EUROPEAN CONFERENCE ON OPTICAL COMMUNICATION

Communication C-26

# Analyse du signal rétrodiffusé dans les fibres monomodes

# *Analysis of backscatter waveforms from single-mode fibres*

GOLD M.P., HARTOG A.H.
UNIVERSITY OF SOUTHAMPTON
Department of electronics
GB- SOUTHAMPTON HAMPSHIRE S09 5NH
GRANDE BRETAGNE

## RESUME

Des mesures de rétrodiffusion ont été faites à haute précision et avec une bonne résolution spatiale dans des fibres monomodes. Les mesures décellent des variations apparentes de l'atténuation localisée qui se déroulent sur de courtes distances et qui sont dues à des perturbations du rapport de rétrodiffusivité. Ces dernières sont comparées aux changements connus des paramètres des fibres. Il s'avère notament que le signal rétrodiffusé dans une fibre monomode est moins sensible aux perturbations du diamètre qu'il ne l'eut été dans une fibre multimode. Les perturbations de l'ouverture numérique, du coefficient de diffusion et du rayon du coeur font obstacle à une détermination précise de l'atténuation sur de courtes distances à partir de la rétrodiffusion mesurée à une seule extrémité de la fibre.

## *ABSTRACT*

Backscatter measurements have been made on single-mode fibres with high precision and good spatial resolution. Apparent changes in local attenuation are revealed which occur over short fibre lengths and result from backscatter factor variations. The latter are compared to known fluctuations in fibre parameters. It is found that the backscatter signal is less sensitive to diameter variations in single-mode fibres than in multimode fibres. Longitudinal variations of numerical aperture, scattering loss coefficient or core radius preclude an accurate determination of local attenuation derived from backscatter measurements made at one end only of the fibre.

## INTRODUCTION

Optical time-domain reflectometry (OTDR) is a well established technique for measuring the length dependence of attenuation in multimode fibres. It is also useful for determining the variation of structural parameters such as diameter[1] or numerical aperture[2] along the fibre. OTDR has also been demonstrated in single-mode fibres, but up till now the studies have been primarily concerned either with measuring the variation of the state of polarisation[3] along the fibre, or with techniques for maximising the range[4,5] at which faults can be located in the fibre, at the expense of spatial resolution. We present here the first single-mode backscatter measurements which have been performed with sufficient precision and spatial resolution to enable the presence of variations in the fibre structural parameters to be deduced from the fibre backscatter waveforms. We demonstrate this with examples of the response of the backscatter signal to known changes in fibre properties.

## THEORY

The backscattered power $P_s(t)$ from a point at distance $x = v_g t/2$ from the measurement end of the fibre is given by

$$P_s(t) = P_o \tau \eta e^{-\alpha v_g t} \qquad (1)$$

where $P_o\tau$ is the input pulse energy, $\eta$ is the backscatter factor[6], $v_g$ is the group velocity, and $\alpha$ is the mean attenuation of the fibre over the length from the start to the point under consideration. Thus in the case of a perfectly uniform fibre, for which $\eta$ and $\alpha$ will both be constant, the backscatter signature is a simple decaying exponential.

The value of $\eta$ for a step-index single-mode fibre is dependent on the fibre parameters as follows[7]:

$$\eta = \frac{0.75}{(\omega_o/a)^2 V^2} \; \frac{n_1^2 - n_2^2}{n_1^2} \; \alpha_s v_g \qquad (2)$$

where V is the normalised frequency of the fibre, $n_1$ and $n_2$ are the refractive indices of core and cladding and $\alpha_s$ is the Rayleigh scatter coefficient. The quantity $(\omega_o/a)$ is the spot size normalised to the core radius and is a function of V. Equation (2) shows that $\eta$ is sensitive to variations in $\alpha_s$, NA and, to a lesser extent, the core radius[8].

Deviations in the backscatter signal from a simple decaying exponential can be caused both by variations in the fibre attenuation and by changes in $\eta$. These can be separated by using backscatter traces obtained from both ends of the fibre, a technique[2] used previously for processing multimode backscatter waveforms. By taking the ratio of the two traces the dependence on $\eta$ is eliminated, leaving only the exponential term in equation (1). From this the true length dependence of the fibre attenuation may be extracted. On the other hand, the geometric mean of the two traces removes the exponential term and is directly proportional to $\eta$.

## EXPERIMENT

The experimental arrangement is shown in Figure 1. The Nd:YAG laser is operated at a wavelength of 1.06µm and is Q-switched to produce pulses of 200ns duration. The pulses are launched via a variable attenuator into a short (~ 2m) single-mode launch fibre and thence to the test fibre via a reflection at the beamsplitter. The end of the test fibre is mounted in a launching cell designed to eliminate the Fresnel reflection from the fibre end-face. The cell contains index-matching liquid between the lens and the fibre end and thus the only index change occurs at the outer, curved surface of the lens, the reflection from which diverges rapidly. The scatter return from each laser pulse travels back through the launching cell, passes through the beamsplitter, and is detected by a silicon APD. The detected signal is amplified, digitised and passed to a mini-computer for averaging and processing.

To ensure high-precision single-mode OTDR measurements special care has been taken to avoid (i) polarisation sensitivity in the detection of the backscattered light, and (ii) non-linear processes in the fibre.

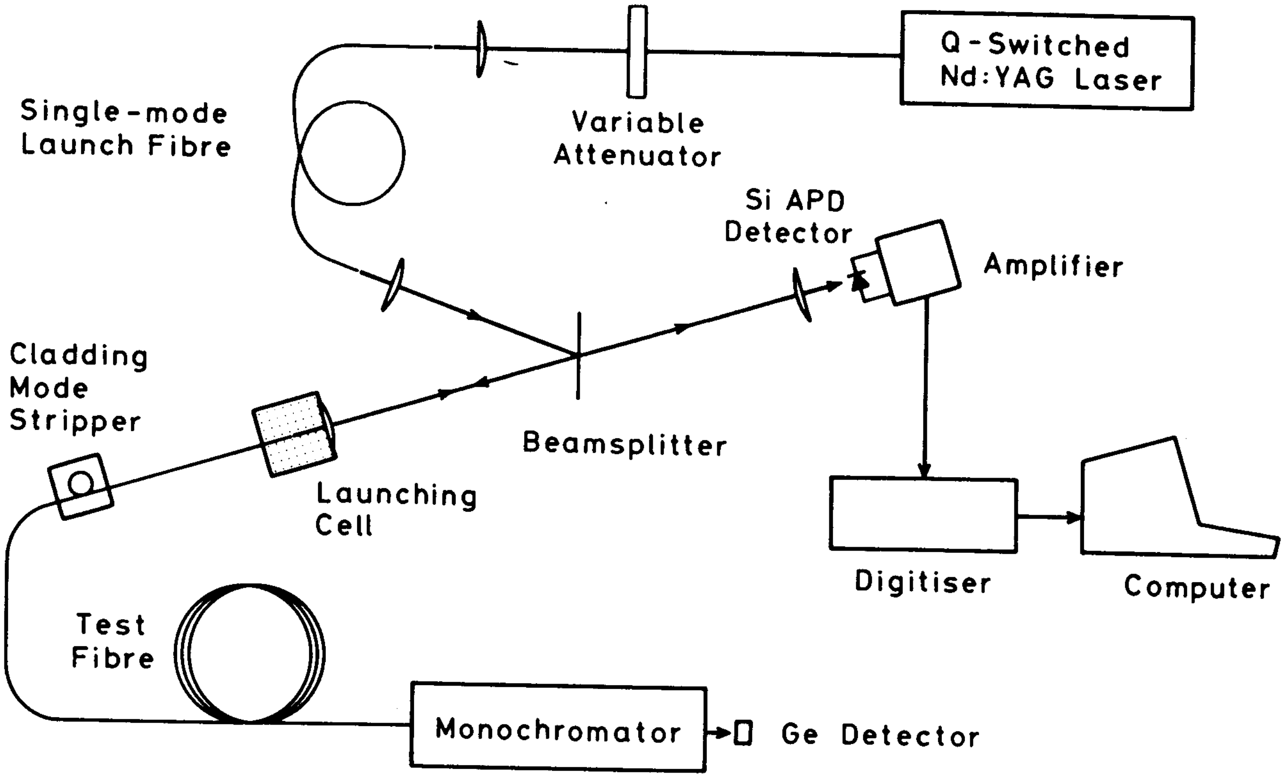

Figure 1 : Experimental Arrangement

The former is achieved by using the beamsplitter at an angle nearly perpendicular to the path of the backscatter signal[3], and by the non-polarising launch cell arrangement. In the latter case, the non-linear process with the lowest threshold, for the laser pulse length and linewidth used, is stimulated Raman scattering. The power level required for the onset of the first Stokes is determined by monitoring the spectrum of the probe pulse at the far end of the test fibre with a monochromator and germanium diode detector. The input power is then reduced by about 3dB from the level at which the first Stokes is just detected. For backscatter measurements, the first Stokes is then at least 40dB (optical) below the power at the pump wavelength. This procedure ensures that no distortion of the backscatter waveform is caused by Raman generation in the fibre which would otherwise alter the backscatter trace owing to the differences in fibre loss and detector responsivity over the range of wavelengths present.

The ratio of the reflected to transmitted paths of the beamsplitter is approximately 10/90. This splitting ratio achieves the maximum backscatter signal level at the detector when a powerful laser source is available, since the backscattered light is not significantly attenuated by passing through the beamsplitter, whereas the power loss in the reflected path for the input pulses is of no consequence. In addition, this arrangement reduces the polarisation sensitivity of transmission losses in the return path to insignificant levels.

## RESULTS AND DISCUSSION

The backscatter traces shown in the upper part of Figure 2 were obtained from both ends of an 850m-long single-mode fibre; the direction of the laser pulses for the measurements is given by the arrows. The outer diameter of the fibre is indicated at the top of the figure. In the regions from 0 to 270m and 290m to 850m the diameter is constant to better than 1μm at the values indicated; in the transition region the fibre diameter tapers between these two values. The diameter change shows up clearly as a change in the power level in the backscatter traces. The local attenuation plots from the backscatter traces are shown in the central part of the figure and were obtained by differentiating the backscatter power (in dB) with respect to distance.

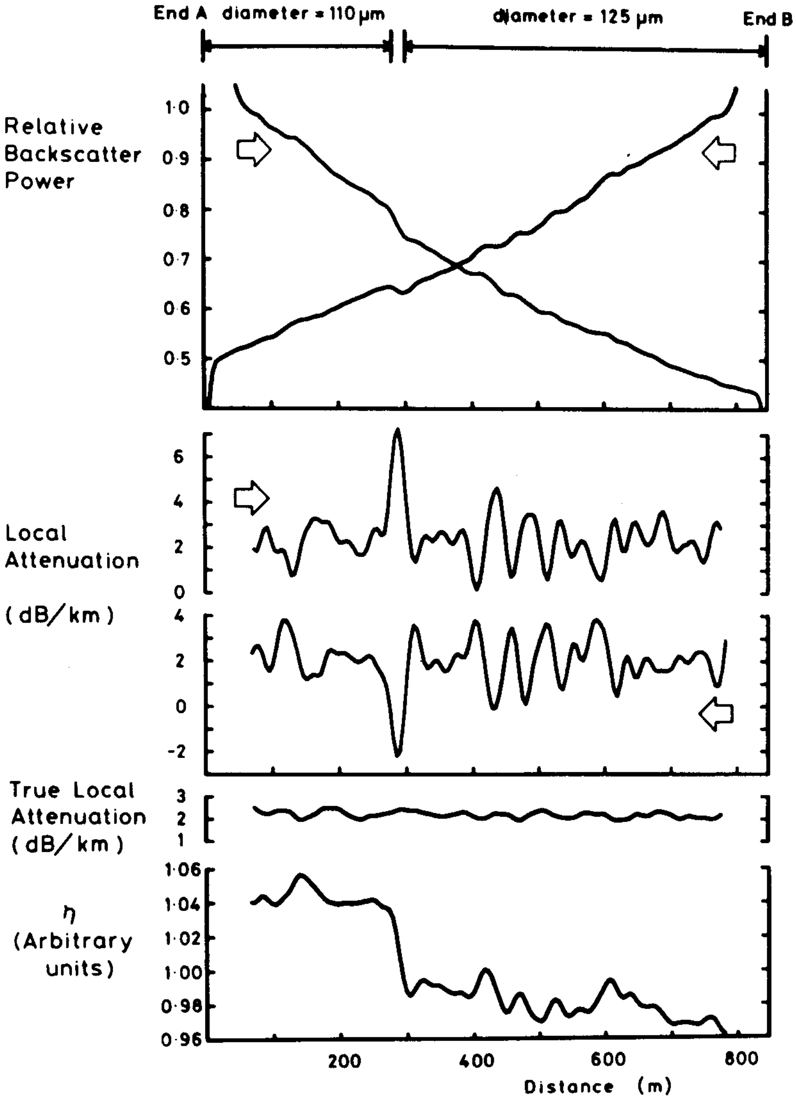

Figure 2 : Backscatter measurement of a single-mode fibre (the fibre diameter is indicated above the figure).

Top: Relative backscatter power measured from ends A and B (as arrowed).

Centre: Corresponding local attenuation.

Bottom: True local attenuation and variation of backscatter factor $\eta$ deduced from the backscatter measurements.

The differentiation was carried out over a length of 20m, which corresponds to the maximum spatial resolution obtainable with a 200ns input pulse width. The diameter taper is apparent in the local attenuation plots as a large deviation which is of opposite sign for the two launch ends. However, in the regions of constant diameter there are many surprisingly large fluctuations in the local attenuation which also anti-correlate. These features are found to be stable and reproducible and therefore cannot be due to either polarisation or coherence effects[9], both of which can cause fluctuations in the backscatter signal. In our measurements both of these potential sources of inaccuracy have been eliminated, the latter being averaged out during the backscatter waveform acquisition by slightly modulating the length of the laser cavity during the measurement.

The almost exact anticorrelation of the two local attenuation plots indicates that the observed fluctuations are due to variations in the backscatter factor, $\eta$ along the fibre, and are not caused by variations in the actual attenuation of the fibre. This interpretation is confirmed by the traces in the lower part of Figure 2 in which the backscatter factor and the fibre attenuation have been separated by the technique described earlier. It can be seen that the true local attenuation is relatively constant, in contrast with the local attenuation plots from the two fibre ends. However, fluctuations are apparent in the backscatter factor trace and these are the cause of the anticorrelated features of the local attenuation plots.

Variations in $\eta$ are often found in multimode backscatter measurements. They are usually due to random fibre diameter variations which give rise to changes in the power distribution amongst the modes and hence significantly affect the received backscatter 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). However, for single-mode fibres a weaker effect exists, since the backscatter capture fraction is dependent on the spot size and therefore on the fibre diameter. In Figure 2, the feature at 280m occurs as a result of the deliberate, large diameter change, but the remaining fluctuations are definitely not attributable to random outer diameter variations. These unprogrammed variations have a substantial amplitude and a high spatial frequency compared with those found in multimode fibres(other than those associated with diameter fluctuations) and have been detected in a range of fibres of differing designs.

The backscatter factor is dependent on the fibre properties (NA, $\alpha_s$, and core radius), as discussed earlier, and is most sensitive to changes in NA. Consequently, small refractive index fluctuations are likely to be the chief cause of the observed features. However, in practice the parameters affecting the backscatter return are not independent. For example, an increase in the core dopant concentration will alter both the numerical aperture and $\alpha_s$. Additionally a change in V-value, which will alter the proportion of the power travelling in the core, will also result in a change in the effective Rayleigh scatter coefficient if the value of $\alpha_s$ differs in the core and cladding.

Figure 3 shows the backscatter traces from both ends of a 470m-long single-mode fibre which was drawn from near the start-of-deposition end of a preform manufactured by the CVD process. The striking feature of these traces is their difference in slopes, which leads to a large discrepancy in the apparent attenuation when measured from the two ends. In one case the backscatter curve indicates an average loss of 1.7dB/km, whereas from the other end the fibre appears to have almost zero loss. The difference suggests that $\eta$ must be steadily decreasing from left to right in Figure 3. This trend was confirmed by measurements of the far-field pattern[10] at several points along the fibre, using a line-scan camera.

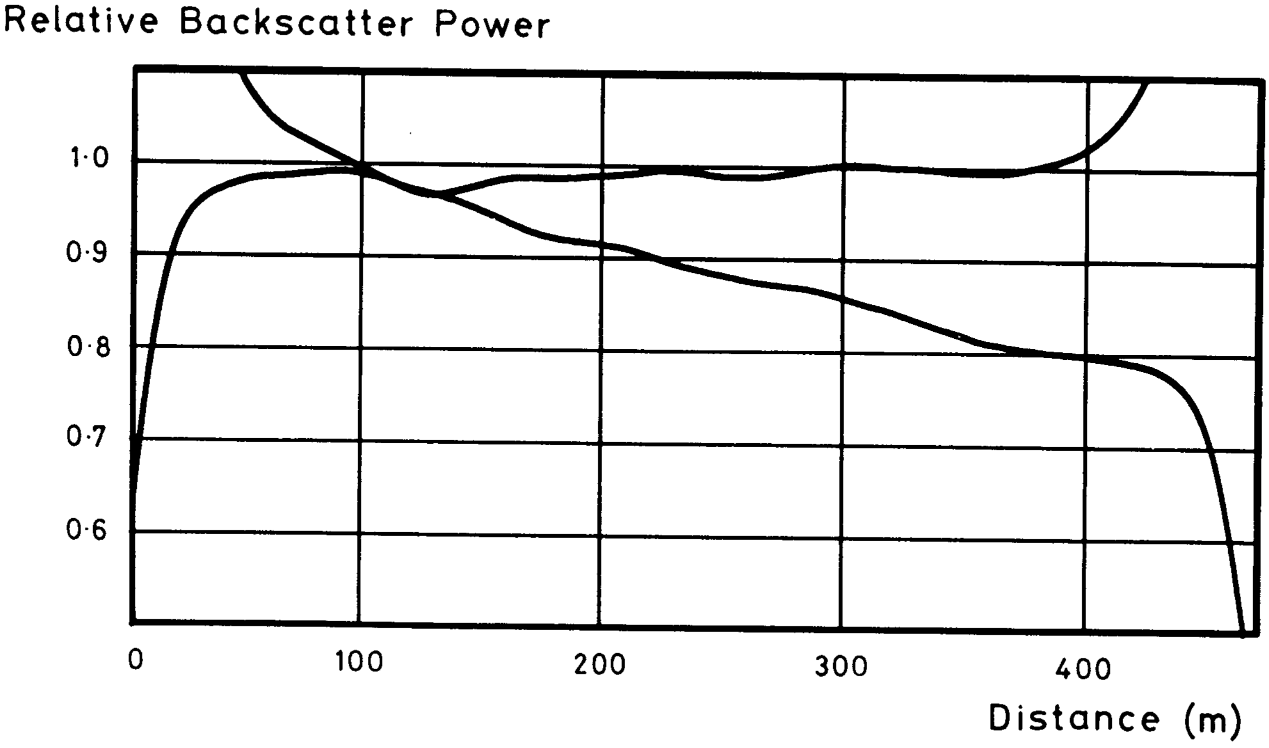

Figure 3: Backscatter traces measured from both ends of a 470m-long single-mode fibre drawn from the end of a CVD preform.

These results show that while the numerical aperture decreases, the core radius increases in rough proportion along the length such that V is approximately constant. This behaviour of the fibre parameters is characteristic of the non-uniformities of structure which occur near the start-of-deposition end of a CVD preform[11]. In this case the first term in equation (2) is constant, and the variation in $\eta$ is primarily due to the changing numerical aperture.

## CONCLUSIONS

We have demonstrated that high-precision measurements of the backscatter signatures of single-mode fibres reveal fluctuations which are attributable to structural parameter variations. In particular the effect on the backscatter trace of changes in fibre diameter and numerical aperture has been shown. The presence of such variations in $\eta$ means that, as for multimode fibres, it is not possible to determine the fibre attenuation accurately from small changes in the backscatter level. However, if backscatter traces are available from both ends of the fibre, the true attenuation can be separated from variations in $\eta$.

The observed fluctuations in the parameters of single-mode fibres suggest that single-point characterisation of fibres may have limited accuracy in determining the overall propagation properties of the fibres. However, measurement of the behaviour of the backscatter factor is a powerful method for identifying variations in the structure of single-mode fibres. It is envisaged that use of this technique will lead to improvements in the fabrication and characterisation of low-loss optical waveguides.

## ACKNOWLEDGEMENTS

We are indebted to R. J. Mansfield and E. J. Tarbox for supplying the fibres. We would like to thank Professor W.A.Gambling and D. N. Payne for their guidance. Financial support from the UK Science and Engineering Research Council is gratefully acknowledged.

## REFERENCES

1. Conduit, A.J., Payne, D.N., and Hartog, A. H.: "Optical fibre backscatter-loss signatures: identification of features and correlation with known defects using the two-channel technique", Proceedings of 6th European Conference on Optical Communication, York, 1980, pp. 152-155.
2. Di Vita, P., and Rossi, U.: "The backscattering technique: its field of applicability in fibre diagnostics and attenuation measurements", Optical and Quantum Electronics, 1980, 11, pp. 17-22.
3. Hartog, A. H., Payne, D. N., and Conduit, A. J.: "Polarisation optical time-domain reflectometry: experimental results and application to loss and birefringence measurements in single-mode optical fibres", Proceedings of 6th European Conference on Optical Communication, York, 1980, post-deadline paper.
4. Healey, P.: "Multichannel photon-counting backscatter measurements on monomode fibre", Electronics Letters, 1981, 17, pp. 751-752.
5. Noguchi, K., Murakami, Y., Yamashita, K., and Ashiya, F.: "52 km-long single-mode optical fibre fault location using the stimulated Raman scattering effect", Electronics Letters, 1982, 18, pp. 41-42.
6. Gold, M. P., and Hartog, A. H.: "Measurement of backscatter factor in single-mode fibres", 1981, 17, pp. 965-966.
7. Brinkmeyer, E.: "Analysis of the back-scattering method for single-mode optical fibres", Journal of the Optical Society of America, 1980, 70, pp. 1010-1012.
8. Gambling, W. A., and Matsumura, H.: "Simple characterisation factor for practical single-mode fibres", Electronics Letters, 1977, 13, pp. 691-693.
9. Eickhoff, W., and Ulrich, R.: "Statistics of backscattering in single-mode fibres" Proceedings of 3rd International Conference on Integrated Optics and Optical Fiber Communication, San Francisco, 1981, pp. 76-78.
10. Gambling, W. A., Payne, D. N., Matsumura, H., and Dyott, R. B.: "Determination of core diameter and refractive index difference of single-mode fibres by observation of the far-field pattern", Microwaves, Optics and Acoustics, 1976, 1, pp. 13-17.
11. Sasaki, I., Payne, D. N., Mansfield, R.J., and Adams, M. J.: "Variation of refractive-index profiles in single-mode fibre preforms measured using an improved high-resolution spatial-filtering technique", Proceedings of 6th European Conference on Optical Communication, York, 1980, pp. 140-143.

Communication C-27

# Effets de polarisation dans les fibres monomodes en W

## *Polarization effects in single-mode W-type optical fibres*

DIANOV E.M. GRUDININ A.B., KHAIDEROV D.V., KONDRATJEV M.A.
P.N. LEBEDEV PHYSICAL INSTITUTE
MOSCOW 117924
URSS

GURYANOV A.N., KHOPIN V.F., IGNATJEV S.V.
MIROSHNOCHENKO S.I.
URSS ACADEMY OF SCIENCES
Institute of Chemistry
URSS

### RESUME

Une étude expérimentale a été faite pour examiner des effets polariseurs des fibres optiques monomodes en W.

La birefraction lineaire et circulaire des fibres eprouvées a été mesuré. En utilisant la dépendance spectrale de le degré maximum de polarisation on a apprecié le coefficient de couplage parmi des modes leakys et fondamentales. On a etabli l'influence de la largeur spectrale de source sur la conservation de polarisation, dont le degré se maintient s'il n'exist qu'un de modes eigenpolariseurs. Néanmoins, la depolarisation est determinée par le spectre de source, par la longueur et la dispersion polariseure de fibre.

### *ABSTRACT*

An experimantal study was made of the polarization effects of W-type single-mode optical fibers.

The linear and circular birefringence of test fibres has been measured.

Using spectral dependence of maximum degree of polarization the coupling coefficient between leaky and fundamental modes was estimated.

The influence of the source spectral width on the preservation of polarization was found. Polarization degree is preserved when only one of the eigenpolarization modes is excited, while depolarization is determined by the light source spectra, length and polarization dispersion of fiber.