DETERMINATION OF STRUCTURAL PARAMETER VARIATIONS IN SINGLE-MODE OPTICAL FIBRES BY TIME-DOMAIN REFLECTOMETRY

Indexing terms: Optical fibres, Backscatter

Backscatter measurements on single-mode fibres reveal apparent changes in local attenuation resulting from backscatter factor variations. The detailed shape of the backscatter waveforms is compared to known variations of fibre parameters.

Introduction: The backscattering technique is well established for determining the length dependence of attenuation in multimode fibres. The method is useful for determining the variation along the fibre of structural parameters such as the diameter or numerical aperture. The published results on the use of backscatter with single-mode fibres have so far had the emphasis either on the determination of the variation of the state of polarisation along the fibre,[1] or on the maximum range achievable[2] with limited spatial resolution. In this letter the first single-mode backscatter measurements are presented which have been performed with sufficient precision to enable the presence of variations with length of the fibre structural parameters to be deduced from the fibre backscatter signatures. In particular, examples are shown of the response of the backscatter signal to known changes in fibre properties.

Experimental arrangement: Backscatter signals were obtained from single-mode fibres using *Q*-switched Nd:YAG laser pulses of 200 ns duration at a wavelength of 1·06 μm. The optical path of the backscattered power from the fibre to the receiver was designed to eliminate any polarisation sensitivity[1] by the use of small angles at the beamsplitter and by mounting the end of the test fibre in a nonpolarising index-matching cell. The laser pulses are attenuated to a level well below the threshold for Raman generation in the fibre to avoid nonlinear effects. The scattered return is detected by a silicon APD, amplified and digitised, and then fed to a minicomputer for averaging and processing.

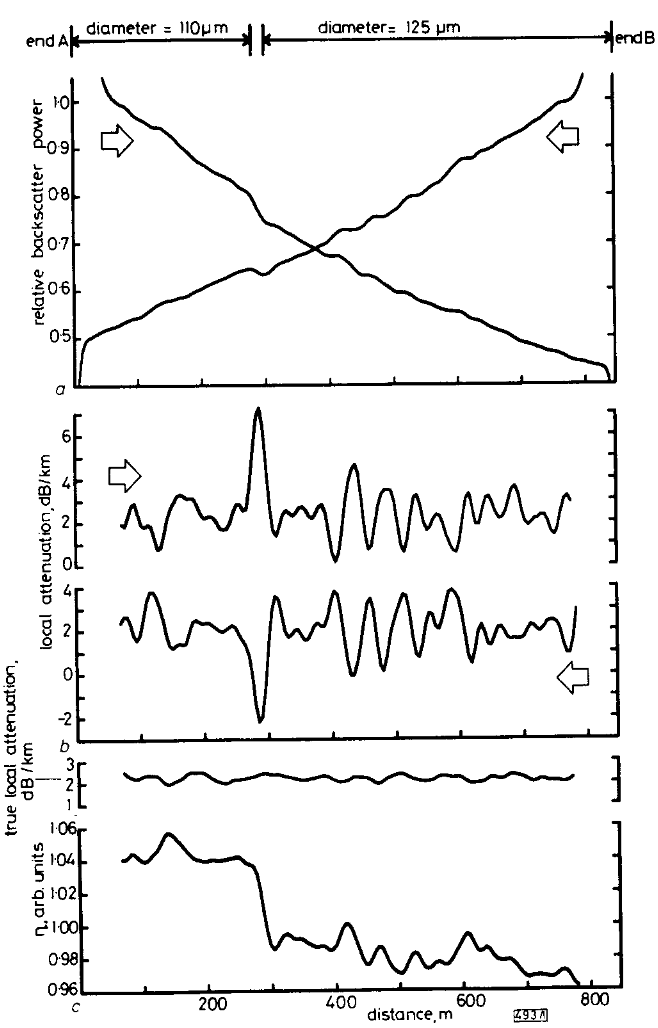

Fig. 1 *Backscatter measurement of a single-mode fibre*

Fibre diameter indicated above Figure

a Relative backscatter power measured from ends A and B (as arrowed)

b Corresponding local attenuation

c True local attenuation and variation of backscatter factor η deduced from backscatter measurements

Results and interpretation: The uppermost curves of Fig. 1 show the backscatter traces obtained from each end (A and B) of an 850 m-long single-mode fibre. The diameter of the fibre (indicated at the top of the Figure) increases from 110 μm to 125 μm over a 20 m region 280 m from end A, but elsewhere is constant to better than 1 μm. This diameter change shows up clearly in the backscatter traces as a change in the power level. The local attenuation plots, obtained by differentiating the two backscatter traces, are also given in Fig. 1, and the diameter taper is apparent as a large fluctuation which is of opposite sign for the two attenuation plots. However, there are many other surprisingly large fluctuations in the local attenuation (which also anticorrelate) in regions of very constant diameter. These variations are found to be stable and reproducible and are not caused by polarisation or laser coherence effects,[3] both of which can cause fluctuations in the backscatter waveform. These features are due to variations along the fibre length of the backscatter factor[4] (i.e. the ratio η of the backscattered power to the pulse energy). Such fluctuations in η are often found in multimode fibres and are usually due to random diameter variations[5] which cause redistribution of power amongst the modes and consequently significantly affect the backscattered power. This mechanism cannot occur in fibres which propagate only one mode (provided that the changes are sufficiently slow to preclude coupling between bound and unbound modes). Nevertheless, a weaker effect exists which is associated with a change in the backscatter capture fraction as the mode volume adjusts adiabatically to the local waveguide conditions. Thus, for single-mode fibres, a large diameter change will cause a fluctuation in the local attenuation as shown in Fig. 1, but the other features observed are definitely not attributable to random outer diameter variations.

The backscatter factor variations can be separated out from the fibre attenuation by a method[6] previously used for processing multimode backscatter waveforms: the true local attenuation is given by the mean of the local attenuation plots measured from each end of the fibre, and the backscatter factor variations are obtained by taking the geometric mean of the two backscatter traces. These two quantities are shown in the lower part of Fig. 1. Note that, by contrast with the large variations found in the local attenuation plots from the two ends, the true local attenuation is relatively constant. The backscatter factor graph shows the fluctuations which cause the anticorrelated features in the local attenuation plots. These have a substantial amplitude and a high spatial frequency compared with those found in multimode fibres (other than those associated with diameter instabilities); they are found to be present in a range of fibres of differing designs.

The dependence of the backscatter factor on the parameters of single-mode fibres has been predicted[7] and, more recently, verified experimentally,[4] and is such that fluctuations in the following parameters will cause variations in η: numerical aperture, Rayleigh scatter coefficient α_s and core diameter. These are listed in order of the relative sensitivity of the backscatter factor to the parameter. Thus η is most sensitive to NA variations which are likely to be the chief cause of the observed features. However, these parameters are in practice interrelated: for example, a change in numerical aperture is associated with an alteration in the dopant concentration which will affect α_s. Also, a change in V-value, which will alter the proportion of the power travelling in the core, will result in a change in the effective α_s unless the values of α_s in the core and cladding are similar.

The variation of the local attenuation plots in Fig. 1 show that the attenuation of a single-mode fibre cannot be reliably determined over a short length from the backscatter signature

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obtained only from one end. This fact is illustrated dramatically by Fig. 2 in which the backscatter traces from both ends of a 470 m-long fibre are given. The slopes of the two traces are markedly different, the measurement from end A indicating an average loss of 1·7 dB/km, whereas from end B the fibre appears to have no loss over most of its length. This discrepancy indicates that η is steadily decreasing along the fibre from end A to end B. This was confirmed by cutting the fibre at several places and determining the NA and V-value at these points by measuring the far-field pattern[8] with a line-scan camera. The results show a decreasing numerical aperture and increasing core radius along the length such that V is virtually constant. The variation in η for this fibre is primarily due to the changing numerical aperture. The fibre was pulled from near the end of a preform manufactured by the CVD process, and the measured variation in NA and core radius is characteristic of the nonuniformities of structure which occur towards the ends of such preforms.[9]

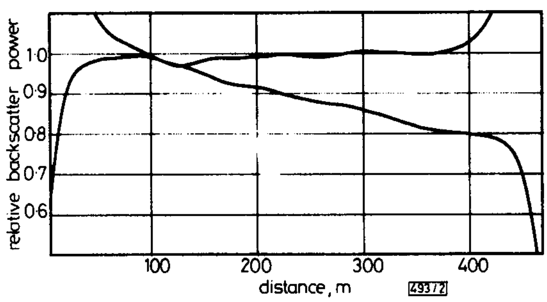

Fig. 2 *Backscatter traces measured from both ends of a 470 m-long single-mode fibre drawn from end of CVD preform*

Conclusions: We have measured the backscatter signatures of single-mode fibres with high accuracy and have shown that the traces contain fluctuations which are attributable to structural parameter variations along the length of the fibres. The presence of such variations affects the accuracy with which the propagation characteristics of the fibre can be deduced from waveguide parameters measured at a single point. It also means that, as for multimode fibres, care must be exercised in the determination of the fibre attenuation from small changes in backscatter level unless backscatter signatures from both ends of the fibre are used to enable the separation of the true attenuation from fluctuations in η. It is envisaged that measurement of the behaviour of η will be invaluable for identifying structural variations in single-mode fibres, and will lead to improvements in fabrication techniques and in the characterisation of low-loss optical waveguides.

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