MEASUREMENT OF BACKSCATTER FACTOR IN SINGLE-MODE FIBRES

Indexing terms: Optical fibres, Scattering, Attenuation

The ratio of the backscattered power to the input pulse energy is measured in single-mode optical fibres. The results provide confirmation of single-mode backscatter theory and show that measurement of this ratio can be used to determine α_s, the Rayleigh scatter coefficient.

Introduction: The backscattering method[1] is now widely used for the assessment of the length dependence of attenuation in multimode fibres. Although backscatter traces have been measured in single-mode fibres,[2] experimental values of the backscatter factor (i.e. the ratio η of backscattered power to the energy launched) have not been reported.

A theoretical analysis of backscatter in step-index single-mode fibres has been published,[3] in which the following equation was derived for the backscatter power P_s returned from an input pulse energy $P_0\tau$:

$$\frac{P_s(t)}{P_0\tau} = \frac{0.75}{(\omega_0/a)^2V^2}\,\frac{n_1^2-n_2^2}{n_1^2}\,\alpha_s v_g e^{-\alpha v_g t} = \eta e^{-\alpha v_g t} \qquad (1)$$

where V is the normalised frequency of the fibre, n_1 and n_2 are the refractive indices of core and cladding, α_s is the Rayleigh scatter coefficient, and α is the overall attenuation constant. v_g is the group velocity in the fibre, which may be determined from the refractive indices, n_1 and n_2, and the waveguide parameters. The quantity (ω_0/a) is the spot size normalised to the core radius, and can be calculated from V.

This letter describes a new experimental method which provides the first measurement of the ratio η of the backscattered power to the input pulse energy in a single-mode fibre. The results from this method are compared with those predicted by eqn. 1, and the close agreement achieved gives experimental evidence for the validity of this equation. It is therefore possible to apply the technique described here to the determination of α_s, a parameter which is required for the design of low-loss single-mode fibres. Although α_s may be measured by other methods, such as microcalorimetry[4] or the use of integrating spheres[5] or cubes,[6] these require careful design and calibration and are likely to be imprecise in single-mode fibres.

Experiment: The experimental arrangement is shown in Fig. 1. The Nd:YAG laser is operated at a wavelength of 1·064 μm and is Q-switched to produce 300 ns-wide pulses at 1 ms intervals. The orientation of the beamsplitter allows the silicon APD to receive both the backscattered light which emerges from the front end of the test fibre and the forward-travelling light pulses from the far end of the fibre. The latter pass through a computer-controlled shutter and then through a set of four neutral-density filters, which attenuate the pulses by 55 dB, so that both optical signals have a similar amplitude at the detector. Note that both ends of the test fibre are mounted in angled launching cells to eliminate Fresnel reflections, and that the beamsplitter is used at near-normal incidence, so that its reflectivity is insensitive to polarisation.[2]

In order to avoid launching light into the far end of the test fibre, the two beams emanating from each end of the fibre are slightly displaced at the beamsplitter (displacement not shown in the Figure).

Measurement of the quantity η requires the relative attenuation of the optical paths of the backscattered signal and the forward-travelling pulses to be accurately known. In our experiment, both paths contain identical launching cells and lenses at the two ends of the fibre, and also the same lens in front of the detector. The only differences are that the forward-travelling path is attenuated by the set of filters, and that one path is transmitted and the other is reflected at the beamsplitter. The filter densities and the beamsplitter reflection/transmission ratio were accurately calibrated and are known to a combined standard error of 1·5%.

The signals from the detector are fed to a transimpedance amplifier and then averaged in a digital oscilloscope whose timebase is triggered after each laser pulse by a delay generator.

The ratio η was measured at a position halfway down the fibre, since from this point the backscatter and forward light travel the same distance in the fibre and so reach the detector at the same time. They also suffer the same attenuation in the fibre if its loss is uniform. η is evaluated from sets of three oscilloscope traces which are obtained in rapid succession to avoid errors due to instrument drift and variation in laser output. These consist of:

(i) the forward travelling pulse together with backscatter from halfway down the fibre, obtained with the shutter open

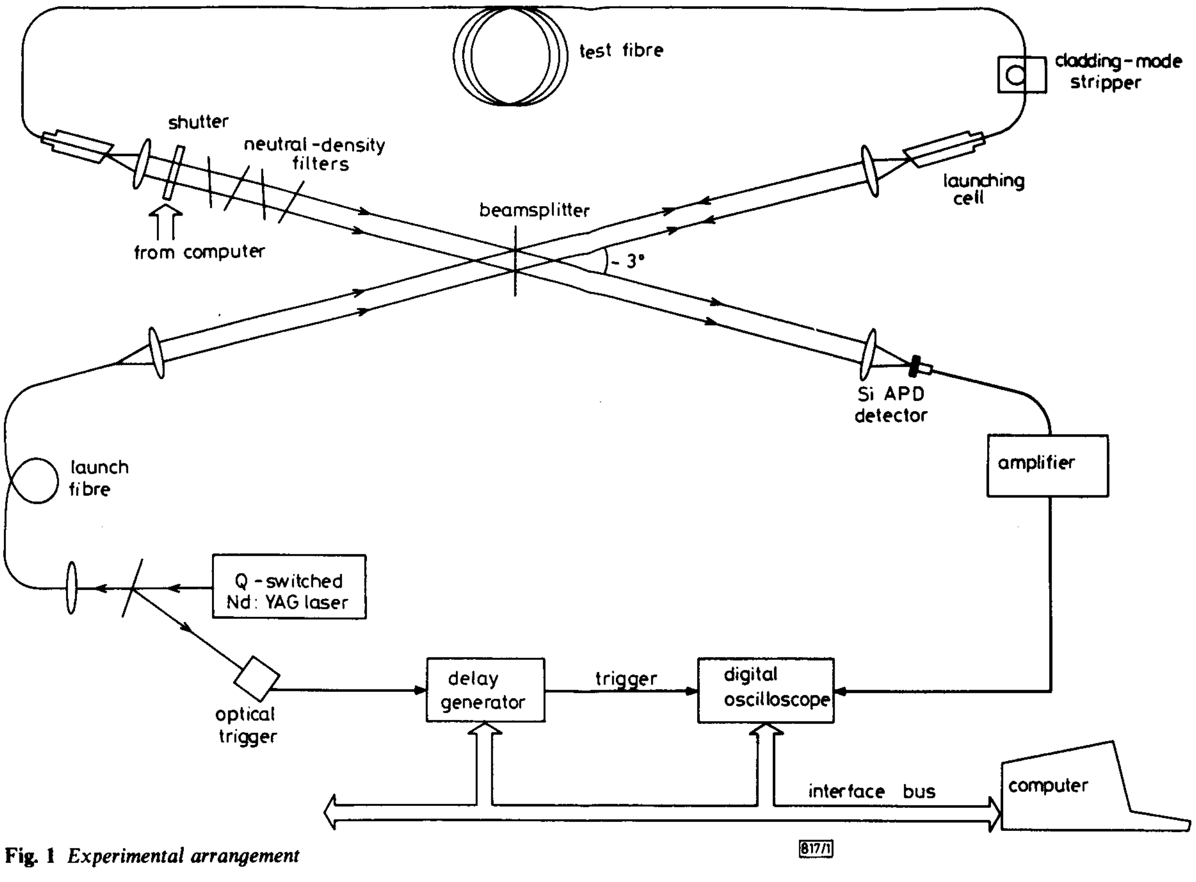

Fig. 1 *Experimental arrangement*

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(ii) backscatter only, with the shutter closed
(iii) background level after the backscatter has ceased, acquired by increasing the delay in the trigger signal.

The forward pulse energy is obtained by integrating the difference between traces (i) and (ii). In order that the numerical integration may be performed with suitable accuracy, the oscilloscope timebase has been carefully calibrated. The backscatter power is given by the difference between traces (ii) and (iii).

Results: Measurements were made on two fibres having germanosilicate cores and borosilicate claddings and whose properties are given in Table 1. For each fibre, two values for η were determined by launching successively into each end of the fibre, and the results are shown in Table 2. The differences between the values obtained for the two ends can at least in part be explained by differing losses for the two halves of the fibres, which could be observed from the backscatter traces.

Table 1 PROPERTIES OF FIBRES USED

Fibre number	Length	V-value at 1·06 μm	NA	Attenuation at 1·06 μm	α_s at 1·06 μm
	m			dB/km	dB/km
347	472	1·88	0·101	0·9	0·59
348	532	1·99	0·114	1·1	0·62

Table 2 COMPARISON OF EXPERIMENTAL AND PREDICTED VALUES OF η

Fibre number	Launch end	Experimental values η	σ	mean	Predicted values
		W/J			W/J
347	A	13·4	0·4	14·5	15·1
	B	15·6	0·5		
348	A	20·4	0·6	19·6	20·3
	B	18·9	0·5		

However, taking the mean of the results from the two ends cancels out the effect of any variation in loss along the fibres, and so these mean values are given in Table 2. The standard deviations σ shown in the Table represent the sum of the relative uncertainties in the measured power/energy ratio and the calibration factors.

Calculation of theoretical value of η: In order to compute the theoretical value of η for each fibre, the V-value, numerical aperture, and α_s are required for a point halfway down the fibre.

Measurement of V and NA: The theory of Brinkmeyer[3] assumes the fibre profile to be steplike, although in practice this is not quite true. Equivalent-step values for the numerical aperture and V-value were therefore used and these were determined from measurements of the far-field pattern[8] using a line-scan camera.

Estimation of α_s: Values for α_s were obtained from Reference 9, in which the $1/\lambda^4$ dependent component of the loss of multimode fibres is given as a function of the relative index difference for various core dopants. Since our test fibres have a cladding whose refractive index is depressed by boron doping, α_s is determined by the relative index difference Δ_c attributable to the core germania dopant concentration. Δ_c was obtained by subtracting from the measured index difference the value of the cladding depression, the latter being given by refractive index profiles of the fibre preforms.[10] Although these estimates of α_s do not allow for any possible differences in scattering between core and cladding materials, in practice most of the power ($\sim 70\%$ for our fibres) is carried in the core region, which thus has the dominant contribution to the overall scattering loss. In addition, Δ and Δ_c are both small in our test fibres so that the cladding is expected to have a scattering loss similar to that of the core. This approximation is sufficiently accurate for the purpose of comparing measured and calculated values of η. In fibres of different design, however, it would generally be necessary to take into account the difference in values of α_s for the core and cladding materials.

Discussion: Comparison of the measured and predicted values of η in Table 2 show good agreement for both fibres. The major cause of the difference in values is probably the uncertainty in the magnitude of α_s, but the close agreement obtained nevertheless provides evidence of the validity of eqn. 1 in describing the amount of backscattered power from single-mode fibres. To be specific, the values of η obtained from our backscatter measurement are within 5% of those calculated using the data given in Reference 9.

With the accuracy of the theory established, measurement of η in the manner described in this letter, together with a knowledge of the relevant fibre parameters, provides a new technique for the determination of α_s in single-mode fibres. The value of α_s obtained in this way is a mean of the scattering coefficient in the core and cladding weighted by the mode power distribution; it is this weighted mean which gives the attenuation of the fibre due to Rayleigh scattering at the measurement wavelength. The proposed technique would therefore prove useful in the design of low-loss single-mode fibres.

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