HIGH-RESOLUTION MEASUREMENT OF DIAMETER VARIATIONS IN OPTICAL FIBRES BY THE BACKSCATTER METHOD

Indexing terms: Optical fibres, Backscatter

The backscatter signal measured with high resolution from optical fibres with complex diameter variations is shown to follow precisely the diameter profile. The local attenuation which is anticorrelated from opposite ends of the fibre is compared with a simple theoretical model.

Introduction: The scattered light returned by a pulse travelling in an optical fibre contains detailed information about the length-dependence of attenuation.[1] In a previous publication,[2] it was shown that backscatter local-attenuation measurements made from each fibre end frequently exhibit anticorrelated fluctuations associated with fibre diameter variations. Numerical aperture variations in the fibre resulting from glass composition changes along the length would produce a similar effect,[3] as would changes in the scatter coefficient. However, owing to the nature of the CVD fabrication process, any preform composition changes which occur are extended over hundreds of metres by the drawing process. On the other hand, fibre drawing itself can cause diameter fluctuations with a wide range of spatial period;[4] moreover, the use of diameter feedback control limits the variations present to those having a short spatial period (~1 m). Thus short-length variations seen in the backscatter trace are likely to be caused by diameter fluctuations, whereas similar effects with longer spatial period will probably be caused by compositional variations.[5]

In a recent publication,[6] a simple theory describing the features seen in the measured backscatter loss at a diameter taper was proposed in which the change in loss of the scatter return is assumed to dominate that of the forward-travelling power. Thus, for propagation into an expanding taper, some of the scatter return is radiated on re-encountering the taper (which appears contracting in the reverse direction) thus producing an apparent increase in local attenuation.

Conversely, at a contracting taper, two mechanisms can occur: (i) returning cladding modes excited downstream of the taper can re-enter the core at the taper, since it expands in the reverse direction; (ii) the returning core power is converted from high- to low-order modes at the taper and this enables it to escape subsequent differential mode attenuation (DMA), provided this is present in the return path. Both mechanisms give an increase in return signal and thus an apparent decrease in local attenuation.

In general, if it is assumed that all core modes are equally excited by the scattering process, the observed loss A as a function of length l is expected to be proportional to the change in core area. Thus

$$A(l) = A_0 - \frac{1}{2}\frac{d}{dl}\left[10 \log_{10} \frac{r_0^2}{r^2(l)}\right] \qquad (1)$$

where A_0 is the intrinsic fibre loss, $r(l)$ the fibre radius and r_0 the baseline fibre radius.

In the present contribution, we examine with high resolution the backscatter from more complex diameter features. The general form of eqn. 1 is verified and the reciprocity of the apparent attenuation fluctuations is confirmed. The importance of the contribution due to cladding modes is emphasised.

Experiment: A pulling tower giving very close control of the fibre diameter[4] was used to produce fibres having specified diameter variations. An analogue input proportional to the desired diameter deviation was added to the error signal in the diameter-control feedback loop, which consists of a scanned laser diameter monitor and three-term controller acting on the speed of the take-up drum. The analogue voltage was obtained from a D/A convertor controlled by a computer and a record of the fibre diameter was taken from the output of the diameter monitor. Backscatter signals at a wavelength of 904 nm were acquired using a transient recorder interfaced to a computer[7] and the local attenuation obtained by differentiation.

Results: Fig. 1 shows the backscatter waveforms obtained from each end (A and B) of a graded-index fibre contianing a series of stepped diameter changes (the fibre diameter profile is indicated at the top of the Figure). The features extend over a length of 40 m and are positioned 210 m from end A of the 1·26 km fibre length. The only other diameter variation present is a reducing taper located at 390 m from end A (See Fig. 1). The pulse width (10 ns) and the amplifier bandwidth (15 MHz) together give a spatial resolution of ~2·5 m, which allows the effect of all four diameter changes to be readily observed.

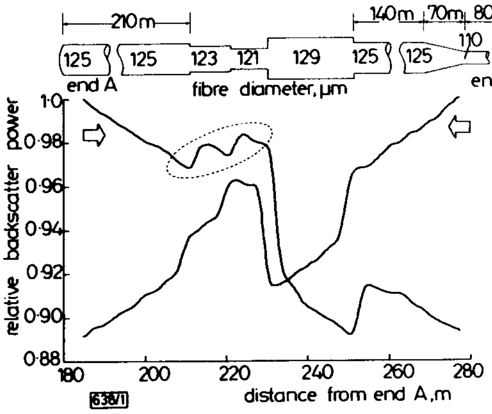

Fig. 1 *Variation of backscattered power with distance in a graded-index, multimode fibre containing stepped diameter changes*

Launching end (A or B) indicated by arrow. Fibre diameter shown schematically at top of Figure

The curves in Fig. 1 show a remarkable degree of symmetry, despite the fact that measurements from end A would not be significantly affected by DMA, whereas those from end B would involve considerable DMA, resulting from the taper located prior to the feature. In particular, the first two increases in return signal in the end A measurement (ringed in Fig. 1) can only be caused by the mechanism involving cladding modes,[6] since no significant prior DMA exists.

Comparison of the form of the curves with the diameter profile indicates that the local attenuation follows the derivative of diameter, as predicted in eqn. 1. However, closer examination reveals that the magnitude of the individual signal variations is about a half that expected, as reported in Reference 2 and subsequently in References 6 and 8. The reason for the discrepancy is that the backscattered light does not fully excite the guide, but excites a subset of high-order modes,[9] which depends on the mode excitation condition in the forward direction. The latter is itself affected by traversing the taper. Experiments performed with differing fibre excitation conditions showed only a small variation in the magnitude of the features, which endorses this view. Moreover, it was found that radiation of forward-travelling light at a contracting taper could be induced only by highly exciting the fibre, thus verifying our assumption of no forward loss under normal circumstances. This forward radiation loss was observed as a sudden marked increase in backscatter local-attenuation at a point along the taper.

To quantify further the effect of diameter variations on the local attenuation, a second 1 km fibre was programmed with sinusoidal diameter variations. The profile of the central 500 m section is shown at the top of Fig. 2. Four cycles of a 5 μm peak-to-peak sinusoidal variation were impressed on the nominal 120 μm diameter; a further unprogrammed diameter spike appears 50 m further down the fibre.

The amplitude of the backscattered power (Fig. 2, centre) measured from each end faithfully reproduces the variations in diameter, a decrease in diameter leading to an increase in scatter return. Moreover, the plots of local attenuation (Fig. 2, bottom) are precisely anticorrelated, both for the programmed and unprogrammed features. Again, the amplitude of the variation is somewhat smaller than that of eqn. 1, owing to partial excitation of the gyide by the backscattered light. The theoretical curve has been superimposed on the Figure (dashed) and it can be seen that the form of the variation closely follows that predicted. A similar amplitude variation was recently found and reported in Reference 10.

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Note that the backscatter power curve returns to the expected exponential decay after the diameter variations and that the local attenuation curves are symmetrical about the fibre median loss of 2·5 dB/km. This indicates that no forward loss was caused by the diameter fluctuations, again confirming our assumption. Experiments on fibres programmed with up to 4 μm RMS bandlimited Gaussian diameter random variations similarly showed no excess loss.

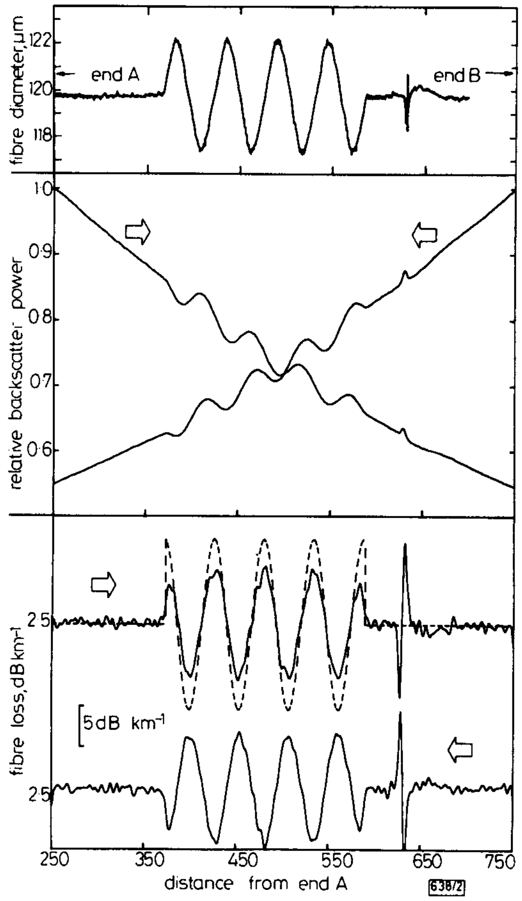

Fig. 2 *Backscatter measurements in a graded-index, multimode fibre having sinusoidal diameter variations*

Top: Variation of fibre diameter over central 500 m section of 1 km-long fibre

Centre: Backscattered power measured from ends A and B (arrowed)

Bottom: Corresponding variation of local attenuation (solid curves). Broken curve is calculated from diameter profile using eqn. 1

Conclusions: High-resolution backscatter measurements on fibres having rapid and complex diameter changes show that the scatter return faithfully follows the detailed form of the diameter profile. The simple theory previously developed accurately describes the shape of the anticorrelated local attenuation measured from each fibre end, but does not give the magnitude of the effect owing to the assumption of full excitation of the guide by the backscattered light.

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