Application of the Backscattering Technique to the Determination of Parameter Fluctuations in Multimode Optical Fibers

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Abstract—**An experimental study of backscattering traces from fibers with random variations of core diameter and numerical aperture has been carried out. The "mode-filtering" technique, which is employed in the measurements, is shown to be a powerful means of separating the parameter fluctuation effects from the actual exponential power decay. The experimental results are then found to be in excellent agreement with the predictions of a recent backscattering theory. It is shown that backscattering measurements can easily be used to place upper limits on the magnitudes of parameter fluctuations in present day fibers.**

I. Introduction

The backscattering technique was originally applied to the problem of fault location [1], [2] and later to that of attenuation determination in multimode fibers [3], [4]. The original theoretical work on backscattering [4], [5] ignored the explicit dependence of the backscattering factor on fiber parameters other than numerical aperture. It was Di Vita and Rossi [6], [7] who first discussed the dependence of the backscattered signal on fiber parameters and proposed a method to separate loss mechanisms from fluctuation effects. Subsequent work by Conduit *et al.* [8] indicated that core diameter variations were a major source of the commonly observed fluctuations on backscattered waveforms. The relation between diameter and backscattered power level was empirically derived [9] and subsequently explained theoretically in terms of mode dependent effects in multimode fibers [10].

Shibata *et al.* [11] were first to put forward a general theory of backscattering which explicitly includes the effect of all parameter fluctuations. Unfortunately, this theory does not agree with the empirically derived relation of [9]. Recent general theories put forward by Mickelson and Eriksrud [12], and independently by Di Vita [13], do explain the empirical relation for diameter fluctuations. Furthermore, the dependence of the backscattered power level on numerical aperture has recently been verified [14] to agree with the relation of [12], in disagreement with the relation of [11].

It is the purpose of the present work to apply the theory of [12] to the prediction of backscattering signatures in multimode optical fibers. Certain verifications of the theory are presented. Discussion is given to the conditions under which numerical aperture and core diameter fluctuations within an optical fiber can be separately determined from a pair of backscattering measurements. Some discussion of the practical limitations of the technique as a fiber diagnostic are presented.

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II. Theory

The power backscattered from a fiber can in general be written as

$$P(z) = K(z) \exp - \int_0^z (\gamma_f + \gamma_b)\, dz \tag{1}$$

where $K(z)$ represents an effective scattering coefficient and γ_f and γ_b are the attenuation coefficients of the forward and backward traveling waves, respectively. The longitudinal coordinate z is related to the reception time by the average group velocity.

It should be noted here that excitation (and therefore reception) at fiber coordinate $z = 0$ will be denoted as end A excitation and that excitation at $z = L$, where L is the fiber length, as end B excitation. The corresponding received backscattered power will be denoted as $P_A(z)$ and $P_B(z)$, respectively. From (1), one can then form the combinations

$$\left[\frac{P_A(z)}{P_B(z)}\right]^{1/2} = \left[\frac{K_A(z)}{K_B(z)}\right]^{1/2} \exp - \int_0^z (\gamma_f + \gamma_b)\, dz \cdot \exp \frac{1}{2} \int_0^L (\gamma_f + \gamma_b)\, dz \tag{2a}$$

$$[P_A(z) \cdot P_B(z)]^{1/2} = [K_A(z) \cdot K_B(z)]^{1/2} \cdot \exp - \frac{1}{2} \int_0^L (\gamma_f + \gamma_b)\, dz \tag{2b}$$

where it should be noted that the terms farthest to the right simply denote the dc level of the processed signal. It was first realized by Di Vita and Rossi [6] that if the scattering coefficient $K(z)$ is independent of propagation direction, then the processing indicated in (2) forms a complete separation between parameter fluctuation and loss mechanism (exponential power decay). In general, $K(z)$ must be dependent on

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direction. In [12] it is shown that for a class of excitations, $K(z)$ is independent of direction, and that, therefore, for this class of excitations one can define a loss function $L(z)$ and a parameter fluctuation function $F(z)$ by

$$L(z) = \left[\frac{P_A(z)}{P_B(z)}\right]^{1/2} \tag{3a}$$

$$F(z) = [P_A(z) \cdot P_B(z)]^{1/2}. \tag{3b}$$

We refer to the excitations for which the backscattered signals satisfy (3) as mode-filtered excitations. The basic idea behind a mode-filtered excitation is that if a test fiber is excited by another fiber which supports fewer modes than can propagate at any point in the test fiber, then the forward traveling pulse in the test fiber can suffer no excess loss. The nature of propagation back to the receiver (source) end of the fiber is then determined by the nature of the Rayleigh scattering process and not the energy distribution of the scattered pulse. Therefore, mode-filtered excitations lead to experimental results which are (almost) independent of the launching conditions.

For mode-filtered excitation of multimode graded-index fibers which can be considered to have longitudinally varying parameters, the normalized backscattered power can be written as [12]

$$\frac{P(z)}{P(0)} = \exp - \int_0^z (\gamma_f + \gamma_b)\, dz \left[\frac{N(0)}{N(z)}\right]^{\alpha(z)/(\alpha(z)+2)} \frac{\alpha_R(z)}{\alpha_R(0)} \frac{\Delta(z)}{\Delta(0)} \cdot \frac{\int_0^1 dR p_0^f(R)\, R^{(1+4/\alpha(0))} \left[1 - \frac{2}{\alpha(z)+2} R^{2(\alpha(z)/\alpha(0))(\alpha(0)+2)/(\alpha(z)+2)}\right]}{\int_0^1 dR p_0^f(R)\, R^{(1+4/\alpha(0))} \left[1 - \frac{2}{\alpha(0)+2} R^2\right]} \tag{4}$$

where $N(z)$ is the total number of propagating modes at coordinate z, $\alpha_R(z)$ is the Rayleigh scattering coefficient, $p_0^f(R)$ is the incident modal power distribution at $z = 0$, R is the mode continuum parameter defined in terms of the normalized propagation constant $\beta/n_1 k$ by [15]

$$R^2 = \frac{1}{2\Delta}\left[1 - \frac{\beta^2}{n_1^2 k^2}\right], \tag{5}$$

and $\Delta(z)$, $a(z)$, and $\alpha(z)$ can be defined through the relation for the radial-longitudinal variation of the refractive index

$$n^2(z,r) = n_1^2 \left[1 - 2\Delta(z)\left(\frac{r}{a(z)}\right)^{\alpha(z)}\right]. \tag{6}$$

In the limit where the α value can be considered (approximately) constant, the backscattered power becomes completely independent of launching conditions and (4) reduces to the simple form

$$\frac{P(z)}{P(0)} = \frac{\alpha_R(z)}{\alpha_R(0)} \left[\frac{\Delta(z)}{\Delta(0)}\right]^{2/(\alpha+2)} \left[\frac{a(0)}{a(z)}\right]^{2\alpha/(\alpha+2)} \cdot \exp - \int_0^z (\gamma_f + \gamma_b)\, dz \tag{7}$$

and (3) can then be expressed in the form

$$\frac{L(z)}{L(0)} = \exp - \int_0^z (\gamma_f + \gamma_b)\, dz \tag{8a}$$

$$\frac{F(z)}{F(0)} = \frac{\alpha_R(z)}{\alpha_R(0)} \left[\frac{\Delta(z)}{\Delta(0)}\right]^{2/(\alpha+2)} \left[\frac{a(0)}{a(z)}\right]^{2\alpha/(\alpha+2)}. \tag{8b}$$

III. Experimental Arrangement

The backscattering apparatus used for the experiments is illustrated in Fig. 1. The output from a single heterostructure laser diode operating at 850 nm is launched into the mode-filtering fiber pigtail by imaging (unity magnification) the emitting area of the laser onto the core. The mode-filtering fiber is butt-jointed (with index matching fluid) to the test fiber. The launched pulses are 80 ns wide and the backscattered power is deflected by a beam splitter into an avalanche photodetection system with 50 MHz bandwidth. Waveform acquisition and averaging (1000 times) is performed by a digital processing oscilloscope (Tektronix 7854) interfaced to a computer with X-Y plotter for hard-copy outputs of the processed signals.

One basic feature of the measurement procedure is the use of the mode-filtering fiber which controls both the transmitted (forward) and received (backward) mode distribution. Short lengths (50–100 m) of low numerical aperture, small core diameter graded-index fibers were used as mode filters to ensure that the mode volume at the excitation/reception point is less than the mode volume at any longitudinal position of the test fiber.

The various test fibers, which were employed to demonstrate the sensing of fiber parameter fluctuations with the backscattering technique, are MCVD fabricated with GeO_2-P_2O_5 doped cores. Stated values of numerical aperture are defined by the angle comprising 99 percent of the radiated power from a 2 m long piece of (overexcited) fiber.

IV. Results

A. Core Diameter Fluctuations

Fig. 2 illustrates the value of the mode-filtering technique in extracting smooth loss functions. Fig. 2(c) illustrates the loss function processed from two rather bumpy backscattering traces [Fig. 2(a) and (b)] which were measured from either end of a graded-index fiber. The bumpiness of the measured traces is due to core diameter fluctuations. This is clearly illustrated in Fig. 3 which displays the parameter fluctuation function $F(z)$, together with the outer fiber diameter trace $b(z)$, which was measured during the fiber drawing process.

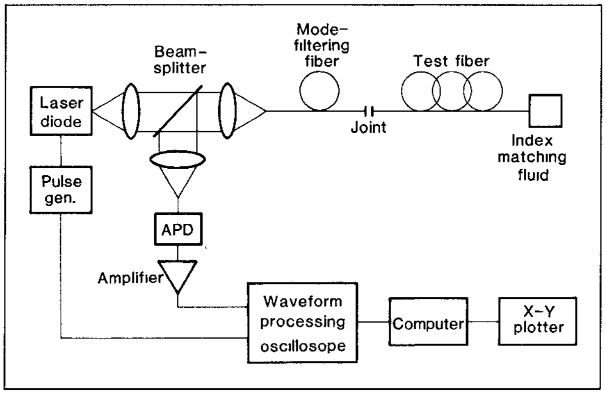

Fig. 1. Experimental arrangement.

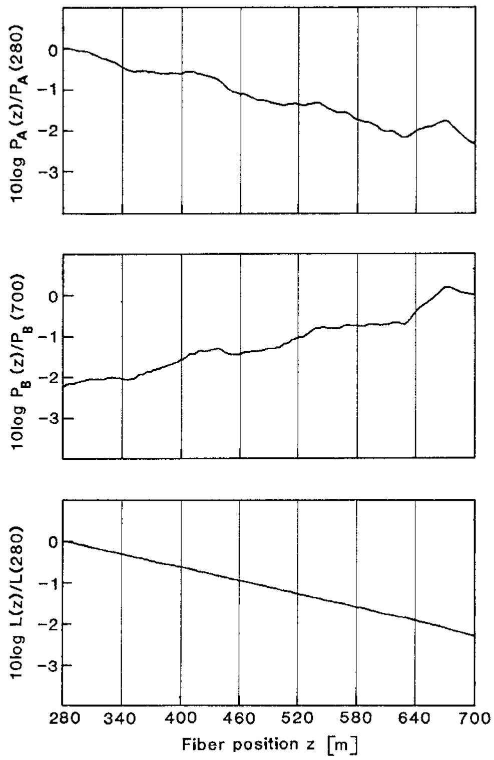

Fig. 2. Backscattered waveforms of a graded-index fiber with random core diameter fluctuations (mode-filtered excitation). (a) Backscattered power measured from end A. (b) Backscattered power measured from end B. (c) Loss function obtained from dividing the measurements from ends A and B.

The remarkable agreement between the parameter fluctuation function and the diameter trace indicates the efficacy of the backscattering technique in determining random core diameter fluctuations. This result also manifests that the core diameter relates directly to the outer diameter. As a 125 μm outer diameter corresponds to a 50 μm core diameter, the results of Fig. 3(a) and (b) reveal that core diameter changes of a few tenths of a micrometer can easily be detected by the backscattering technique. The magnitude of the variation in the parameter fluctuation function corresponds with high accuracy to the one theoretically predicted for near parabolic index profiles.

The local attenuation curve in Fig. 3(c) is obtained by differentiation of the backscattering trace (log scale) measured from end A. This figure is included to indicate the fallacy of

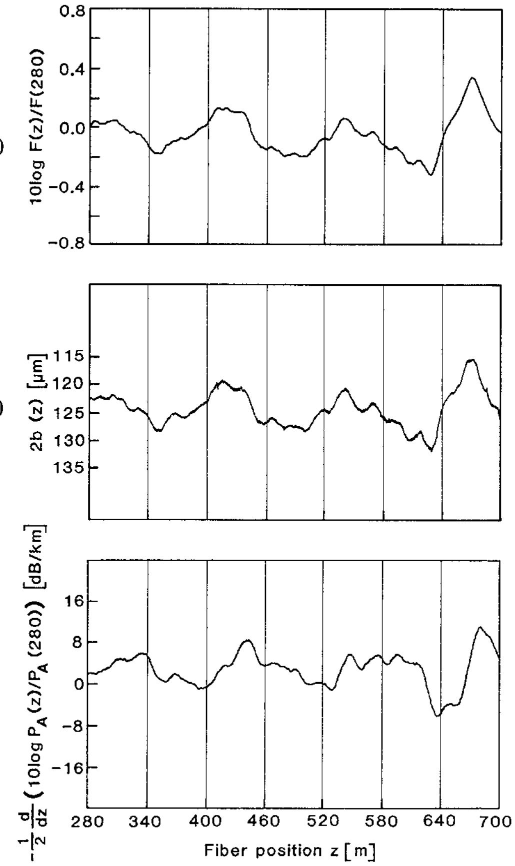

Fig. 3. Comparison between processed backscattered signals and fiber diameter (same fiber as in Fig. 2). (a) Parameter fluctuation function. (b) Outer fiber diameter trace (measured during fiber drawing). (c) Local attenuation curve (obtained from the slope of the Fig. 2(a) waveform).

trying to determine the actual core diameter trace from the derivative of a one-ended backscattering trace [16]. It is also readily seen that Fig. 3(c) does not give accurate information on the loss coefficient associated with the exponential decay. The actual loss coefficient, however, can be derived from the loss function as will be illustrated in the following section.

B. Numerical Aperture Variations

In contrast to core diameter fluctuations which primarily originate from instabilities in the fiber drawing process, numerical aperture variations occur mainly during the deposition process. The subsequent drawing tends to greatly elongate the distance over which a fluctuation of a given magnitude occurs. This causes the length scale of numerical aperture variations to exceed the length scale of core diameter variations introduced by fiber pulling.

Numerical aperture variations are related to changes in concentration of core dopants. The Rayleigh scattering coefficient also depends on the dopant concentration, and therefore these two effects must be interrelated. From curves contained in a paper by Yoshida *et al.* [17], it is notable that, for small variations of the numerical aperture ($NA = n_1\sqrt{2\Delta}$), the relation between the Rayleigh scattering coefficient and the square of the numerical aperture can be assumed to be linear in germania doped fibers and can therefore be written in the form

$$\alpha_R = C(1 + kNA^2) \quad (9)$$

where C is a normalization coefficient and k is a constant of proportionality. For germania doped fibers with numerical aperture variations, (9) should then be substituted into (7) and (8). Indeed, this has been experimentally confirmed in [14] where the value of the constant k was empirically determined to be about 20 for GeO_2-P_2O_5 doped graded-index fibers with varying GeO_2 content. However, it should be stated that (9) is not expected to be universally true. If, for example, variations in concentration of more than one dopant occur, there is no reason to believe that the scattering coefficient follows a relation as (9).

Fig. 4 shows backscattering traces measured from a graded-index fiber which exhibits a significant change in numerical aperture from one end of the fiber to the other. The effect of mode filtering is clearly demonstrated, and Table I summarizes average loss values calculated from the displayed traces which were measured in a 460 m long section.

The values of the numerical aperture at the two ends of this fiber section were measured to be 0.210 (at $z = 50$ m) and 0.199 (at $z = 510$ m), respectively. This corresponds to a theoretical change of 0.44 dB in the parameter fluctuation function. The measured change was about 0.4 dB as is illustrated in Fig. 5. The fiber was drawn without a diameter control feedback system, and the rapid variations of the parameter fluctuation are due to core diameter fluctuations. The slowly decreasing level towards the 510 m position is, however, believed to represent the variation in numerical aperture.

In cases where (9) holds, it should, in principle, be possible to separate core diameter variations from numerical aperture variations. If one considers the exponential decay of backscattered traces to be related to a Rayleigh scattering term α_R and a non-Rayleigh term α_{nR}, then one can express the derivative of (8a) in the form

$$\frac{1}{2}\frac{d}{dz}\left[10\log\frac{L(z)}{L(0)}\right] = -\alpha_{nR} - C[1 + kNA^2(z)] \quad (10)$$

with the aid of (9). If the loss coefficient α_{nR} and the coefficients C and k are constant along the fiber length, then $NA(z)$ can be determined from (10). This result can then be substituted into (8b) for $F(z)$ to enable one to determine $a(z)$. Evidently, an important limitation of this method is its resolution. For example, the change in numerical aperture over the fiber length displayed in Fig. 5, corresponds to a change of about 0.15 dB/km in the Rayleigh scattering coefficient at the 850 nm wavelength. The effect of numerical aperture variations is therefore much less prevalent on the loss function than on the parameter fluctuation function. However, increased sensitivity can be achieved by performing the loss measurements at shorter wavelengths where the Rayleigh scattering loss becomes larger.

Fig. 6 illustrates the slope of the loss function obtained by numerical differentiation of the curve in Fig. 4(c). There seems to be a gradual decrease in the loss coefficient towards the low numerical aperture end. The more rapidly varying loss fluctuations are of non-Rayleigh type.

The quantitative effect of numerical aperture variation together with core diameter variation is illustrated in Fig. 7, which compares the measured $F(z)$ with one calculated from measurements of the fiber's numerical aperture and core diameter at various longitudinal positions (illustrated in Fig. 8). The calculated values are obtained from the relation

$$\frac{F(z)}{F(0)} = \frac{1 + 20\,NA^2(z)}{1 + 20\,NA^2(0)} \cdot \frac{NA(z)}{NA(0)} \cdot \frac{a(0)}{a(z)} \quad (11)$$

which comes from (8b) and (9) in the case of near parabolic

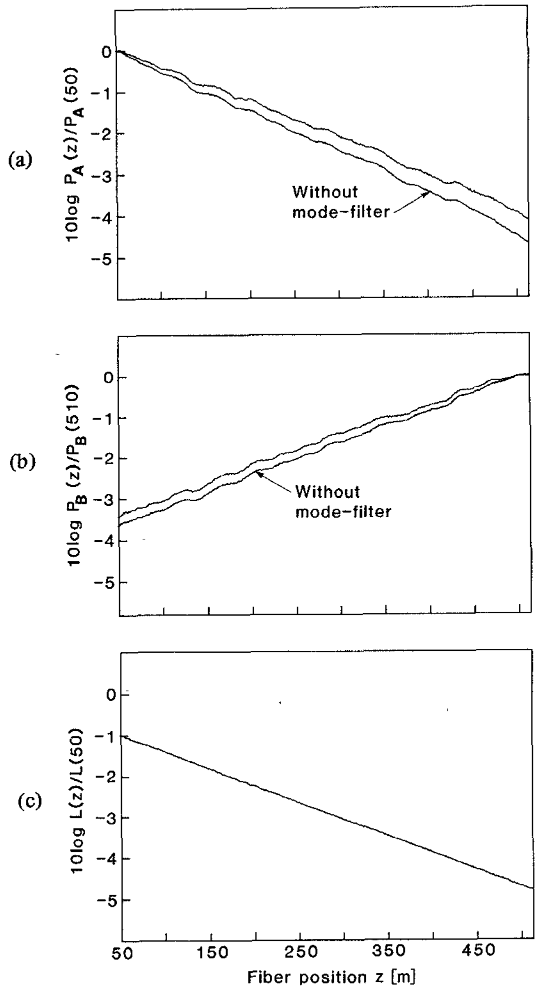

Fig. 4. Backscattered waveforms of a graded-index fiber with numerical aperture varying between one fiber end and the other. (a) Backscattered power from end A. (b) Backscattered power from end B. (c) Loss function obtained from the mode-filtered measurements from ends A and B.

TABLE I
LOSS COEFFICIENTS IN dB/km OBTAINED FROM THE VARIOUS BACKSCATTERED WAVEFORMS [$P_A(z)$, ($P_B(z)$, AND ($L(z)$)] IN FIG. 4. THE LOSS COEFFICIENT REPRESENTS AVERAGE POWER LEVEL CHANGE OVER THE 460 m LONG FIBER SECTION

	Without mode-filter	With mode-filter
$P_A(z)$	5.06	4.49
$P_B(z)$	3.99	3.69
$L(z)$		4.09

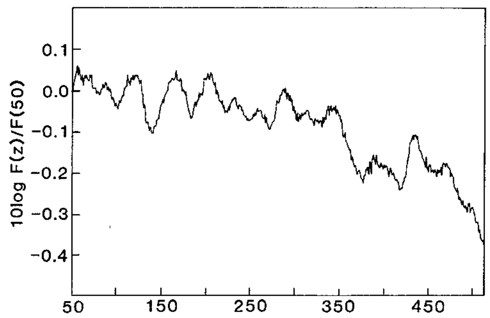

Fig. 5. Parameter fluctuation function (same fiber as in Fig. 4).

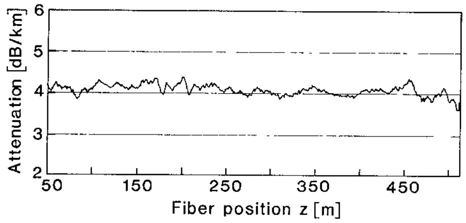

Fig. 6. Local attenuation curve obtained from the slope of the loss function [Fig. 4(c)].

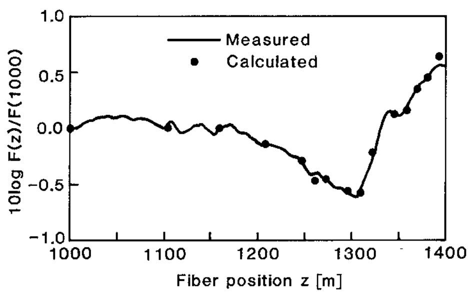

Fig. 7. Parameter fluctuation function of a 400 m long section of graded-index fiber.

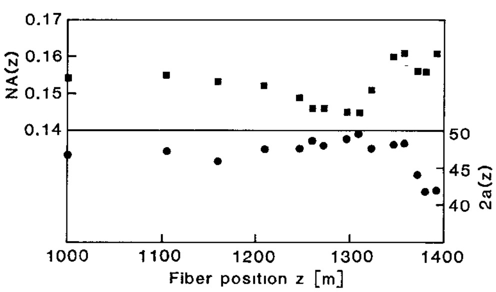

Fig. 8. Numerical aperture and core diameter measured at various longitudinal positions along the fiber section displayed in Fig. 7.

index fibers ($\alpha \sim 2$). The agreement between theory and experiment is seen to be excellent. It should be noted that the fiber section which exhibits the most considerable change in both numerical aperture and core diameter was drawn from a preform section which was located nearest to the gas input during deposition. Gas flow instabilities and thermal nonequilibria are predominating effects in this section of the starting tube [18].

C. Profile Variations

Reference [12] discusses the magnitude of change in backscattered power caused by changes in the profile exponent of an α profile fiber. These changes were theoretically found to be completely negligible for near-parabolic profiles ($1.5 < \alpha < 3$) in the case of mode-filtered excitation. However, it is very hard to imagine that actual profile changes could be modeled as pure changes in the profile exponent (i.e., without attendant changes in core diameter or numerical aperture). For this reason, it was deemed necessary to program a severe profile change in an experimental attempt to set an upper limit on the profile change effect.

Fig. 9 shows the measured fluctuation function $F(z)$ of a fiber with a profile change programmed to occur between positions C and D. The actual profiles at these two positions are illustrated in Fig. 10 which presents near-field scans, measured after the fiber was cut.

Fig. 9 illustrates that there can be significant changes in the backscattered power level induced by profile change. The level of the $F(z)$ function can be seen to rise by 0.5 dB from position C to D. However, after perusing Fig. 10, this result becomes not so surprising. If one were to attempt to fit the two profiles with α profiles, it is easily seen that the two fits would require drastically different core diameters. A rough calculation shows that indeed this effective diameter can be used to account for the change in backscattered level. Amazingly, a change of 0.5 dB in the $F(z)$ function is calculated from (8b) by using the effective core diameter given by the fitted curve dotted in Fig. 10(b). However, it is questionable how well the measured curve of Fig. 10(b) can be fitted to an α profile.

Finally, it should be noted that the more rapid fluctuations of the curve in Fig. 9 are due to core diameter fluctuations induced in the nonfeedback controlled drawing process.

V. Discussion

Fig. 11 shows a trace of the parameter fluctuation function measured on a 1700 m length of high quality commercial fiber. This trace contains information on how fiber parameters vary along the fiber length. The fiber is of parabolic type and has a nominal core diameter of 50 μm and a numerical aperture of 0.20. The effect of 2 percent longitudinal variation in these parameters is shown for illustration in the figure. It is clearly seen that the actual variation is much less than that. The maximum variation of the displayed parameter fluctuation function is about 0.04 dB which corresponds to a change of 0.5 μm in the core diameter (i.e., 1 percent) or 0.001 in the numerical aperture value (i.e., 0.5 percent). This result illustrates the feasibility of the backscattering technique for determining tolerances on the longitudinal variations of the fiber's intrinsic parameters. However, it is hard to say whether the observed increase in the $F(z)$ function around the midpoint is due to a slight core diameter or numerical aperture variation. Usually though, it can be said that fluctuations introduced by the drawing process (i.e., basically core diameter fluctuations) appear as more rapid perturbations than those originating from the deposition process.

VI. Conclusion

The relation between the parameter fluctuation function measured by two ended mode-filtered backscattering measurements and the intrinsic fiber parameters has been investigated experimentally. An excellent quantitative agreement

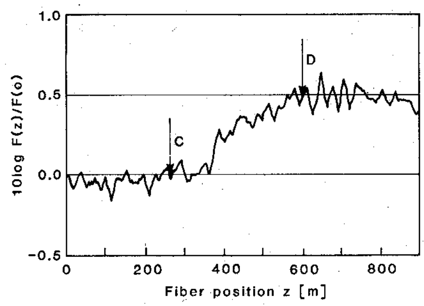

Fig. 9. Parameter fluctuation function of a fiber with a programmed profile change between positions *C* and *D*.

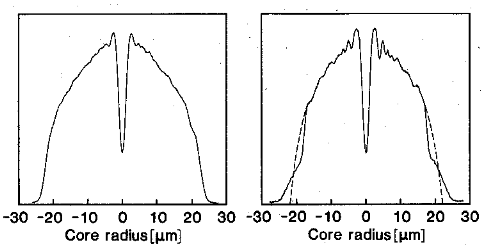

Fig. 10. Near-fields measured at positions (a) *C* and (b) *D* of the fiber with programmed profile change (Fig. 9). The broken line in (b) represents a theoretical fit to a smoother profile.

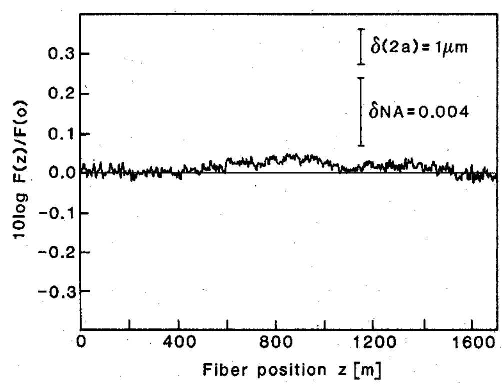

Fig. 11. Parameter fluctuation function of a 1700 m long commercial graded-index fiber.

between theory and experiment has been found, and the experimental results show that longitudinal variations of less than 1 percent in core diameter and numerical aperture are easily detected by the proposed technique. Thus, it is possible to easily place limits on the fluctuations of the fibers' parameters with backscattering measurements.

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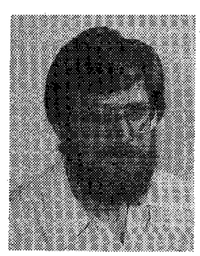

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