ESI DETERMINATION FROM PETERMANN MODE-FIELD DIAMETER MEASUREMENTS AND REFRACTIVE INDEX PROFILE MEASUREMENTS ON SINGLE-MODE FIBRES

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Introduction

The two main approaches to the characterization of single-mode fibres: viz. Equivalent Step Index (ESI) and Mode Field Diameter (MFD) are still causing confusion [1,2,3] and no real standard procedure has won the confidence of laboratory users.

In a previous paper [4] we have shown that in principle, a self consistent method can unify both the ESI and MFD approaches. For instance, it has been shown that the two parameter of the ESI approximation as derived from the moment theory of single-mode optical fibres [5] can be determined independently from either measurement of the Petermann MFD or from measurements of the refractive index profile. This duality feature makes the moments description of single-mode fibres unique amongst a whole range of experimental and theoretical characterization methods.

In this paper we implement and critically assess our new approach using three independent measurement procedures. The ESI parameters as obtained from (i) MFD measurements, (ii) preform profile measurements and (iii) fibre profile measurements are compared for a nominally step index fibre fabricated by the MCVD process.

A statistical approach is adopted in analysing the measurement data, thereby reducing the influence of measurement error and other inherent uncertainties. Results show that while the preform and the fibre profile measurements produce essentially the same equivalent core radius and the same equivalent numerical aperture (with allowance for diffusion effects) the ESI parameters produced by the MFD are substantially different.

The discrepancy arises from the use of the "effective" cut-off wavelenght, as derived from the MFD measurements, instead of the "theoretical" cut-off wavelength (corresponding to a $\overline{V}$ value of 2.405) in the evaluation of the ESI parameters.

However, it is found that if the cut-off wavelength as derived from the profile measurements, is used in the interpretation of the MFD data then, the three measurement approaches predict very similar ESI parameters. While only one fibre-preform is reported here, one other nominally step-index fibre-preform exhibited similar trends.

Measurements

(i) MFD: The near field Petermann's MFD was obtained from the inverse of the r.m.s. far-field width measured by the variable aperture method

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using commercial equipment. Cut-off wavelength was measured using two techniques: a) The Millar procedure from the variation of MFD as a function of wavelength [6] and b) the transmitted power technique as recommended by CCITT [7].

Table 1 show the values measured for the Petermann's MFD at four wavelenghts. In theory for the determination of the ESI parameters the cut-off wavelength together with the MFD at any one wavelength is sufficient. In practice, if we try different wavelengths we obtain different results. Our approach is to take the average value of the ESI parameters predicted from each of the four wavelengths in table 1. Table 2 shows the average value of these ESI parameters for the two different measured cut-off wavelengths.

(ii) and (iii) Profile measurements: Figs 1a) and 1b) show the refractive index profile (r.i.p.) of the preform and the fibre respectively. 1a) and 1b) were measured using commercial equipment (Spatial Filtering Technique and Refracted Near Field Technique respectively). The ESI parameters were derived from the moment analysis of the r.i.p. for the preform and the fibre. Problems in implementing this procedure arise because both the core radius and the refractive index levels of the core and the cladding are not well defined. Because of this, 6 limits were proposed as sketched in the insets of Fig 1. When using the preform data, the same measured core radii as used for points 1,2,3,4,5 and 6 in Fig 1b) were assigned for the corresponding points in Fig 1a). Assuming circular symmetry only the right hand half of each profile has been used.

The ESI parameters resulting from the profile measurements also differ slightly from one choice of profile to another. Table 2 also shows the average ESI parameters resulting from the six profiles both for the fibre and the preform.

Discussion of results:

Taking the results for the profile measurements in table 2, it is found that the two parameters a_e and NA_e are in good agreement between the fibre and the preform. However, there is a slight increase in a_e and a slight decrease in NA_e in the transition from preform to fibre, this is consistent with the occurrence of diffusion during fibre drawing. The fact that there is only a slight variation in these parameters from preform to fibre is interesting since these two parameters are derived from the first two even moments of the profile shape function and as such they rely on the average properties of the r.i.p. which are not expected to change very much in the fibre draw. It should be pointed out that the poor resolution in the fibre profile measurement will also appear as diffusion, however, even within error bounds there is an overall true diffusion effect. In addition, the theoretical cut-off wavelengths as derived from:

$$\lambda_{co} = 2\pi a_e NA_e / 2.405 \qquad (1)$$

are in very good agreement.

On examining the results from the MFD measurements it is found that the results are completely at odds with those from the profiles. The discrepancy is due to the use of the measured cut-off wavelength (λ_{mco}) in eq. (1). On substituting the average theoretical cut-off

λ_{co} value deduced from the profiles (i.e. λ_{co}=1222 nm) into the MFD analysis the parameters values as shown in table 2 are obtained. These parameters are now in remarkably good agreement with those derived from the fibre profile.

Conclusion:

We show that the theoretical cut-off wavelength as defined by eq. (1) is the key to obtaining a self consistent model for characterizing single-mode fibres which unites the ESI and MFD models. The measured cut-off wavelength, which for a given fibre remains consistent between different reference measurement techniques, does not have a definite relationship to the theoretical cut-off wavelength when comparing different fibres. As such the measured cut-off wavelength can only lead to confusion when used as a reference wavelength in determining the ESI parameters. This conclusion is drawn not only from the results from a single fibre as presented here, but also from other experimental results in our laboratory (a more comprehensive paper is in preparation which will present these) and from the results quoted by other workers such as in references [8] and [9].

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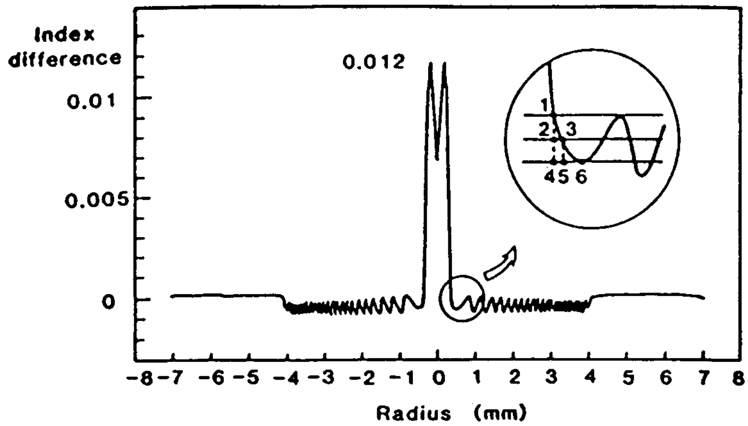
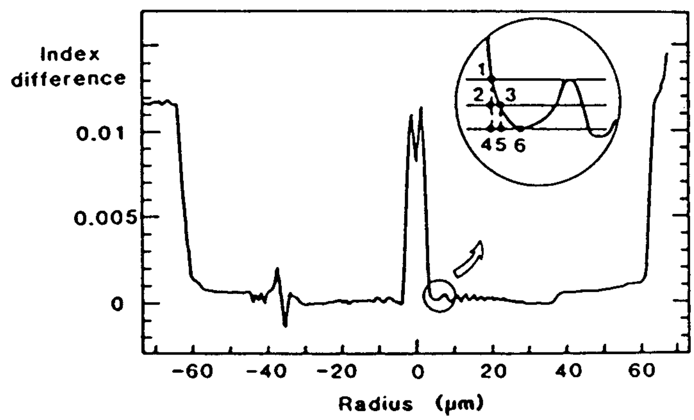
λ (nm)	Petermann's MFD (μm)
1300	6.47 ± 1%
1350	6.72 "
1400	6.85 "
1450	7.07 "

Table 1: Near-field Petermann's MFD at four wavelengths for the MCVD fibre used in the comparative analysis.



(a)



(b)

Figure 1: Refractive index profile of (a) preform and (b) fibre. The insets show the six different core sizes and cladding levels used.

Table 2: Average ESI parameters derived from MFD measurements and profile measurements. The uncertainty quoted is the standard deviation.

Parameter	Mode Field Diameter (MFD) measurements			Profile measurements	
				Fibre	Preform
λ_{co} (nm)	1275 ± 25 (CCITT)	1295 ± 25 (MILLAR)	1222 Average theoretical	1226 ± 25	1217 ± 25
a_e (μm)	2.97 ± .02	3.01 ± .02	2.88 ± .01	2.86 ± .12	2.71 ± .01
NA_e	.1634 ± .0009	.1648 ± .0007	.1623 ± .0006	.164 ± .005	.1722 ± .0007