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Technical Digest - Symposium on Optical Fiber Measurements, 1980

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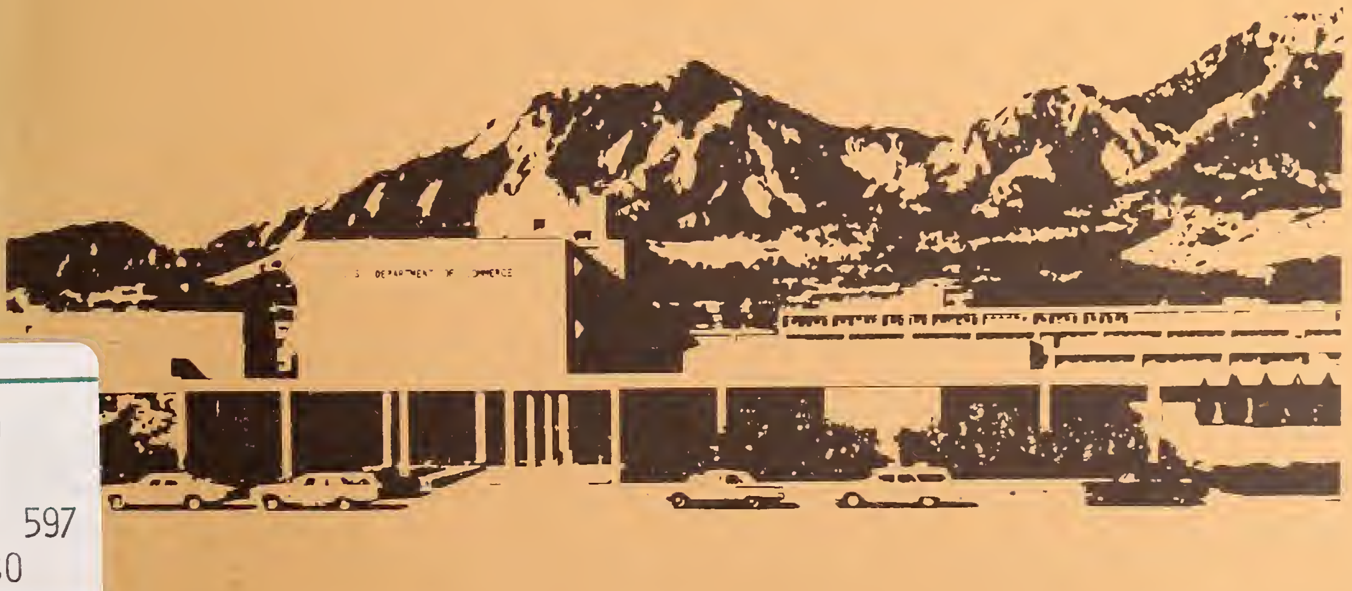

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PREFACE

As optical communications technology matures, the need for better characterization of components becomes more pressing. The requirements arise in three partially distinct areas. R and D laboratories need measurement techniques to support product development. Trade and commerce require product specifications that can be established by measurements that are precise (reproducible) and economical. And for the system designer, data on each component must be such that the performance of an entire system can be predicted. Some measurement problems, particularly the determination of those parameters most directly related to system performance, are common to all three areas, though with different emphasis. Others relate to only one area and within each there are more specialized problems.

This situation is not unique to the optical communications industry. It does seem at this time, however, that several unique characteristics of optical waveguides, notably mulitmode propagation, make many measurements on these components more difficult than on analogous components in other communication technologies. One consequence of differential mode effects is the difficulty encountered in predicting the performance of a link from data on individual transmission elements and joints. Another is that measurement requirements in all the areas cited above become very dependent on the intended application of the component. Measurements designed to predict the performance of long concatenated systems using laser diodes, for instance, are of little use in predicting the performance of short systems using light emitting diodes.

Optical fiber measurements are a frequent topic in the technical literature and have been the subject of sessions at several meetings. Several groups are now developing standards for fiber and fiber measurements. The importance of the issues being considered in these forums as well as their difficulty and diversity has led the National Bureau of Standards to sponsor this Symposium as an opportunity for intensive discussion of fiber measurement problems.

The program includes eight invited papers: four on technical topics, three on standards, and a meeting report. A total of twenty-one contributed papers was accepted by the committee. These cover the technical areas of attenuation, bandwidth/distortion, index profile and geometric measurements, joint/defect characterization, single mode fibers, and applied measurements. The distribution of papers submitted suggests the current emphasis of work in various laboratories. The most frequent topic was attenuation followed by joint/defect characterization. Within these two areas a number of papers involving the application of optical time domain reflectometry (OTDR) to very long systems were submitted. The number of papers concerning single mode fiber measurements suggests a growing emphasis in this area.

A particularly important feature of the Symposium is the time allocated for discussion. One-hour workshops have been scheduled on each of the following topics: attenuation, bandwidth/distortion and index profile, joint/defect characterization, and field measurements. In addition, extended discussion of fiber measurement standards has been scheduled.

Twenty-four different laboratories are represented among the total of twenty-nine papers. Twelve papers involving fifteen different laboratories originated outside the United States.

The National Bureau of Standards is indebted to the IEEE Transmission Systems Subcommittee on Fiber Optics (COMMSOC), the Optical Society of America, and members of the conference committee for their assistance in organizing this Symposium.

G. W. Day
D. L. Franzen
Boulder, Colorado
October 1980

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Multimode Waveguide Attenuation Measurements

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Several multimode optical waveguide attenuation measurement techniques are described in terms of the basic phenomenological propagation model. Previous interfacility variations can be explained primarily on the sensitivity of modern low-loss waveguides to the effective mode volume of the launch conditions and the state of mode coupling in the test length. Direct measurement of EMV transfer and EMV dependent attenuation is seen to be a possible method of reducing variations.

Attenuation measurement in optical waveguides is probably the measurement most widely studied over the longest period of time because of its tremendous functional impact on waveguide systems. With the evolution of the technology and the continually decreasing attenuation, now in the 0.5 to 1 dB/km range, variations in the measurement of this parameter, both intra- and inter-facility, can be a substantial fraction of this value. The purpose of this paper is to examine various attenuation measurement techniques using a recently developed phenomenological model of the propagation characteristics. The necessity of some practical model has been demonstrated clearly by the results of Figure 1 where measurements from various laboratories differ by over 1 dB/km for the same waveguide.[1] To be useful, the framework should not only explain these results but indicate ways for reducing these interfacility variations.

There are two basic views of OWG attenuation measurements. One holds that the waveguide should be characterized by an insertion loss value (i.e. dB loss over a fixed length). The other asserts a simple exponential length dependence of power (i.e. dB per unit length). These viewpoints are probably the natural result of the two roles of user and manufacturer where the latter produces unit lengths for use in arbitrary length installations. Of course these views are great oversimplifications of the physics involved in optical waveguide power propagation. The fact is that both viewpoints are partially incorrect because they use the common viewpoint that the waveguide can be thought of as a two terminal device. It is now becoming increasingly clear that multimode waveguides should be treated as at least an N terminal interconnected network where N is the number of propagating mode groups in the waveguide.

While the basic multimode propagation model has not changed, the quality of waveguides available has improved significantly. Recent papers[2,3] indicate that the strength of coupling between mode groups can be very low. Thus the power launched into a mode group tends to propagate in that group with loss characteristics that may be quite different from other mode groups. This differs from past results[4] that power was redistributed among mode groups in a fairly short length of waveguide (.5-2 km). Now, however, attenuation measurements must take into account the entire model including at least three factors: (1) differential model attenuation rates, (2) mode coupling, and (3) input modal power distribution. If these can be controlled or measured then interfacility variations should be significantly diminished. The techniques that exist[5,6] for directly measuring differential attenuation have been primarily used by research and engineering laboratories to study propagation phenomena and are generally expensive.

One practical approach to the variability problem is to describe an equilibrium modal power distribution. If a stochastic balance exists involving high-order mode loss and mode coupling, then after some length a valid attenuation rate can be measured, which will be independent of excitation conditions. For this description to be useful, however, equilibrium must be obtained in a reasonably short length. Recent measurement by Holmes[2] have shown that the attenuation rate of the 10th 1-km length of a concatenation experiment is still dependent on the launch conditions into the 1st kilometer length, therefore, this situation may not exist.

A similar approach is used to measure "steady state" properties where the "steady state" is defined as a condition where the modal power distribution near the input of the test length is the same as obtained at the long length.[6] Rigorous attenuations are thus obtained. One drawback of this method is that design constraints for a particular system may not allow the flexibility of choosing a source that will launch the same "steady state" distribution. Possibly more serious is that mode coupling or conversion at splices or in-line devices such as splitters or couplers will effectively re-excite a non-steady-state distribution causing unpredictable results for the attenuation of subsequent lengths of waveguide.

The empirical technique proposed by Holmes[2] is another attempt at minimizing measurement variations with the added value that predicted attenuations for long length systems of graded index waveguide can be accurately made from short (1 km) measurements. The basic method used is the standard cutback technique where the effective attenuation rate is determined by measuring through-put power of a 1-km length and a power after 2-m and calculating the rate as $-\frac{10 \log}{\Delta L}(P_{long}/P_{short})$. Additionally, a quantity called effective mode volume (EMV) is calculated from the measured FWHM diameter of the near-field power density distribution, D_{eff}, and the sine of the angle at the HWHM of the measured far-field radiant intensity distribution, NA_{eff}. The EMV is $(D_{eff} \cdot NA_{eff})^2$ and is defined for both long and short fiber lengths. The short length EMV can be varied by changing the aperture limits of the excitation spot size (aperture A) and excitation NA (aperture B) as shown in Fig. 2. Figure 3a and 3b show the measured long length

EMV and attenuation rate for a typical Corning graded index waveguide as a function of the short length EMV respectively. Also shown are measurements of the same waveguide with moderate mode coupling introduced by a microbending perturbation. As one would expect, a small launch EMV is broadened and a large one reduced. A long length of such a perturbed waveguide would rather quickly approach an equilibrium EMV of about 5.

Using the measured EMV transfer and measured EMV attenuation rate on 9, 1.1 km lengths of waveguide which were subsequently fusion spliced, a prediction of the concatenated attenuation was made and compared with the actual measurement. The predictions are shown in Fig. 4 and the measured values in Fig. 5. Based on other data the deviations from predicted values can be explained completely by "weak" mode coupling at the fusion splices. Note that this method is nearly source-independent since it is based on measured distributions within the waveguide.

Based on the cummulative probability distribution, 80% and 98% of the absolute losses are predicted within 0.5 and 1.0 dB of the measured values for any launch and/or length condition. While this is a demonstration of what should be possible, a major drawback of this technique is the cost of the large number of measurements required to specify the EMV transfer and attenuation rate dependence.

Much cost advantage would be gained by choosing 2 or 3 launch EMV's if the general shape of the attenuation and mode volume transfer could be assumed constant. Figure 6 shows results of

EMV transfer measurements for 7 Corning waveguides. A total of about 50 waveguides has been done with the results agreeing with this figure. Corning has instituted spot size and NA controls in all measurement facilities that launch an EMV of about 9 $(\mu m)^2$. In addition to closely approximating the EMV for which the attenuation rate is nearly constant an added benefit has been to reduce the 95% confidence level for interfacility agreement from 0.75 to 0.5 dB/km.

In conclusion it is clear that the $1\sigma = \pm 1$ dB/km variations of Fig. 1 can be explained by varying mode coupling, differential modal attenuation and launch power distributions among several laboratories. As indicated by the close agreement between predicted and measured attenuation values it also appears that the effective mode volume is the relevant parameter to track and/or specify in order to minimize these inter- and intra-facility variations. It also appears possible to select a single EMV in some cases for which the attenuation characteristics remain stationary over fairly long distances. What remains unclear is whether a single launch EMV will be suitable for all types of fibers as well as satisfy the needs of systems designers, sales engineers and purchasing agents. If this single EMV cannot be found then more extensive transfer measurements will be required which can generate extremely good concatenation prediction but at a cost to the technology. This trade off between increased measurement cost and increased system design precision must be evaluated as the technology matures.

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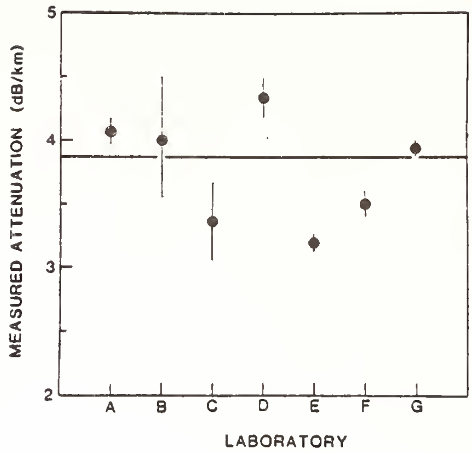

Fig. 1. Typical interfacility variations. (after Day et al, Amsterdam, 1979)

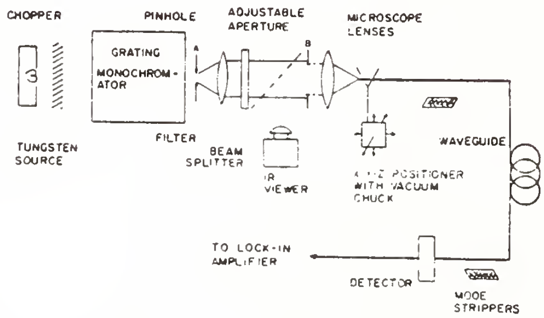

Fig. 2. Launch optics for controlling EMV.

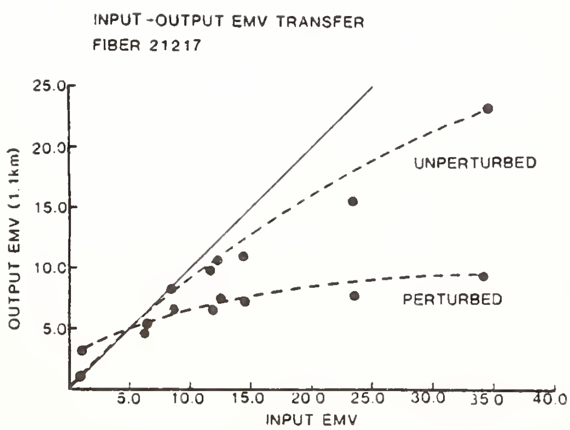

Fig. 3a. EMV transfer measurements for 1 km.

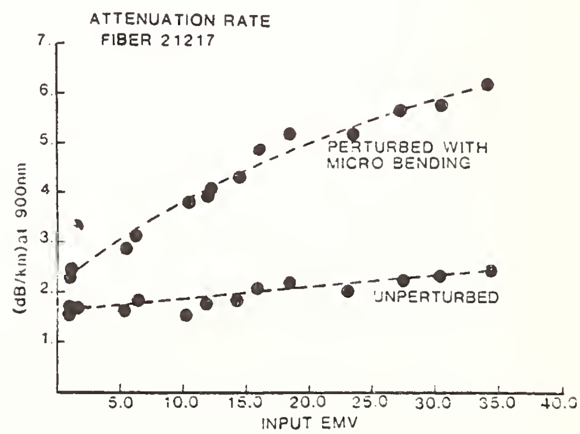

Fig. 3b. EMV dependent attenuation in 1 km.

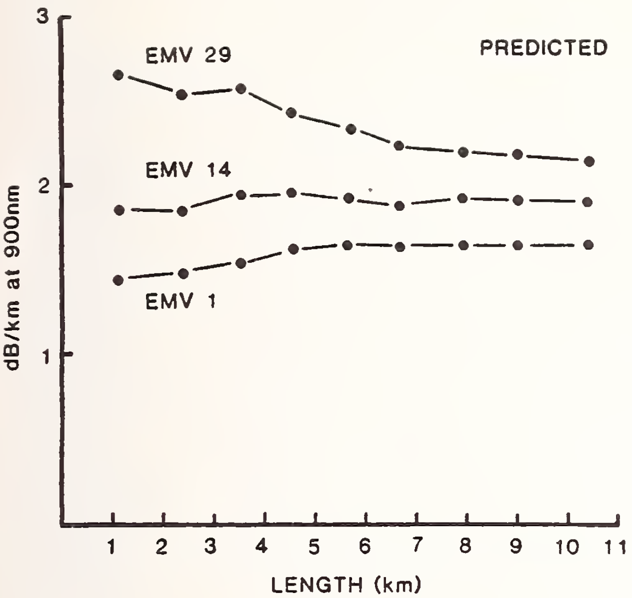

Fig. 4. Predicted attenuation rate for 10 km concatenation.

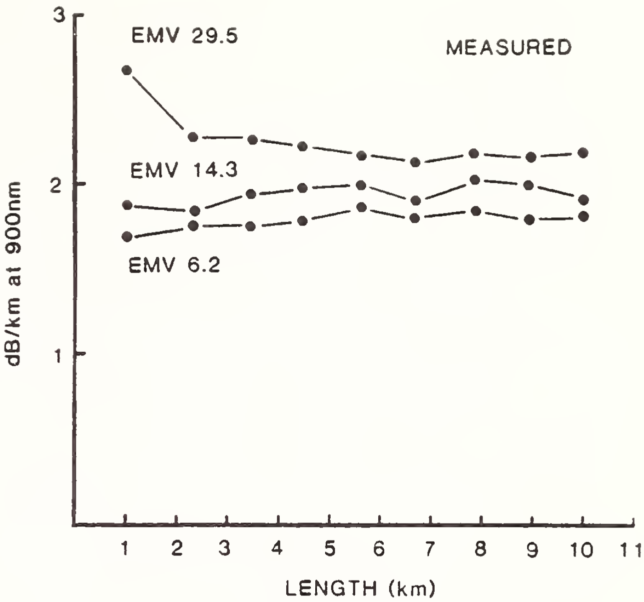

Fig. 5. Measured attenuation rate for 10 km concatenation.

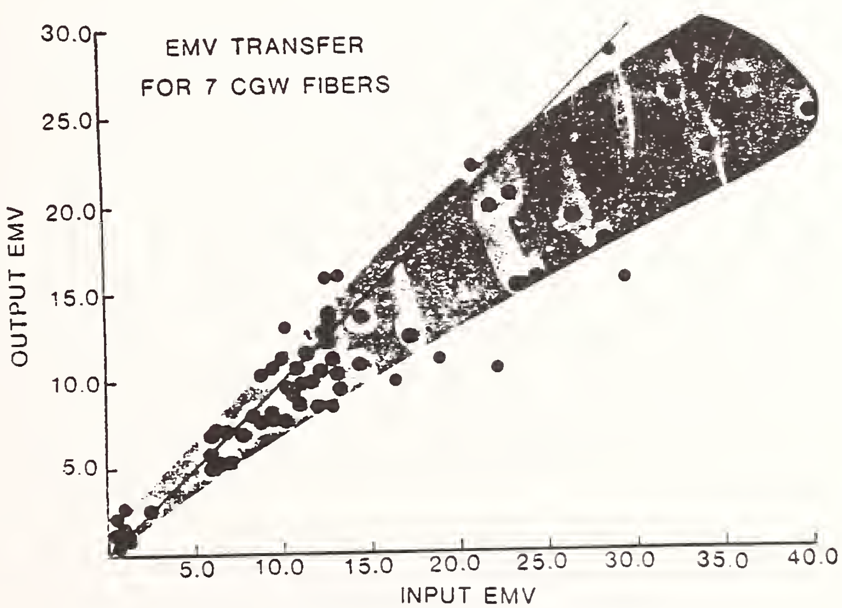

Fig. 6. Measured EMV transfer for 7 Corning waveguides.

LOSS MEASUREMENTS OF GRADED-INDEX FIBERS: ACCURACY VERSUS CONVENIENCE

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INTRODUCTION

Because of differential mode attenuation, the transmission losses of multimode graded-index fibers depend on the mode distribution propagating in the fiber, and accurate loss data which can be extrapolated to arbitrary fiber lengths are only achievable with an equilibrium mode distribution (EMD). The EMD establishes itself as a result of the selective loss of the various mode groups and the replenishing of their power via coupling from other modes. Since the distance within which this occurs may amount to more than 10 km's in recent low-mode-mixing fibers, techniques have been proposed to approximate this distribution by using restricted-numerical-aperature and spot-size excitation[1,2,3], mode filters[4], mode scramblers[5,6,7], and long reference or dummy fibers[8]. However, the use of most of these techniques, per se, does not guarantee the creation of an EMD. For example, a low-mode-mixing fiber excited with lower-order modes does not establish the EMD even for a many-km fiber length. A necessary condition for the existence of the EMD is the constancy of the far-field radiation pattern (FFP) along the fiber as has first been utilized for the length-independent loss measurements of plastic-clad silica fibers[9].

MATCHED-BEAM EXCITATION

In order to establish the EMD in graded-index fibers, it is essential to control both the launch numerical aperture (NA), as well as the spot size of the focused beam as can be accomplished with the set up shown in Fig. 1. The 25μm pinhole, together with the optics indicated, resulted in an approximately 50μm diameter (20 dB width) spot size at the launch point, which closely matched the 50μm diameter core of the test fibers. A typical set of far-end (FE) and near-end (NE) patterns for different launch NA's, together with simultaneously measured spectral losses, are shown in Fig. 2a. While the FFP's widen and norrow for under- and over-excitation, respectively, they remain essentially constant for steady-state (SS) excitation conditions, corresponding to a launch NA of 0.23 in this particular case. The associated SS losses of 5.12 dB/km for the 3.5-km-long fiber were 0.27 dB/km higher than the small-angle losses of 4.85 dB/km. The SS losses were confirmed for 1-km-long sections cut from above fiber within the measurement accuracy of ±0.1 dB. (While the normalized loss in terms of dB/km is meaningful only in conjunction with the EMD, we continue to use it also for non-equilibrium conditions - bearing in mind its limited meaning).

The removal of the pinhole spatial filter (Fig. 1) resulted in an essentially uniform power distribution across the core of the fiber, with ensuing over-excitation and excess losses even for the smallest launch NA (Fig. 2b). Inspite of the fact that the 50% width of the NE pattern for lowest-angle excitation was still narrow and comparable to that of Fig. 2a, its 20dB width significantly exceeded the width of the corresponding FE pattern, and excess losses amounted to 0.33 dB/km (above 5.12 dB/km) for the 0.23 launch NA. Since most of the transient loss associated with over-excitation already occurs within the first km, the error incurred is about 3.5-times higher for a 1-km sample length of this fiber, or on the order of 1 dB/km. An error of such magnitude was also obtained with a different fiber measured under these conditions as depicted in Fig. 3 (Fiber #2, uppermost curve).

The identification and establishment of the FFP belonging to the EMD is time-consuming and difficult, and the question arises, to what degree this is necessary for obtaining a desired loss measurement accuracy. As a general rule, it is important to avoid launching highest-order and leaky modes, while the relative power distribution of lower modes is typically not critical. Since a long 'tail' in the NE pattern is indicative of the presence of such highest modes, it is essential that the 20 dB width of this pattern does not exceed the width of the corresponding radiation pattern at the FE point. From Fig. 2b it becomes apparent that an agreement of the widths at the 10 dB point is not sufficient, and an agreement at the 13 dB (or 5%) point may be marginal, depending on the shape of the NE pattern near the baseline.
In order to evaluate how critical it is to launch the EMD exactly, let us consider the loss-versus-launch-NA representation of several nominally identical fibers drawn from different preforms (Fig. 3). While the loss steadily increases for fiber #1, the loss is higher for lower-mode-excitation, passes through a minimum for intermediate-NA excitation, and increases again for over-excitation in case of fiber #2. This feature is characteristic for low-mode-mixing fibers, with the excess losses of the lower modes being attributable to dopant-related compositional-fluctuation Rayleigh scattering[1], or contaminants such as OH. Within the fiber NA, a minimal NA-dependence was observed with a recent Ge-P-doped graded-index fiber (Fig. 3, #3). Obviously, a superior measurement accuracy and reproducibility can be achieved with fibers exhibiting the loss-versus-NA dependencies of fibers #2 and #3.

MANDREL-WRAP EXCITATION

As follows from above discussion, for higher-quality fibers the losses are insensitive with respect to the exact launch condition, as long as over-excitation with highest-order and leaky modes is avoided. This feature can be utilized to substantially simplify the loss measurement by initially over-exciting the fiber, and eliminating the excess higher modes with a mode filter. In its simplest form, such a filter may consist of a few turns of fiber wrapped around a mandrel, with the filter action being mainly determined by the bending radius, but also by micro-bending (Fig. 4). For the 50μm diameter core, 0.23 NA graded-index fibers considered, five 1.2cm diameter turns were found to reduce the 20dB width of the NE patterns of Fig. 2b to match those of the FE patterns.

As shown in Fig. 3, the losses obtained with the mandrel-wrap (MW) filter are nearly independent of the launch NA, and typically agree within 0.2 dB/km (max) with SS losses measured with matched-beam excitation (as identified by the SS NA of 0.21; the SS NA is typically 5 to 10% lower than the fiber NA based on Δn, depending on the degree of microbending, and the core-cladding interface quality). An excellent agreement was achieved between losses measured with the MW filter and 1-km-long, initially-overexcited reference fibers, an example of which is presented in Fig. 3a.: Similarly as the MW filter, the reference fiber effectively eliminates excess higher modes.

Because of chromatic aberrations of the microscope objective lenses, the launch optics has to be readjusted for NA-dependent loss measurements in the 1.3μm wavelength region. The loss-versus-NA dependencies of several sub-1 dB/km Ge-P-doped fibers measured at 1.3 μm are similar to those observed at 0.82μm (i.e., some with a steadily increasing, and some with a parabolic dependence) (Fig. 5). MW data were typically within 0.1 to 0.2dB/km (max. difference) of the steady-state losses determined with matched-beam launch optics.

CONCLUSIONS

A high accuracy in the loss measurement of graded-index fibers can be achieved by combining a two-point loss measurement with scans of the FE and NE radiation patterns, which enable the identification of the EMD. Because of an observed nearly stationary loss dependence of higher-quality fibers for excitation near the EMD distribution, an exact matching of the steady-state values is not necessary: A good agreement of the loss data (within 0.1 to 0.2 dB, max.) can be achieved by using a mode filter such as a long reference fiber, or, more conveniently, a properly dimensioned (using FE and NE scans of the radiation pattern) mandrel-wrap filter for the elimination of excess higher-order modes of an initially over-excited test fiber.

Because mode coupling and differential microbending loss may change during the fiber jacketing and cabling operation, the EMD and steady-state losses are not necessarily constant. Furthermore, because of potentially other wavelength-dependent differential-mode-attenuation mechanisms (such as OH penetration from the substrate tube), the EMD also may vary with wavelength.

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The test fibers were made available by S. R. Nagel, M. Saifi (WE Engineering Research Center), and the WE Company, Norcross, GA. N. K. Cheung and T. Baker contributed with some of the loss measurements.

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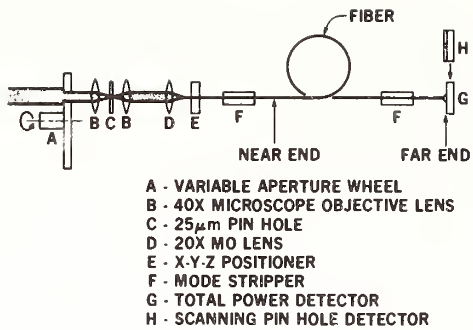

Fig.1 Loss Measurement Set-Up For Matched-Beam Excitation

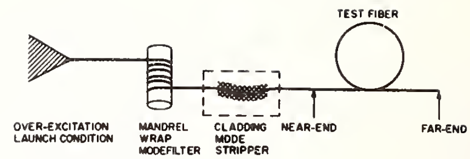

Fig.4 Loss Measurement Set-Up For Mandrel-Wrap Excitation

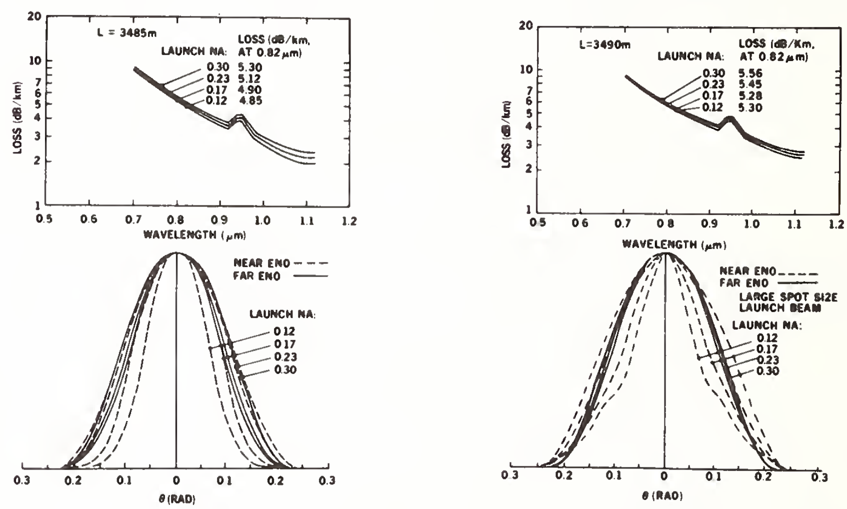

Fig.2 NA-Dependent Spectral Losses and Radiation Patterns For

a) Matched-Beam Excitation

b) Large-Spot-Size Beam Excitation

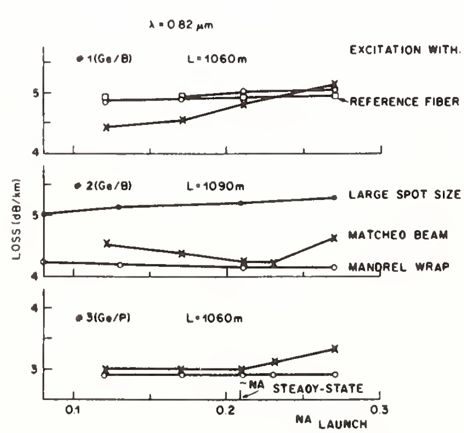

Fig.3 Launch-Dependent Losses of 3 Different Fibers Measured at 820nm

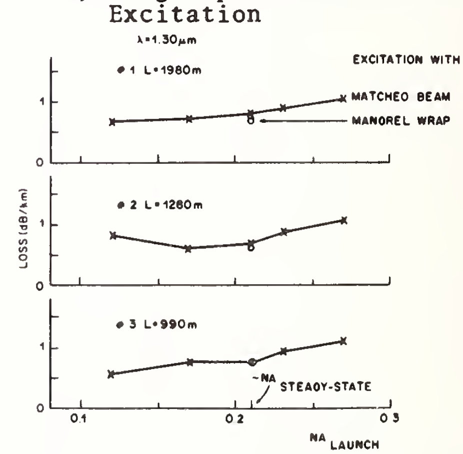

Fig.5 As Fig.3, But For 3 Additional Fibers Measured at 1300nm

An Accurate Method for the Measurement of Fiber Attenuations

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1. INTRODUCTION

It is widely known that one of the most serious problems in the measurement of multi-mode fiber attenuations is the influence of the excitation conditions at the input of the fiber. We have developed a precision instrument that can measure the optical power of a stable source with an error of less than 0.05 % , implying that power changes in individual modes can be detected. This capability allows us to accurately study the effect of modal distributions upon attenuation, and for the first time makes it possible to accurately measure the loss of even a single low-loss (e.g. fusion) splice that is excited by the steady-state modal distribution of one fiber and "pumps" another long fiber in which steady-state is once more reached before measurement.

In this paper, we briefly outline the essential features of this instrument, and go on to describe a measurement technique that can be used to minimize the influence of cladding as well as leaky modes. Moreover, the use of a simple correction factor allows the determination of the attenuation of the fiber both for selective and for complete excitation.

2. MEASUREMENT SET-UP

The main departures of our apparatus (Fig. 1) from the conventional are in the receiver and lamp circuits. The latter consists of a 220 V over-head projector lamp driven at 110 VDC, by a current source that is feed-back controlled by the lamp voltage. The main voltage has been A.C. stabilized before rectification.

The receiver consists of a Ge detector (at room temperature) whose output $S(t)$ is synchronously sampled to produce a "signal" pulse train $S_1(t)$ and a "background-and-dark-current" pulse train $S_2(t)$. The difference of $S_1(t)$ and $S_2(t)$ is integrated and displayed on a DVM. Integration times are determined by counting pulse pairs from $S_1(t)$ and $S_2(t)$, while all other timing operations are controlled from a crystal oscillator. The minimum integration time is set to be about 20 s, corresponding to exactly 4096 pulse pairs, and can be doubled in each of 4 steps to a maximum of 65536 pulse pairs. With fiber attenuations of up to about 10 dB, and the minimum integration time, the random error (standard deviation to mean) of the system is better than 0.05 %, while the drift of the mean over a 24 hour period is about 0.1 %. The drift over a day-time period of less than 8 hours is not separable from the random variation.

3. MEASUREMENT METHOD

An important aspect of mode control which is rarely mentioned is the effect of mode filtration upon detection. For example, the use of butt-jointed windowed detectors with relatively small active areas can be one source of inadvertent mode filtration. In our method, we exploit the above possibility by deliberately introducing mode filtration in the following way. One end of the fiber is excited by a beam with large numerical aperture and spot size. The near field of the opposite end is magnified, and a circular field stop of the same diameter as the magnified core is centered at the image. The limited image is then de-magnified and focused onto the detector. Comparison of the outputs of a long and a short fiber then yields the attenuation A_T for uniform excitation of all guided modes.

The influence of leaky modes in the above measurement can be reduced by using a sufficiently small aperture, as can be inferred from e.g. [1]. In this case, the powers from the long and short fibers are also measured with the small aperture, to yield the attenuation A_L of the lower order modes only. This can be related to the attenuation of all guided modes by:

$$A_T = (\eta_i/\eta_o)A_L \quad , \tag{1}$$

where η_o is the ratio of small-to-large aperture powers from the long fiber, and η_i is the ratio of the small aperture power to the power in all guided modes. For uniform excitation, and a sufficiently short fiber, η_i can be obtained from the near-field or refractive index profile of the fiber [2]. With the assumption of an α profile, integration over the core region yields the following result:

$$\eta_i = (r/a)^2[1-2(r/a)^\alpha/(\alpha+2)]/[1-2/(\alpha+2)] \quad , \tag{2}$$

where r is the radius of the aperture, and a is the radius of the magnified fiber core. The behaviour of η_i as a function of α is shown in Fig. 2, from which we can conclude that η_i is not very sensitive to profile shape, and can be simply evaluated for $\alpha = 2$ (Fig. 3). If the measured refractive-index profile is available, accuracy can be improved by numerically evaluating η_i.

Preliminary measurements on a fiber with a specified attenuation of 3 dB/km at 1.1 μm gave the following results: 4.120 dB/km with only partial filtration of cladding modes, 3.049 dB/km with their complete removal ($r/a = 1$), and 2.860 dB/km with a field aperture of $(r/a) = 0.8$. The random error of these values is estimated to be about ± 0.004 dB/km. The last of these measurements ($r/a = 0.8$) includes almost all weakly-attenuated leaky modes, and, indeed, use of (1) and (2) yields a corrected complete-excitation value of 3.050 dB/km, in excellent agreement with the measured result for (r/a) = 1.

4. CONCLUSION

We have outlined the essentials of a new method for attenuation measurement based on a precision instrument that, to our knowledge, yields accuracies that are at least an order of magnitude better than the best values reported in the literature. The advantages of the method are:(1) that it allows unambiguous specification of measurement conditions, and should therefore be easily repeatable in other laboratories, and (2) that it avoids the use of primary-coating solvents.

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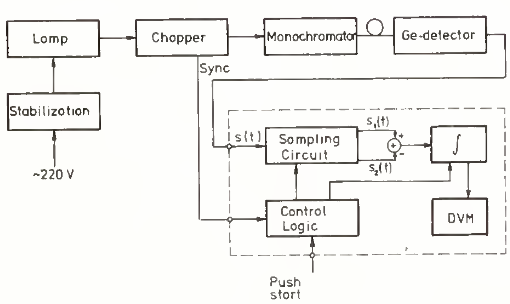
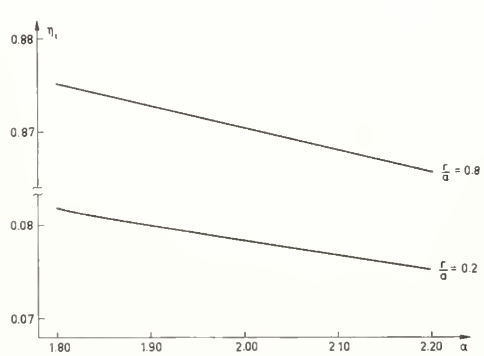
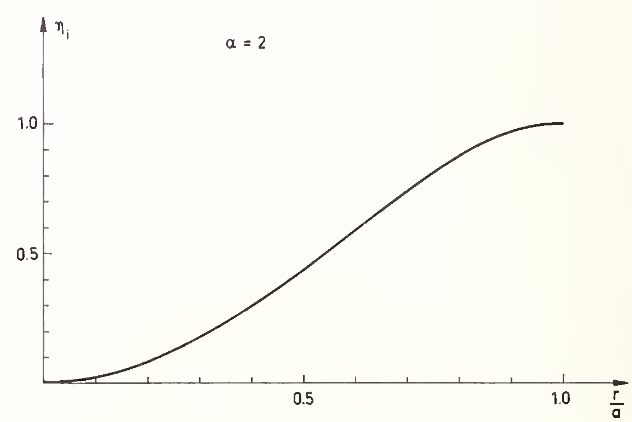


Fig. 1. Top left.

Fig. 2. Bottom left.

Fig. 3. Bottom right.





A FIBER CONCATENATION EXPERIMENT USING A STANDARDIZED LOSS MEASUREMENT METHOD

by

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INTRODUCTION

The emergence of optical fibers as an important communications medium has created the need for standardized test procedures for evaluating fiber transmission characteristics.

Because of differential mode attenuation, the loss measured in multimode optical fibers depends on how the source launching conditions distribute the power among the propagating modes of the fiber. To obtain repeatable and accurate attenuation measurements of optical fibers, standardized launch conditions must be established. Figure 1 shows a block diagram for a two point attenuation measurement that uses a mode filter to establish the launching conditions. The mode filter is selected to generate a far field radiation pattern at point A at the input end of the test fiber that is matched to the width of the far field pattern after a long length at point B. In this paper a proposed standardized loss measurement method using a mode filter to establish input launching conditions is described and evaluated. An operational method for selecting mandrel wrap mode filters is given along with results from a concatenation experiment to provide the reader with an indication of the accuracy (length scaling predictability) of the loss measurement method.

MODE FILTER CHARACTERIZATION

Figure 2 illustrates a two step operational method for selecting a mode filter. First, the test fiber is overfilled in numerical aperture and spot size at the input end and its far field radiation pattern measured at its output end. The output far field pattern of a mode filter overfilled at its input end is then measured. The widths of the patterns, at the 5% points, of the test fiber (θ_2) and the mode filter (θ_1) are obtained and their percent difference $\Delta\theta$ calculated. $\Delta\theta$ is a measure of how well the mode filter approximates the far field energy distribution at the output of a long length of test fiber.

The mode filter selection procedure was applied to determine the characteristics of five turn mandrel wrap mode filters of different diameters. For a 1 km test fiber, (110 μm OD, 55 μm core diameter, $\Delta \approx 1.3\%$, $\alpha \approx 2$) Figure 3 shows how $\Delta\theta$ varies as a function of mandrel wrap diameter. The loss of the test fiber was then measured with an overfilled input strap (no mode filter) and with five different mandrel wrap mode filters ranging in diameter from 3/8" to 1".

Figure 4 is a plot of the loss of the test fiber as a function of $\Delta\theta$. For a range of $\Delta\theta$ from 0 to -7% (range specified by Electronic Industries Association test procedure) three mode filters (1/2", 5/8" and 3/4") could be selected for the standard loss measurement. The choice of a specific mode filter is not critical since the standard deviation of the loss measured with the three mode filters in this range was σ = 0.15 dB/km. This deviation was less than the uncertainty of the loss measurements (0.3 dB/km) in a recent Bell System interlocation round-robin study.[1]

CONCATENATION EXPERIMENT

Using a five turn 1/2" diameter mandrel wrap mode filter, the loss of five 1 km multimode graded index fibers of similar characteristics (110 μm OD, 55 μm core diameter, $\Delta \approx 1.3\%$ $\alpha \approx 2$, $\lambda = .82$ μm) were measured and compared with the loss of a 5 km concatenated link formed by these fibers. Figure 5 shows the results of this experiment. The total concatenated loss including splice losses (22 dB) differed from the sum of the losses of the individual section plus measured splice loss by .5 dB. This amounts to 0.1 dB/km, which is well within the interlocation standard deviation of 0.3 dB/km.[1]

REFERENCE

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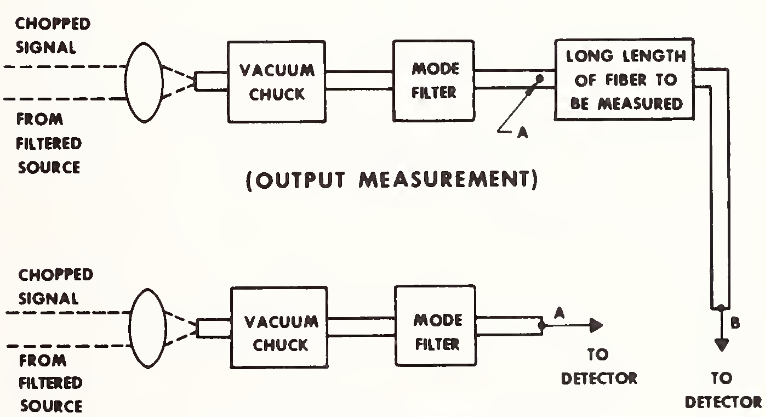
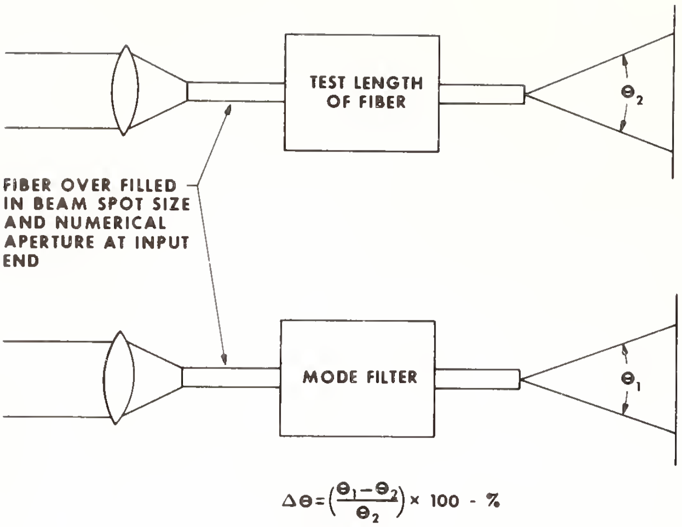
TWO POINT ATTENUATION MEASUREMENT



(INPUT REFERENCE MEASUREMENT)

FIGURE 1



$$\Delta\theta = \left(\frac{\theta_1 - \theta_2}{\theta_2}\right) \times 100 \text{ - \%}$$

FIGURE 2

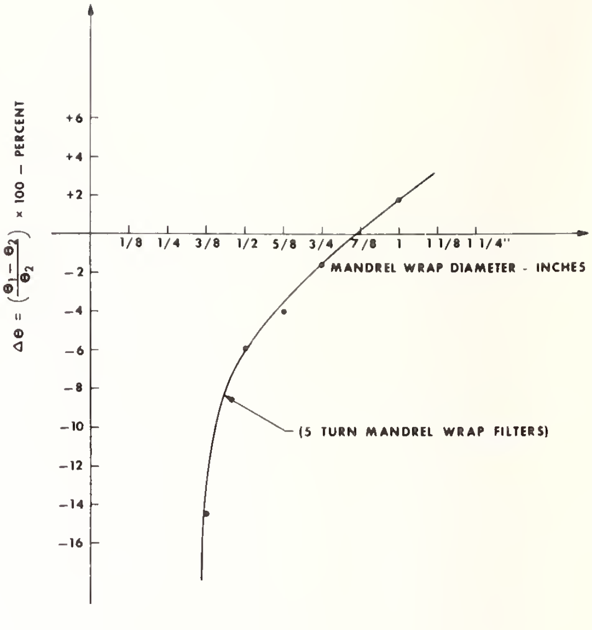


FIGURE 3

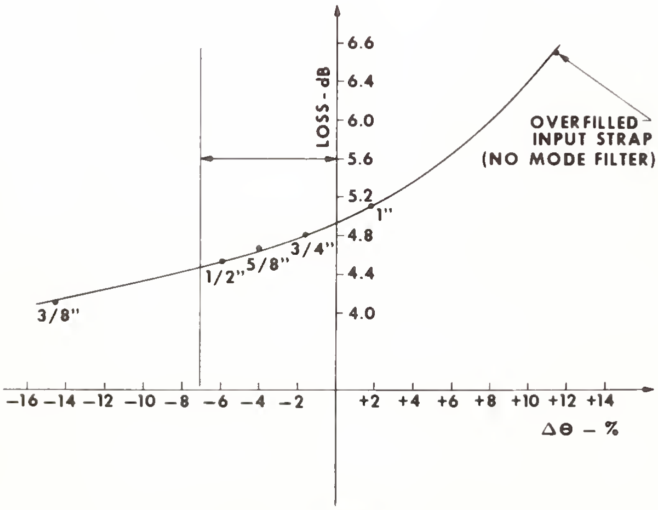


FIGURE 4

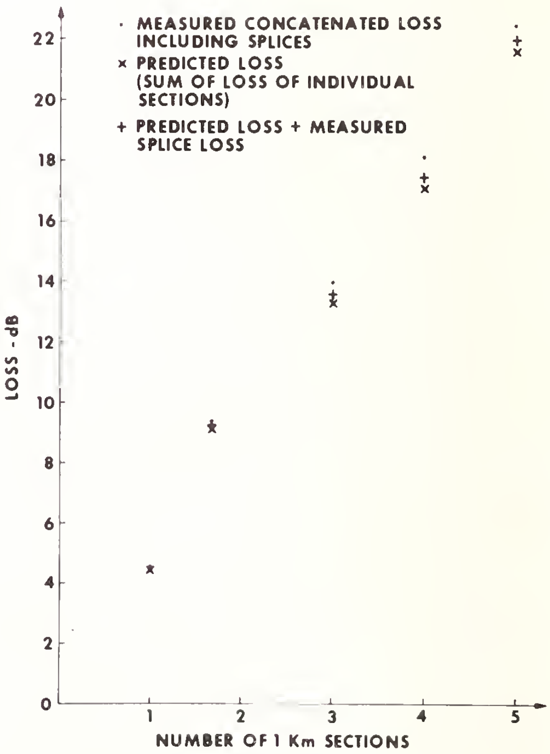


FIGURE 5

AUTOMATED LOSS MEASUREMENT SET FOR OPTICAL CABLES

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INTRODUCTION

The Bell System standard lightwave transmission system (designated FT3) employs ribbon-based cables containing relatively large numbers of fibers. Each ribbon contains 12 fibers and is factory terminated at both ends in silicon chip array connectors.[1] An automated optical loss measurement set has been developed for final factory testing of these cables which employs a non-destructive insertion loss measurement technique. The test can measure a 144-fiber cable in one hour to an accuracy of ± 0.4 dB (2σ), and has been used successfully to measure cables shipped to several Bell System fiber optic installations. In comparison, manual 2-pt measurement techniques are unsuitable since they are destructive and require about 24 hours for a 144 fiber cable.

GENERAL DESCRIPTION

The test set is illustrated in Figure 1. The optical power source used is a 0.82 micrometer feedback stabilized Gallium-Aluminum-Arsenide laser. The light is launched through a single fiber "pigtail," whose end is clamped in a stationary position. A multiple fiber array connector which terminates two 12-fiber ribbons is mounted on a pair of X-Y micropositioner stages in close proximity to the pigtail end. The micropositioners are controlled by a microcomputer and are used to align the ribboned fibers, one at a time, to the launch pigtail (essentially a 1x24 optical, servo loop switch).

One of the 12-fiber ribbons leads directly to a receive photodiode and is used to monitor any drift in the laser and receive electronics. The second ribbon passes around a mandrel-wrap equilibrium mode simulator and has been cut and then terminated on each end with single ribbon array connectors. Ribbons to be measured are temporarily spliced into the optical circuit here.

The test set is initially "zeroed" by measuring the power transmitted through a one-meter section of ribbon. The power values measured for each individual fiber are recorded and used as the input values for measurements which follow. A ribbon whose loss is to be measured is then spliced into the optical circuit in place of the reference ribbon, and the output of each of its fibers is measured. The loss of each fiber is then found by subtracting this measured value from the reference value for that path. During a measurement, the center of each fiber is found by using a computer controlled search algorithm. The fiber is searched from side to side and from top to bottom, moving the stages one micron at a time until the edges are found. During this center search, a record is kept of the maximum value found. The stages then return to this preliminary maximum point and a second, more detailed, peak search algorithm is performed to determine the maximum output value for that fiber.

TEST RESULTS

The precision of the test set was checked by making repeated measurements on the one-meter reference ribbon. The reference ribbon was measured 20 times and the temporary array splices were disconnected, flipped over (fiber 1 to fiber 1, then fiber 1 to fiber 12) and reconnected in between each pass. The standard deviations of the ten measurements of each fiber path were computed and the mean was only 0.04 dB. Figure 2 is a histogram showing the distributions of these deviations.

The accuracy of the test set was checked with another test. Here, a 12-fiber ribbon approximately 1 km in length was measured several times by the widely accepted two-point technique. The same ribbon was then measured several times by the insertion loss technique using the automated test set. Figure 3 is a histogram of the fiber-by-fiber differences between the two sets of measurements. The insertion loss measurements averaged 0.14 dB greater than the two-point loss measurements (offset). This result was anticipated and is due to differential splice loss effects of the two array splices. The standard deviation of the differences was 0.2 dB. Test results on over 50 reels of production cable have confirmed both the offset and deviation values.

SUMMARY

An automated test set has been developed for final factory loss measurements on connectorized fiber optic cables. The set is presently in use on production cables and has proven to be accurate, fast and easy to use by production personnel.

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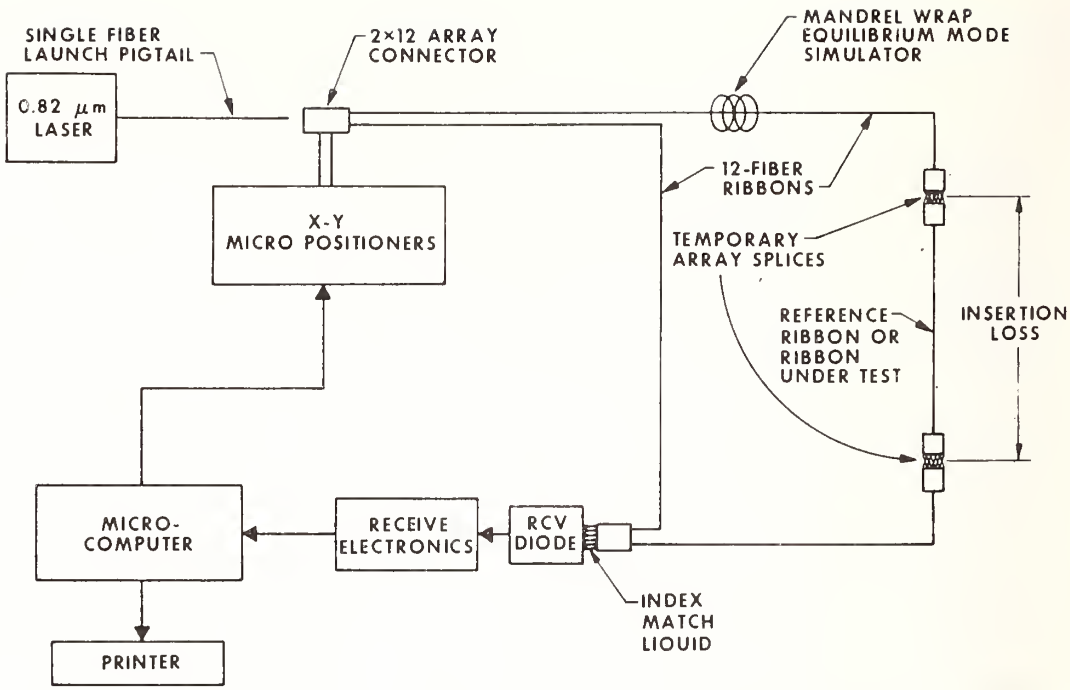

FIGURE 1. AUTOMATED LOSS SET FOR OPTICAL CABLES

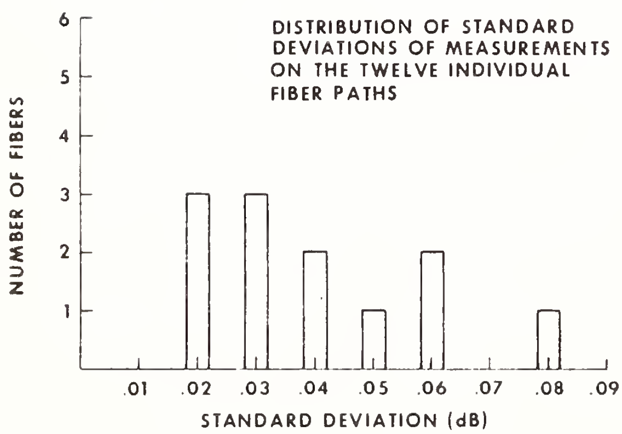

FIGURE 2. TEST SET REPEATABILITY

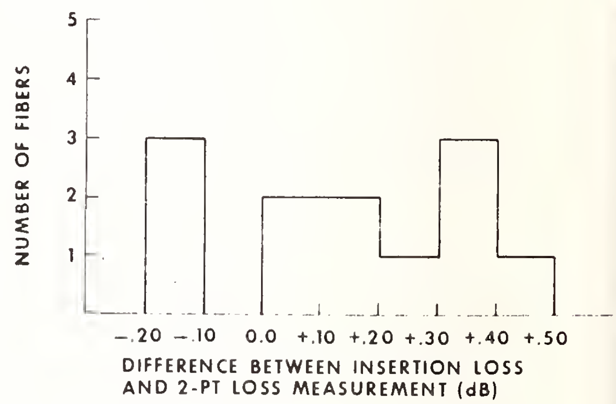

FIGURE 3. TEST SET ACCURACY

Comparative measurements regarding the attenuation of optical fibres for the Eindhoven - Helmond field trial.

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xxxx N.V. Philips' Gloeilampenfabrieken, Product Division Glass.

Abstract

Equipment measuring the attenuation of optical fibres is compared. Using the far field pattern of the short fibre adjustment of the steady state, conditions can be performed. Hence, the influence of different launching conditions is minimized. Doing so, the values measured in four laboratories, each with their own equipment, harmonize reasonable well. Comparison was necessary to investigate the Eindhoven - Helmond field trail.

Introduction

In the spring and summer of 1980 extensive measurements were performed on a number of fibres used in the 13,5 km, 140 Mb/s field trial Eindhoven - Helmond in the Netherlands. Besides the field measurements carried out by P.T.T., measurements were also done by Philips after drawing and by N.K.F. after cabling the fibres. In addition P.T.I., being the system designer, participated in the measurements. To be able to compare the results extensive consultations were necessary.[1)] In the end the results harmonized reasonably well. This paper gives the precautions taken and the attained result.

Measuring equipment

The attenuation is measured applying the cut-back method (1,5 m). Such launching conditions are used to approximate the steady state in the fibre under test from the beginning.

To compare the measuring methods used, a six fibre bundle on reel with fibres typical of those in the field trial was sent round the four laboratories. The measurements showed that the equilibrium mode distribution of the six fibres corresponds with a numerical aperture NA_{10} (defined at 10% of the maximum photometric intensity of the far field radiation pattern) of about 0,19. An additional parameter, the form factor $\gamma = NA_{50}/NA_5$, was used to describe the far field distribution more accurately[2]; the equilibrium values turned out to be 0,56 approximately. The theoretical NA of the fibres is about 0,28.

The far field radiation patterns of the fibres were measured either by a far field meridional scan or by an integrating method (P.T.T.). Here a large area detector is shifted along the axis of the radiation pattern. This method enables low level measurements as may occur in the field. Moreover the measurements are less affected by coherence effects in short pieces of fibre. However, the results are not comparable directly with those of the other method.

The equilibrium values as mentioned above are created by applying a mode scrambler, a one to one lens coupler and a well-chosen diaphragm between light source and fibre under test. Each laboratory made its own equipment using different components. The mode scrambler, a round or rectangular type, is based on the random distribution of ball-bearings in several sizes[2]. The fibre in this scrambler was selected independently by each participant. One participant (Philips Glass) used a halogen lamp with filters as a light source, the others a laser diode.

Launching conditions

Using the cut-back method it is simple to compare the far field radiation pattern both of the long and the short fibre. It appeared to be important to observe the differences between them as it influences the attenuation value obtained.

In table I two sets of measurements are shown.

Set A was performed by simply projecting the output distribution from the fibre in the mode scrambler 1 to 1 (NA_{10} = 0,20; γ = 0,58) on the fibre to be measured. At first glance this was a reasonable approximation to the steady state values. But the values after cutting back (1,5 m) went upward instead of approaching the steady state values (NA = 0,19; γ = 0,56). Even the long fibres showed too high values.

For the second series of measurements on the same fibres (B) the launching parameters were varied to attain the desired value of the NA and γ after 1,5 m of the first fibre. These values were also used for the remaining 5 fibres.

A change of attenuation is perceivable, although the inaccuracy of the measurement itself should be taken into account.
A repeatability of 0,05 to 0,1 dB gives an uncertainty of 0,1 to 0,2 dB between measurements. The trend, however, is present. These measurements were performed with the same set-up using a halogen lamp and a 10 nm broad filter at 850 nm.

Comparative measurements, results

After the importance of the launching conditions had been demonstrated, it was easy to agree that the far field pattern after 1,5 m fibre is to approximate the steady state distribution. For practical reasons the measurements were performed in such a way that for one fibre the launching conditions were adjusted and then left unaltered for the other fibres. As the first fibre was independently chosen in each laboratory, this may account for a part of the differences still present in the values of the four laboratories. Other reasons may be the far field pattern of the short fibre being inaccurate if an LD is used in combination with a meridional scan and that the temperature of the bundle must be kept within limits. Room temperatures in the four buildings were different, but not measured accurately.
Yet, one value measured by P.T.I. (yellow) shows an unexplained difference.
Table II shows the results of the measurements so far. The results of two of the participants are corrected for the wavelength difference (nearly 0,1 dB/10 nm.km). The length of the fibre bundle was approximately 1200 m.

Conclusions

It is possible to achieve reasonable to good agreement between the attenuation values measured at different places with different equipment.
It is mandatory, however, that the measurement conditions be equal and are measured in the right way.
The launching conditions agreed on must be kept within small margins.
A good approach is to use the far field radiation pattern of the cut-back length to determine the launching conditions.

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Table I

Changes in attenuation values due to launching conditions

Fibre colour	Group A	Group B	Short fibre NA_{10}	Short fibre γ	Long fibre NA_{10}	Long fibre γ	Attenuation λ = 850 nm (dB) L=1,2km
Blue (	1		0,21	0,58	0,20	0,59	5,5
(		1	0,19	0,52	0,19	0,56	5,2
Black (	2		0,22	0,58	0,21	0,62	5,3
(		2	0,19	0,55	0,18	0,58	5,0
Yellow (	3		0,22	0,59	0,19	0,61	5,1
(		3	0,22	0,58	0,19	0,57	5,0
White (	4		0,22	0,59	0,20	0,60	5,2
(		4	0,20	0,55	0,19	0,58	4,9
Red (	5		0,22	0,60	0,20	0,60	5,0
(		5	0,20	0,51	0,19	0,58	4,9
Green (	6		0,21	0,57	0,20	0,61	5,4
(		6	0,20	0,52	0,18	0,56	4,9

Table II

Results of comparative measurements in the four laboratories.

Laboratory	Attenuation at 850 nm (dB) L = 1,2 km						Measuring wave-length (nm)
	Red	Blue	Yellow	Green	Black	White	
Philips A[x]	5,0	5,5	5,2	5,4	5,3	5,2	850
Philips B	4,9	5,2	5,0	4,9	5,0	4,9	850
NKF I[xx]	4,8	5,2	5,0	5,1	5,0	4,9	859
NKF II[xxx]	4,9	5,1	4,9	4,9	4,9	4,9	859
PTI I	5,0	5,4	5,6	4,9	-	-	858
PTT I	4,8	-	5,0	4,8	5,0	4,8	850

x Different launching conditions.

xx Before transportation to another laboratory (80 km).

xxx After transportation from that laboratory.

PROFILE CHARACTERIZATION OF OPTICAL FIBERS AND PREFORMS

by

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The light transmission properties of optical fibers are determined by the dielectric materials from which they are made. In particular, it is the shape of the refractive index profile that is responsible for the impulse response and hence the bandwidth of optical fibers. There is, therefore, a definite need for precise techniques for measuring refractive index profiles.

Because the index profile of the preform is faithfully reproduced in the fiber, it would suffice to measure only index profiles of preforms. However, since most techniques are not applicable to preforms, profile measurements are often performed on fibers. Most preforms are made by a vapor phase method (MCVD) that deposites glass in concentric layers. Consequently, the index profiles of preforms are rich in structure whose transverse dimensions become small compared to the wavelength of light and hence unobservable once the fiber is drawn. Only in a region near the fiber axis, where the deposition layers are thickest, is a ripple structure usually observed in the fiber.

How accurately profile measurements should be made and what technique is best for making them are difficult questions to answer since they involve trade-offs of many factors. To be included are time, cost and effort considerations, all of which one would like to minimize. Then there are sensitivity, accuracy and resolution which one would like to maximize.

A handle on the question of accuracy is provided by the following considerations. The theoretical bandwidth that can be realized with an optimum power-law index profile is about 8000 MHz·km for a fiber with a maximum index difference of 0.02. To achieve this high bandwidth requires that the exponent g of the power-law profile have a definite optimum value near $g = 2$. A departure of only 0.05 from the optimum value is sufficient to reduce the fiber bandwidth by more than one order of magnitude. Clearly, techniques for determining g to better than 0.05 are required if a meaningful correlation between fiber performance and index profile is to be obtained. In order to achieve this accuracy, $\Delta n(r)$ [the difference between the refractive index profile of the fiber core and its cladding value] must be measured with a precision of 1 part in 10^4.

Very slight local distortions of the refractive index profile from its optimum shape also decrease the fiber bandwidth markedly. A distortion of ten sinusoidal periods over the fiber radius with an amplitude of 1 percent of the maximum index difference reduces the bandwidth from 8000 MHz·km to about 200 MHz·km. The precision of the $\Delta n(r)$ measurement would again have to be about 1 part in 10^4 to detect the 1 percent distortion.

As to which technique is best for making these measurements, let us consider the trade-offs connected with one of them - interference microscopy.

This is a very accurate method for measuring the index distributions of fibers and preforms, that can be used as the standard with which other methods are compared. There are two different interferometric methods. In the slab method, a slab must be cut out of the preform (generally its tip) or fiber and polished so that the faces are flat and parallel, requiring approximately one day of sample preparation. An interference microscope is required to observe the samples. Interference-lens-attachments to ordinary microscopes generally require passing the light twice through the specimen thus compounding possible errors. Best results are obtained with a single-pass Mach-Zehnder interference microscope.

Index values accurate to about two parts in 10^4 can be realized routinely and by electronically processing the image of the microscope, measurements accurate to about one part in 10^5 have been achieved. Automatic computer processing of the output also serves to reduce analysis time. Spatial index resolution is somewhat limited in that it is not possible to combine maximum lateral resolution and exact phase measurements in a single instrument.

The need for sample preparation can be eliminated by use of the transverse interferometric method. In this technique, the fiber is immersed in matching oil on the stage of the interference microscope and illuminated at right angles to its axis. The matching oil removes the influence of the outer cladding boundary. The total optical path length of a light ray is expressed as an integral and the index distribution is obtained from the measured fringe shift by solving an integral equation. Unlike the slab approach, transverse interferometry assumes circular symmetry and hence geometric variations, which can affect the profile, will not be detected unless special care is taken to make several measurements for different rotational positions of the fiber. By automating the measurement, index profiles of a fiber can be obtained only a few minutes after manufacture. The accuracy of the method is about an order of magnitude less than that of the slab approach and it is subject to a very large error in the region near the fiber axis.

The transverse interferometric method cannot be applied directly to preforms because the fringe shift becomes too large to observe. However, a transverse differential method can be utilized. In this approach, one of the two beams passing through each arm of a Mach-Zehnder interferometer is shifted by a shearing prism. The fringe shift now represents the differential of the optical path-length difference and can be made appropriately small by regulating the shearing distance. The accuracy is estimated to be about 1 percent of the index difference.

There are many other methods for measuring refractive index profiles of fibers. In the ray tracing method it is the deflection suffered by rays passing transversely through the core that is used to compute the index profile. The deflection can be measured directly, or can be deduced from the intensity distribution of the focused light (focusing method).

Light scattering in forward and backward directions transversely to its axis has been used for finding the index profiles of fibers. The dependence of the reflectivity of the fiber end face can also be used for determining the index distribution (reflection method).

Index profiles can be deduced from the intensity distribution of incoherent light traveling through a short section of fiber (near-field method) or, conversely, by the distribution of light refracted out of the fiber (refracted near-field method). Furthermore, the refractive index can be found by comparison with index matching fluids (immersion techique) or from observation of the etch rate (etching technique) or with the help of x-ray microprobes.

Table 1 summarizes the various techniques and provides comments on each of them.

TABLE 1

Some Profiling Methods

METHOD	COMMENTS
Interferometry	
Slab	Very accurate, a standard, time-consuming sample preparation
Transverse	Fast, nondestructive, requires expensive microscope, assumes symmetry
Focusing	Accurate, fast, applicable to fibers and preforms, assumes symmetry
Ray Tracing	Only applicable to preforms, high resolution
Scattering	
Forward	Complex in interpretation and implementation, fibers only
Backward	Fibers and preforms, simple implementation, limited applicability
Reflection	Simple implementation, fibers only, surface layer problems
Near-field	Simple implementation, leaky mode corrections necessary
Refracted near field	No leaky mode corrections, fibers only, good resolution
Immersion	Simple, limited in accuracy
Etching	Mainly qualitative observations
X-ray	
Microprobe	Sophisticated instrumentation, limited resolution, difficult calibration

LINEARITY AND RESOLUTION OF REFRACTED NEAR-FIELD SCANNING TECHNIQUE

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Refracted near-field scanning is an attractive method for precisely determining the index profile of an optical waveguide. This method was first proposed and demonstrated by Stewart[1] and later refined by White.[2] In an earlier paper, I analyzed the linearity and precision of the method;[3] this paper additionally discusses resolution and related areas.

Lambertian and non-Lambertian sources

Refracted near-field scanning depends upon measurement of the power that is refracted through the cladding of the fiber and beyond an opaque stop. If the source is Lambertian, then, in principle, the power transmitted around the stop is a precisely linear function of $(n^2 - n_L^2)$, where n is the index of the fiber (core or cladding) at any point and n_L is the index of the fluid that surrounds the fiber.[4] If n and n_L are approximately equal, the transmitted power is very nearly a linear function of $(n - n_L)$.

Many non-Lambertian radiances may be approximated by a function proportional to $\cos^m \theta$. If the radiation pattern is circularly symmetric, the power transmitted around the stop is proportional to $1 - \cos^{m+2} \theta$; the system is not linear in index to the extent that this function is not proportional to $\sin^2 \theta$. (The power that a Lambertian source radiates into a cone is proportional to $\sin^2 \theta$.[5]) Figure (1) shows the function $1 - \cos^{m+2} \theta$ vs $\sin^2 \theta$ for several values of m. $m = 0$ is a Lambertian source, $m = -1$ is a uniform point source, and $m = 4$ and 8 are rough approximations to sources like edge-emitting LEDs and lasers. The function is linear over almost any small range; a Lambertian source is not strictly required for refracted near-field scanning. However, calculations based on the radiometry of Lambertian sources may be in error by a large factor.[4]

Linearity and calibration

To calibrate the system and determine the linearity of the output power as a function of refractive-index difference, I use a quartz fiber with each of several index-matching fluids and plot transmitted power vs index difference. Figure (2), which is taken from Reference (3), shows such a plot. Each of three quartz-fiber samples was tested with each of four oils to produce the twelve points in the figure. Figure (2) also shows a line of best fit and estimates of the random and systematic errors of the system. I have shown further in Reference (3) that relative values of index (such as core-cladding difference) may be measured to $\pm$ 0.0005 if the temperature of the fluids is held sufficiently constant.

Resolution limit

White has argued that the spatial resolution limit of the system is that of a diffraction-limited lens with an opaque central stop.[2] The work presented here does not entirely support this argument; rather, the resolution limit of the system is more nearly equal to that of the lens without the stop. This is so because the condensing lens associated with the stop is not an imaging system but merely a collector of light.

The solid line of Figure (3) shows an exact calculation of the edge-response width (10 - 90% points) of a diffraction-limited annular lens as a function of the fraction ε of the diameter that is obscured by the stop.[6] The resolution limit RL is taken to be equal to the edge-response width; the vertical axis is normalized to the Rayleigh limit, $0.61\ \lambda/NA$. The discrete points are data obtained by scanning across the edge of a cleaved quartz fiber immersed in mineral oil. Figure (4) shows a typical set of scans. The value of ε varies by about 10% depending upon whether the light is focused into the fiber or the oil; the numbers in Figure (4) are the averages of the two values.

Data derived from scans like those in Figure (4) are shown in Figure (3). Whereas there is some effect resulting from increasing ε, the data do not agree well with the theory and show that the resolution is diffraction limited as long as ε is less than about 0.7. When ε exceeds 0.7, resolution suffers, probably because of diffraction of the light outside the narrow conical shell by the sharp edge of the fiber.

Comparisons with other methods

At the time of this writing, we are just beginning comparisons. Figure (5) shows measurements on a step fiber by the refracted near-field method and by near-field scans of the exit faces of meter- and kilometer lengths using over-filled launch conditions. The former method resolves the central index dip and shows structure in it, and also shows the presence of a complicated barrier layer. Core-diameter measurements agree to about 10%. Comparisons with at least one other laboratory are still at an early stage.

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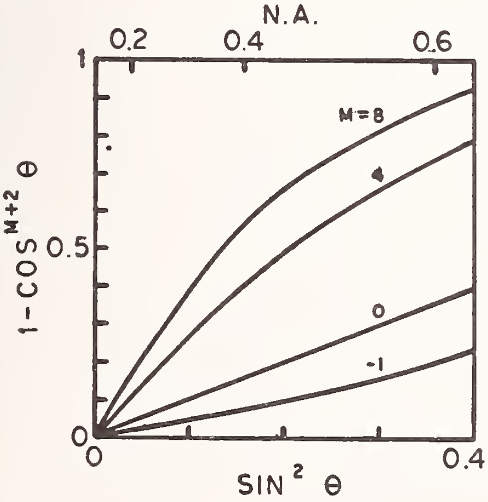

Figure 1. A function useful for describing non-Lambertian sources.

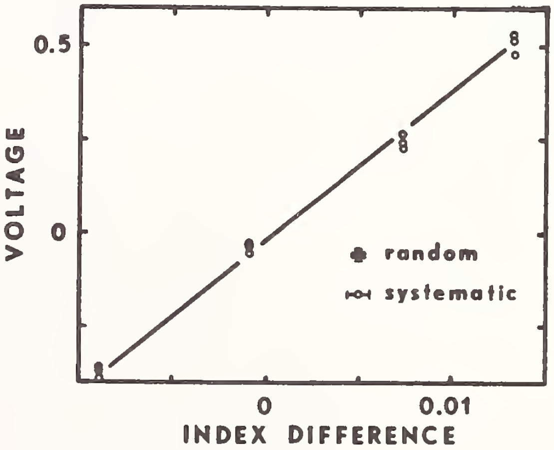

Figure 2. Normalized recorder voltage vs. difference of refractive index between the quartz fiber and each of four immersion fluids.

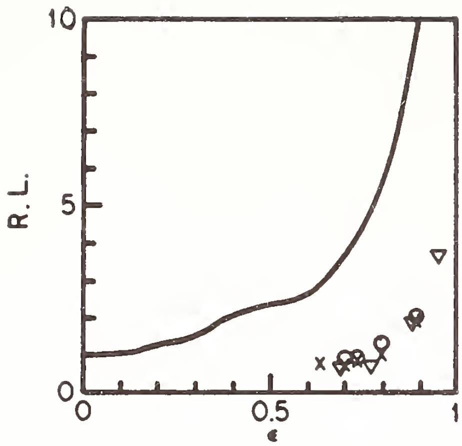

Figure 3. Normalized resolution limit as a function of relative diameter. RL = 1 corresponds to the Rayleigh limit.

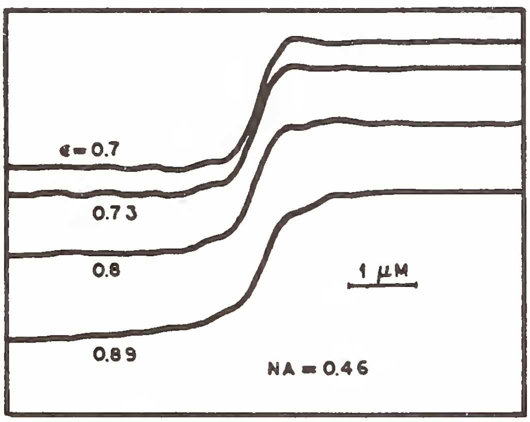

Figure 4. Scans across the edge of a cleaved quartz fiber. The fiber is to the right of the step.

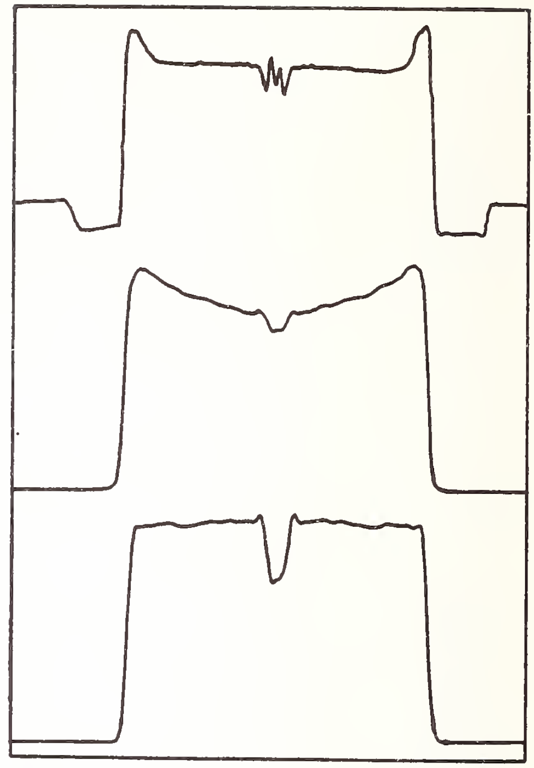

Figure 5. Scans of the core of a step fiber.
Top: refracted near field scan.
Center: scan of exit face of 1-m length.
Bottom: scan of exit face of 1-km length.

A COMPARISON OF TECHNIQUES TO MEASURE THE DIAMETER OF LIGHTGUIDE FIBER

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INTRODUCTION

The dimensional quality of lightguide fiber determines connector design and splice loss in high-quality lightguide communication systems. Consequently, the outer diameter and the ellipticity of the lightguide fiber are important factors to be measured and controlled during the manufacturing process.[1] For compatible system components, it is imperative that calibrated diameter measurement techniques exist.

Three methods of measuring fiber diameter are examined: a microscope technique, a light-scattering technique, and an interferometric technique. Microscope measurements are commonly used for static measurement of fiber cross-section. Interferometric measurement offers an alternate static measurement technique. Light-scattering measurement may be used as a static measurement or as a real time diameter monitor during fiber drawing.

MEASUREMENT TECHNIQUES

The cross-section dimensions of the fiber are measured with a microscope by preparing a short fiber sample to have a well-cleaved end, and carefully mounting the sample such that the surface to be examined lies in the focal plane of the microscope objective. The sample may be illuminated by reflected light or light transmitted through the fiber sample (Figure 1). A filar eyepiece, which has been calibrated with a stage micrometer, is used to locate the edges of the fiber sample, or a camera system[2] may be used to automatically measure the fiber dimensions.

The interferometric micrometer (Figure 2) measures the fiber diameter by interferometrically determining the separation of two fused silica probes, between which the fiber is located. The surfaces of the probes which contact the fiber must be plane and parallel. Fiber diameter is measured by zeroing the interferometer[3] with the probe surfaces together, inserting the fiber between the probes and measuring their displacement. It has been found that the measured diameter is independent of contact force for forces less than 20 gms.

The light-scattering technique uses a laser beam to illuminate the fiber, generating a scattering pattern containing interference fringes. The fiber diameter is determined by measuring the angular range, in the forward-scattered pattern, containing a fixed number of fringes.[4] The fiber is located on the axis of a spectrometer table and illuminated by a HeNe laser (Figure 3). A detector is located on the rotating arm of the table approximately 10 cm from the fiber. As the detector is translated through an arc of approximately 60°, the fringe pattern is observed and the precise angular range for 120 fringes measured.

EXPERIMENTAL RESULTS

In order to compare the relative accuracy and repeatability of the three measurement techniques, a fiber sample was drawn from a centerless-ground 15 mm diameter fused-silica rod. The rod was measured to be round within .03%.

The fiber diameter measured with the interferometer was 109.1 ± .1 μm based on over twenty measurements of the fiber sample, regardless of orientation. The diameter measured by the forward light scattering was 109.0 ± .2 μm based on three independent measurements. The measurements made by microscope were less consistent. For samples which were illuminated by white light reflected from the top of the fiber sample, the measured diameter was 110 ± .5 μm. When the sample was illuminated by transmitting light through the fiber sample, the measured diameter was 108.9 ± .5 μm. The microscope measurements represent the average and spread of more than forty independent measurements per sample. These results are representative of measurements made on many different fiber samples other than the specially prepared sample.

Microscope measurement yielded a result comparable to those of the other techniques only when the sample was illuminated by transmitted light, and then only when a large number of measurements were averaged. When reflected illumination was used, the average measured diameter was significantly higher than the results of all other techniques. The scatter in the measured diameters results from operator judgment, chromatic aberation in the microscope, and the difficulty in focusing over the entire fiber end. The bias in the measurement when using reflected light for illumination resulted from an incorrect perception of the edge of the fiber due to poor edge definition[5].

CONCLUSION

The interferometric micrometer and forward light scattering technique provide the most accurate measure of fiber diameter. The interferometer is easily implemented and could be used for production control and fiber standardization measurements. The commonly used microscope measurement techniques are inconsistent and may introduce significant bias into the diameter measurement.

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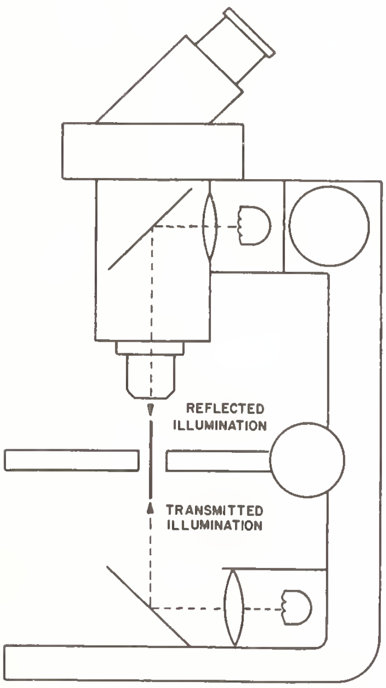
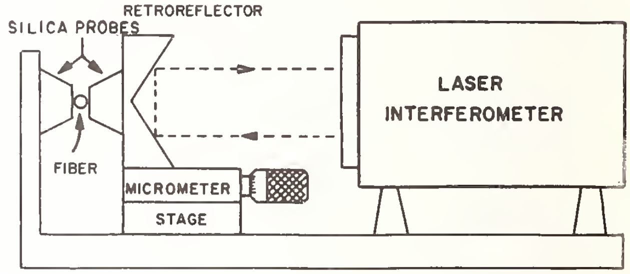


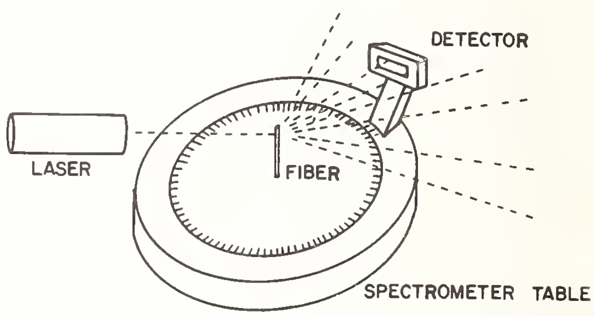
MICROSCOPE MEASUREMENT

Figure 1



INTERFEROMETRIC MICROMETER

Figure 2



FORWARD LIGHT SCATTERING

Figure 3

AN AUTOMATIC INSPECTION SYSTEM FOR SINGLE FIBER CONNECTOR PLUGS

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INTRODUCTION

Transfer-molded, biconical single-fiber connectors with a mean insertion loss of 0.21 dB without index match have been reported[1]. In order to achieve this low loss, both the intrinsic fiber characteristics such as core diameter and numerical aperture (NA), and the external alignment parameters such as transverse offset, tilt angle, and end separation must be accurately controlled. This paper describes an automatic inspection system which measures the aforementioned parameters, and provides statistical information as a rapid feedback to the molding runs.

SYSTEM CONSTRUCTION

The system is a computer-controlled microscope that measures core diameter, core eccentricity, fiber NA and fiber deflection angle of a connector plug in an one-step operation by scanning both the near field of the core, and its radiation pattern. The block diagram of the measurement set-up as shown in Fig. 1 is an adaptation of the video-scanning system described by H. Presby et al[2,3]. The connectorized test cable is excited by a 0.82 μm LED via a launch jumper containing a fiber with nominal parameters. The test plug is seated in a steel gauge sleeve anchored into a sturdy bridge-like stage plate of an inverted microscope. With this construction, the center of the sleeve drifts by less than 0.2 μm over long periods of time. The near and far-field pattern of the connectorized fiber is imaged onto a silicon vidicon camera whose output is coupled to a video digitizer. There, the intensity along any selected vertical line segment is digitized, and the data are sent to the computer. In addition to providing data acquisition, storage, and analysis, the computer controls the LED brightness, focuses the microscope, monitors the distance between the microscope objective lens and the fiber end face, and records the output current of a photo-diode used to measure the light intensity through the jumper cable. The last function detects cracks and discontinuities along the test jumper.

METHOD OF MEASUREMENT

(i) Core Eccentricity and Diameter

The core eccentricity of a test plug can be obtained by a single measurement of the core center position after the exact center location of the steel gauge sleeve has been determined at the beginning of a series of measurements. This sleeve center determination is made by rotating a plug with nominal parameter inside the sleeve four times in 90° steps and measuring the core center at each position. The four points lie on a circle whose center is the center of the sleeve. In the subsequent measurement for each test plug, the computer first locates an approximate core center position by trial scans. Two orthogonal scans are then made through this point and parabolas are fit to the data between 10 percent and 80 percent of the maximum signal level after correction for background level (Fig. 2). The axes of the parabolas determine the coordinates (x_o, y_o) of the core center and the distance between (x_o, y_o) and the center of the gauge sleeve gives the eccentricity. The core diameter D_o is defined as the distance between the points at which the parabola crosses the background level.

Fig. 3 shows a scatter plot of the eccentricities of a group of 433 plugs in an exploratory development run. The plugs are loaded into the gauge sleeve with a specific orientation so that the distribution of the cluster of points give important information on the molding process. For example, the centering of the alignment hole in the molding die can be deduced from the centroid of the points. If the fiber O.D. is much smaller than the I.D. of the alignment hole, the points will be spread out from the centroid instead of forming a small cluster. The points on the far left hand side of Fig. 3 indicate that the fibers of these plugs have been bent as a result of molding defects. The 3 μm circle on the plot sets the current tolerance limit within which the contribution to the connector loss by the eccentricity alone is less than 0.1 dB under steady state excitation[4].

(ii) Numerical Aperture and Fiber Deflection Angle

For graded index fibers with near parabolic profile, the caustic of the rays exiting from the fiber can be approximated by a hyperboloid. Because of accuracy and instrumental considerations, the NA is not measured from the sine of the half apex angle of the far field, but rather from the spot size D (20 dB points) at a distance d ($\approx 5D_o$) from the end face. Using the hyperboloid approximation, the NA is then given by

$$NA = \sin\left(\arctan\left(\frac{D_o\sqrt{(D/D_o)^2 - 1}}{2d}\right)\right),$$

and is in good agreement with that computed from the index profile data. The fiber deflection angle is obtained at the same time from the tilt of the radiation pattern at distance d.

Both the magnitudes and azimuths of the fiber deflection angles for the above group of 433 plugs are shown in Fig. 4. The one degree circle on the plot sets the tilt angle limit for the plugs, which together with the 3 μm circle in Fig. 3, helps to achieve the low connection loss reported in Ref. 1.

ESTIMATION OF ERRORS

The major sources of the errors of the apparatus are due to the improper seating of the plug in the gauge sleeve and the uncertainty in the location of the sleeve center, apart from the occasional presence of dust on the tapered surfaces of the plug and the sleeve.

These instrumental errors are estimated by repeating the measurements for a set of 33 plugs: The standard deviation of the differences between the two measurements for the core eccentricity is 0.35 μm and for the core diameter is 0.39 μm. Those of the NA and fiber deflection angle are 0.004 and 0.08^{o}, respectively. No long term variation has been observed.

Provided the test jumper is over-excited, the core diameters from this method agree with those measured with photo-micrographs and index profile data by better than 2%, while the NA agrees with that from the index profile data by better than 5%. The fiber deflection angle for 17 plugs have been checked by actual measurements of the fiber stubs after molding with an average difference of 0.05^{o} and a standard deviation of the differences of 0.12^{o}. The core eccentricity can be checked by rotating the plug in the sleeve as described earlier. The eccentricity is determined from the radius of the circle of the core center to a precision of 0.1 μm.

CONCLUSION

A computerized connector inspection system for the characterization of single fiber connector plugs has been constructed. In an automated operation of less than 1-1/2 minutes duration, the system measures the plug parameters (eccentricity and tilt angle) and fiber parameters (core diameter and NA) of a connector. The accumulated plot and statistical analysis of the plug parameters identify the quality of the fabrication process, enable the screening of out-of-spec units, and also serve as a feedback on the molding runs. The information on fiber parameters is important to assure that the fibers used meet the specification required for low loss connectors.

ACKNOWLEDGEMENTS

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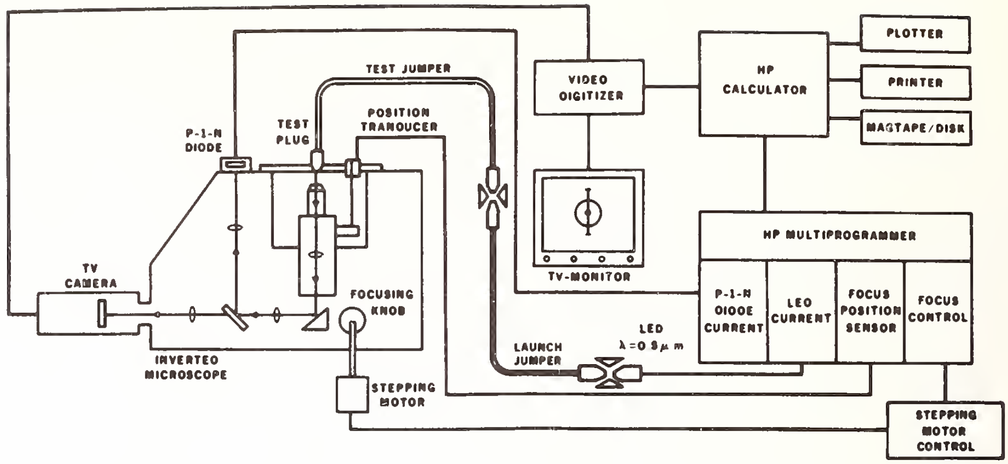

Fig. 1 Schematic of the Automatic Measuring System

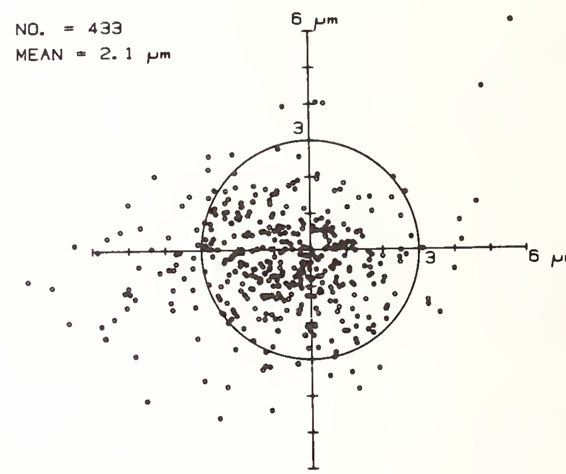

Fig. 3 Scatter Plot of Core Eccentricities of 433 Plugs

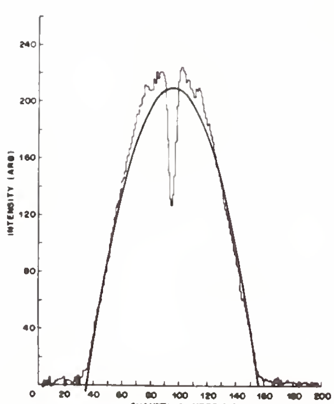

Fig. 2 Typical Near Field Scan Data and the Fit Parabola

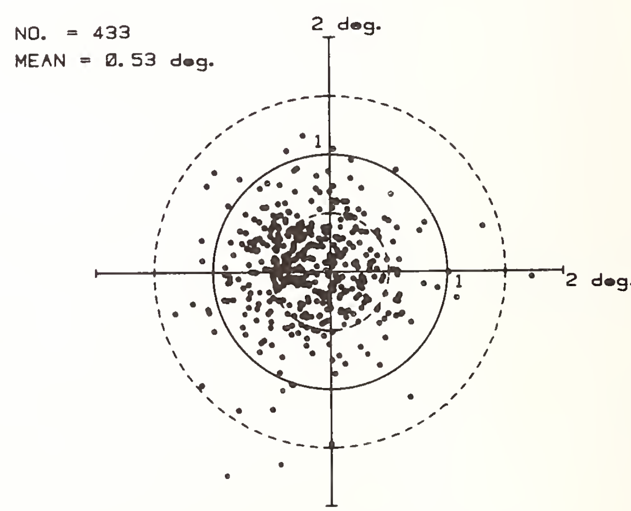

Fig. 4 Scatter Plot of the Fiber Deflection Angle of 433 Plugs

BANDWIDTH MEASUREMENT IN MULTIMODE OPTICAL FIBERS

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1. Introduction

Precise measurements of the baseband frequency response of multimode fibers are required in order to characterize them and to predict their behaviour when designing optical fiber transmission systems. Until about the middle of the '70's, these measurements had been performed mainly by the pulse-broadening technique (PBT) [1]. Recently, however, improvements in laser diode characteristics, such as in stable CW-operation and in wide-bandwidth modulation, has enabled us to apply effectively the swept-frequency method (SFM) to such fiber bandwidth measurements [2] [3].

This paper presents a comparative study of these two methods, a review of the recent results in fiber bandwidth measurement in Japan, and some discussion on the future course of these measurements.

2. Performance Comparison between Swept-Frequency Method and Pulse Broadening Technique

Ideally, under conditions of a completely linearly responding system, the swept-frequency method is equivalent to the pulse broadening technique, because a given frequency response can be transformed into the corresponding impulse response. However, there are real operating conditions that can affect in different ways the results obtained in bandwidth measurements using SFM and PBT.

For example, the beam pattern from a laser diode is dependent upon its operating conditions and will be different for CW- or pulsed-operation. Consequently the different distributions in the modes of the fiber launched will cause different fiber bandwidths to be measured by the two techniques.

In favour of the SFM technique we have the fact that nonlinear characteristics of a photo-detector cause larger errors in the PBT measurement which requires the larger dynamic range. Also the SNR of SFM is, as mentioned in the next section, much superior than that of PBT.

On the other hand, PBT, in addition to its relatively simpler setup, provides intuitively understandable results which correspond directly to the sources of pulse distortion in a fiber, especially to the index-profile control error of a graded fiber. Therefore, this technique has been applied for checking the quality of graded fiber on mass production lines.

In a comparison without regard to system complexity the SFM technique is the more powerful because it provides more precise results with its advantages in SNR. Figure 1 shows the fundamental layouts. SFM adopts a vector-volt meter, comparing the amplitude and phase of input and output baseband signals through a fiber. In PBT the input and output waveforms are compared and the fiber response then calculated.

2.1 SNR Comparison

Figure 2 shows the calculated SNR for the two methods. SFM has the two major advantages of narrow receiving bandwidth and the fact that transmitted power can be concentrated on a line spectra. That is, even if SNR improvements that can be achieved by averaging are taken into account, PBT is inferior to SFM because not only does PBT require a receiving bandwidth as wide as the fiber bandwidth but also each frequency component of a transmitted pulse is much smaller than the corresponding line spectra power of SFM.

Therefore, the SNR that can be achieved using PBT is significantly degraded in the higher-frequency region, the case of a wide-bandwidth fiber. In general then, SFM is superior in SNR to PBT.

2.2 On Phase Measurement

The accuracy in phase measurement of PBT is bounded by sampler timing error, which is, now, around 50 psec corresponding to $\pi/10$ at 1 GHz. On the other hand, as the phase is measured by a vector-volt meter in SFM, the accuracy here depends on the stability of the signal frequency, which ideally

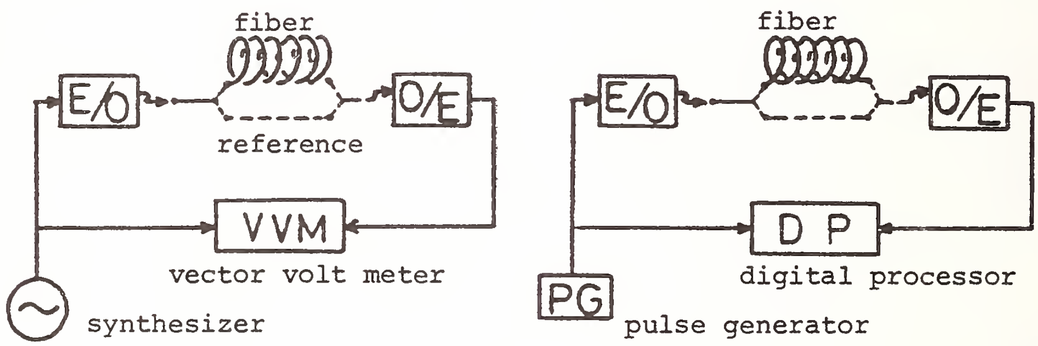

Fig.1 Measurement Layouts for Swept-Frequency and Puls Broadening Methods

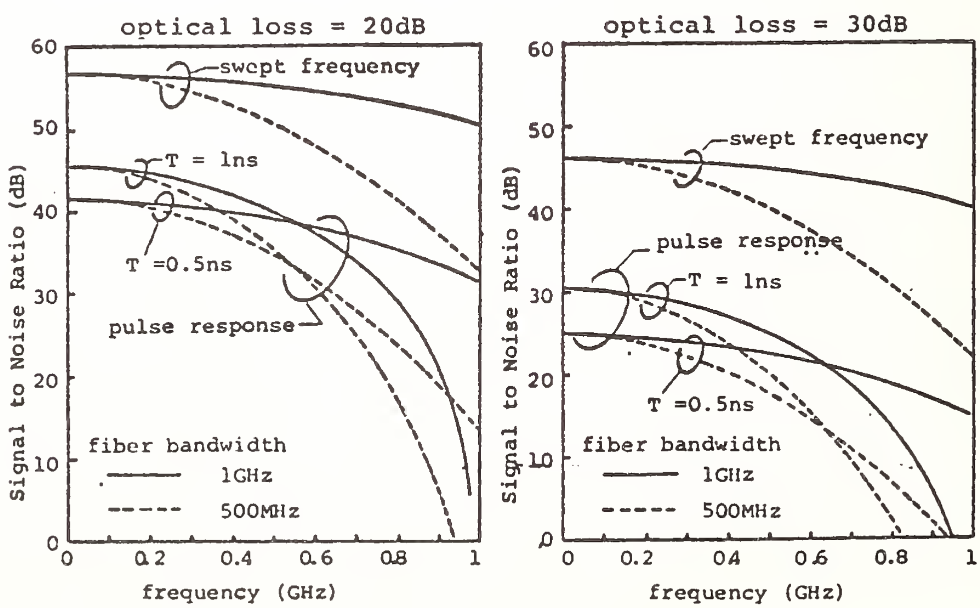

Fig.2 SNR Comparison between the Methods

should be kept constant during the time that the light propagates through the fiber. In practice the frequency is usually stable enough for this purpose and it is easy to measure the phase precisely at several GHz, where the dominant source of error is random noise.

2.3 Examples of Measurement Results

In the above discussion it was concluded that SFM is superior to PBT for the precise bandwidth measurement of fibers. This section demonstrates this conclusion by comparing the results measured using SFM and PBT.

Figure 3 shows the measured baseband response of a 2 km long graded fiber, including both amplitude and phase. These results show that SFM provides more precise measurement and a wider measurable range than PBT.

There is a little difference in the bandwidths measured using the two techniques. Fiber bandwidth dependency on wavelength was a possible source for a difference, because the PBT measurement used a 0.83 µm GaAlAs laser diode with 2.0 nm spectral-width as a light source and the SFM used a 0.87 µm diode with 1.3 nm spectral width.

3. Field Measurement

Three kinds of measuring sets have been developed [4] for use in NTT's field research in '78 [5]: a standard type has been designed for far-end automatic measurement, a portable type for far-end manual measurement with battery power supply, and a near-end measuring set with visual output displayed on a CRT. Figure 4 shows the internal response of the standard measuring set and an example of a measurement.

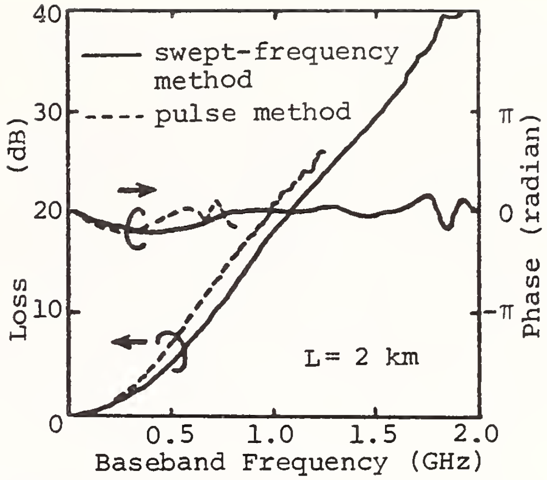

Fig.3 Measurements by SFM and PBT

4. On Some Subjects for the Establishment of Accurate Measurement

4.1 Launching Conditions

Light launching conditions can significantly affect the frequency response of multimode optical fibers, because they determine the initial power distribution among the guided modes, and hence, through differences in modal delay, form the most important factor in the multimode fiber response. Although mode mixing could in principle remove such effects from fiber response, it is well-known that the recent low-loss optical fibers do not in themselves create enough mode mixing that the response even of a 1 or 2 km long fiber is independent of the launching conditions.

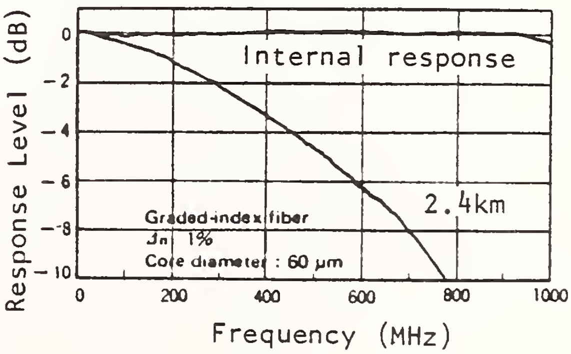

Fig.4 Measurements on the Spot

The measurements on bandwidth converge monotonically toward a unique response as the length of fiber measured is increased. There are two possible ways to deal with this inherent scatter in the measured response of multimode fiber: one way is to measure all possible responses with varied launch conditions, and the other way is to define the launching conditions in detail and thus define one standard measurement for the response of a fiber.

Figure 5 shows the reproducibility of the measurement using a mode exciter, consisting of step-, graded-, and step-index short fibers connected in series [6].

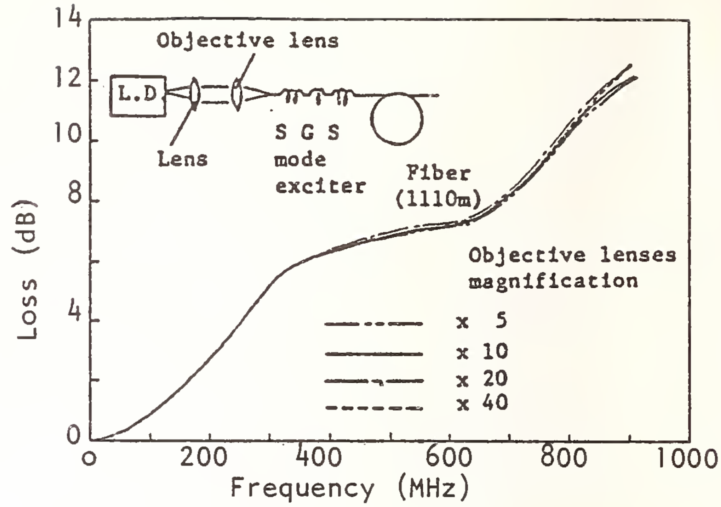

Fig.5 Reproducibility of Measurement Using a Mode Exciter

In either case, there remains the problem of how to evaluate the effective fiber response in its individual application. These difficulties reflect the fact that multimode fibers cannot be regarded simply as linear response systems in baseband electrical signal domain.

4.2 On Reproducibility of the Internal Response of Measuring System

The internal response characteristics of the measuring system must be reproducible for reliable measurements, especially in the case of far-end measurements in which calibration of this response is difficult.

The dominant factor in such lack of stability stems from the laser diode. This component possesses three kinds of instability: a drift due to operating conditions such as the ambient temperature, intrinsic nonlinear effects such as output power saturation, negative gain, and self-pulsation [7], and nonlinear effects induced by external disturbances, such as optical power reflected into the active region of the diode.

Negative feedback technique is an effective method of removing many kinds of source instability, but is ineffective to control negative gain, self-pulsation, and complicated nonlinear effects. Fortunately, progress in the laser diode manufacture has now led to single-mode operation and has overcome the negative-gain and self-pulsation problems.

There then remains the problem of light reflected into a laser diode. This problem is fundamental to the laser diode structure and its sensitivity to multiple resonant structures. Some techniques have been proposed to prevent reflections, such as an isolator or a coupler adopting a numerical aperture mismatch [8]. Several fundamental research papers on laser diode characteristics have been contributed to the solution of these problems [9].

4.3 Speckle Noise Problems

Coherent light, propagating along multimode fiber, generates dynamic speckle patterns which can lead to enough noise as to make impossible accurate bandwidth measurements. However, with multimode operation of a laser diode, most of the speckle pattern noise is suppressed, and reproducible measurements are obtained. Such a multimode operation is achieved, for example, by superimposing a high-amplitude cyclic wave on the signal driving the diode. Figure 6 shows the spread of bandwidth measurements taken with and without this technique to suppress speckle pattern effects.

4.4 Discussions on Fundamental Problems in Fiber Bandwidth Measurement

The fiber bandwidth measurement is based on taking the ratio of two signal amplitudes or, more exactly, a ratio of intensity-modulation indices. However, no effective method is known for measuring the modulation index directly as a ratio of the absolute light powers.

Rather, the bandwidth measurements in practice are based on the indirect method of detecting the

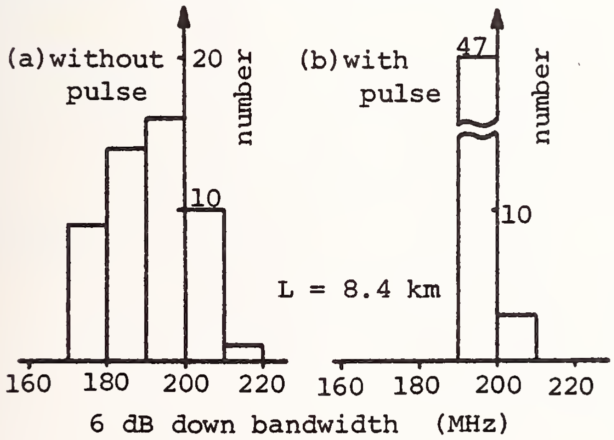

Fig.6 Speckle Noise Effect in Bandwidth Measurement

light with a photodiode and trusting to its small-signal linearity.

Another problem area stems from the fundamental multimode nature of the optical fiber guide. A fiber bandwidth is defined in the baseband electrical signal domain. This definition contains no parameter to describe multimode phenomena in detail and, consequently, includes some ambiguities. For example, a fiber can change in frequency response, when new splicing points are introduced and mode distributions accordingly changed.

Intrinsically, therefore, the response of a long spliced fiber cannot be deduced with certainty directly from the responses of its component short fiber pieces.

5. System Design Requirements on Fiber Bandwidth Measurement Accuracy

Fiber transmission system designers require precise, reproducible and accurate fiber response. Most of their requirements are met by measurement techniques now employed.

There are, however, some other aspects to the bandwidth of fibers which the designer must also know. One of the most important of these is how to determine the response of a long fiber consisting of many short pieces, if the response of each short component is known. The frequency response of the long fiber is not a simple linear sum or convolution of short-fiber responses. A powerful bandwidth-evaluation method has been proposed by Electrical Communication Laboratories [10]. In this method the long-fiber response is determined by using the bandwidth values of each fiber piece at several wavelengths.

It is necessary thus to measure fiber bandwidth at different wavelengths of the source and, in general, a wide-bandwidth measurement is required in order to check the characteristics of short-fiber pieces.

Since a laser diode is not available at such wide-bandwidth, typically several GHz, and especially not available at several wavelengths, ECL has built up a measuring system consisting of a gas or solid-state laser and electro-optical crystal modulator, which can operate up to 18 GHz [11]. Figure 7 shows examples of the results taken with this system.

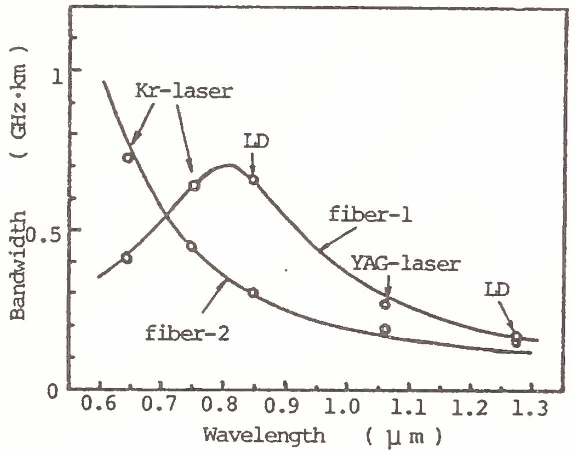

Fig.7 Measured Bandwidths at Several Wavelengths

In a word, the difficult requirement from a system design point of view is to determine precisely the fiber response under actual operating conditions, when no long fiber has been installed yet and there remains some inherent ambiguities in short-fiber measurement.

6. Conclusion

This paper has reported successful measurement results using the swept-frequency method, some techniques for its practical application in the field, and discussions on problems involved with the definition of multimode fiber bandwidth and its measurement.

In order to establish a well-defined useful measuring method, it seems unavoidable to investigate more deeply several phenomena inherent to the multimode nature of optical fibers.

Acknowledgement

The author would like to thank the members of Yokosuka ECL of NTT in Japan for their co-operation in this work and the members of CRC of DOC in Canada for their helpful advice.

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AN INTERRELATIONSHIP BETWEEN LOSS AND DISPERSION IN MULTIMODE FIBERS

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This paper describes an interrelationship between loss and dispersion which can result in a high bandwidth over a much wider wavelength region than predicted for perfect power-law profiles.(1) The fibers studied were drawn from MCVD preforms with germania phosphosilicate (GeO_2-P_2O_5-SiO_2) cores and phosphoborosilicate (P_2O_5-B_2O_3-SiO_2) barrier layers which separate the cores from silica (SiO_2) claddings. Results are compared for two fibers. Fiber #1 has a moderately high OH ion concentration and a core profile shape that is well graded for the 0.8-1.1μm wavelength region.(2) Fiber #2 is a low-loss fiber containing very little water.

Figure 1 illustrates bandwidth versus wavelength curves for fibers #1 and #2. Data points at 0.825μm and 1.25μm wavelengths were obtained with pulsed injection laser sources. Remaining dispersion data, within the 1.06-1.7μm wavelength region, were obtained with an automated fiber characterization system which uses a near infrared fiber Raman laser source.(3,4)

The dotted curve, applicable to fiber #1, is the theoretical bandwidth spectrum for a 0.19 NA fiber whose profile shape is optimized for operation near 1-μm wavelength. The maximum theoretical bandwidth(5) is

17GHz·km and the measured peak fiber #1 bandwidth is more than 1.6GHz·km. The measured fiber #1 spectrum behaves qualitatively according to theory for $\lambda<1.2\mu m$. However, the bandwidth does not continue to decrease but remains higher than 1GHz·km for wavelengths between 1.2 and 1.53μm. In fact, bandwidth peaks occur at wavelengths where water absorption causes loss peaks near $\lambda=1.24\mu m$ and $\lambda=1.38\mu m$. By comparison, the bandwidth spectrum for fiber #2 has lower peaks than fiber #1 (due to the lower level of OH ion concentration). It has a 20-percent larger NA=0.236 and its profile shape is not as well graded.

It is also instructive to show loss spectra in Figure 2 for fibers #1 and #2. Fiber #1 has significant water absorption peaks near $\lambda=0.95\mu m$, 1.24μm, and 1.38μm. Its minimum loss is 1.2 dB/km near $\lambda=1.17\mu m$. Fiber #2 has lower losses. Only one significant water peak occurs near $\lambda=1.38\mu m$. Losses remain less than 1 dB/km everywhere else between 1.06μm and 1.6μm. The minimum loss is 0.45 dB/km near $\lambda=1.55\mu m$. In general, the loss differences between fibers #1 and #2 are most dramatic for wavelengths longer than $\lambda=1.2\mu m$. That is also the wavelength region where the shape of the bandwidth spectrum for fiber #1 most differs from theory.

Comparisons between curves in Figures 1 and 2 highlight a clear interrelationship between loss and dispersion. Its cause was determined by making wavelength-dependent far-field radiation pattern measurements with the same launching conditions that were used to make bandwidth measurements. Generally, radiation pattern shapes dramatically broadened in wavelength regions corresponding to high water absorption. Detailed results were used to deduce that high OH ion concentrations near the center of the core caused differential attenuation of low-order modes relative to high-order modes. This resulted in bandwidth peaks at the same wavelengths where water absorption peaked.

Perhaps the most important thing to learn from this paper is that comparisons between the shapes of loss and bandwidth spectra can enlighten interpretations of modal dispersion charactersitics of graded-index fibers.

We are grateful to M. J. Buckler (Bell Labs, Atlanta) for supplying fiber #1 along with bandwidth data at λ = 0.825 μm. and λ = 1.25 μm. We also thank J. Stone (Bell Labs, Crawford Hill) for the fiber #1 loss spectra used in Figure 2. Finally, we would like to thank M. A. Saifi (Western Electric, Engineering Research Center) for many useful discussions.

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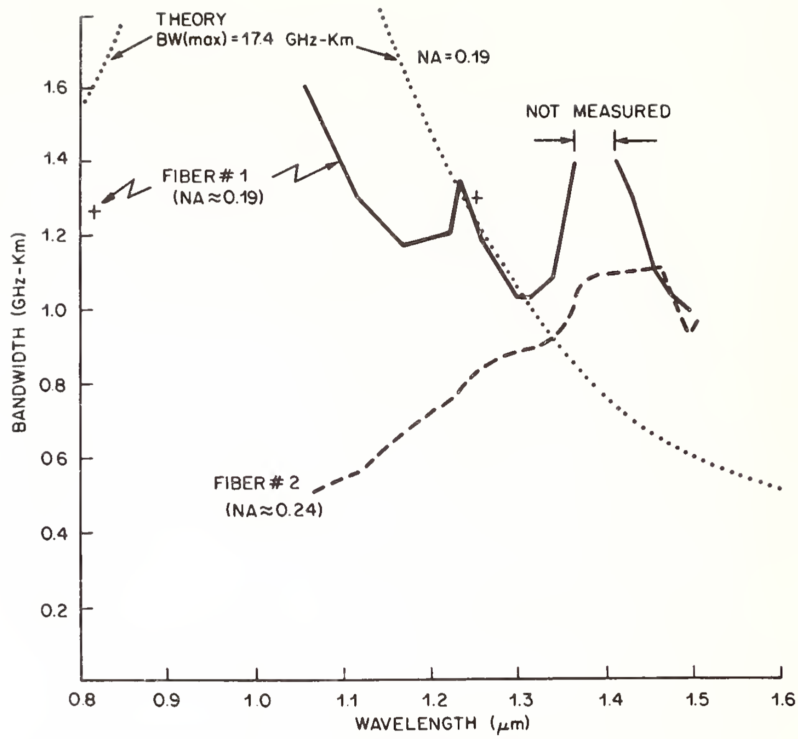

FIGURE 1 BANDWIDTH SPECTRA

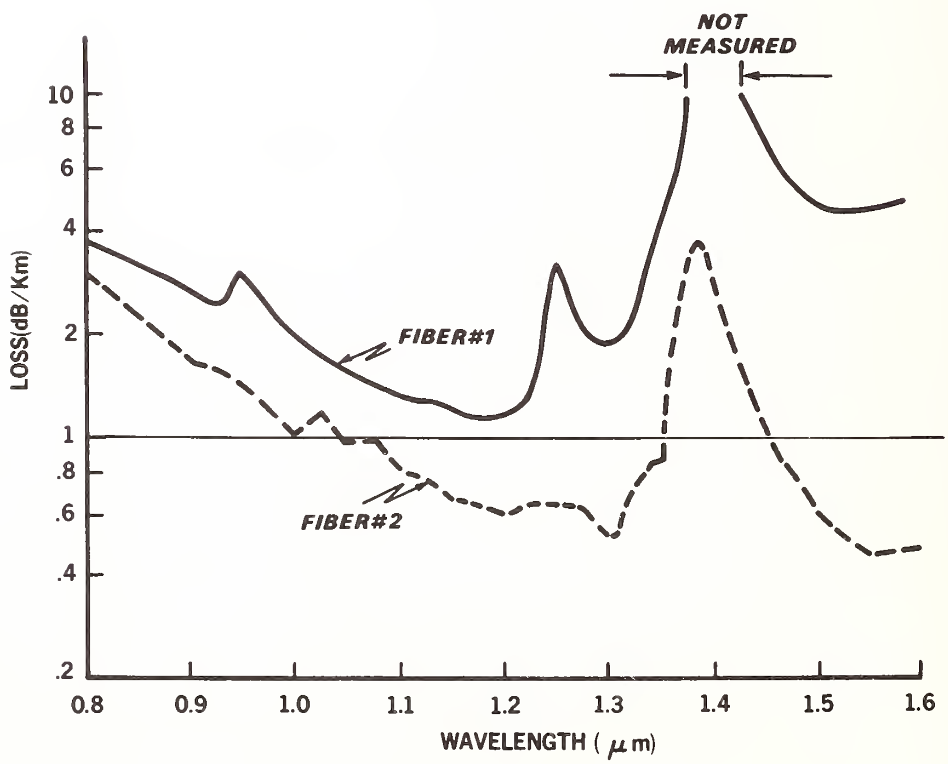

FIGURE 2 LOSS SPECTRA

OPTIMIZATION OF CONCATENATED FIBER BANDWIDTH VIA DIFFERENTIAL MODE DELAY

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ABSTRACT

A novel differential group delay time measurement system has been used to analyze the detailed features of pulse broadening in concatenated multimode graded-index optical fibers. For the first time optical modal delay equalization has been confirmed by measuring the delays of individual mode groups. It has been found that when concatenating fibers with minimal excess loss using low loss splices, the differential mode delay characteristics are additive. Thus, optical fiber routes could be tailored, if necessary, for maximum information carrying capacity.

I. INTRODUCTION

At the present time most optical fiber routes are constructed by interconnecting lightguide cables in a random fashion. In some installations[1] it has been found that the total route bandwidth can be a function of the order of fiber concatenation. It has been shown that selecting adjoining fibers to have over- and under-compensated refractive index profiles provides some modal delay equalization, thus resulting in improved total link bandwidth. However, to arbitrarily select alternating fibers to have compensating profiles is at best only a good rule of thumb. For ultimate concatenated fiber bandwidth it is necessary to know a priori the modal delay characteristics of each individual fiber, and to then use this information to select adjoining fibers for optimal modal delay equalization.

For the experiments reported here, fibers were judiciously concatenated and modal delays were precisely measured to show for the first time, that modal delay equalization has indeed taken place.

II. EXPERIMENTAL APPARATUS

The experimental arrangement is depicted in Figure 1. This measurement system has been described in detail in Reference 2. The unique features of this system, which enhance its capabilities relative to other differential mode delay measurement systems are: (1) selective mode excitation using a single mode fiber, (2) reduction of time jitter to ±10 ps using the Hewlett Packard 5359A digital delay generator, (3) the use of minicomputer time averaging to increase the signal to noise ratio, (4) large screen CRT display for increased visual sensitivity, and (5) the elimination of beam optics.

After precise alignment and initial positioning of the adjustable splice, translation in one direction is used to vary the radial (r) alignment of the single mode fiber launch into the multimode fiber (or concatenated fibers) under test. With high-precision micropositioners the radial resolution is better than 1 μm. For each selection of radial position, 2^n averages ($2 \leq n \leq 9$) are taken and the result is displayed on the large screen CRT. The time delay through the digital delay generator can be adjusted in steps of 10 ps until the displayed pulse peak is aligned with a CRT screen vertical graticule. The output pulses corresponding to different r values are thus observed, and the time shift of the peak of the pulses as a function of core radial position is measured. The radially dependent time delay can be measured with a precision of ±10 psec.

III. RESULTS AND ANALYSIS

All of the fibers used for these experiments were of the SiO_2-P_2O_5-GeO_2 type with a 0.23 NA. In order to minimize the amount of modal power disturbance at the interconnection points all fiber concatenations were built using loose tube splices (∿0.05 dB each).[3] Early on in the experiments it was found that the usefulness of the differential mode delay data is directly influenced by the amount of fiber excess loss due to microbending, i.e., coating induced loss. Thus, three well controlled experiments were conducted using fibers with varying degrees of mode coupling.

EXPERIMENT I: Nearly Complete Intermodal Coupling

For this experiment two fibers (designated A and B) were selected which had a wavelength independent externally induced excess loss of b ∿1 dB/km (optical loss = $a\lambda^{-4} + b + c(\lambda)$). Initially, the differential mode delay (DMD) characteristics of each individual fiber were measured. The two fibers were then interconnected with a loose tube splice and the modal delay characteristics were remeasured for both directions of transmission (A into B, and B into A). Figure 2 shows a plot of the measured DMD data for both the individual fibers and the concatenations. For comparison purposes the arithmetic summation (A + B) of the individual A and B data is shown as a dashed curve. From this data it is obvious that the concatenation results do not obey the rule of reciprocity. In fact, the initial fiber in the link seems to control the final link characteristics.

EXPERIMENT II: Weak Intermodal Coupling

For this experiment fibers (designated C and D) were selected which exhibited a low excess packaging loss, b ∿0.3 dB/km. Figure 3 shows the plots of DMD data for the individual fibers and for both directions of concatenation. For this case the concatenation results are almost identical for both directions of transmission, and are very close to the simple sum of the individual fiber DMD curves, although the first fiber in the link still seems to have slightly more influence.

EXPERIMENT III: Negligible Intermodal Coupling

Two uncoated fibers (designated E and F), each 1 km in length, were used for this experiment. The DMD data for this experiment is plotted in Figure 4. Despite the very non-monotonic nature of this data, note how well the concatenation results agree with the sum of the individual curves. Moreover, reciprocity holds with respect to the order of concatenation. Also note that at the radial positions where the two fibers have modal delays on opposite sides of zero, modal delay equalization does take place, as expected. Thus, for this case of negligible externally induced loss and low loss splices (<0.1 dB), it is possible to choose the fibers to be connected so as to minimize the magnitude of the DMD and thus improve cumulative bandwidth relative to a random choice of fibers.

IV. CONCLUSIONS

In the past it has been assumed that selecting adjoining fibers in a concatenated link to have over- and under-compensated refractive index profiles would result in some form of modal delay equalization-improved bandwidth performance. Optical modal delay equalization has been confirmed directly for the first time by measuring the delays of individual mode groups. It has been found that for fibers with low b values ($b_{.} < 0.3$ dB/km) and with low loss splices (<0.1 dB), the DMD characteristics are simply additive for concatenations. Thus, optical fiber routes could in this case be tailored, if necessary, for maximum information carrying capacity. Moreover, as previously reported,[4] the precise DMD data measured for each fiber can also be used to optimize the preform processing parameters to enhance the individual fiber bandwidths.

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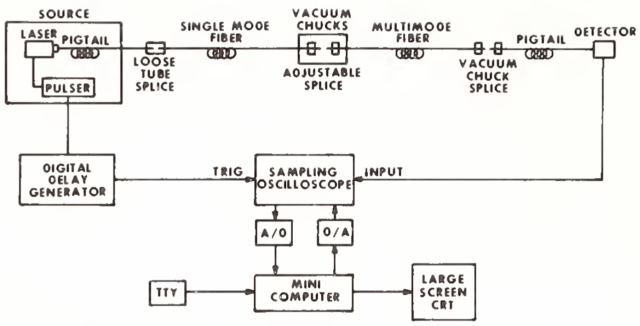

FIGURE 1. DIFFERENTIAL GROUP DELAY MEASUREMENT SYSTEM

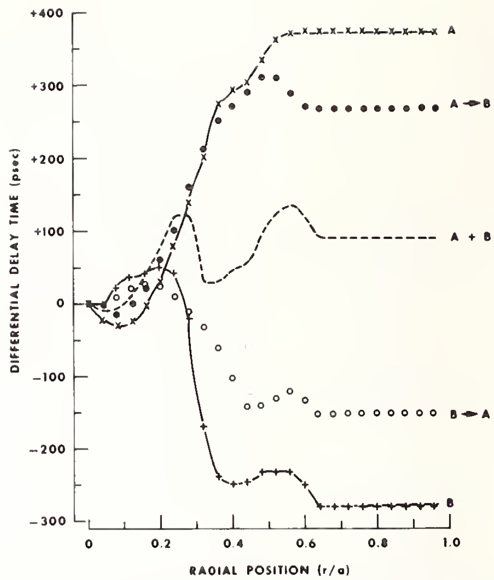

FIGURE 2. DIFFERENTIAL MODE DELAY DATA FOR FIBERS WITH NEARLY COMPLETE MODE COUPLING.

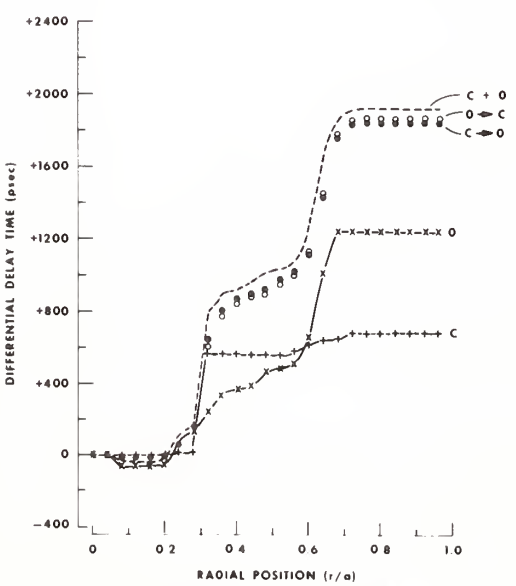

FIGURE 3. DIFFERENTIAL MODE DELAY DATA FOR FIBERS WITH WEAK MODE COUPLING

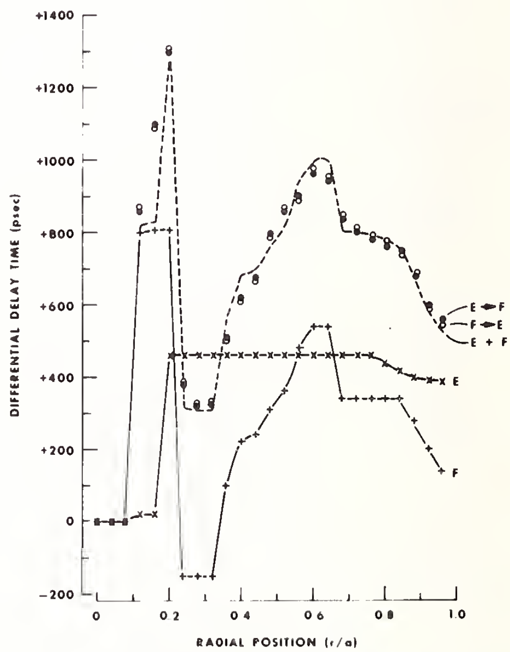

FIGURE 4. DIFFERENTIAL MODE DELAY DATA FOR FIBERS WITH NEGLIGIBLE MODE COUPLING.

ATTENUATION AND PULSE BROADENING ALONG CONCATENATED FIBER LINKS

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In this paper we investigate some new attenuation and pulse broadening properties measured along several fiber links. The ICVD graded-index fibers had a 0.17 NA and 50/125 μm core/clad diameters.

1. Attenuation

1.1 Spectral Dependence of Mode Volume

Optical loss measured in concatenated fiber links is generally lower than might be expected from totalizing attenuation measurements made on typically 1 km individual fiber lengths. Although several approaches simulating long-length conditions have been reported, investigations to date have not concerned the wavelength dependence of a restricted mode volume along concatenated links. We present here, for the first time, the wavelength-dependent loss (spectral attenuation) of both fibers and splices along a link.

1.2 Experiments

The measurement utilized a tungsten lamp/monochrometer combination, over filling launch optics, and had a repeatability of 0.01 dB over the wavelength range 750 to 1100 nm. The 10 fibers (each ~1.1 km long) were fusion-spliced together and the 11 km link attenuation measured using a 5 m cutback length. The power spectrum was measured at the output of the 10th fiber and again as the link was cut to within 5 m of the 9th splice; this yielded the in-situ spectral attenuation of the 10th fiber. A cutback just prior to the splice and measurement of power out of the 9th fiber then yielded the in-situ spectral attenuation of the 9th splice. The next cut was within 5 m of the 8th splice and so on until the spectral attenuations of all fibers and splices were obtained. The link was then remade and the measurements repeated for propagation in the opposite direction; mean values are used below.

During link assembly, splice loss was monitored by OTDR from the far-end. Qualitative agreement was found with the measurements below.

1.3 Results

Figure 1 shows the spectral loss (upper curve) for the jointed link and for the sum of the individual measurements (lower curve). Note that the difference is about 0.1 dB/km. Figure 2 shows the average spectral loss for the three splices nearest the source (upper curve) and for the remaining six splices (lower curve).

The difference is substantial, and there is a strong wavelength dependence in the vicinity of the water peak. This presumably results from the reduction in mode volume due to the OH radical present in the cladding tube.

2. Pulse Broadening

2.1 Experiment

The influence of mode volume upon fiber dispersion is less understood than for attenuation. The purpose here was to attempt to fit data according to several simple concatenation 'rules'. We used a GaAs injection laser diode at 0.9 μm and an InGaAsP diode at 1.3 μm; lenses were used to overfill both the NA and core of the fibers. The use of a mode scrambler consisting of graded-step-graded fibers did not affect some of the preliminary results, so it was decided not to use it during concatenation measurements so as to avoid the extra loss penalty.

All pulse widths were FWHM, with the fiber responses obtained by the usual quadrature subtraction of the output and input pulse widths. For each fiber n of length L_n, the fiber FWHM broadening T_n was measured. The fibers were then spliced into a link of N fibers of total length $L(N) = \sum_n^N L_n$ and the broadening T(N) measured. The link was progressively cut back to each splice and the pulse broadenings successively recorded. This was repeated for several links and both wavelengths. At 0.9 μm, a chromatic dispersion correction of 0.264 ns/km (corresponding to a 3.3 nm FWHM source) was made, again by quadrature subtraction.

2.2 Data Fitting

The measurements and fits were logarithmically computer-plotted as shown in Figure 3 to 5. For a least-square continuous fit, the pulse broadening T(L) is expressed as a function of link length L:

$$T(L) = T(1)\, L^p \qquad (1)$$

Here T(1) is an effective 1 km broadening and 'p' is expected to range between ½ and 1, with the latter indicating little mode mixing. A second least-squares fit [1] is

$$T(N) = \left(\sum_{n=1}^{N} T_n^{1/q} \right)^q \qquad (2)$$

where the parameters 'q' ranges between ½ (quadrature addition) and 1 (linear addition). A third exact fit [2] is

$$T^2(N) = \sum_{n=1}^{N-1} \left(T_n^2 + 2T_n T_{n+1} R_{n,n+1} \right) \qquad (3)$$

where $R_{n,n+1}$ are derived 'joint correlation coefficients. Its magnitude is expected to range between 0 and 1 for heavy and little mode-mixing, respectively; it can be negative in the equalizing situation of having fibers of opposite mode delay compensation on either side of the joint. Finally, we can take $R_{n,n+1}$ to be constant and by least-squares define an effective joint correlation coefficient

$$R = (T^2 - \sum_n T_n^2) / 2 \sum_n T_n T_{n+1} \qquad (4)$$

2.3 Results

Figure 3 shows data at 0.9 μm without correction for chromatic dispersion; Figure 4 includes the correction. Note that the effect of the latter is negligible at 1 km but amounts to almost 1 ns over an extrapolated 15 km. Figure 5 shows data at 1.3 μm, though with the joints remade. The fits of Equations (1,2,4) are about equally good, but further data will be presented. The Table gives joint correlation coefficients corresponding to Figures 3 to 5. The appearance of coefficients greater than unity probably results from measurement inaccuracy or the approximation of using the FWHM instead of FWRMS in Equation (3).

3. Acknowledgments

Thanks are due to D.S. Brombal, R.F. Hughes and G.K. Pacey for experimental assistance, and to K. Abe for useful discussions.

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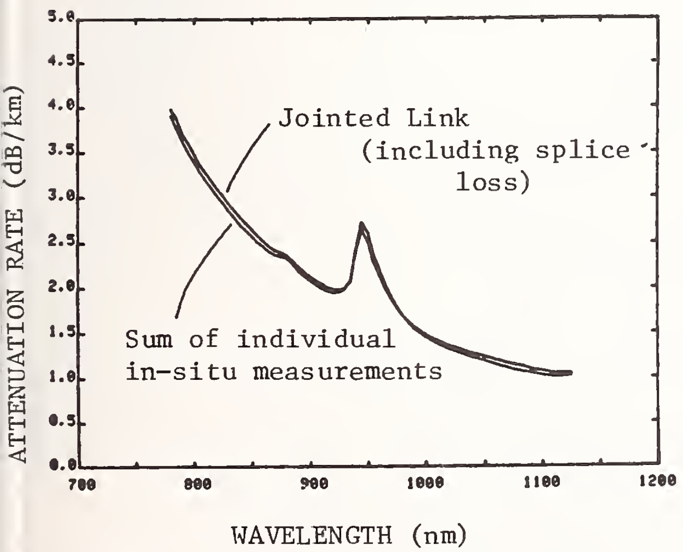

FIGURE 1 Fiber Spectral Attenuation

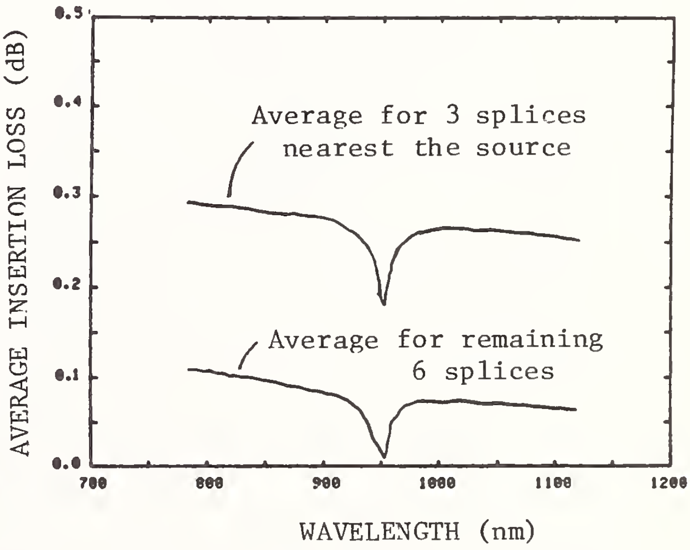

FIGURE 2 Splice Spectral Loss

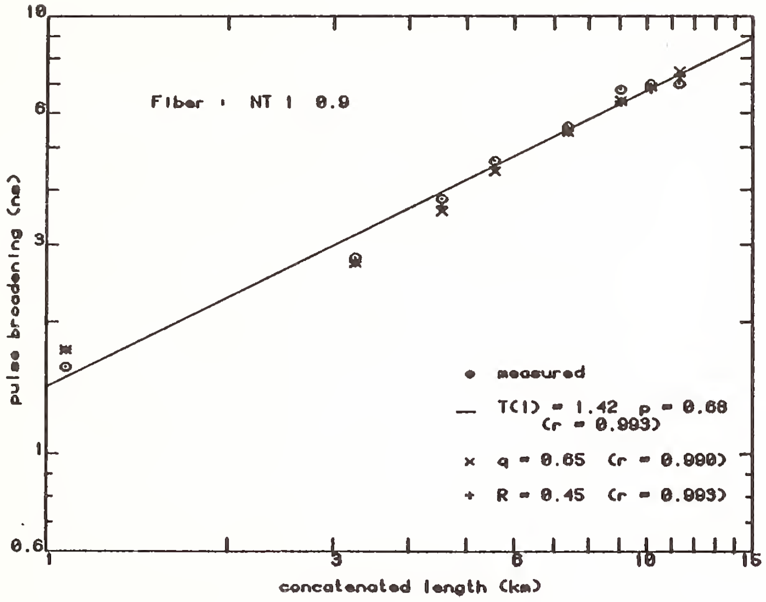

FIGURE 3 0.9 μm Data, Uncorrected

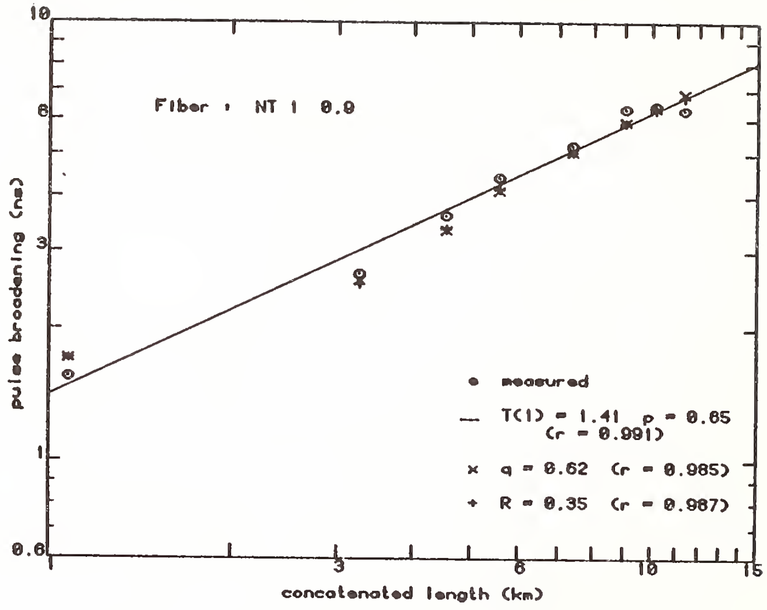

FIGURE 4 0.9 μm Data, Multimode Dispersion only

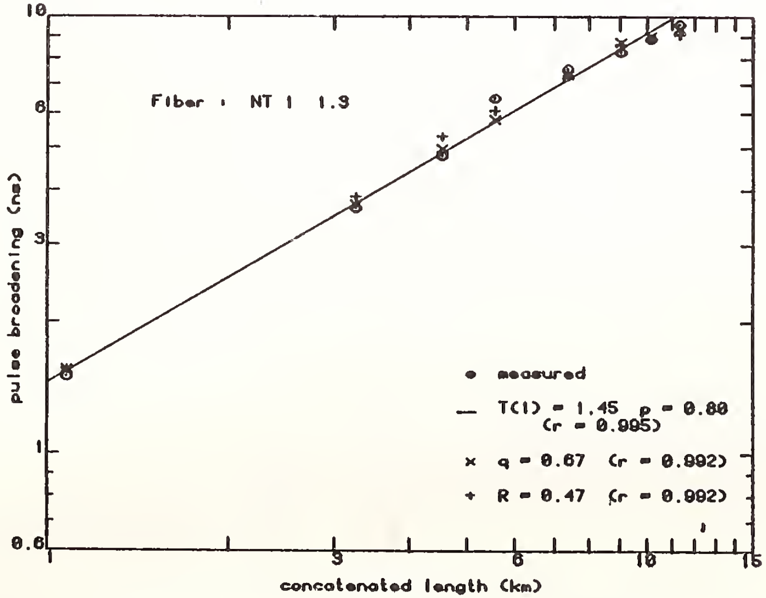

FIGURE 5 1.3 μm Data

TABLE of joint correlation coefficients

	Figure 3	Figure 4	Figure 5
R_{12}	0.30	0.27	0.20
R_{23}	0.57	0.51	0.23
R_{34}	0.52	0.43	1.52
R_{45}	0.45	0.30	0.38
R_{56}	0.81	0.68	0.02
R_{67}	0.02	-0.17	1.17
R_{78}	0.58	-0.88	3.42

DIFFICULTIES ENCOUNTERED IN THE MEASUREMENT OF OPTICAL FIBER INTERCONNECTION PERFORMANCE

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Introduction

Splices and demountable connectors allow for flexibility in the installation and maintenance of optical fiber links and, as such, are indispensable. Permanent joints (i.e. splices) usually have less effect on system performance than rematable joints (i.e connectors), but, in general, they only offer one-time installation. Joints can however profoundly influence system performance and, since both attenuation and fiber bandwidth are affected, they warrant careful study.

To date there exists very little in the way of standard procedures for measuring the transmission loss occurring at an interconnection between two optical fibers. Furthermore, although the term "insertion loss" (which is normally used to describe this loss) is well understood, its use to describe the loss encountered at a joint between two optical fibers can be misleading. Thus we prefer to use the term "joint loss," and one definition of this term might be "the additional loss seen by the system over that which would have occurred if the interconnection had been perfect and between identical fibers." Note that in this definition the joint loss includes the losses due to differences in fiber parameters such as might occur when going from a fiber with a higher numerical aperture to one of a lower numerical aperture, as well as those due to mechanical misalignments. However, in a practical system the case of jointing identical fibers does not normally arise and so another definition of joint loss might read "the additional loss seen by the system over that which would have occurred if the interconnection had been perfect" (i.e. no misalignments). Although the na mismatch loss, for example, is not included in this definition it will nevertheless affect the observed joint loss. This state of affairs has, in turn, led to the idea that the joint loss can be attributed to extrinsic and intrinsic factors, but once again considerable confusion exists. For example, loss due to fiber parameter mismatch is referred to in the literature as both "intrinsic" and "extrinsic." To avoid this ambiguity we propose to describe those losses caused by fiber misalignments as internal factors and those losses resulting from fiber parameter mismatches and fiber transmission properties as external factors (note that the former will to some degree be affected by the latter).

Referring back to the description of joint loss we believe the first-mentioned definition to be the most useful, for in practice it is the additional loss experienced by <u>the system</u> that is of interest. This qualification is necessary since, in general, the observed joint loss will depend on the location of the joint within the system, the number and location of any upstream joints, and the intitial excitation conditions. In view of the aforementioned lack of standardization for joint-loss measurement, we have decided to devote the written part of this contribution to outlining the difficulties of these measurements and to bias our spoken contribution towards a review of the experimental results obtained to date.

Review of Factors Affecting Joint Loss

The four factors affecting joint loss are mechanical misalignments, fiber parameter mismatch, the physical properties of the medium separating the fiber ends and the excitation conditions existing in the fiber immediately prior to the joint.

The mechanical misalignments of general interest are:

(a) Offset: this describes the lateral misalignment between the fiber axes, and is usually the dominant cause of loss in a fiber interconnection,
(b) Tilt: this describes the angular misalignment between fiber axes and is normally well controlled,
(c) Gap: this describes the distance between the endfaces of the fibers being jointed and its influence on joint loss will be mainly determined by fiber numerical aperture and whether or not an index-matching medium fills the gap.
(d) Face angle: this describes the angle of the cleaved fiber face w.r.t. the fiber axis.

The fiber parameters which primarily influence the joint loss between two fibers are:

(a) Numerical aperture mismatch
(b) Index-profile mismatch
(c) Core-diameter mismatch
(d) Core ellipticity
(e) Core/cladding concentricity

These parameters (except perhaps the last (e)) give rise to losses external to the joint.

To date many studies have been made investigating the effect of these parameters - either in isolation from one another or in combination. Measurements on the group comprising mechanical misalignments have usually been performed by breaking a continuous length of fiber and manipulating the ends, whereas measurements relating to the guidance parameter mismatches have necessarily been performed on different fibers. Both techniques have inherent problems. In the former case rotation of the fiber ends after the fiber has been broken must be avoided as core ellipticity and index-profile asymmetries will influence the results, whilst, in the latter case, isolation of any particular parameter is usually very difficult due to fiber manufacturing tolerances. Furthermore, as stated previously, the configuration of the link can profoundly affect the results of joint-loss measurements and it is perhaps this phenomenon that causes most uncertainty in the measurement of interconnection insertion loss. In a series of detailed experiments Gordon (1) has shown that losses due to offset when using a short transmitting fiber and a long receiving fiber are greater than for the case of a long transmitting fiber and a short receiving fiber. This effect arises from the spatial transient (2) occuring after the joint and is generally attributed to the launching of leaky modes in the receiving fiber. The leaky modes have a length-dependent attenuation (3) and the amount of power contained in the leaky modes after a joint will be a function of the fiber parameters (i.e. core diameter na; index-profile), the excitation conditions existing immediately prior to the joint (including the source wavelength), and the distance downstream of the observation point from the joint. Thus we are led to the concept that it is perhaps the mode-mixing effects of a joint which are important rather than the insertion loss per se. The joint could therefore be considered as a mode-mixing component in which the power contained in the guided-modes (and to a lesser extent the leaky-modes) of the upstream fiber is coupled into the guided, radiation and leaky modes of the downstream fiber. The power coupled into the radiation-modes will be immediately lost and is responsible for a localized loss at the joint whereas the power coupled into the leaky modes will result in a joint-loss figure that is dependent on the location of the observation point from the joint, a situation which is further compounded by differential-mode attenuation in the fiber. Since the mode-mixing effect of the joint depends on the power distribution amongst the modes in the upstream fiber, the initial excitation conditions of this fiber will affect the results and this has already been demonstrated with led and laser excitation (1).

In order to overcome the problem of initial excitation conditions joint-loss measurements have been made using restricted excitation conditions in a similar manner to that pioneered by workers at Corning (4) for fiber attenuation measurements. However, although this is probably a satisfactory technique when considering one joint in isolation it may be difficult to reliably extrapolate the results to a series of closely cascaded joints, as the downstream joints will, in general, "see" a larger mode volume and thus appear to be more lossy.

Optical Time-Domain Reflectometry

Although the most common method of determining joint loss has been that of measuring its insertion loss, some attempts have also been made to estimate the loss using optical time-domain reflectometry (OTDR). This technique obviously has many advantages for measurements in the field, and some workers claim good results, although there still seems to be some doubts about obtaining quantitative results. This problem arises because the fibers on either side of the joint may possess differing scattering coefficients and furthermore, the modal distribution set up by scattering will, in general, differ from the distribution seen by the fiber in the system environment. In an attempt to overcome these problems, some workers have taken OTDR measurements from both ends of the link and shown that greater accuracy can be obtained. Another suitable technique for measuring joint loss using OTDR could be the double-pulse method originated by workers at Southampton University (5), but as yet no results are available for joint-loss measurements made using the technique.

Measurement of the Influence of Splices on System Bandwidth

The mode-mixing characteristics of the joint affect not only the attenuation, but also the bandwidth of the link and this aspect of fiber interconnection technology has been even less explored. Cherin and Rich (6) have studied the effect of gap and offset in the middle of a 1.35 Km link and found that when strong mode mixing exists in the fiber these misalignments have little effect on pulse width. However when fiber mode mixing was small, a change in pulse width of 80% was produced by offset. The mode-conversion effects of splices in step-index fibers have been investigated, and it was found that even very low-loss splices induce significant mode mixing. These results are thus consistent with our concept of a joint behaving as a mode-mixing device. Experiments in other laboratories (7) using multiple connections over 2 Km of fiber have shown that the mode-mixing effects of the joints can improve bandwidth, and one connector manufacturer claims a design which helps to preserve bandwidth by deliberately mixing the modes (8).

Modal-Noise Effects

One further aspect of joints has yet to be investigated in detail; namely, their effect on the linearity of systems using coherent sources such as semiconducter lasers. Epworth (9) has already demonstrated that modal-noise originating at interconnection imperfections can reduce the system signal-to-noise ratio of an optical-fiber link, and it is possible that the linearity of the system is also affected. A detailed knowledge of such effects would be very useful for the design of analog systems.

Conclusion

We have presented the concept of the joint as a mode-mixing device and, as such, it will modify the distribution of power amongst the modes propagating in the upstream fiber establishing a new modal power distribution in the fiber following the joint. Since, in general, some power will be coupled into both radiation modes and leaky modes the joint will exhibit both a localized "insertion loss" and a length-dependent "insertion loss." The mixing of the modes will also affect the bandwidth of the link although the results of this will, in general, only be observed many meters downstream from the interconnection point.

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LOSS CHARACTERIZATION OF BICONIC SINGLE-FIBER CONNECTORS

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INTRODUCTION

Fiber connection losses are affected by intrinsic fiber parameter mismatch, by extrinsic misalignment such as off-set, tilt, and end-separation, by the end-face polishing quality, and by the modal power distribution existing at the connection point. The modal power distribution itself depends on the fiber transmission characteristics, i.e. differential mode attenuation and mode coupling, the location of the connector or splice, and the launch conditions. Unique, steady-state losses are only obtained for an equilibrium mode distribution (EMD) at the splice point[1,2] which establishes itself, in general, after a few kilometers, or which can be created within a much shorter distance by controlled-beam excitation, or with mode filters[1-4]. Recently, the EMD losses of graded-index fibers have been measured with high accuracy using a simple, mandrel-wrap (MW) mode filter.[1,3]. The main function of this filter, which consists of five turns of fiber wound around a 1.2-cm diameter mandrel (as optimized for 50μm-core, 0.23-NA, graded-index fibers), is to eliminate excess higher-order and leaky modes inadvertently launched by typical excitation conditions. Since, in general, the MW filter does not generate the EMD exactly, the question arises as to the accuracy of connector loss measurements performed with this filter.

CONNECTOR DESIGN, AND LOSS MEASUREMENTS

The connector used for this study was the transfer-molded biconic, single-fiber connector (Fig. 1), in which Fresnel reflection losses were virtually eliminated by physical contact of the fiber end-faces.[5] Average losses of 0.21 dB have previously been reported for 65 connector plugs when measured against a reference plug (Fig. 2)[5]. While the fiber end faces were dry-polished in above case, the losses of the same set of connectors decreased to 0.11 dB after wet-polishing with a 0.3μm polishing compound (Fig. 3). It should be noted that for the purpose of determining the highest performance achievable, the loss of each plug was minimized by rotating the plugs relative to each other. The average losses are generally higher, and depend on a variety of factors as noted earlier, and as also discussed further below.

The significance of the MW loss data, in addition to other tests, was ascertained with a set of five jumper cables (1.5m long) whose measured minimum and maximum losses and calculated average losses for different test conditions are listed in Table I. The specific test conditions were: a) Direct excitation with a pigtailed LED; b) Excitation with MW filter, followed by a short reference fiber (F1); c) As under b, but with test cable sandwiched between two (input and output) reference fibers (F1 and F2); and d) Test jumper sandwiched between F1 and F2, which were preceded and followed by approximately 1-km long input and output fibers. It should be noted that test conditions c) and d) contained two connectors.

Without discussing the complete information contained in Table I in detail, the average losses of the five test cables, i. e., 0.33 and 0.30 dB for conditions c) and d), respectively, demonstrate that loss data obtained with the MW filter and with long input and output reference fibers, are essentially the same. Furthermore, results obtained with the simpler set-up of Fig. 2 (test condition b) agree with the 'sandwich' data of test condition c) and d) within 0.1 dB, which represents an excellent agreement.

CONCATENATION LOSSES

In order to eliminate the bias associated with using a particular reference fiber, plug, and coupling sleeve, more realistic loss data are obtained for a concatenation of several connectorized test cables. Yet, the 0.11 dB average loss of above 65 connector plugs increased only to 0.16 dB for a minimized-loss concatenation of the 32 jumper cables (Fig. 4), and to 0.23 dB for a random, concatenation (Fig. 5) Again, about the same losses (within 0.1 dB) were measured when the concatenated jumpers were preceded and followed by 1-km-long reference fibers. It is worth noting, that the loss of one specific connector was the same whether it was measured as the first or last connection in the concatenated string (using MW excitation).

While the 1.5m-long test cables discussed thus far were sufficiently short so that fiber losses could be ignored, the determination of the joint losses when long fiber sections are involved requires the accurate measurement of the fiber losses. For example, "negative" splice losses may be obtained, if the losses of the individual fibers are measured too pessimistically, or if the connectorized, concatenated fiber section is under-excited, while the fiber losses were obtained for EMD conditions. The requirements on the accuracy become particularly severe in the longer-wavelength region (say, at 1.3μm), where total fiber losses amount to less than 1 dB/km. To illustrate this point, the losses of five 1 to 2 km-long Ge-P-doped graded-index fibers were measured at 1.3μm, using both the matched -beam (MB) and MW-filter technique, with the MW method typically yielding slightly lower (by 0.15 dB/km, max.) values. During the concatenation process, for which the loss of the individual connectors was again minimized by rotational adjustment of the plugs, the loss of each section added was recorded and is listed in Table II. Depending on whether MB or MW fiber loss data were used, the average connector losses were either 0.14 or 0.27 dB, respectively, thus illustrating the limitations of the accuracy of connector loss measurements because of the uncertainty of the fiber loss measurement. (Because of the higher accuracy of the MB method, the 0.14 dB avg. connector loss is considered the more representative value).

CONCLUSIONS

Using low-loss biconic connectors, insertion loss measurements performed with a MW filter and long reference fibers agree within 0.1 dB. The accuracy of connector loss measurements depends critically on establishing an approximate equilibrium-mode distribution at the connection point, and knowing the EMD losses of the fibers to be interconnected as can be ascertained through matched-beam, or MW-filter excitation. While connector losses well below 0.3 dB (without index match) can be achieved with biconic connectors containing tightly-toleranced fibers, it is obvious that inferior geometrical and optical fiber characteristics can result in significantly higher insertion losses.

ACKNOWLEDGEMENTS

The Ge-P-doped fibers were supplied by M. Saifi, S. R. Nagel and F. V. DiMarcello, and WECo, Atlanta. The connectors were molded by R. Spicer, and a preliminary evaluation with an automated test set[6] was performed by R. Ragbir.

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TABLE I

Minimum, maximum, and average connector losses of five, 1.5m-long test fibers measured under different conditions as described in text:

	Fiber #1				#2				#3			
Loss (dB)	a)	b)	c)	d)	a)	b)	c)	d)	a)	b)	c)	d)
Minimum	.28	.08	.13	.19	.41	.13	.14	.23	.28	.10	.17	.06
Maximum	.58	.32	.58	.74	.66	.41	.62	.83	.63	.35	.79	.74
Average*	.43	.20	.24	.33	.54	.27	.26	.44	.46	.23	.33	.23

	Fiber #4				#5				Average, #1 to #5			
Minimum	.25	.10	.22	.11	.27	.11	.29	.19	.30	.10	.19	.16
Maximum	.68	.44	.85	.78	.60	.36	.84	.56	.63	.38	.74	.73
Average*	.47	.27	.38	.28	.44	.24	.43	.28	.47	.24	.33	.30

*The average loss in case of input- and output reference connectors (test conditions c) and d)) is calculated from: Avg. Loss = (3xMin. Loss + Max. Loss) /4 (λ=0.82μm)

TABLE II

Normalized and total loss of five fibers measured with the matched-beam (MB) and mandrel-wrap (MW) technique at 1.3μm. Concatenated loss per section added, and connector losses based on MB and MW fiber data:

	Length (m)	Loss dB/km		Loss (dB)		Loss/ Section (dB)	Connector Loss (dB) Based On	
		MB	MW	MB	MW		MB	MW
Fiber #1	992	.75	.75	.74	.74	.61	-.13	-.13
Fiber #2	1278	.70	.60	.89	.77	1.01	.12	.24
Fiber #3	1160	.85	.70	.99	.81	1.28	.29	.47
Fiber #4	1983	.80	.65	1.59	1.29	1.71	.12	.42
Fiber #5	1199	.80	.75	.96	.90	1.25	.29	.35
Tot. Loss (dB)				5.17	4.51	5.86	.69	1.35
Avg. Con. Loss (dB)							.14	.27

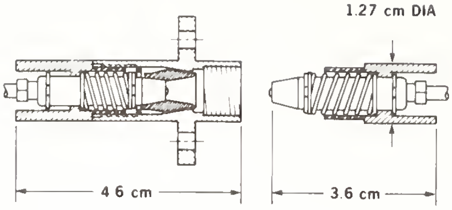

Fig.1 Spring-Loaded, Biconic Connector

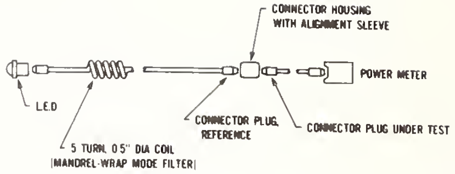

Fig.2 Schematic of Loss Test Set

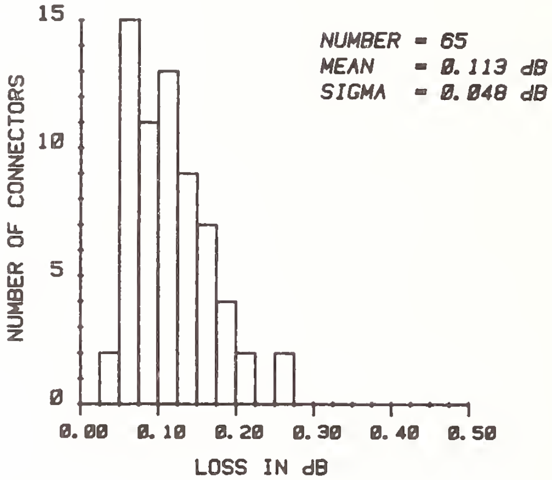

Fig.3 Losses of 65 Connector Plugs Measured Against Reference Plug And Minimized

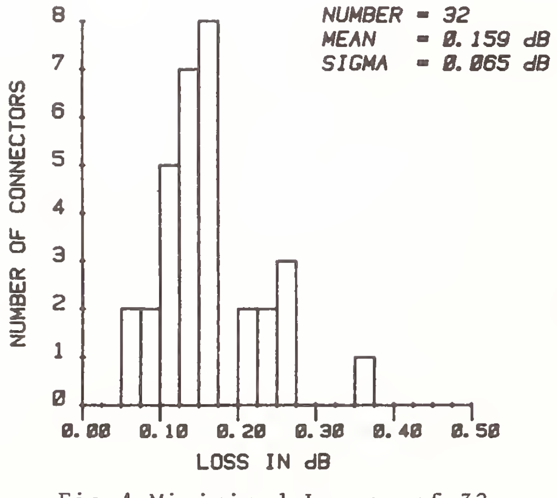

Fig.4 Minimized Losses of 32 Concatenated Connectors

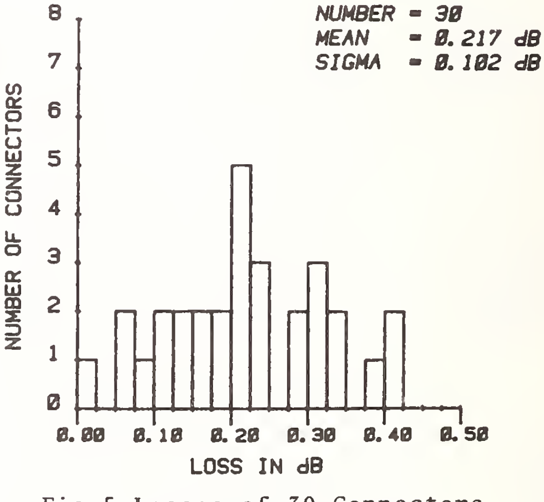

Fig.5 Losses of 30 Connectors Concatenated Randomly

CONTRIBUTION TO SPLICE LOSS EVALUATION BY THE BACKSCATTERING TECHNIQUE : A STATISTICAL COMPARISON WITH INSERTION LOSS DATA

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INTRODUCTION

This paper deals with the possibility of field testing of splices by the backscattering technique. Among the methods presently available, this technique presents well known advantages, among which are its cost-effectiveness and low time-consumption. We will try to assess on a statistical basis the pertinence of the results for the system designer.

Many parameters have been identified as responsible for the insertion loss of an optical fiber splice. On the first hand, extrinsic parameters (i.e alignment), those on which the splice manufacturer can have an action, are tilt, offset, end face preparation and separation. On the second hand, intrinsic parameters will be at the origin of unavoidable "primary" attenuation, which is the lowest possible value if the extrinsic parameters are perfectly matched (i.e zero). Those last parameters, of great importance, are numerical aperture, core radius mismatches, and α - profile shape. Leaving apart the α-parameter because of its relatively lower importance, as stated in [1], the great difference, when comparing backscattering to insertion loss, is that the extrinsic parameters only are the cause of oriented attenuation.

1 - Local transmission coefficient under the gaussian asumption

Table 1 shows the four possible combined effects of core radius and numerical aperture mismatches. Case 1 is a splice from a large core-low NA fiber to a small core-high NA fiber giving insertion loss due to core mismatch only and showing in the reverse direction (case 4) that insertion loss is due to NA mismatch only.

Case #	Definition	Insertion	Backscatt
1	R1 > R2, NA1 < NA2	$\alpha_J(\delta R, 0)$	$\frac{1}{2}(\alpha_J(\delta R,0)+\alpha_J(0,\delta\Delta))$
2	R1 > R2, NA1 > NA2	$\alpha_J(\delta R, \delta\Delta)$	$\frac{1}{2}\alpha_J(\delta R,\delta\Delta)$
3	R1 < R2, NA1 < NA2	$\alpha_J(0,0) = 0$	$\frac{1}{2}\alpha_J(\delta R,\delta\Delta)$
4	R1 < R2, NA1 > NA2	$\alpha_J(0,\delta\Delta)$	$\frac{1}{2}(\alpha_J(\delta R,0)+\alpha_J(0,\delta\Delta))$

Table 1

We chose the gaussian hypothesis [1, 2, 3] to calculate the local transmission coefficient α_J which is a function of two variables, $\delta R = (R2 - R1)/R1$, the relative core radius variation and, $\delta\Delta = (\Delta 2 - \Delta 1)/\Delta 1$, the relative peak index variation The approximation was made that the backscattered light follows the same $\alpha_J(\delta R, \delta\Delta)$ low as the forward propagation, the splice parameters being changed in the backward direction, of course.

2 - Statistical analysis

We considered that the splices were made from the random gaussian population of fibers defined below, which represent the manufacturing variations [1]:

Mean core radius 60 μm, standard deviation 3 μm

Mean NA 0,20 standard deviation 0,01.

The attenuations, α_{JI} (INS) and α_{JB} (BKS), of 10,000 splices were computed according to table 1. The distribution is given in figure 1 for insertion and in figure 2 for backscattering together with their mean m and standard deviation σ, respectively m_I, m_B, and σ_I, σ_B. The better centering, $\sigma_B < \sigma_I$, is due to the property of backscattering measurement to average the values in both directions, and the bias $m_B > m_I$ is related to the presence of 25% of 0dB insertion loss (probability of case 3, table 1) whereas the backscattering shows no 0dB splices at all. The cumulative distribution shows 90% of less than 1 dB (INS) splices but a problem is the existence of a tail of out of range values, some of them being undetected by the backscattering. So the probability of "undetectable bad splices" is not zero, and that problem will be discussed later.

The distributions, α_{JI} and α_{JB}, are far from gaussian but the variables are correlated by a coefficient r such that :

$$r = \frac{\mathbb{E}(\alpha_{JI} - m_I)(\alpha_{JB} - m_B)}{\sqrt{\mathbb{E}(\alpha_{JI} - m_I)^2 \mathbb{E}(\alpha_{JB} - m_B)^2}} \approx .56$$

A knowledge of α_{JI} is given by α_{JB}, suggesting the estimation problem : find the best estimator $\hat{\alpha}_I$ of insertion loss α_{JI} when BKS-loss α_{JB} only has been measured. Let us define ε as the mean square error (m.s.e) of a given estimator $\hat{\alpha}_I$ by

$$\varepsilon = \mathbb{E}(\alpha_{JI} - \hat{\alpha}_I)^2$$

where $\mathbb{E}$ stands for the expected value.

1) the most attractive estimator is to take for $\hat{\alpha}_I$ the backscattering value itself. The m.s.e is then :

$$\varepsilon_1 = \mathbb{E}(\alpha_{JI} - \alpha_{JB})^2$$

which is simply the standard deviation of the distribution of the differences INS-BKS, plotted figure 3, curve (A), with the computed value ε_1 = 0,112 dB. The confidence interval is found by the cumulative differential loss distribution given fig. 4. The conclusion is that 60 % of the splices are correctly measured by backscattering within a ± 0,1 dB approximation.

2) A better estimator is found by the linear regression : $\alpha_I = \lambda \alpha_{JB} + \mu$ then the m.s.e $\mathcal{E}_2 = \mathbb{E}(\alpha_{JI} - \lambda\alpha_{JR} - \mu)^2$ has a minium value of $\mathcal{E}_2 = \sigma_I^2 (1 - r^2)$ for a convenient choice of λ and μ , whose mathematical calculations will not figure here for clarity. The main conclusion is that the m.s.e $\mathcal{E}_2$ decreases from $\mathcal{E}_1$= 0,112 dB to $\mathcal{E}_2$= 0,110 dB which is not significant compared to the computational difficulty.

Figure 4, curve B is the cumulative distribution which shows the previsible slight increase of the confidence interval ± 0,1 dB.

3) Classicaly, the absolute estimator is the non-linear function of α_{JB} defined as :

$$\hat{\alpha}_I = \mathbb{E}(\alpha_{JI} \mid \alpha_{JB})$$

which is the mean of the conditional probability density of α_{JI} if α_{JB} is known. At the cost of an extremely time-consuming procedure $\hat{\alpha}_I$ can be estimated itself and the conditional density $\alpha_{JI}|\alpha_{JB}$ is given and averaged to find $\hat{\alpha}_I(\alpha_{JB})$
For instance, 400 splices over 10^4 are selected to be measured at 0,1 ± 0,05 dB by the backscattering technique. Then $\hat{\alpha}_I$ = 0,099 dB with a standard deviation of 0,084 dB. Other considerations lead to the conclusion that the confidence interval formerly found with poorer estimators is not much increased.

CONCLUSION

We tested on a random population of splices the possible discrepancies of insertion loss versus backscattering on the worst case basis of unsymetrical intrinsic parameters. It is shown that if the backscattering value is taken as an estimation of insertion loss, 60 % of the results be in the ± 0,1 dB range.

If the extrinsic (symetrical) parameters were taken into account, we believe that the masking effects on attenuation would still increase that confidence interval, thus validating the method for field testing on a statistical basis. Nevertheless the important problem of the tail of high discrepancies remains and needs some more investigation.

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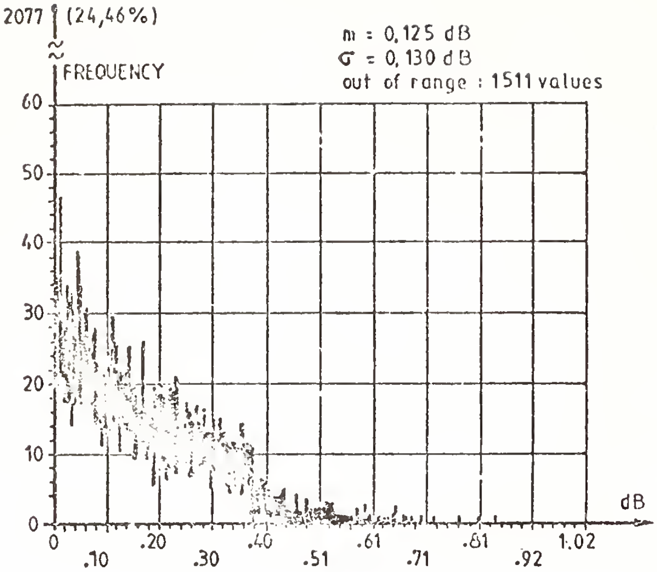
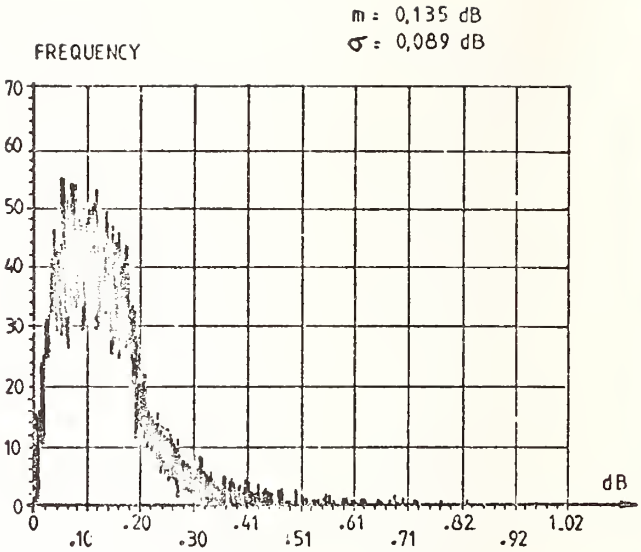


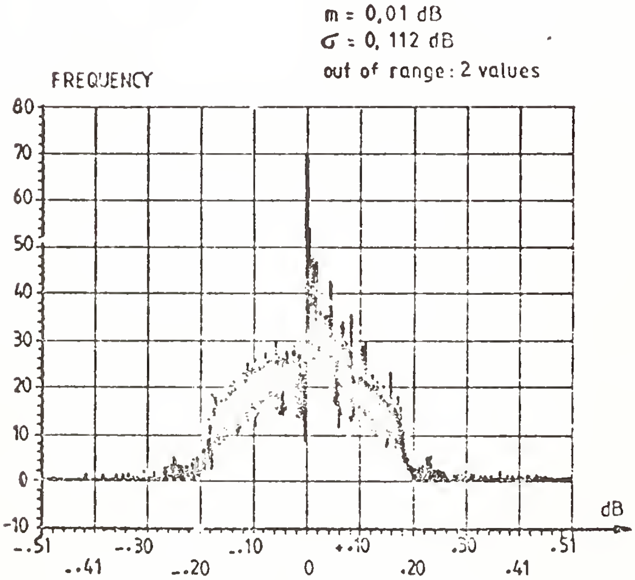
INS. LOSS DISTRIBUTION

fig. 1



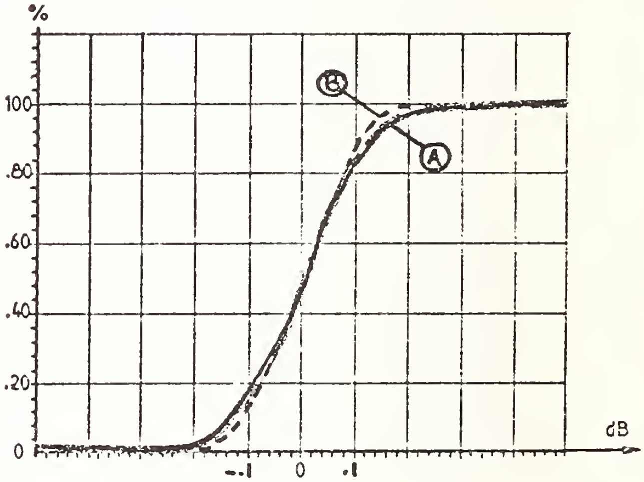
BKS. LOSS DISTRIBUTION

fig 2



DIFFERENTIAL BKS.-INS LOSS DISTRIBUTION

fig 3



CUMULATIVE DIFFERENTIAL LOSS DISTRIBUTION

fig. 4

Optical Cable Fault Location Using a Correlation Technique

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Abstract; Development is underway to realize practical application of optical fibers for optical communications in a low loss wavelength region (1.3 μm or 1.55 μm). Regarding optical cable fault location measured in the low loss wavelength range, the conventional isolated pulse method was inadequate for long-distance measurements because of the small light source power, lowered sensitivity of the light receiver, and feeble backscattering light. The technique described here using pseudo-random noise (PN) pulses has realized a long-distance measurement of 10 km in an optical cable of 0.8 dB/km in optical loss at 1.3μm wavelength.

1. Introduction

Optical cable transmission systems using optical fibers have begun to be put to practical utilization, and tests in the field are steadily underway.

In optical cable fault location using backscattering light, measurements over a distance of 8 km in an optical cable of 2.5 dB/km in optical loss are now possible at the 0.85μm wavelength. This is performed in the isolated pulse method using a pulse laser diode, which transmits isolated pulses from one end of an optical fiber to observe the light backscattered from the optical fiber. This performance is possible because a light source capable of a fiber input of +20 dBm and over and a received optical gain of 30 dB and over have been realized in the 0.85 μm wavelength band.

Nevertheless, the 0.85 μm band where the optical loss is large in optical fibers is not suitable for a long-distance communications system. For this reason, development is in rapid progress in communication systems in the 1.3μm and the 1.55 μm wavelength bands where the optical loss in optical fibers is at a minimum. In these wavelength bands, the repeater spacing may be extended to several tens of kilometers. If a light source and light receiver having capabilities equal to those used in the 0.85 μm are completed in the low loss wavelength bands, it would also be possible to perform by the isolated pulse method cable fault location up to several tens of kilometers.

In the present state of the art, however, compared with the level difference in the 0.85 μm wavelength band, low loss wavelength bands are lower by 30dB and more in the total value of the transmitting optical pulse power and the received optical sensitivity. Thus, it is difficult to perform measurements by the isolated pulse method.

The present paper describes the PN pulse method that permits long-distance measurements using currently available light sources and light receivers in the low loss wavelength bands.

2. Comparison of the PN Pulse Method with the Isolated Pulse Method

The simple isolated pulse method is inadequate for obtaining a sufficiently low S/N ratio. Therefore its S/N ratio is usually improved by averaging through sweeping and adding up the received signal on the time axis. On the other hand, in the PN pulse mehtod, the received signal is added up repeatedly at every delay time in a correlating process. Here the delay time corresponds to the fiber distance.

In the long wavelength band, the pulse laser diode is unable to produce a high power (a few watts) and is limited to certain repeated periods and pulse widths. The CW laser diode used for the PN pulse method, however, although small in power, has the advantage of setting the equivalent power, repeated period and pulse width in a wider scope by the M-sequence and auto-correlation technologies.

The correlator comprising only an analog switch and an analog integrator, thus far simpler in design, makes the PN pulse method superior to the isolated pulse method requiring an averager of a more complicated construction.

3. Principles of the PN Pulse Method

The M-sequence code from among the PN pulse code system is used as the correlating code since the auto-correlating function of the M-sequence code is a triangular wave and data can be transmitted continuously for correlating it with the data returned without causing errors by the omission of a portion of a pulse train in the time domain. The M-sequence code auto-correlation can be expressed by the following formula.

$$h(\tau) \propto \int_0^{NT} x(t) \cdot x(t-\tau)\, dt \quad \ldots\ldots\ldots\ldots \quad (1)$$

where $h(\tau)$: impulse response

T: the period of the PN pulse sequence

N: the number of the PN pulse sequence (averaging count)

$x(t)$: the PN pulse signal

τ: the delay time

The shorter the bit time of the PN pulse train, the higher the resolution of the distance but the lower the sensitivity. On the other hand, increasing T while fixing the bit time of the PN pulse train will increase the power. Increasing N of averaging in conjunction with increasing T will improve the sensitivity or the S/N ratio. But this improvement is limited by the measuring time which cannot be indefinitely prolonged.

A block diagram of the PN pulse method is shown in Figure 1. The output pulse from the oscillator is put into the frequency divider which determines the resolution of the measuring distance in the optical fiber.

The laser diode converts the delayed advance PN pulse signal from a electric level into an optical level. The light obtained by this conversion is sent through the directional coupler to the optical fiber and is returned as backscattered light to the directional coupler to be put into the APD.

The output correlated between the output of APD converted from an optical level into an electric level and the reference PN pulse signal is approximated to a signal pulse response. The averaging counter performs the averaging procedure by repeating the advance PN pulse signal of the same delay time. The correlator having a CR integrating circuit can very the gain.

4. Experiment

It is anticipated that a 20 km transmission is achieved in the 1.3 μm optical transmission systems and such systems will require a fault location capability of at least 10 km and possibly 20 km.

The feasibility of the PN pulse method was tested in an experiment carried out using a 10 km long fiber. Experimental parameters are shown in Table 1, and the backscattered level from the 10 km long fiber is shown in Figure 2. In Fig. 2, a Fresnel reflection from a fiber end-face is eliminated by using a refraction matched liquid. The results indicate that 10 km long fault location is obtainable.

Figure 3 shows a logarithmic conversion of the result obtained in Fig. 2.

5. Conclusion

A new optical cable fault location method is proposed. An experiment confirmed that a broken point 10 km distant from the source can be detected using a 1.3 μm wavelength. It is expected that the measuring distance can be extended through a few improvements as this low loss wavelength band in the optical fiber. The method is also effective for measuring fiber loss distribution.

6. Acknowledgement

The authors wish to thank Drs. S.SHIMADA and H.ISHIO for their great encouragement and beneficial discussion.

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(a) Fault Locator Parameters

Peak power of laser diode (within a fiber)	1 mW
Wavelength of laser diode	1.32 µm
Pulse repetition	250 kHz
Word length × N	255 × 64 bits

N: Number of averaging

(b) Fiber Parameters

Fiber loss at 1.32 µm wavelength (including splice loss)	0.8 dB/km
Outer diameter	150 µm
Core diameter	60 µm
Index profile	graded index

Table 1

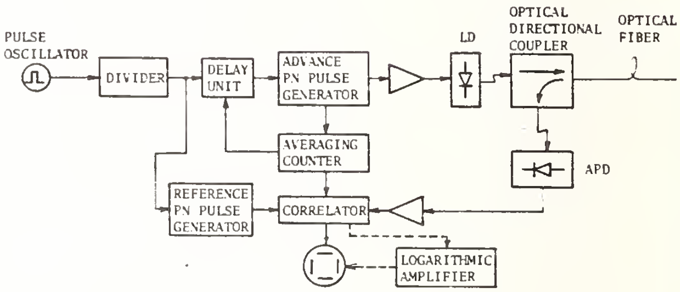

Fig. 1 Block diagram of the pseudo-random pulse method

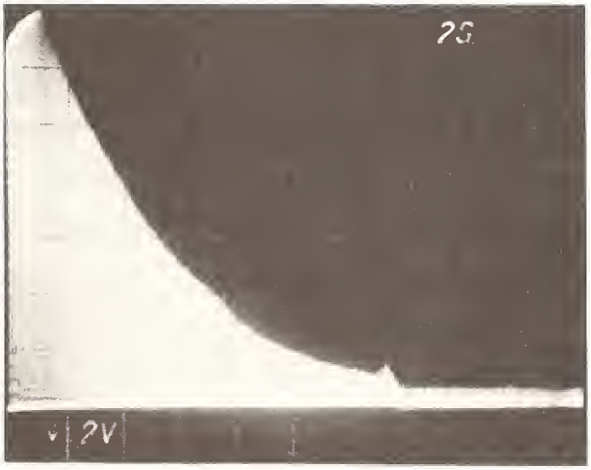

Fig. 2 Measured backscattered level from a 10 km long fiber

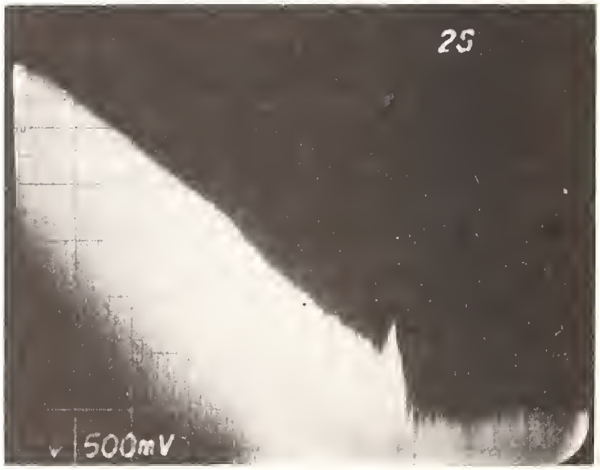

Fig. 3 Logarithmic conversion (3 dB/div.)

OPTICAL TIME DOMAIN REFLECTOMETRY BY PHOTON COUNTING

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Introduction

At the 1979 IEEE Workshop on Fiber Optic Measurements, we expressed doubt that OTDR or "backscatter" would ever have sufficient range to penetrate a full repeater section because of launch power limitations and the necessary dynamic range of the apparatus. Analogue signal recovery techniques appeared then to limit the range to about 25 dB of one-way fibre loss. A law of rapidly diminishing returns applies to any straightforward method of increasing the sensitivity, e.g., averaging a larger number of samples. However, we can now report a substantial improvement in the range of OTDR achieved by using a photon counting technique. We have succeeded in locating non-reflecting fibre breaks through one-way attenuations exceeding 40 dB and we believe there is scope for further progress. When there is a reflection associated with the break, the range already exceeds 50 dB which is sufficient for many fibre systems.

The Photon Counting Technique

When an avalanche photodiode is operated in a "Geiger tube" breakdown mode, it is biassed above its normal operating voltage and breakdown may be initiated by a single photon (1,2). In our case for example, an RCA C30902E has a normal room temperature operating bias of 203 V. The avalanche gain over the active area of the diode is not uniform and gradually increasing the bias beyond 203 V causes some regions of the surface to approach breakdown before others. The number of regions above breakdown grows with increasing bias until complete breakdown occurs at 211 V. At intermediate voltages, bulk leakage causes local breakdown and a compromise must be found between the ease with which an area of high sensitivity can be located and the background count rate. The time constant made up of the device capacitance and the external load acts as a quenching circuit by causing the bias voltage to fall temporarily below the breakdown level after a pulse. It is this time constant, rather than the input pulse length, which determines the output pulse length and hence the 25 m resolution of the apparatus.

Experimental Apparatus

Figure 1 shows a schematic diagram of the apparatus. Much of it is conventional - the distinctive features of the apparatus lie in the signal processing area. The digital delay generator triggers the laser and generates two pulses which gate the input to a counting circuit. The first pulse can be stepped through the period of the return signal thus admitting photon counts and background (leakage) counts to the processor. The second pulse admits background only. Photons can then be counted by computing the running difference between these two rates. When a count of sixteen is reached, the sampling interval moves to the next point and thus automatically progresses at a rate determined by the signal strength. As the fibre end is passed, the count rate drops sharply and the dwell time at each point rises correspondingly. Because of statistical fluctuations in the leakage, counts continue to be recorded after the fibre end, but provided that the dwell time increases by a factor of two or three, the end is readily located.

Experimental Results

Figure 2 shows the result of an experiment to locate the end of a fibre with an attenuation of 33 dB at 850 nm. The core diameter was 40 μm, the numerical aperture was 0.18 and the distant end was refractive index matched to suppress any reflection. Beyond the fibre end, the dwell time rises by a factor of more than fifty. Figure 3 shows the result of a similar observation made on the same type of fibre but with an attenuation of 40.5 dB. Here, the average dwell time rises by a factor of about three which is still clearly discernible.

Conclusion

The photon counting approach greatly extends the range of OTDR. It also leads to a considerable simplification of the necessary electronics through the application of digital techniques.

Further improvements appear possible by cooling the avalanche photodiode and by optimising the number of photon counts before stepping the sampling interval. Cooling a photodiode reduces the leakage current and thus permits a higher bias voltage. This increases the detection probability and eases optical alignment problems by increasing the useful area of the device. It may also be possible to dispense with the wideband transimpedance amplifier used at present. The optimum number of photon counts made at each sampling point may differ from the current sixteen which is a convenient and somewhat arbitrary number. Theoretical investigations are in progress.

It is hoped to report on both these points at the Symposium.

Acknowledgement

The authors would like to thank the Director of the British Telecom Research Department (part of the Post Office) for permission to present this paper.

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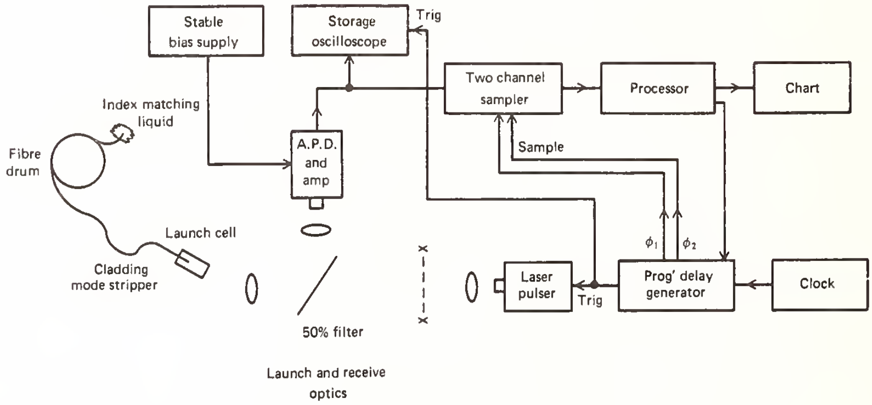

Figure 1: Schematic diagram of the apparatus

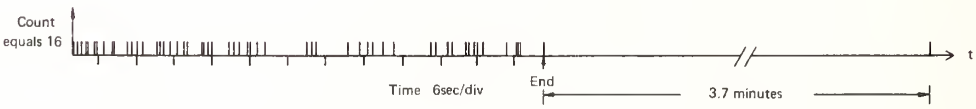

Figure 2: Dwell time for 16 counts with 33 dB of fibre loss

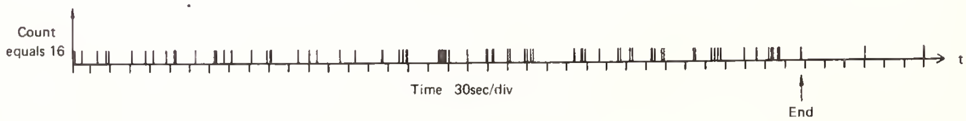

Figure 3: As above with a one-way fibre loss of 40.5 dB

CHARACTERISATION OF SINGLE MODE FIBRES

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INTRODUCTION:- We report various loss, dispersion and index profile measurements on single mode fibres and show how the dispersion and mode cut-off predicted by the profile agree with the experiment.

LOSS:- The spectral attenuation, measured by the insertion loss method, is presented in fig. 1. While the fibre used for this set of measurements has a minimum loss of 0.75 dB/km, more recent fibres have significantly lower losses [1]. The crosses on fig. 1 represent the absorption component of the total attenuation. This was measured calorimetrically [2] using Krypton and Yag lasers. The absorption was lowest (0.24 dB/km) at 1.06 μm. The apparatus has the sensitivity to measure less than 0.05 dB/km per Watt of guided power. The difference between total loss and absorption gives the scatter loss - shown by the dots on fig. 1. By plotting the same data against λ^{-4}, fig. 2, the basically Rayleigh nature of the scattering is revealed. There is less than 0.1 dB/km of wavelength independent scatter beyond 1 μm. Thus, the total loss is determined and resolved into absorption, Rayleigh scatter and wavelength independent scatter.

MODE CUT-OFF:- The insertion loss apparatus can also be used to indicate mode cut-offs. The transmission of a short length of fibre with a tight bend is compared with that of the same fibre when straight [3]. The LP_{11} mode cut-off peaks around 870 nm - fig. 3. The feature on the total attenuation plot at this wavelength is thus verified as due to the mode cut-off.

DISPERSION:- The dispersion of a single mode arises from the material and waveguide properties of the fibre. Also, any deviation from cylindrical symmetry will lift the mode degeneracy giving two orthogonally polarized modes. This intermodal dispersion was measured using the 1.06 μm mode-locked pulse train from a Yag laser. The spectral width of this laser line is sufficiently small for the material and waveguide dispersion to be neglected. For a 6 km section fibre, the mean $\frac{1}{e}$ input and output pulse widths were measured at 185 ps and 195.8 ps by a GaInAs photodiode. Deconvolution yields 11 ps/km as the monochromatic impulse response of this fibre.

A pulsed tunable source for group delay measurements can be obtained by employing the stimulated Raman effect [4]. We have used a single pass of the 1.06 μm mode-locked, Q-switched line through 300 m of single mode fibre [5]. The output from this fibre is passed through a monochromator, into the test fibre and onto a photodiode. The variation of group delay with wavelength is presented in fig. 5. A linearised Sellmeier equation was used to obtain the fitted curve. The derivative of this gives the wavelength of minimum dispersion as 1.37 μm. These two dispersion measurements give the wavelength of minimum dispersion and the value of that minimum.

INDEX PROFILE:- The refracted near field technique [6] is ideal for single mode fibres as it is simple and direct. The profile of this fibre is shown in fig. 6. The diameter is 100 μm and the core FWHM is 6.7 μm. As the profile is obtained across the full diameter, the fibre geometry can be checked. The absolute index difference across the core is also obtained. One limitation to the spatial resolution is the point spread function of the focus of the, effectively, annular aperture lens used. This can be deconvolved from the measured profile by a newly developed [7] two-dimensional Fourier transform process.

THEORETICAL PREDICTIONS:- Only a small approximation is involved in treating the profile as a step of diameter 6.7 μm and index difference 0.00347. These values predict a LP_{11} mode cut-off at 870 nm in good agreement with the experiment. The fibre dispersion can be obtained approximately from the material dispersion of silica and the waveguide dispersion for this profile [8]. The circles on fig. 5 are the theoretical points. The agreement is very good for an approximate model. This is because including the effect of different core and cladding material dispersion would increase the wavelength of minimum dispersion by 7 nm while the deviations from a step profile have the opposite effect [9].

ACKNOWLEDGEMENTS:- Acknowledgement is made to B J Ainslie, K J Beales D Colthorpe and C R Day for providing the fibre, to C J Todd for supporting discussions and to the Director of the British Telecom Research Laboratories for permission to publish this paper.

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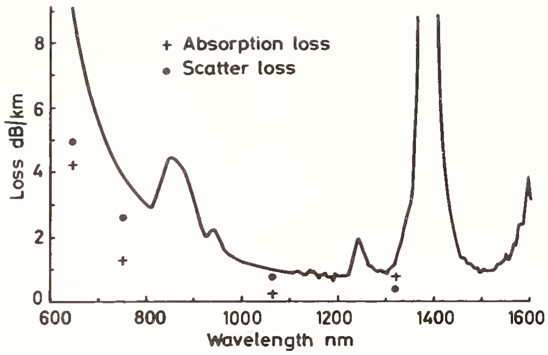

Fig. 1. Fibre loss

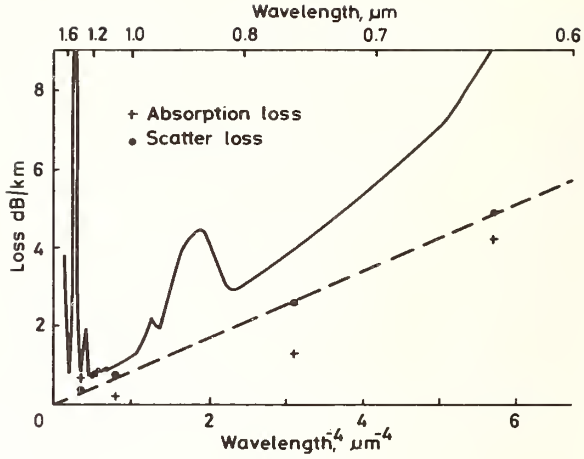

Fig. 2. Fibre loss

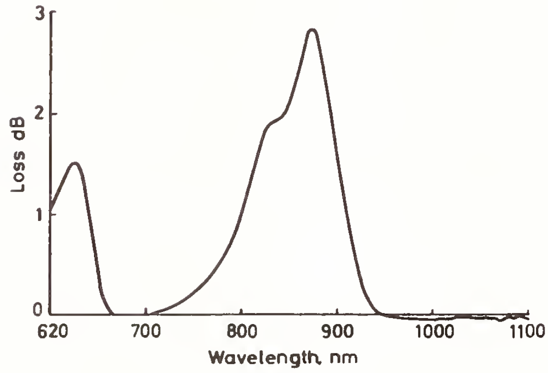

Fig. 3. Mode cut - off

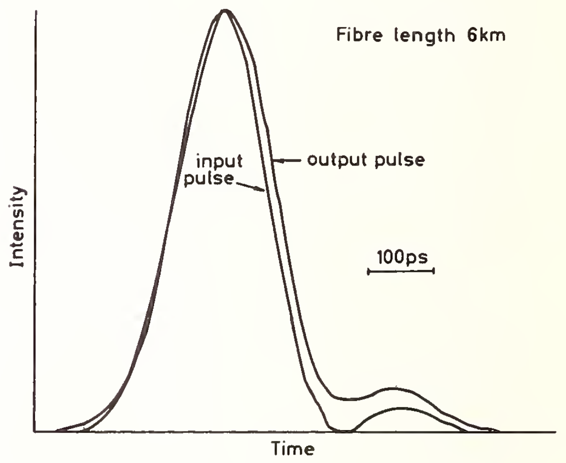

Fig. 4. Monochromatic impulse response

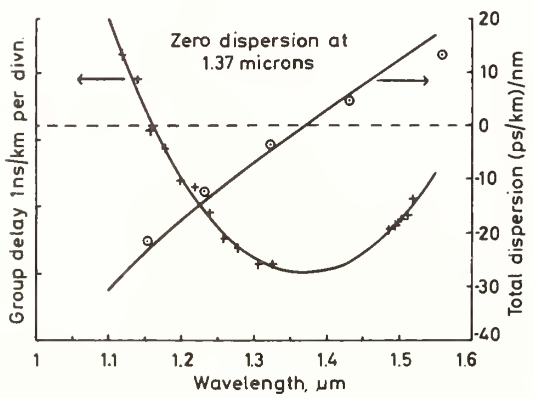

Fig. 5. Fibre group delay and dispersion

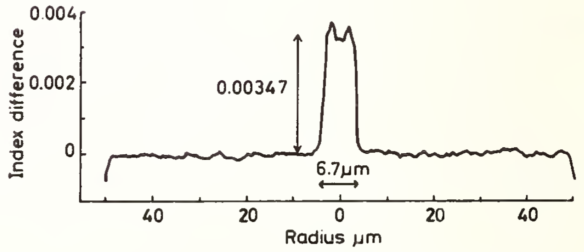

Fig. 6. Single mode fibre profile

Effect of Curvature on the Cutoff Wavelength of Single Mode Fibers

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A very simple procedure for the determination of mode cutoff wavelengths in low mode number fibers has been developed. This technique has been used to study the sensitivity of mode cutoff to preform processing conditions and to various external perturbations on the fiber.

The measurement technique involves plotting the power transmitted through a fiber as the wavelength of the light is increased. Mode cutoff is indicated by a rapid decrease in detected power. Figure 1 shows how the second mode group cutoff wavelength, λ_c, is identified with the intersection of the slope of the power decrease with the power curve in the single mode region. Fiber lengths from 100 cm to 1000 m have been used for determining λ_c. The uncertainty in λ_c is $\pm.002$ μm.

We have studied how λ_c behaves when curvature is introduced in the fiber. Figure 1 shows a family of cutoff curves made as the radius, R, of a single loop in the fiber is decreased from 80 mm (curve g) to 7.5 mm (curve i). Increasing curvature, R^{-1}, caused λ_c to shift rapidly to shorter wavelength. Figure 2 shows the dependence of λ_c on R^{-1}. The solid curve is the best fit of the function $\lambda_c = \lambda_c^{\infty} + A\,R^{-1} + B(R^{-1})^2$ to the data. Here λ_c^{∞} is the value of λ_c in a perfectly straight fiber, and A and B are two additional fitting parameters. This data shows how shifts in λ_c can be used to measure fiber curvature introduced during coating, jacketing and cabling of single mode fibers. Also it is clear that any technique that measures λ_c by use of fiber curvature will contain a significant error introduced by the curvature.

In this talk we will discuss our measurements of λ_c and higher mode group cutoff, the curvature sensitivity of λ_c, the use of λ_c to test for fiber index and geometry uniformity, and the use of λ_c as a diagnostic for curvature introduced during fiber processing.

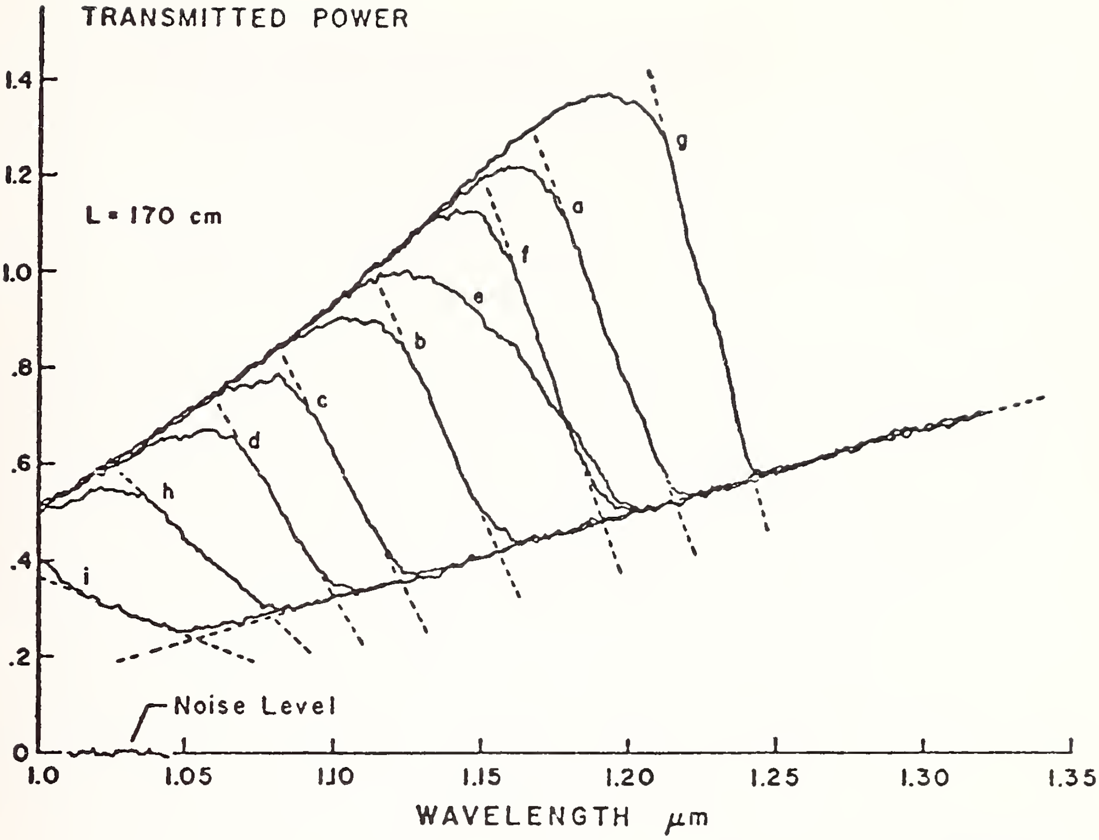

FIGURE 1

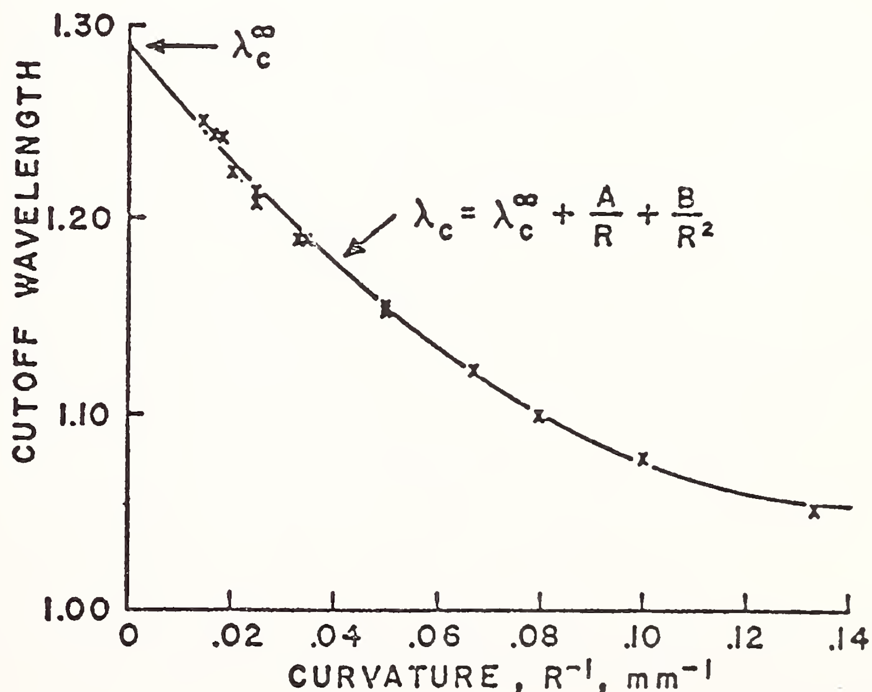

FIGURE 2

Optical Time Domain Reflectometry on Single Mode Fibers Using a Q-Switched Nd:YAG Laser

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In investigating loss mechanisms in optical fibers, it is important to know how the loss is distributed along the fiber length. Identifying a high loss region aids in the diagnosis of fiber manufacturing problems and, in addition, may make it possible to salvage a usable length of lower loss fiber. The optical time domain reflectometer (OTDR) has been used in the past for this purpose, but only with multimode fibers.

The aim of this study is to extend optical time domain reflectometry to single mode fibers. Because of their lower numerical aperture, single mode fibers capture much less Rayleigh backscatter than multimode fibers. The half width at half maximum, θ_m, for the far field pattern of a graded index multimode fiber of maximum index difference $\Delta = (n_2 - n_1)/n_1$ is given by $\sin \theta_m \approx n_1 \sqrt{2\Delta}/2$. The corresponding propagation angle inside the core is $\arcsin\sqrt{\Delta/2}$, which is 4.6° for $\Delta = 0.013$. The half width at half maximum for the far field pattern of the HE_{11} mode in a single mode fiber of core radius 5 μm and normalized frequency $V = 2.27$ is[1] $\theta_h = 1.29°$ at a wavelength of 820 nm. This corresponds to a propagation angle of 0.89° inside the core of the fiber, assuming the refractive index to be 1.45.

Assuming equal source-fiber coupling efficiencies for the two fibers, equal Rayleigh scattering coefficients, and isotropic backscatter, the ratio of the solid angles within θ_h and θ_m will be the ratio of the backscattered signal powers in single and multimode OTDRs. Since $(0.89°/4.6°)^2 = 0.037$, the decrease in backscattered power from multimode to single mode fibers will be 14 dB at 820 nm under these assumptions.

Most OTDRs using GaAlAs lasers are only able to perform loss measurements over about 15 dB of one-way fiber loss. On the basis of the above calculation, there is little hope of making a single mode fiber OTDR with a GaAlAs laser. In practice the coupling efficiency into single mode fibers is less than for multimode fibers, so that the situation becomes even more hopeless.

In order to increase the amount of power launched into a single-mode fiber, a Q-switched Nd:YAG laser was used as the source. This laser emits up to 6 watts of power in a CW mode or up to 12 KW of power in a Q-switched mode at 1064 nm. The experimental arrangement is illustrated in Figure 1. At high power levels, it is possible to produce stimulated Raman gain in both single-mode[2] and multimode[3] optical fibers. It was possible to observe this effect in the fibers studied here by a splitting of the return pulse as the power level was increased. The onset of stimulated Raman gain represents an upper limit on the amount of power which may be coupled into a fiber for OTDR purposes. A variable attenuator was used to reduce the laser intensity to a point below the onset of stimulated Raman gain. The pulse rate was set at 500 pps and the laser was operated well above threshold in order to have stable laser output pulses. The backscattered radiation was signal averaged on a digital processing oscilloscope and plotted on an HP-9862 plotter.

The decay in dB for a single-mode fiber is plotted in Figure 2. This fiber shows a fairly uniform decay with no gross imperfections. Taking half the slope yields a loss of 4.95 dB/km along the length of the fiber. The standard two-point loss measurement gave 10.3 dB/km. Two hundred meters were then removed from the far end in Figure 2 and the two-point loss dropped to 5.2 dB/km, in reasonably good agreement with the value measured by OTDR. Removing subsequent sections of the fiber did not change the loss within the error of the two-point loss measurement.

While the present system is not optimized, it demonstrates that useful OTDR data can be obtained on single mode fibers with a Q-switched Nd:YAG laser at 1064 nm. A 1.5 km single-mode fiber with greater than 30 dB round trip loss was studied and a high loss region identified. Thus a useful dynamic range is achievable below the threshold for nonlinear effects.

Since splice loss is essentially wavelength independent, this instrument may also be useful for characterizing splices.

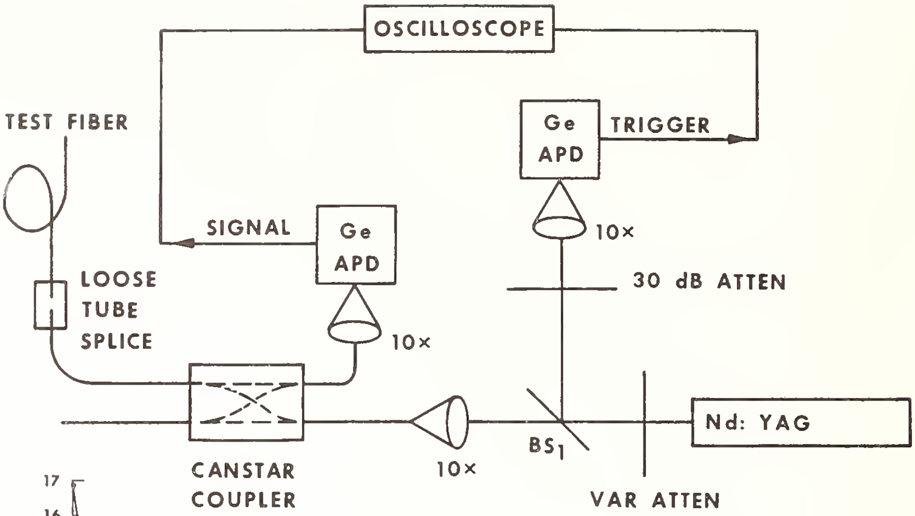

FIGURE 1

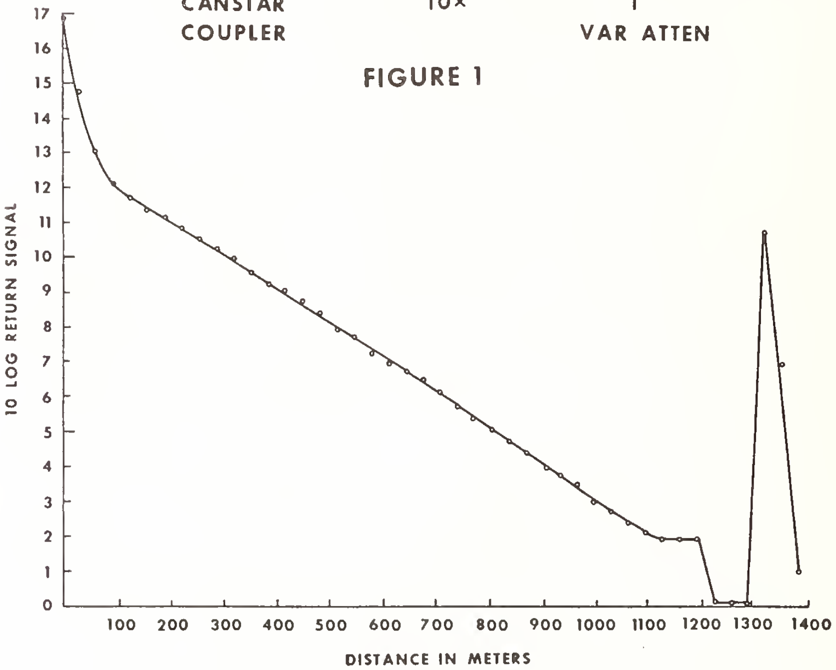

FIGURE 2

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INTERFEROMETRIC TECHNIQUE FOR THE DETERMINATION OF DISPERSION IN A SHORT LENGTH OF SINGLE MODE OPTICAL FIBER

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The typical methods of measuring the dispersion of single mode optical fibers are the pulse broadening technique[1] and the pulse delay technique.[2] Both of these methods require the use of sophisticated techniques for the generation and detection of very short temporal duration optical pulses. These methods also require relatively long lengths of single mode optical fiber, typically on the order of a kilometer.

In this paper we present an interferometric technique for measuring the dispersion of single mode optical fibers. This method utilizes a Michelson interferometer, a broad spectral width C.W. source and a short length of single mode optical fiber located in one arm of the Michelson interferometer.

The use of a wide spectral width semiconductor laser to illuminate the interferometer results in a series of narrow peaks in the envelope of the interferogram. The addition of the dispersive fiber into only one arm of the interferometer results in a broadening of the width of the peaks in the envelope of the interferogram. Measuring the width of the interferogram peaks, both for the case with the fiber in the interferometer and for the case without the fiber, allows the total dispersion of the optical fiber to be determined. The amount the peaks are broadened is a function of the dispersion of the fiber and the spectral width of the laser. The complicated spectral content of the multimode semiconductor laser results in difficulties in interpreting the interferograms, but a relatively simple model of the spectra yields a reasonable approximation to the interferograms obtained. An example of the central interferogram peaks obtained for the laser operating with a spectral width of 4 nm and the optical fiber of length 1 m is shown in Figure 1. Figure 1.a shows the central interferogram peak without the fiber in the system, the full width at half maximum corresponds to a path length variation of 80 μm. Figure 1.b shows the central interferogram peak with the fiber in the system, the full width at half maximum corresponds to a path length variation of 200 μm.

The semiconductor laser used was multimode and emitted at 0.87 μm. The spectral width was dependent upon the drive current and was capable of being varied between approximately

2.5 nm and 5 nm, this range allowed the convenient use of fibers from 0.2 m to 1 m in length. The fiber used had an 8 μm diameter core and approximately a 0.8 μm cutoff wavelength for single mode operation. By the interferometric technique outlined, the second derivative of the longitudinal wave number with respect to frequency was determined to be approximately 1.22×10^{-24} sec^2/m at 0.87 μm. This corresponds to a temporal pulse broadening of 77 psec/nm-km.

In conclusion an interferometric technique has been developed to measure the dispersion of single mode optical fibers. This technique is characterized by the use of a Michelson interferometer, a broad spectral width C. W. source and a short length of single mode optical fiber.

Acknowledgment:

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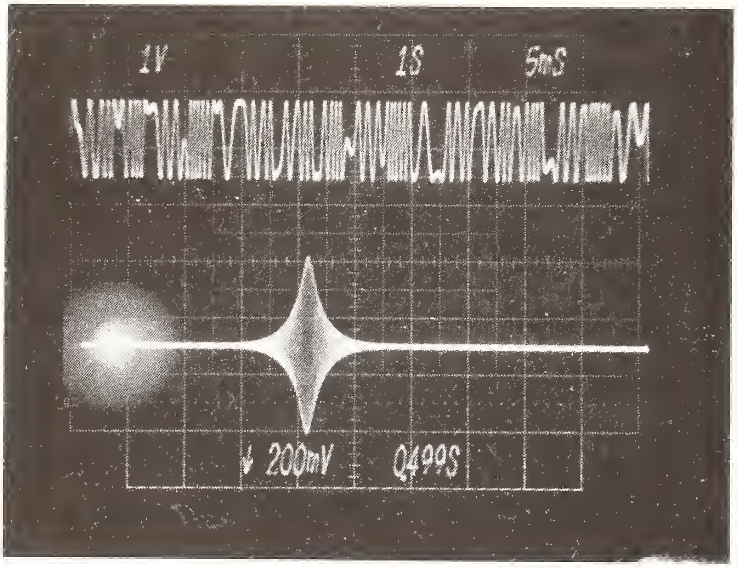

FIG. 1a. Interferogram obtained without fiber in the system.
Upper Trace: .633um laser reference interferogram.
Lower Trace: .87um laser interferogram.

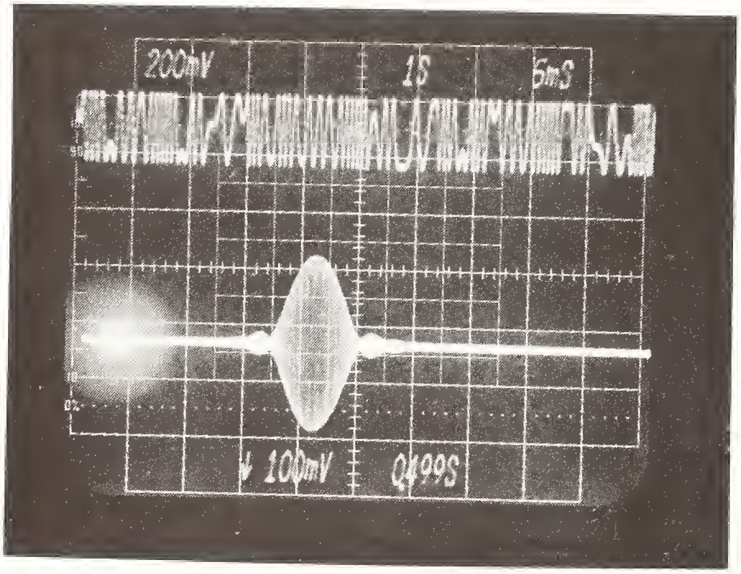

FIG. 1b. Interferogram obtained with the fiber in the system.
Upper Trace: .633um laser reference interferogram.
Lower Trace: .87um laser interferogram.

INDUSTRIALIZED SYSTEM FOR THE AUTOMATED MEASUREMENTS OF THE OPTICAL PROPERTIES OF WAVEGUIDE FIBERS.

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INTRODUCTION

This paper describes an automated Quality Assurance Measurement System designed for production testing of optical waveguide fibers. The system utilizes a mini computer capable of operating a number of optical measurement stations. The measurement philosophy used assures data reliability with built in checks of measurement conditions and precision.

The thru-put requirement is in excess of 4 fibers per hour per station depending on the type of fiber being characterized, i.e., double window graded index fiber, single window graded index fiber, or short distance fiber.

The measurement techniques that have been implemented utilizes Corning Glass Works preferred launch and measurement conditions[6] including limited phase space launch conditions for attenuation measurements[2] and mode scrambled launch conditions for optical bandwidth measurements[3,8].

QUALITY ASSURANCE PHILOSOPHY AND MEASUREMENT CONDITIONS

It is current policy to assure adherence to waveguide fiber specification by measuring all production fibers. This automated measurement system was designed to perform this function with high thru-put and no operator interaction or adjustment of the measurement equipment. Calibration checks are done every four hours with known fibers in addition to the system's built in continuous self checks. The results of the measurement of the known fibers are corrected for any length dependency and compared against 95% confidence limits knowing the measurement uncertainty.

ATTENUATION RATE

The attenuation rate of the fiber under test is determined by the two point method[1] with the addition of the limited phase space launch conditions recently developed[2,4]. A narrow spectral band of light with spot size 70% of the nominal core diameter and 70% of the nominal N.A. are launched into the long length of fiber and the transmitted intensity measured. The measurement is repeated for the first two (± 0.5) meters of the same fiber using the same launch conditions and without disturbing the input end of the fiber. The fiber is wrapped on a suitable measurement spool and optical interference filters with spectral width of 10 nanometers are used for this measurement.

OPTICAL BANDWIDTH

The optical power bandwidth of the waveguide is determined by measuring the pulse-broadening characteristics of a full length of fiber. An approximate 300-picosecond (FWHM) pulse of light is launched into the fiber, and the output pulse is Fourier transformed into the frequency domain. The Fourier spectrum of a reference input pulse -- determined from a standard two-meter length of fiber -- is analytically deconvolved from the Fourier spectrum of the output pulse by dividing the output frequency spectrum by the reference frequency spectrum. The frequency at which the amplitude of the deconvolved spectrum drops three decibels, relative to the zero frequency component, is the bandwidth of the fiber. The fiber is wrapped on a suitable measurement spool and semiconductor lasers with spectral width of 2.1 nanometers (FWHM) and center wavelength of 850 and 1300 nanometers are used.[6] In addition, the temperature of each laser diode is controlled to ±0.1°C to ensure short term stability.

NUMERICAL APERTURE

The numerical aperture of the waveguide is calculated from the far-field optical power distribution (watts/sr) exiting from two (± 0.5) meter of fiber[5]. Launch conditions are: constant radiance, numerical aperture of .55, spectral width of 25 nanometers and center wavelength of 850 nanometers.[6]

CORE DIAMETER

The core diameter of the waveguide is calculated from the near-field optical power distribution exiting from two (± 0.5) meters of fiber[5]. Launch conditions are: constant radiance, numerical aperture of .55, spectral width of 25 nanometers and center wavelength of 850 nanometers.[6]

SYSTEM DESCRIPTION

The overall measurement system is shown in Figure 1. A multi-user mini computer is used to control multiple stations. This required some off loading of repetitive functions, two examples of which are control of stepper motors by preset indexers and data collection for bandwidth measurement by Tektronix Digital Processing oscilloscopes. The computer consists of a Digital Equipment Corp. 11/34 computer with Industrial Control Subsystem Process I/O and high speed digital and analog inputs and output. It is possible to control up to 6 stations by a single mini computer with the advantage of sharing the cost over multiple stations.

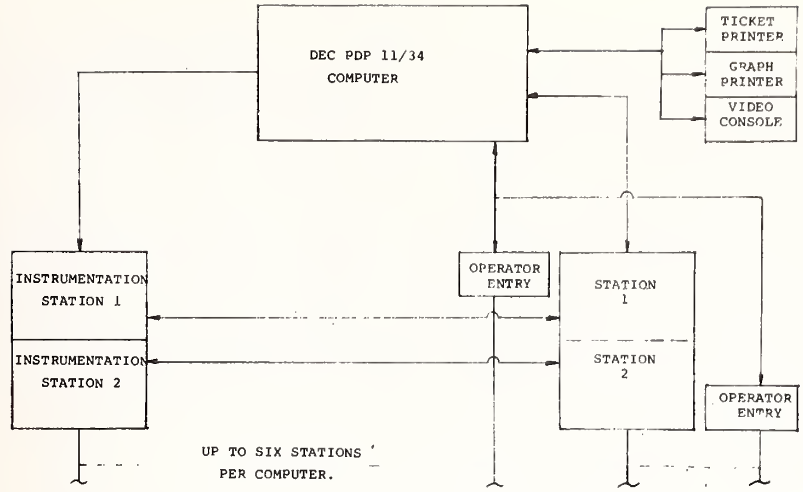
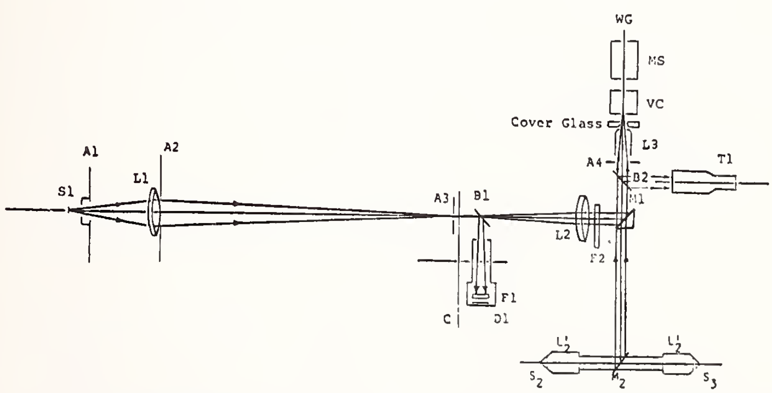


FIGURE 1 - OWG QUALITY ASSURANCE MEASUREMENT SYSTEM

The system is composed of the 11/34 computer and the following major subsystems for each station: Source and Launch Optics, receive and detection optics, instrumentation and detection electronics, operator interface and fiber end preparation machine[8].

SOURCE AND LAUNCH OPTICS, Fig. 2

Light from both an incandescent tungsten source, S_1 and two pulsed injection lasers, S_2 and S_3 are launched into the fiber under test.



S1	Tungsten Source	F1	Long-Pass Filter	M2	Launch Rotating Mirror
A1	Source Apertures	L2	Collimator Lens	S3	Laser Source 1300 nm
L1	Condenser Lens	F2	Filters on Wheel	VC	Vacuum Chuck
A2	Condenser Aperture	M1	Launch Selector Mirror	S2	Laser Source 850 nm
A3	LPS Aperture Wheel	B2	Beam Splitter	MS	Mode Stripper
C	Chopper	A4	Aperture Wheel	WG	Waveguide
B1	Beam Splitter	L3	Launch Lens	T1	Visible Light Telescope
D1	Source Monitor Detector			L2	Laser Condenser

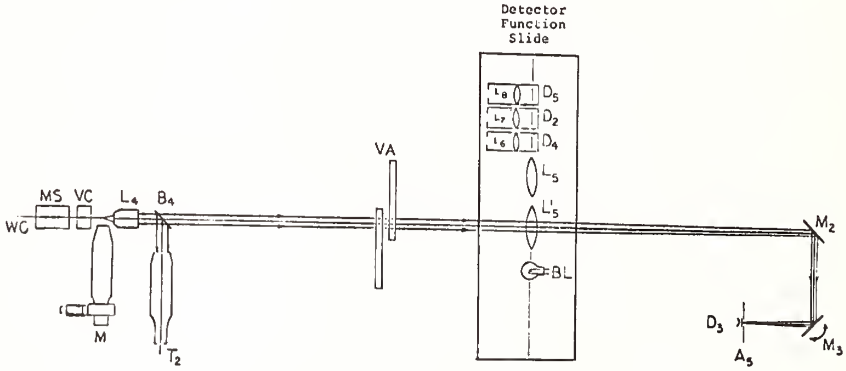
Figure 2: Source and Launch Optics

A magnified image of a tungsten filament is constructed on the Limited Phase Space Aperture Wheel, A_3. Lens L_2 collimates the tungsten light and Filter Wheel F_2 permits selection of various single wavelengths filters.

The Launch Selector Mirror, M_1, folds the tungsten light toward the Launch Lens, L_3, which is used to image tungsten and pulsed laser light onto the fiber under test. The Aperture Wheel, A_4, permits selection of the launch numerical aperture. The test fiber is held in the Vacuum Chuck, VC, and is positioned properly by means of XYZ adjustment. Telescope T_1 aids in alignment.

DETECTION AND RECEIVE OPTICS, Fig. 3

The output end of the test fiber is held in Vacuum Chuck, VC, and is positioned with XYZ adjustments until properly aligned. The Telescope, T_2, and Microscope, M, aid in the fiber alignment.



WG - Waveguide	D_2 - Attenuation Detector (820-1060)	D_5 - Attenuation Detector (1300)
MS - Mode Stripper	M_3 - Scanner Mirror	VA - Variable Attenuator
VC - Vacuum Chuck	A_5 - Detector Pinhole	L_6 - Pulse Detector Lens
L_4 - Projection Lens	D_3 - Near-and-Far Field Detector	D_4 - Pulse Detector
L'_5 - Near Field Lens	M - Visible Light Microscope	BL - Back Light
L_5 - Far Field Lens	B_4 - Beam Splitter	M_2 - Folding Mirror
L_7 - Attenuation Lens	L_8 - Attenuation Lens	T_2 - Visible Light Telescope

Figure 3: Detection and Receive Optics

Light from the test fiber is collimated and projected by the Receive Lens, L_4, toward the Detector Function Slide, DFS. The DFS moves perpendicular to the optical axis, and contains: two attenuation detectors, a germanium APD for bandwidth measurements, a near field and a far field lens.

Far Field and Near Field Measurements are performed as previously reported[5].

The Variable Attenuator, VA, automatically scales the amplitude of the pulsed laser signals for bandwidth measurement.

DETECTION ELECTRONICS, Fig. 4

The Analog Detection Electronics is accomplished as shown in Figure 4.

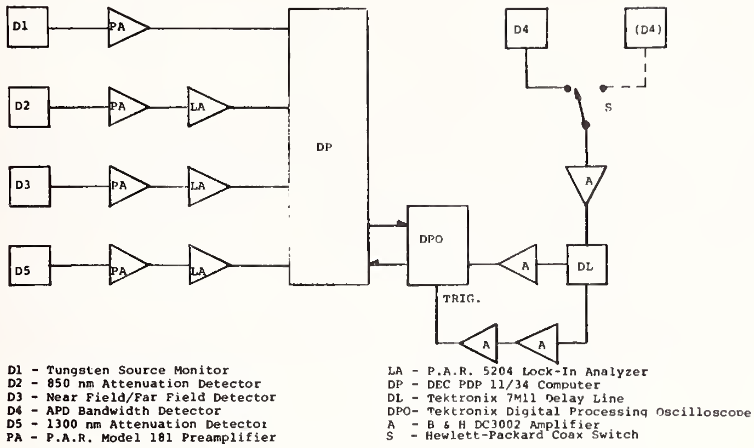


FIGURE 4 - DETECTION ELECTRONICS

The Bandwidth Signal Acquisition is done with a Tektronix Digital Processing Oscilloscope. A coax switch, S_1, is used to share one oscilloscope for each pair of measurement stations, both located on the same optical bench. The DPO digitizes and averages the time domain pulse data before sending it to the DEC 11/34.

Data Acquisition software provides the control for automatically performing the required measurement. Since multiple tables are in operation simultaneously on the same controller, the multi-programming executive RSX-11M was chosen as the operating system. Application programs in Fortran IV were developed to control the measurements.

MEASUREMENT PROCEDURE

Fiber ends are prepared by removing any coating and are scribed and broken with the end preparation machine[8]. The operator is directed through the set up of the fiber by the computer.

The input waveguide face is optically aligned and the end quality is visually examined using telescope T_1. If any damage extends into the core, a new end is prepared and this step is repeated. The output waveguide face is aligned by using telescope T_2 and microscope M_1, respectively. With this arrangement, the fiber end can be positioned with a precision of about one micron.

The fiber length is entered into the operator panel and the automatic sequence begins. At the proper time the operator is directed to repeat the set up for the short length measurements.

ATTENUATION RATE

The transmission data at the desired wavelength is recorded by measuring the intensity multiple times. All intensity measurements of lock-in amplifiers are divided by the output of the source monitor detector. These measurements are averaged and the long length intensity is stored.

The output fiber end is removed and the waveguide is broken two meters from the input stage and a new end is prepared, mounted in the output stage, and aligned as before without disturbing the input end. The above steps are repeated and the short length intensity is obtained.

The logarithm of the intensity ratio between the long length and short length is calculated and normalized to 1000 meters.

BANDWIDTH

The detector output is displayed on the digital processing oscilloscope (DPO) for each station and the pulse amplitude is adjusted by a computer algorithm. The DPO is commanded to collect and average a large number of samples. The average value of the first 25 points is used to establish a base reference level corresponding to zero light intensity. The Fourier transform of this data is determined using a Fast Fourier transform.

The optical power frequency spectrum of the fiber is calculated by dividing the output pulse frequency spectrum by the reference frequency spectrum. The frequency corresponding to one-half of the magnitude of the zero frequency is the optical power bandwidth.

RESULTS AND PERFORMANCE

Qualification tests conducted in conjunction with other CGW laboratories using waveguide fibers have shown good correlation. This measurement system with multiple stations has met or exceeded all design parameter and expectations. It has proven to be highly reliable, with minimum downtime.

ACKNOWLEDGEMENT

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Wavelength Meters for Optical Cable Transmission Systems

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1. Introduction

With the recent progress of optical transmission technology, optical cable transmission systems have come into practical use. In field tests of optical transmission systems, optical measurement equipment,including a wavelength meter and an optical spectrum analyzer, are required to be miniaturized, simply operated and portable.

Normally, peak wavelength of a light source is measured by a monochromator. In this paper, we propose two new types of wavelength meters, which can read wavelength directly by using an interference filter or a quartz rotator. We also describe a commector launching optical spectra analyzer manufactured for measuring plural wavelengths and spectra of light sources.

2. A-type Wavelength Meter

An interference filter is used in the A-type wavelength meter. The ratio of transmitted power to reflected power depends on the wavelength of the input light source.

Fig.1 shows the scheme of the A-type wavelength meter, and Fig.2 shows the characteristics of the interference filter in use. In Fig.1, light from an optical connector is collimated, and input into the interference filter, then the ratio of transmitted power to reflected power indicates the wavelength required. However, when using the interference filter shown in Fig.2 without linearlity compensation, measurement error is caused by the nonlinearlity of the filter. Thus a ROM is used to correct the measurement error.

Fig.3 shows measurement error against input optical power in the A-type wavelength meter. In the A-type wavelength meter manufactured, we have realized a measurement error of ± 1 nm in the 810-890 nm range. Measurable minimum input power is -40 dBm at the 850 nm wavelength.

Moreover, the A-type wavelength meter can measure the input optical power by summing up the reflected optical power and the transmitted optical power of the interference filter. Additionally, when this measurement equipment is used as a power meter, it can detect optical power in the -40 $\sim$ 0 dBm range.

3. B-type Wavelength Meter

In the A-type wavelength meter, wavelength can be measured only in a 100 nm range which is limited by the characteristics of the interference filter. As a result, we recommend the B-type wavelength meter, where the quartz rotator is used instead of the interference filter, for a wider wavelength measurement. This is because the rotation characteristics of the quartz rotator are dependent on the wavelength.

Fig.4 shows the schema of the B-type wavelength meter. In this experiment, the B-type wavelength meter operates in the minimum level detection mode to avoid measurement error that is caused by input power variance. Consequently, wavelength can be measured, where the optical output power is minimized, by rotating the analyzer angle. Fig.5 shows the characteristics of the quartz rotator in use. In this figure, the solid line gives the characteristics in the 600-1200 nm range, and the broken line gives the characteristics enlarged in the 800-900 nm range. Since the quartz rotator has good linearlity in the LED's spectral width range, the peak wavelength of the LED can be measured. At this point, the B-type wavelength meter has wide application in comparison with the A-type wavelength meter, apart from resolution.

Fig.6 shows some measurement examples by using the B-type wavelength meter. This figure shows the analyzer output level against the analyzer rotation angle, when beams of LD or LED are input into the polarizer. This figure also indicates that the peak wavelength of either LD or LED is measured with good resolution.

4. Optical Spectrum Analyzer

In wavelength division multiplexing transmission systems, where more than two different wavelength lights are launched into an optical fiber, each wavelength must be measured. Moreover, in high speed transmission systems, spectral bandwidth of a light source must be known in order to grasp the material dispersion. Therefore, we have studied and manufactured a curve-tracer-type optical spectrum analyzer, which is adaptable to an optical connector.

Fig.7 shows the scheme of an optical spectrum analyzer, and Fig.8 shows theoretical resolution value against the slit width. The longer the collimating length, the better the resolution. However, the length is limited by the equipment size. The resolution requirement is determined by the longitudinal mode space of LD, which is 0.2 $\sim$ 0.3 nm. For example, if the resolution is required within 0.1 nm for a graded index fiber of 50 μm diameter core, the collimating length requirement is more than 500 mm. LD's spectrum is shown in Fig.9, when the collimating length is 530 mm. This figure indicates that less than 0.1 nm spectrum can be distinguished.

5. Conclusion

We have proposed wavelength meters based on new principles and optical spectrum analyzer, and have confirmed their realization. These measurement apparatuses are used in field test at the present time.

6. Acknowledgements

The authors are indebted to Drs. S.Shimada, H.Ishio and K.Hashimoto with Yokosuka Electrical Communication Laboratory, N.T.T., and Mr. T. Hanabusa, Mr. E.Tanaka and Mr. H.Yamamoto with Ando Electric Co.,Ltd. for their useful suggestions and guidance.

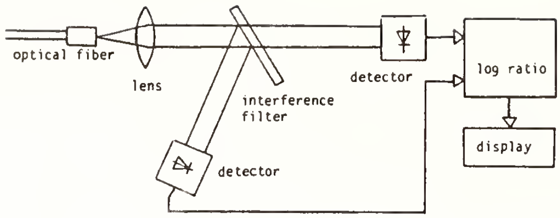


Fig.1 Schema of A-type Wavelength Meter

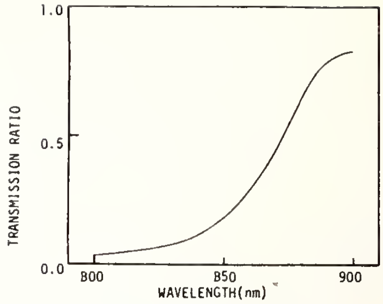


Fig.2 Transmission Characteristics of Interference Filter

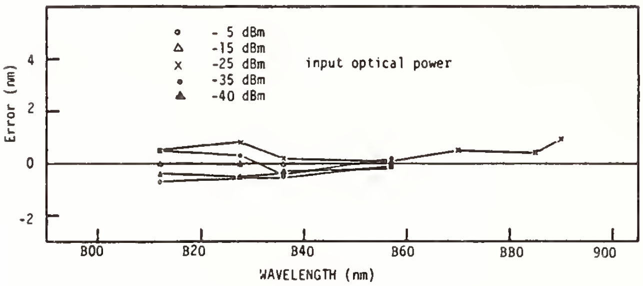


Fig.3 Error in A-type Wavelength Meter

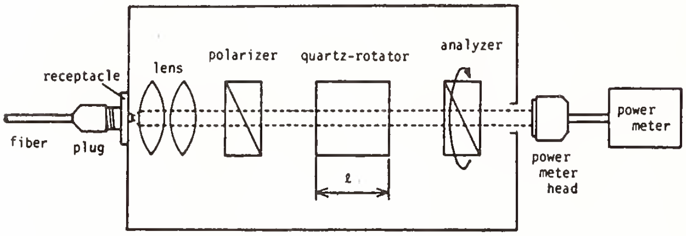


Fig.4 Schema of B-type Wavelength Meter

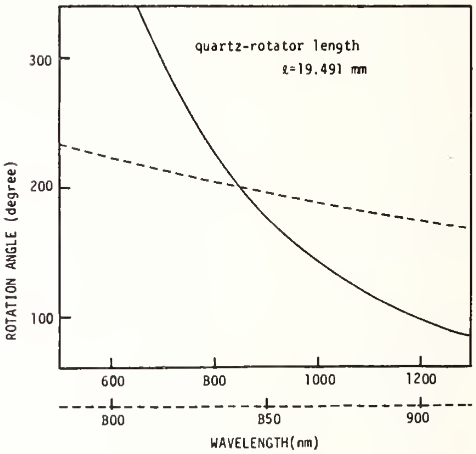


Fig.5 Rotation Angle of Quartz-Rotator against Wavelength

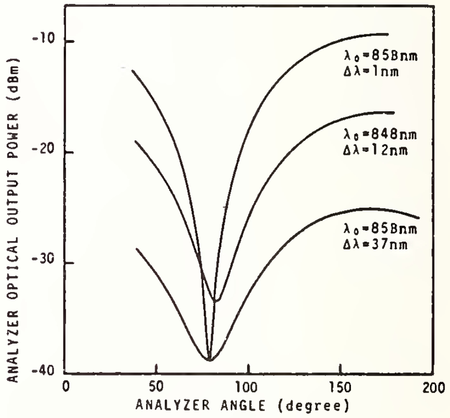


Fig.6 Analyzer Optical Output Power for Three Optical Sources

λ_0 = Peak Wavelength

$\Delta\lambda$ = Spectral Bandwidth

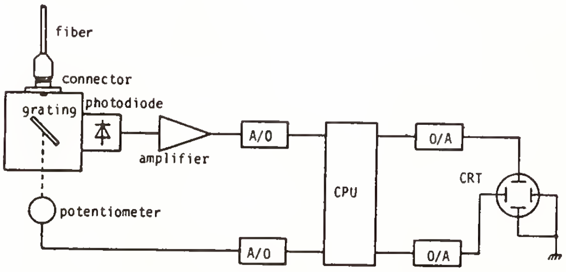


Fig.7 Schema of Optical Spectrum Analyzer

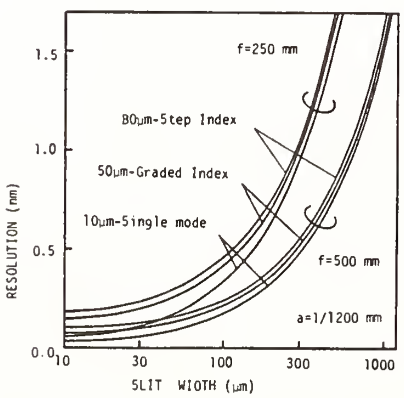


Fig.8 Resolution against Slit Width

f=Collimating Length

a=Groove Spacing

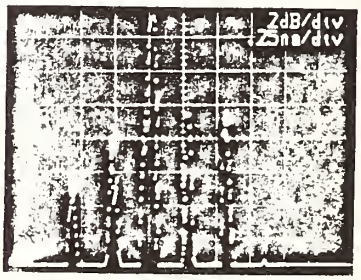
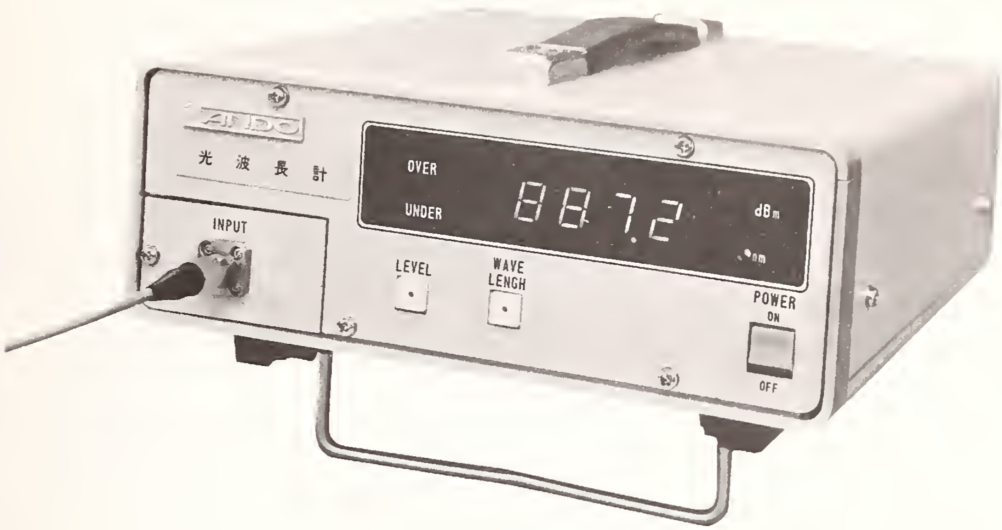
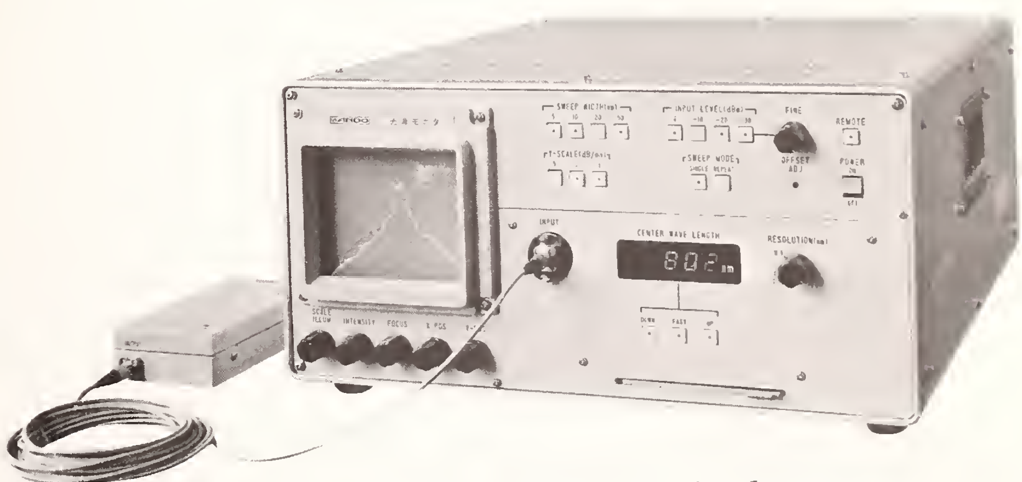


Fig.9 Spectrum of Laser Diode



A-type Wavelength Meter



Optical Spectrum Analyzer

Fiber Measurement Techniques in West-Germany

J. Feldmann

Deutsche Bundespost

This talk will provide a summary of a meeting on "Measurement Techniques in Optical Telecommunications" held in Berlin, October 2-4, 1980. Topics for the conference were as follows: attenuation measurements to 1.8 μm, OTDR, investigation of fiber cables, measurements on test links, laser measurements, splices, connectors, and standards. Forty-eight papers were given and an exhibition was held.

The Preparation of Standards for "Optical Fibres and Cables" Within the International Electrotechnical Commission

A summary prepared for the Symposium on Optical Fibre Measurement.
Boulder, Colorado, October 28 - 29, 1980.

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Secretary IEC/SC46E-WG1

Introduction

The International Electrotechnical Commission has assigned the preparation of standards for fibre optics to its subcommittee SC 46E with the following terms of reference:

" To prepare fibre optics international standards intended for application in telecommunication equipment and in devices employing similar techniques. This activity includes terminology, essential characteristics, measuring methods, and functional requirements to ensure satisfactory performance for, but not restricted to, the following:

single fibers and bundles of optical fibres, fibre optic cables, fibre optics connectors, fibre optics accessories , fibre optics terminal devices, and fibre optics transmitting and receiving assemblies or sub-systems containing solid state devices and other components, which are specified as SUB-SYSTEMS for purposes of trade and commerce."

During the first meeting in Florence in 1978, SC 46E decided to set up a number of Working groups, consisting of experts, to assist its secretariat in the preparation of standards.

SC46E-Working Group 1 - "Optical Fibres and Cables" was formed to draft specifications concerning the materials, dimensions, construction, characteristics (transmission, mechanical and environmental) and measuring methods for optical fibres and cables. Other working groups are preparing standards for connectors, safety and vocabulary.

Working Group 1 now consists of 23 members of 10 different industrialised countries of North America, Japan, and Western Europe. There have been five WG meetings accompanied by intensive correspondence. The working group intends to present its recommendations and conclusions to the plenary meeting of SC 46E in June 1981.
It is emphasized that the International Electrotechnical Commission adheres to strict procedures of presentation, discussion and final decisions on proposals for standards by the National Committees which constitute the IEC. Therefore, the working group proposals and documents must be seen as preparations for possible standards only and cannot be used as standards for the present time.

This paper is the author's personal summary of the discussions and work of SC 46E/WG1.

1. Procedures

In the preparation of standards for optical fibres and cables the working group has used IEC Guide 102 as a basis. This Guide outlines the structure of a specification system consisting of a series of interrelated documents. Various levels of specifications can be distinguished

- basic
- generic
- sectional
- detail

For optical fibres and cables, IEC 46E/WG1 is primarily concerned with generic and detail specifications. Basic specifications are already in existence within IEC for a number of general requirements which are relevant also for many other products than optical fibres and cables. Some other basic specifications, such as those concerned with terminology are under preparation in other IEC quarters.

In preparing generic and detail specifications for optical fibres and cables, IEC 46E/WG1 can thus restrict itself to those parameters which are particularly and sometimes uniquely relevant to the fiber optics technology in a wide or narrow sense. As a working rule, the group tries to avoid specifying a parameter unless a test method can be described to measure the actual value of this parameter and, therefore its compliance to a specified range of values. This method creates a degree of flexibility in so far that new values of parameters can be standardized within an already standardized measuring method.

To illustrate this method with an example:

The cross section specifications of a fibre can contain as parameters the diameters of the core, the cladding, the primary coating and the buffer layer and their non circularity. In addition, a reference surface may be chosen and acceptable tolerances allocated to all parameters. Finally the concentricities of various parameters can be specified in relation to each other. This rather elaborate set of requirements must be accompanied by a test method for each one.

If one would attempt to arrive at a full, academically complete, set of values for the parameters and their measuring methods, the chances of success in solving this problem (which started by being a relatively straight forward one) become miniscule.

Only an approach where the practical limitations of measuring methods are used as a starting point may succeed in solving the problem for the sake of trade and commerce.

2. Parameters of optical fibres to be standardised.

The following parameters of optical fibres have been considered by IEC 46E/WG1 for possible standardisation:

A. Dimensions

a) core diameter; core non-circularity
cladding diameter ; cladding non circularity
primary -
coating diameter ; prim. coating non circularity
buffer diameter ; buffer non circularity

b) fibre length
c) reference surface allocation
d) concentricity errors
e) tolerances

B. Mechanical characteristics

Screening
Tensile strength
Bending
Torsion
Vibration
Flexing
Abrasion
Physical defects

C. Transmission characteristics:

Attenuation
Impulse response
Baseband frequency response
Backscattering
Numerical aperture
Refractive index profile
Microbending sensitivity
Effective core size*
Effective numerical aperture*
Fibre acceptance angle*
Mode volume transfer function*
Material dispersion*
Modal dispersion*
Wave guide dispersion*
Cut off wave-length
* provisional

D. Climatic/Environmental characteristics
(i.e. the ability of a fibre to meet environmental requirments)

Maximum temperature
Minimum temperature
Temperature cycling
Humidity
Contamination resistance
Mould growth
Nuclear radiation
Flammability

E. Packaging requirements.

In accordance with the working rules, for each of the above parameters, standardisation can only occur when suitable measuring techniques have been agreed upon. International agreement is normally only possible when the measuring methods have proven to adhere to acceptable criteria of reproducibility and repeatability.
Some examples of measurement techniques under discussion in the working group are given in the next sections of this paper.

3. Some examples of measuring methods discussed in WG 1

a) measurements of fibre cross sectional dimensions.

As outlined in the introduction a complete set of measurements of dimensions is very difficult to achieve.
However there is an urgent need to specify and propose standards for some basic parameters of the fibre such as nominal/basic core and cladding diameters. On the basis of an operational definition of the core size (also used in CCITT*) and a generally accepted definition for the cladding, some standard fibre sizes have been proposed, measured on the basis of optical power transmission.

e.g. for graded index fibres	core dia	50 μm
	cladding dia	125 μm
for glass core plastic clad step index fibres	core dia	200 μm

while the above dimensions have been formally proposed within IEC, other diameters, especially for "(quasi) step index all silica fibres" are under discussion. e.g.

80-90	μm core	dia
125	μm cladding	dia
100	μm core	dia
140	μm cladding	dia

Proposals are also emerging for fibres manufactured by double crucible processes.
In addition to these nominal values a measurement method is being proposed to verify all the cross sectional dimensional parameters. This method, the "four circle method", gives evidence whether the fibre fits its specification. It is based upon a template containing two sets of two concentric circles for core and cladding diameters respectively. The two circles of one set define an acceptance field for tolerances, non circularity and concentricity errors. A fibre will pass the test, in the context of trade and commerce, if a position can be found where both core contour and cladding contour lie completely within their two circles.

*core: the smallest cross sectional area of a fibre (excluding any "centro dip") contained within the locus of points where the refractive index

$n_3 = n_2 + k(n_1 - n_2)$

with: n_1 = max. refractive index

n_2 = refr. index of cladding

k = 0.005 (prov.)

b. Mechanical tests.

For both proof testing and destructive strength testing of fibres it is neccessary to define test set ups. These test set ups contain some aspects which are arbitrary in nature but should yield reproducible results. They must pay respect to known phenomena related to strength of glass fibres and can be used for the sake of trade and commerce when international acceptance can be gained in some considerable detail including clamping and pulling instructions and reporting disciplines.

c. Transmission and Optical tests.

In this field the working group, recognising the difficulty of specifying transmission parameters which are absolute from a theoretical point of view,accepted two requirements for standard proposals of transmission test methods:

- test values must be reproducible and repeatable. (which causes some aspects of the test set up to be arbitrary)
- the test must be such that, when applicable, the test values can be used to predict the performance of a system e.g. a concatinated length.

The problems involved with this are manyfold and the discussion in the working group proved extremely time consuming.
As an example and also as the first result from these discussions a proposed test method for the measurement of attenuation is presented in some detail in the next section.

4. Standards for measuring methods of transmission parameters

a. Attenuation measurements

One objective has been to find an attenuation coefficient, (i.e. the attenuation of a fibre per unit of length) such that the total attenuation of a (long) length of fibre can be accurately predicted by multiplying length and attenuation coefficient. This however requires a set of launching conditions which approximate equilibrium mode distribution, understood to exist when the power distribution of field patterns at the output of the fibre is independent of the length of the fibre.
Initially attempts were made to propose standards for a hardware "equilibrium mode simulator" based upon mode mixing effects obtained in devices making use of either microbending phenomena or of coupling effects from/into different types of fibers.
More recently an approach has been favoured which tries to verify the existence of equilibrium mode distribution empirically for different types of fibres.
In comparing various results obtained at different laboratories the WG will submit the following proposal for a standard set of launching conditions for graded index optical fibres.

- A standard set of equilibrium mode launch conditions exists for a fibre of category A1 ("multimode graded index fibres") with a typical theoretical numerical aperture of .19 to .23 and nominal core diameter of 50 micrometer as follows:
  " a light spot with a full width half maximum intensivity value : $D_{0.5} = 26 \pm 2\ \mu m$
  is launched whereby, after the light has travelled through the fibre over a distance of 2 meters, the far field pattern is measured to have a full width half maximum value numerical aperture:
  $NA_{0.5} = .11 \pm .02$ and the near field pattern still indicates a spot diameter of $26 \pm 2\ \mu m$.

End of summary

CCITT studies on optical fibres cables measurements

By : Fabio Bigi (CCITT Secretariat - ITU) and Gastone Bonaventura (Chairman of the Working Party on optical fibres of Study Group XV - ASST, Ministry of Communication, Italy)

Abstract

This article indicates the general approach of CCITT with respect to measuring methods and measuring equipments and gives the particular solution chosen for optical fibres measurements.

The particular approach adopted for optical fibres measurements consists in the adoption, as far as possible, for each defined characteristic of a corresponding "test reference method". The article, on the basis of the contributions received, underlines the agreement reached on the definition of the various characteristics and on the corresponding measuring methods at the end of the present study period (1977-1980). Finally it indicates trends for the studies to be undertaken by CCITT during the next study period.

1. Introduction

The studies undertaken by the CCITT (International Telegraph and Telecommunication Union) are mainly aimed to allow international interconnections of telecommunication equipments and networks. Several Study Groups have been specifically involved with different aspects of measuring methods and measuring equipments for telecommunication and have issued corresponding CCITT Recommendations. In particular, the O series of Recommendations, mainly originated by Study Group IV (Transmission maintenance of international lines, circuits and chains of circuits, maintenance of automatic and semi-automatic networks), are dedicated to measuring equipments. Study Group IV has also originated the Recommendations of the M series dealing with maintenance for telephony, telegraphy and data transmission.

In studying the measuring methods and maintenance procedures for telecommunication equipments and networks, Study Group IV considered three types of measurements :

i) acceptance measurements, made by Administrations or private operating agencies, with measuring equipments conforming to the O series of Recommendations, in case a given equipment is to be put into service;

ii) maintenance measurements, made in order to check the normal operation for a given telecommunication equipment. The maintenance could be of a corrective nature or of preventive nature;

iii) specific measurements. made to check a given characteristic or to ascertain, from a particular point, the quality of a telecommunication network by making a determined series of measurements.

Study Group IV generally has a continuous exchange of information with the specialized Study Groups in order to prepare recommendations for suitable measuring equipments following the evolution of the technique. In the case of optical fibre studies are at an initial stage and consequently the relative test methods are rapidly changing and improving in parallel with the evolution of the technique. For this reason the optical fibre measurements have for the time being been treated in the specialized Study Groups, which should first agree on the choice of general test methods before involving Study Group IV with the detailed specifications for the measuring equipments.

2. CCITT studies on optical fibres

The specialized Study Groups entrusted with the studies of optical fibres by the VIIth CCITT Plenary Assembly were Study Group XV (Transmission systems) with its Question 38/XV (Physical characteristics of optical fibres) and Study Group XVIII (Digital networks) with its Question 13/XVIII (Characteristics for digital line sections on optical fibre cables).

The studies have made a progress in particular in Study Group XV, which agreed on Recommendation G.651 dealing with a multimode graded index optical fibres having a core diameter of 50 μm, a reference surface diameter of 125 μm and operating in the 0.8-0.9 μm wavelength range.

The aim of Study Group XV in standardizing test methods has been to achieve comparative results for different measures. It was considered necessary to reach agreement on the possibility to compare data from various Administrations, obtained during different times under different conditions.

At present different values of fibres characteristics could be obtained using different test methods and furthermore it is not convenient to specify only one method for each parameter to be used. Study Group XV agreed on the need to choose one Reference Test Method (RTM) to be used as Reference method for the measure of each fibre parameters. At the same time, Study Group XV recognized that, in practice other test methods could be used and adopted, provided that their results are in accordance with those of the RTM.

In order to allow a wide use of the RTM it was agreed to look for a method having the following characteristics :

- easy to specify and to realize
- capable of giving reproducible results which are of use to the system designer, as fas as possible
- non destructive.

Moreover, RTMs are to be chosen as being applicable to a wide range of optical fibres available at present; but it was not intended that the recommendation of a particular test method should exclude the design of fibres which, although meeting CCITT Recommendations could not, by reason of the constructions, be measured using the RTM. Indeed, the designation of RTM is an indication that there is, at the present time, for a large number of types of optical fibres, sufficient confidence that it can yield accurate results and hence be used as a reference with which to compare the results of other methods.

Such other methods, considered to be suitable for measurements of the same parameter have been designated as Alternative Test Methods.

The main results obtained in the study of optical fibre test methods are annexed to Recommendation G.651 and will be described in the following parts of this article :

3. Geometrical and optical parameters

3.1 General

It is assumed that the geometrical and optical parameters would be measured only in the factory or in the laboratories of certain Administrations wishing to verify these parameters for system design or other purposes. Hence, it is anticipated that the measurements will be conducted either on sample fibre lengths or on samples extracted from cable factory lengths.

The reference surface diameter and non-circularity, which are external fibre dimensions, can be measured readily and accurately by microscope or micrometer methods and present no problem.

The core diameter and non-circularity and the theoretical numerical aperture are defined using the refraction index profile as a basis. The remaining parameter, core/reference surface non-circularity, can be derived from the above through a simple geometrical calculation. Hence, it follows that all geometrical and optical parameters, which are the subject of this Recommendation, and their tolerances as appropriate, can be obtained through two basic tests; one for the reference surface diameter and one for the determination of the refractive index profile.

3.2 Test method for the reference surface diameter

Two methods are generally suggested for measuring the reference surface diameter : a conventional microscope or a micrometer. As a microscope may be more generally available for high precision measurements, it is designated as the "RTM". The "micrometer" method is a suitable "Alternative Test Method". When all of the material within the reference surface is optical material, interferometric methods and the refracted near field technique of refractive index profile measurement can also be used to measure the reference surface diameter.

As it will be necessary to determine the non-circularity, the tolerance of the reference surface, and the concentricity error between reference surface and core, the measurement must be performed along a minimum of two axes.

3.3 Test method for the refractive index profile

Axial interference microscopy seems to be the most generally recognized method of achieving accurate results. However, sample preparation is time consuming and requires high precision and expensive optical equipment. The near field method, although generally recognized as being useful, suffers in that absolute values of the index cannot be determined. Also, leaky modes can cause errors. Some other methods have promise, but have not received the same degree of interest as the above.

In the light of the above, it has not been possible to achieve agreement on a "RTM". However, the following test methods are considered to become the "RTM" :

a) axial interference microscopy
b) near field scanning
c) reflection measurements

d) transverse interferograms

e) forward scattering

f) refracted near field technique.

3.4 Core diameter

It is implicit in the foregoing and from the definition of core diameter that the derivation of core diameter from refractive index profiles taken along a number of axes constitutes the "RTM". A minimum of two axed must be explored. Microscopic observations, chemical etching and the measurements of certain energy density distributions in the output of the fibre are other methods recognized as useful "alternative test methods".

The core centre and core non-circularity can also be determined from these "test methods" and the determination of the concentricity error between the core and the reference surface can be derived from the data.

4. Transmission characteristics

4.1 Cable factory length

4.1.1 Equilibrium mode distribution

There is general agreement that, for measurements on cable factory lengths to be useful in predicting the loss and basehand response of elementary cable sections (regenerator sections), a state of equilibrium mode distribution must exist throughout the fibre under test. It is here understood that an equilibrium mode distribution exists when the power distribution of the fields pattering at the output of the fibre is independent of length. This is to ensure that the total of the losses measured on individual cable factory lengths can be in agreement with the cumulative loss measured at the resulting elementary cable section. A variety of relevant techniques have been proposed by different Administrations. Basically, these proposals concern methods of approximating an equilibrium mode distribution throughout the fibre under test or of producing an equivalent result. The proposed methods can be grouped into two general categories :

i) the use of a mode scrambler at the input of the fibre under test

ii) selection of spot size and launching NA to produce a transmission measurement equivalent to that under equilibrium mode distribution conditions.

In both approaches, it is necessary to restrict the source spectral width in order to remove spectral dependent loss effects and in particular to minimize the effect of material dispersion on the measured basehand require.

A cladding mode stripper is useful to ensure that cladding modes reaching the detector do not distort the results.

Some results have been reported on cumulative loss results by a number of Administrations using either approach outlined above. Hence, the mode scrambler and the selection of spot size and launching NA can be considered practical means of achieving the desired result.

4.1.2 Attenuation

The most commonly used measurement methods are :

a) the cut-back method

b) the insertion loss method

c) the backscatter or TDR method.

The cut-back method is generally recognized as yielding accurate results but suffers from the disadvantage that it is destructive. The insertion loss method introduces additional uncertainties due to splices or connectors. The backscatter method is non-destructive but is limited in range.

Some Administrations were in favour of designating the cut-back method as "reference test method" but the view has been expressed by other Administrations that the choice should be delayed.

4.1.3 Basehand response

Two basic approaches are recognized as being useful. One is based on time domain measurements while the other is based on frequency domain measurements. At present, there is no clear preference for one approach over the other, although some proposals have been made to adopt one or the other as reference.

At present, therefore, both basic approaches are considered as candidates to become the RTM.

4.2 Elementary cable section

It was considered premature to attempt a selection of test methods. Nevertheless, the general principles involved in the measurement of cable factory lengths are also applicable to elementary cable lengths. However, it should be taken into account that in this case non-destructive and portable test methods methods are mandatory while the need for absolute accuracy is not so great.

5. Future studies

Study Group XV intends to study during the next period (1981-1984) a specific question on methods of measuring the characteristics of optical fibre cables (Question I/XV). In this question main objective should be the definition of a single reference test method for each of the fundamental characteristics. The Question recognizes that other test methods could be used if they result more practical, simple and cost-effective for factory and field applications, provided that the result obtained by been accurately relates with the reference test methods. In particular, Question I/XV requests study for the following points :

a) What recommendations are required for the reference, factory and/or field measurements of optical fibre cables to ascertain for example : attenuation, baseband response, material dispersion, refractive index profile, fibre dimensions, the presence and location of faults, cut-off wavelength.

b) How can practical measurement methods be established so that they are suitable for use as alternatives to the reference methods.

As stated in the introduction, at some future date an important part of the detailed work on the specification of measuring methods for optical fibre cables should be transferred to other Study Groups (in particular Study Group IV) in order to allow them to provide recommendations on measuring equipments.

WAVEGUIDE FIBER STANDARDS

DR. ROY E. LOVE
CORNING GLASS WORKS

Standard committees worldwide are in the process of establishing standards for waveguide fibers. This paper will address the key issues currently facing three working groups: namely, Working Group I (SC46E) of IEC, Study Group XV of CCITT and Working Group P-6.6 of EIA (Electronic Industries Association, USA). The IEC and CCITT are international organizations. The rapid evolution of fiber technology and commercial activity, combined with the lack of extensive in-use performance data and experience, has made the task of setting meaningful standards a formidable challenge. Working group members are responding to the urgent need to establish a technical framework for the sale of commercial products, while at the same time attempting to encourage (or at least not inhibit) the development of improved or lower cost products.

The standard-setting process is straightforward in principle. One first defines the fiber parameter(s) of interest. A test method is then proposed, discussed and points of disagreement resolved. Finally, a recommendation is submitted for the approval of the full committee. In some cases, parameter specifications and tolerances are proposed before there is final agreement on definitions and test methods. Test method standards are key documents. They are the means whereby product parameters are assigned a value which in turn determines relative product quality, cost or selling price. The reproducibility of the test method is also very important. Ideally, the standard deviation of the reproducibility error, σ_r, should be about an order of magnitude less than parameter tolerance requirements. Otherwise complex and costly quality assurance procedures must be agreed upon between user and supplier. Last but not least, wherever possible, the measured value of a component attribute or parameter should be directly useful for system design purposes.

These general considerations are fundamental to all standard-setting endeavors. To develop standards that are acceptable to both users and suppliers without compromising sound engineering practices and established scientific principles is a time consuming and often frustrating task. In the case of waveguide fiber the task is a little more difficult than usual since at this time there is considerable pressure to act quickly. Fortunately, support for this work is widespread throughout the industry and both the organizations and individuals involved are to be commended for their efforts to date.

The fiber standards issues I intend to address are listed below:

(1) Light-launch conditions for measurement of attenuation

(2) Light-launch conditions for measurement of information transmission capacity

(3) Information capacity representation (-3dB bandwidth (BW) vs full-width half-maximum (FWHM) pulse broadening)

(4) Numerical aperture definition and measurement

(5) Core diameter definition, measurement, and tolerances

(6) Cladding diameter tolerances

(7) Splice loss specification

Light-Launch Conditions for Measurement of Attenuation

It is generally recognized that an attenuation test method standard must specify the wavelength of the light source, the spectral width of the light source, a temperature range for measurement, the mechanical means of supporting the fiber and, finally, the angular and spatial distribution of the light launched into the test fiber core. This last condition is a critical requirement. The objective is to specify launch conditions such that the measured attenuation of a fiber length, a_i, is additive with respect to predicting the attenuation of concatenated fiber lengths. That is,

$$\sum_{i}^{n} a_i = A \qquad (1)$$

where A is the measure attenuation of a concatenated link ($\simeq$ 10 km long) formed from the n fibers. There is widespread agreement that the launch condition necessary to accomplish this objective is one which simulates equilibrium propagation conditions; that is, the modal distribution that results after light has propagated over long lengths of fiber, the order of 10 kilometers.

Attempts to define and characterize the modal distribution associated with equilibrium propagation conditions have been extremely useful and illuminating. It has been found possible to create launch conditions that satisfy the concatenation condition, Equation (1), using either beam optics or a mode filter. (1) (2) (3) (4) (5) (6) A mode filter device may consist of a mandrel around which a fiber is wrapped with a prescribed tension, an S shaped loop of fiber or a long length of fiber through which the input light traverses before being launched into the test fiber. Beam optics limit the spatial and angular distribution of the input light relative to that defined by the core diameter and numerical aperture of the test fiber. Not surprisingly, the input effective mode volume (EMV), defined as the square of the product of the FWHM near-field and FWHM far-field light distribution from the first 2-meter length of the test fiber, determines the attenuation that will be measured, independent of the means used to create it (the EMV). (7) (8) IEC Working Group I has proposed that light launch conditions be established using this idea. It can be shown that the input EMV required to satisfy the concatenation condition is approximately the same, whether a modal filter or beam optics is used to create the initial launch conditions. More work is needed in this area, but at the last meeting of this Working Group it was tentatively proposed that for 50 micron core diameter, 125 micron clad diameter, graded index fibers, the FWHM value of the near-field should be 26±2 (μm) and the FWHM of the far-field light distribution should be $\sin^{-1}$ (0.11±02). It should be emphasized that these near-field and far-field patterns are to be measured at a point approximately 2 meters removed from the input end of the test fiber.

Light-Launch Conditions for Information Transmission Capacity Measurement

The information-carrying capacity of a waveguide fiber may be measured in either the time or frequency domain. A number of measurement methods for each approach have been proposed and there is general agreement regarding the light-launch conditions. The principle issue here is measurement reproducibility. It is felt that, for graded index fibers, the input light distribution should fill the mode volume of the test fiber no matter which measurement technique is used. That is, all allowed propagation modes should be more or less equally excited. A "mode scrambler" device positioned between the light source and the test fiber will be used for this purpose. By making the measurement less sensitive to differences in the radiation-output distribution between sources and small errors in optical system alignment, the "mode scrambler" markedly decreases the standard deviation of the reproducibility error. (9) (10) (11) (12) (13) (14) If a "mode scrambler" is not used it is possible for individual measurements to differ by 50% between laboratories or between quality assurance facilities.

The next question is, can the measured value of the information-carrying capacity of individual fiber lengths be added together to yield the information capacity of a multi-kilometer concatenated length. The "mode scrambler" approach does not fulfill this requirement and, to the author's knowledge, no other practical test method has been suggested. Currently, emperical relationships based on field experience are used to predict the information-carrying capacity of concatenated fiber lengths. Two of the most commonly used relationships are:

$$(\mathrm{FWHM})^{1/a} = \sum_{i}^{n} \left\{ (\mathrm{FWHM})_i \right\}^{1/a} \qquad (2)$$

and

$$(\mathrm{BW})^{-1/a} = \sum_{i}^{n} \left\{ (\mathrm{BW})_i \right\}^{-1/a} \qquad (3)$$

,

where a is a constant equal to about 0.7, BW is the frequency at which the transfer function in the frequency domain is down by 3dB and FWHM is given by

$$\mathrm{FWHM} = \sqrt{T_1^2 - T_2^2} \quad , \qquad (4)$$

where T_1 and T_2 are the full-width half-maximum of the output and input pulses respectively. These relationships assume the concatenated fibers are of equal length.

This brings us to a question that needs further study and discussion. Namely, what is the most useful and meaningful representation of the information-carrying capacity of a fiber. Both the -3dB point of the transfer function response (Bandwidth) and the FWHM pulse broadening are commonly employed. If the output pulse shape was identical for all fibers (for a fixed input pulse shape), this would not be an issue, since there would exist a simple inverse relationship between these two quantities. Unfortunately, this is not the case.

System designers seem to prefer the frequency domain representation since it is a measure of the fiber transfer function. Digital communication equipment manufacturers and users, on the other hand, seem to prefer the time domain or pulse broadening (FWHM) representation because the equipment is only sensitive to pulse distortion, from which bit error rates may be predicted. Choosing between these two representations is a difficult question for the fiber supplier, since two fibers with the same bandwidth may exhibit different pulse spreading characteristics and conversely two fibers with the same pulse spreading characteristic may exhibit different bandwidths. See Figure 1. Depending upon what measure of information capacity is requested, process yields and fiber costs could be impacted. At this time the standard setting groups have not actually addressed this issue except to acknowledge that both representations appear to have merit. This may be a satisfactory position, since it could be argued that this matter could and should be resolved at the commercial level between users and supplier.

Numerical Aperture Definition and Measurement

The principle issue here is the definition of the term, "numerical aperture". It now appears that it may be possible to reach agreement on the following definition for the numerical aperture of a graded index fiber.

$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2} \equiv \sin\Theta \quad , \qquad (5)$$

where n_1 and n_2 are the refractive indices of the center of the core glass and the cladding glass respectively. This equation also defines Θ, which is sometimes referred to as the light acceptance angle. In practice the numerical aperture, as defined above, may be assigned a value by determining the cone angle that contains essentially 100% of the output light power from a short length of fiber. However, noise limitations associated with the measurement apparatus will dictate that the angle at which 95% to 98% of the total power is contained be accepted as the fiber NA. This would not be a problem since the error is quite small and, in any case, there is little practical consequence. It is critical, however, that a specification for the percentage value be agreed upon and that it be consistent with obtaining a reasonably small value for the standard deviation of the reproducibility error, σ_r (NA). The NA of a fiber may also be determined by measuring n_1 and n_2 directly. This requires the use of microscope interferometry techniques. Unfortunately, the associated apparatus is rather expensive compared to that required for far-field light distribution measurements.

The above definition of numerical is the maximum theoretical numerical aperture. This quantity is useful for input source coupling calculations. Also, fiber manufacturers find it a useful quantity to measure since it enters into the expression for the refractive index profile of graded index fibers. That is,

$$n^2(r) = n^2(0)\left(1-2\Delta\left(\frac{r}{a}\right)^{\alpha}\right) \qquad (6)$$

at $r = a$, $n(a) = n_2$. Also $n(0) = n_1$. Therefore,

$$\Delta = \frac{(NA)^2}{2n_1^2} \qquad (7)$$

Core Diameter Definition Measurement and Tolerances

The CCITT has defined the core diameter of graded index fibers to be that value of the diameter where the core refractive index, n_3, is equal to, $n_2 + k(n_1 - n_2)$ where, k is a constant. It is likely that k will be assigned a value between 0 and 0.05. There appears to be agreement that this is a reasonable definition. Unfortunately, measuring the refractive index profile of the core glass requires expensive apparatus, as mentioned above. This is an issue with some working group members, since it is felt the cost of such apparatus could not be justified for outgoing or incoming inspection of core diameter.

At present, core diameter is determined by measuring n_3 directly using transverse interferometry techniques as well as by scanning and plotting the near-field light output distribution from the fiber core, microscopic examination of the illuminated core and microscopic examination of the core after etching the fiber end in order to create a step at the core-clad interface. It is apparent that the latter three test methods, although very widely used throughout the industry, do not actually measure core diameter, if one accepts the CCITT definition. This poses both conceptual as well as practical difficulties for standardization purposes. It should also be mentioned that there may be considerable disagreement between refractive index and near-field determinations of the core diameter. (15)

The tolerance on core diameter recommended by the CCITT is ± 3 microns, EIA has recommended ± 5 microns, and the IEC has considered proposing a tolerance of ± 4 microns, based upon a four concentric circle gauge method. Agreement must be reached on tolerance recommendations, but is perhaps more important to compare these tolerances with the standard deviation of the reproducibility error, σ_r (core), of the near-field and etchback techniques, which is between 0.5 and 1.0 microns. (The author is not aware of any published data on the reproducibility of the refractive index profile method when used in a manufacturing environment.) For a σ_r (core) of this magnitude, a straight forward statistical calculation shows that single core diameter measurements on the same fiber end at different facilities will agree to within about 2 microns, 95% of the time - provided there is no offset error between the two measurement facilities.

In summary, the issues facing the Working Groups relative to core diameter standards are as follows:

1. Core diameter measurement techniques commonly used throughout the industry do not actually measure core diameter as defined by the CCITT.

2. These commonly used methods are imprecise relative to the tolerance requirements, the 95% confidence interval between two independent measurements being approximately ½ the proposed core diameter tolerances.

Clad Diameter Measurement and Tolerance

The issues here are in some respects the same as those for core diameter. The measurement methods currently used depend upon microscopic examination of the fiber end or micrometer gauges. In both cases the reproducibility error is a large fraction of proposed clad diameter tolerances (σ_r (clad) = 0.5 to 1.0 microns). The CCITT, IEC, and EIA have proposed ±3, ±5, and ±6 micron tolerances respectively. Fortunately, it has been reported that during the fiber drawing process, where clad diameter is controlled online by means of a feedback loop acting between the measurement means (usually an interference diameter microscope) and the draw rate, it is possible to limit fiber diameter variations to a few tenths of a micron. (16) Hopefully, this experience will be duplicated in large scale manufacturing facilities, in which case it may not be necessary to institute accept/reject procedures based on fiber end measurements made at outgoing or incoming quality assurance facilities. End measurements might be made occasionally as a rough monitor of fiber end diameter rather than as a means of insuring that individual fibers meet tolerance specifications.

Splice Loss Specification Proposal

It is interesting to consider the possibility of a splice loss specification for fibers, if by doing so some of the confusion and uncertainty associated with core diameter, clad diameter and NA standards could be alleviated. Such a specification would, of course, be accompanied by a suitable splice loss test method which would have to be sensitive to core and clad diameter variations as well as to numerical aperture and alpha profile variations between fiber ends. A maximum and an average splice loss might be specified. This would be useful quantities for system design purposes, since the splice loss portion of the loss budget could be calculated more easily and reliably. Also, it would allow both users and suppliers to address a functional requirement, namely splice loss, directly rather than indirectly by means of tolerance specifications. Tolerance specifications might still be required, but by addressing functional requirements it might be possible to better optimize the manufacturing process with respect to yield and cost. For example, it may be less costly or easier to maintain tight tolerances on numerical aperture rather than on core diameter. To illustrate this point let us recall that to a first approximation, splice loss - to the extent it is a function of fiber parameter variations - depends equally on the percentage variation in NA and core diameter between two fiber ends. Hence, a 10% tolerance on NA combined with a 6% tolerance on core diameter, as proposed by the CCITT, would result in approximately the same splice loss distribution as 10% and 6% tolerances on core diameter and NA respectively, all other relevant parameters being equal. One potential problem with this argument is that two suppliers may be able to meet the same splice loss specification, but with different tolerance specifications on fiber parameters. In this case, jointing fibers selected at random from one supplier with those from the other would result in a higher splice loss than that indicated by the original specification. Nevertheless, this approach is worth considering, particularly if the tradeoff between cost and parameter variations are similar for most fiber manufacturing processes. Finally, there is a certain elegance and appeal to this concept since it would allow fiber transmission properties to be characterized with only three parameters: namely, attenuation, information capacity 9-3dB BW or FWHM pulse broadening) and splice loss.

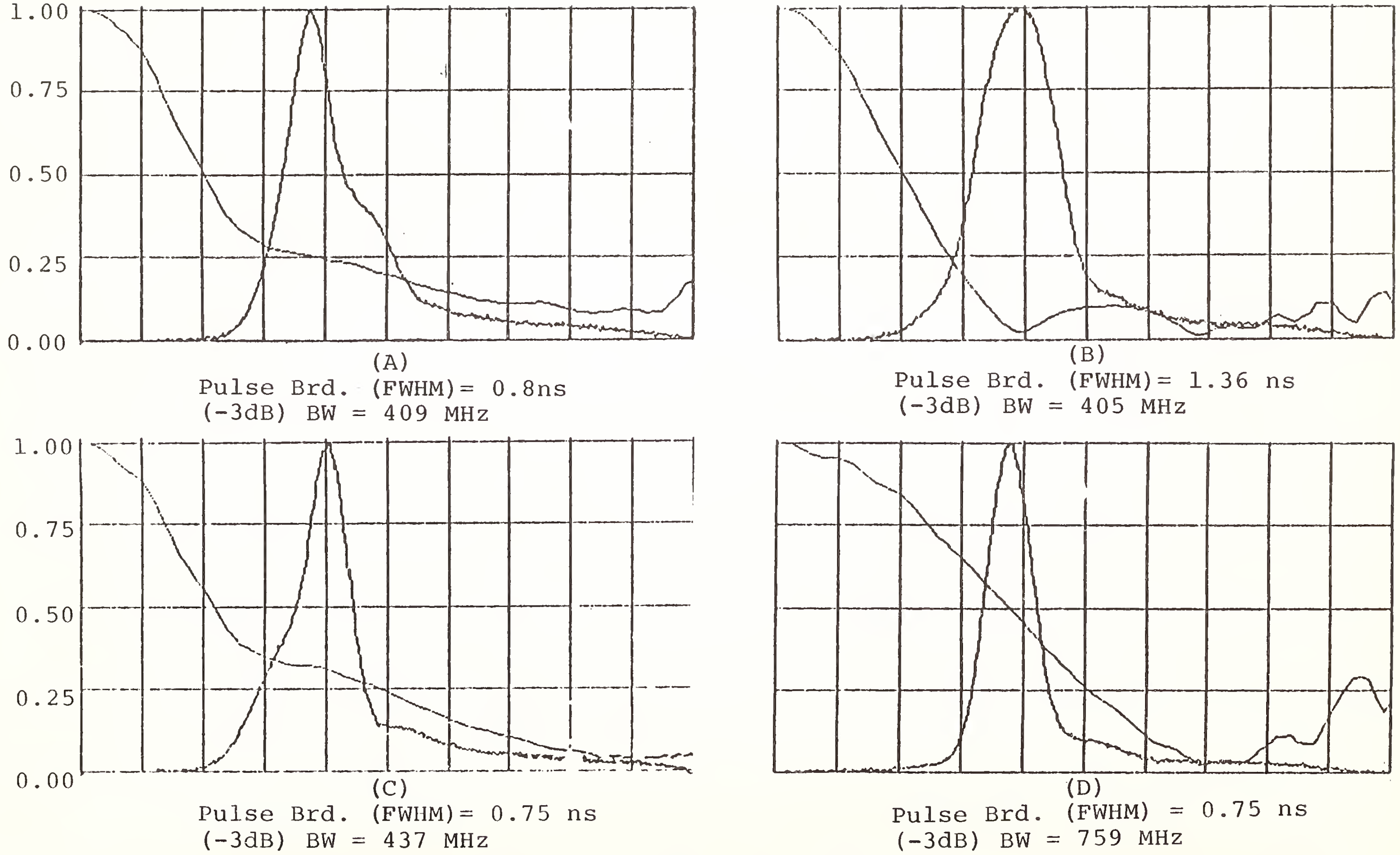

Fig. 1 Comparison of (-3dB) bandwidth and FWHM pulse broadening. Fibers (A) and (B) have the same -3dB frequency response, but different (by 70%) FWHM pulse broadening. (D) and (C) fibers have same FWHM pulse broadening, but -3dB frequency response is different by 70%. Scale: 200 MHz/Div. for frequency response and 1.0 ns/Div for pulse broadening.

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This volume contains summaries of 29 papers presented at the Symposium on Optical Fiber Measurements held October 28-29, 1980, at the National Bureau of Standards in Boulder, Colo. Subjects included are the measurement of attenuation, bandwidth/distortion, and index profile, joint/defect characterization, measurements on single mode fibers, applied measurements, and measurement standards.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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