $C_2= -0.2149$. Thus for a core diameter of $8\mu\text{m}$ the change in λ_o due to changes in core diameter assuming no refractive index change is predicted to be $\sim 30 \text{ nm} \cdot \mu\text{m}^{-1}$. For all the different matched clad fibres that we have measured over a period of several years the range of values of λ_o has been $1310 \pm 15 \text{ nm}$. If a fibre has a 10nm change in λ_o along its length (corresponding to $\sim 0.3 \mu\text{m}$ change in MFD) then provided there is no change in refractive index or dispersion slope this would lead to a change in group index at 1550nm of less than 0.00004 . This value is an order of magnitude smaller than the accuracy of our measurements of N_{eff} which implies that Δ will have to change if there is to be any measurable effect on the group index.

For a step index fibre the theoretical cut off wavelength, λ_{cth} , (7) is given by

$$\lambda_{cth} = \frac{\pi d n_1}{2.405} \sqrt{2\Delta} \quad (2)$$

This predicts that there would be an approximately $\sim 20 \text{ nm}$ change in cut-off for a variation in Δ of 10^{-4} . Previous work on distributed cut-off measurement (2) revealed that λ_c could vary by $\sim 16 \text{ nm}$ along individual fibres and by 80 nm between fibres of the same type from the same manufacturer. This would suggest changes in Δ of 0.00008 and 0.0004 respectively. To get some idea of the changes in N_{eff} produced by such changes in Δ , data for the dispersion of silica and germania (8) were used to calculate the group index of bulk doped material (neglecting any effects due to waveguide dispersion) for typical values of Δ of 0.0034 to 0.0055 . This showed that as expected the changes in N_{eff} were about 1.5 times that of Δ itself, so for the cases outlined above changes in N_{eff} of 0.00012 and 0.0006 respectively are predicted.

3 Measurements

To determine N_{eff} both the physical and optical length (time of flight) of the fibre needs to be measured. The time of flight was measured using a phase shift system operating at 750 MHz. The change in phase, $\Delta\Phi$ (in degrees), when a sample of fibre was introduced into the system was measured. The time of flight, Δt , of the sample is then given by

$$\Delta t = \frac{\Delta\Phi}{360} \times \frac{10^{-8}}{7.5} \text{ sec} \quad (3)$$

To improve the measurement accuracy (9) samples of fibre ~ 820 mm long were used to give $\Delta\Phi$ values close to 6π . This means that the phase changes (as measured by the phase meter which ignores changes of 2π) were typically a few degrees, reducing any error due to non-linearities in the phase response of the measurement system (9). Noise and drift in the system resulted in a phase change measurement uncertainty of $\sim 0.3^\circ$ corresponding to a ~ 0.2 mm uncertainty in fibre optical length.

The physical length of the fibre was measured using an interferometrically calibrated one metre rule. Care was taken to keep the fibre straight and under very low tension. The uncertainty of this measurement was comparable to that for the optical length. Overall uncertainty in N_{eff} was estimated to be less than 0.0004 (one standard deviation).

4 Results and discussion

Because of the small changes in N_{eff} predicted above and by the results of previous work (5), the group index of different fibres of the same type that had previously been measured for MFD etc (1-3) were measured. The results of these measurements and the previous ones are shown in Table 1.

Fibre Identifier	MFD (μm) @1310 nm	Cut-off nm	MAC @ 1310 nm	λ_o nm	N_{eff} @1310 nm
D091072706409/I	9.38	1296	7.227	1309.10	1.4681
D082048106408/O	9.00	1280	7.031	1314.90	1.4684
D1036977866407/I	9.33	1286	7.255	1315.34	1.4679
D093083886452/O	9.16	1252	7.316	1315.64	1.4676
D091086306403/O	9.05	1254	7.217	1316.55	1.4681
D011021806410/I	9.27	1216	7.623	1317.18	1.4676

Table 1: MFD, Cut-off, MAC value(see later), λ_o and N_{eff} for six matched clad fibres.

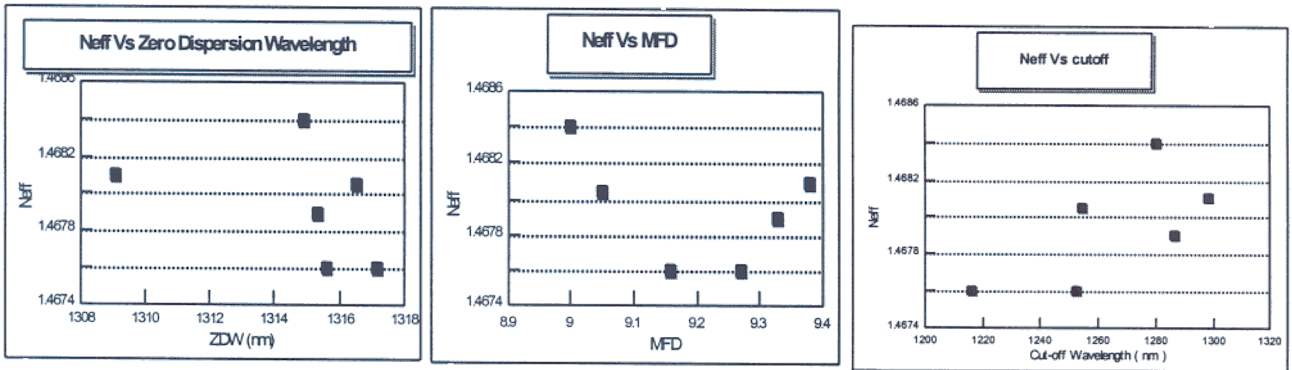


Figure 1. Group index as a function of zero dispersion wavelength, mode field diameter and cut-off wavelength.

We then looked for any correlation between N_{eff} and λ_o , λ_c and MFD. Figure 1 shows the relation between N_{eff} and these parameters. Clearly there is no obvious correlation with λ_o and a possible parabolic relation with MFD, although for the latter five of the six points are within the mean value and the typical measurement uncertainty of 0.0004. There is some evidence of a linear relation with λ_c and the difference between the maximum and the minimum values is ~ 0.0008 compared with 0.0006 predicted from Eqn.2, reasonable agreement considering the measurement uncertainties.

The changes in N_{eff} above are comparable to the measurement uncertainty. It was therefore decided to measure samples of a highly non-uniform fibre from a previous BCR intercomparison (10) which showed much greater variations in MFD, cut-off etc. along its length. This BCR fibre had also had the refractive indices and core diameters measured. The results of present N_{eff} and λ_o measurements and the previous measured values of MFD, λ_c and Δ are given in Table 2.

Distance from end	MFD (μm) @1310 nm	Cut-off nm	MAC	Δ	N_{eff} @1550 nm	λ_o nm
1	7.508	1290	5.820	0.00550	1.4718	1300
3	7.760	1299	5.974	0.00503	1.4706	1297
5	8.394	1311	6.403	0.00415	1.4694	1295
7	8.981	1349	6.656	0.00374	1.4691	1292
9	9.342	1409	6.640	0.00341	1.4682	1285

Table 2: Fibre parameters as a function of distance from one end of a highly non-uniform fibre.

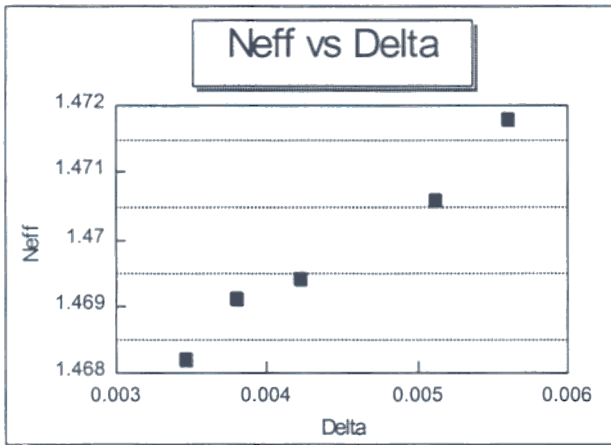


Figure 2. N_{eff} vs. Δ .

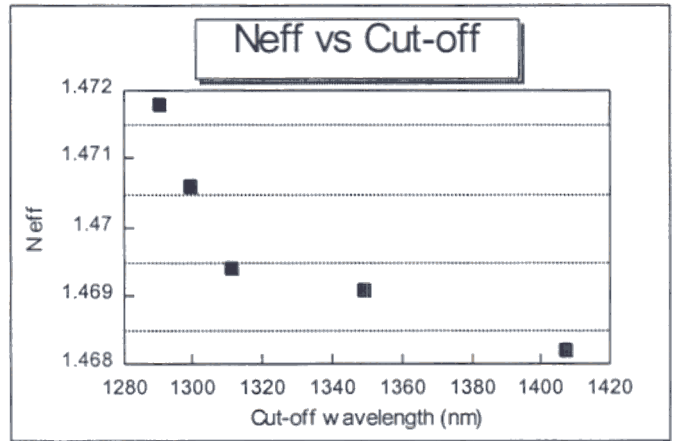


Figure 3. N_{eff} vs. cut-off.

The group index as a function of Δ and cut-off are shown in Figures 2 and 3: N_{eff} is obviously more highly correlated with Δ than with cut-off.

From Eqn. 2

$$\sqrt{2\Delta} = \frac{2.405}{\pi d n_1} \lambda_{cth}$$

$$\Delta = 0.14 \left(\frac{\lambda_{cth}}{d} \right)^2$$

Anderson and Glodis (6) give the empirical relation between measured and theoretical cut-offs as,

$$\left(\frac{\lambda_c}{d} \right)^2 \approx 0.86 \left(\frac{\lambda_{cth}}{d} \right)^2$$

Substituting in Eqn.4 and assuming that $d=MFD/1.12$ (typical of standard fibre at 1310nm), Eqn. (4) becomes

$$\Delta \approx 0.2 \left(\frac{\lambda_c}{MFD} \right)^2 \quad (6)$$

The quantity MFD/λ_c is sometimes known as the MAC number, therefore

$$\Delta \approx \frac{0.2}{MAC^2} \quad (7)$$

Substituting a typical value for the MAC number of 7.4 in Eqn.7 gives a value of 0.0036 for Δ which is typical of a matched clad fibre. For the BCR fibre Eqn.7 predicts a change in Δ of 0.0014 between the ends compared with measured change of 0.0021, not very good agreement even allowing for the approximations involved and the measurement uncertainties.

If we take the change in N_{eff} to be ~ 1.5 the change in Δ as predicted for the bulk material. Eqn. 7 becomes,

$$N_{eff}(z) - N_{eff}(0) \approx 0.3 \left(\frac{1}{MAC^2(z)} - \frac{1}{MAC^2(0)} \right) \quad (8)$$

where $N_{eff}(z)$ is the group index at the point z along a fibre and $N_{eff}(0)$ that at the end. (Or in the case of a set of fibres of the same type $N_{eff}(z)$ is the group index of the z^{th} fibre and $N_{eff}(0)$ is the group index of one of the fibres from set for which the group index is known). Equation 8 predicts a slope of 0.3 for a graph of N_{eff} versus MAC^{-2} .

Figs 4 and 5 show N_{eff} as a function of $(1/MAC)^2$ for both the BCR fibre and for the different fibres. The degree of correlation was 0.92 and 0.76 respectively. For the group of fibres the slope was 0.275 is in good agreement with the predicted value but the BCR fibre it was 0.42, about 30% higher than predicted.

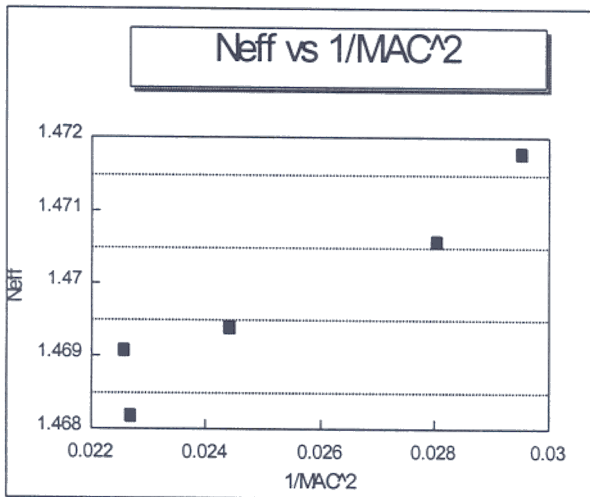


Figure 4. Group index vs. $1/MAC^2$ for the BCR fibre.

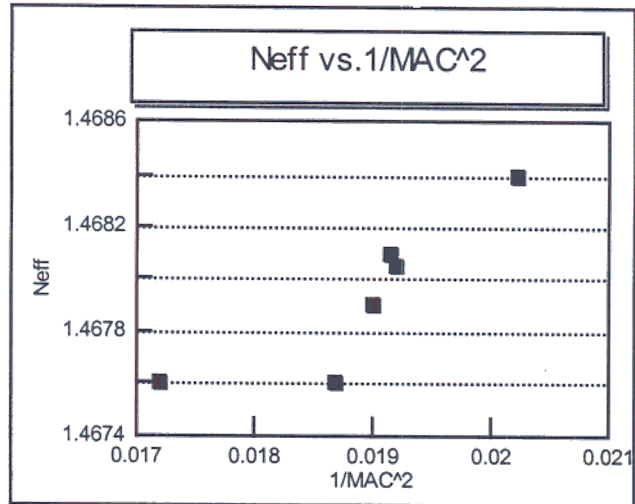


Figure 5. Group index vs. $1/MAC^2$ for six matched clad fibres.

The above analysis was repeated for the BCR fibre this time using MFD and λ_c values measured at one end of the fibre combined with analysis of the bi-directional OTDR backscatter trace. This is shown in Figure 6. The agreement with the theory is now rather better with the slope now being 0.31.

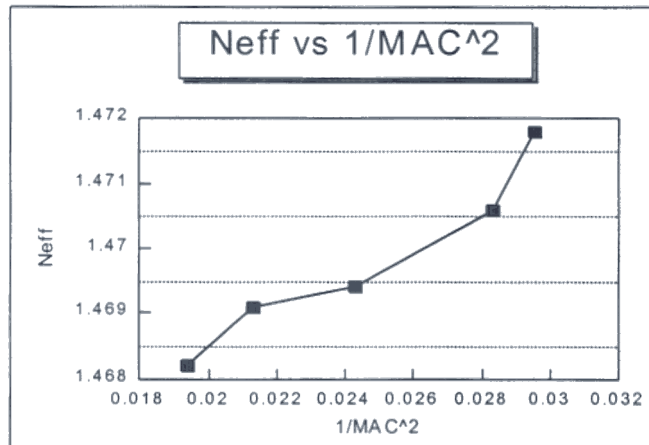


Figure 6. Group index for the BCR fibre vs. $1/MAC^2$ values derived from OTDR backscatter analysis.

This however may be fortuitous as λ_c predicted from the OTDR derived MFD values at 9 km is 1339 nm compared with the measured value 1409 nm. This discrepancy may be due to the fibre being bi-moded at 1310 nm at this distance; the change in the λ_c value changes the MAC value which in turn alters the slope.

5 Conclusions

It has been shown that changes in group index along fibres or amongst fibres of the same type from the same manufacturer can be related to changes in MAC^2 multiplied by a constant. This constant was 0.275 for the set of matched clad measured close to the theoretical value of ~ 0.3 . For the highly non-uniform fibre this factor was 0.42. Further work is required to see how this factor varies with fibre type. Taking 0.42 as being the worst case, then limits can be set on group index variations along fibres from variations in the MAC number.

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