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NBS TECHNICAL NOTE 1046

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Measurement of Optical Fiber Bandwidth in the Frequency Domain

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Measurement of Optical Fiber Bandwidth in the Frequency Domain

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Kim, E. M., Franzen, D. L. Measurement of far-field and near-field radiation patterns from optical fibers. Nat. Bur. Stand. (U.S.) Tech. Note 1032; 1981.

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Day, G. W., editor. The characterization of optical fiber waveguides--A bibliography with abstracts, 1970-1980. Nat. Bur. Stand. (U.S.) Tech. Note 1043; 1981.

Chamberlain, G. E., Day, G. W., Franzen, D. L., Gallawa, R. L., and Young, M., Attenuation measurements on multimode optical fibers, Nat. Bur. Stand. (U.S.) Tech. Note in preparation.

Measurement of Optical Fiber Bandwidth in the Frequency Domain

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The design, evaluation, and performance of a system for determining the magnitude of the transfer function (hence, the bandwidth) of a multimode optical fiber are presented. The system operates to about 1450 MHz using a tracking generator/spectrum analyzer combination for narrowband detection. It is constructed, almost entirely, from commercially available components. The system is less complex and easier to use than an equivalent time domain system and the measurement precision is comparable. Background information on time and frequency domain specifications, fiber bandwidth limitations, and alternate frequency domain techniques is also presented.

Key words: fiber optics; optical communications; optical fiber bandwidth; optical fiber distortion; optical fibers.

1. Introduction

In determining the parameters of optical fibers, measurement practice is evolving rapidly as the accumulated experience of manufacturers and users and the work of standards groups lead toward uniformly accepted techniques. This Technical Note is one of a series (see pg. iv) intended to describe the present design and capability of fiber measurement systems now in use at the National Bureau of Standards. These systems are perhaps representative of current practice in the industry. Many of the techniques described will also be relevant to future systems. The topic of this particular document is the measurement of fiber bandwidth as a means of specifying the maximum rate at which information may be transmitted thruogh the fiber. In particular, it describes a frequency domain measurement system generally used to characterize graded index fibers in the 820 nm spectral region. Much of the discussion is general and can be applied to other bandwidth measurement systems.

Sections 2 and 3 are tutorial and are designed to facilitate an understanding of the later sections. Section 2 is a compilation of the concepts and terms used in the specification of the bandwidth of any transmission medium. Both time domain and frequency domain concepts and correspondence relations are included to accommodate those who may have a preference for one or the other approach. Section 3 is a review of those characteristics of fibers that determine bandwidth limitations. It is, by necessity, only a brief overview though the indicated references should be sufficient to guide the reader to more complete treatments.

Various frequency domain methods have been used for fiber characterization. Section 4 summarizes these methods and discusses some of the relative merits of each.

Section 5 describes the design of the system now in use at NBS in some detail. Section 6 describes the measurement procedure used and the quality of measurements obtained.

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2. Time Domain and Frequency Domain Specifications. Concepts and Terminology

Most frequently, information is transmitted through an optical fiber by intensity modulating an optical carrier. The modulation may be digital, that is, in the form of discrete states, or it may be analog. In either case, the maximum rate at which information may be transmitted is determined by the way that the fiber, through various mechanisms, acts to modify or distort the modulation. In this section we discuss the different ways that these limitations may be specified, before examining the specific limiting mechanisms in section 3.

In all cases we assume that the fiber will behave linearly with respect to the intensity rather than the amplitude of the optical field. We know that this will be true for a sufficiently incoherent source, that is, a source having a sufficiently broad spectral width. It will not be true for a coherent or monochromatic source. Generally the assumption of linearity in intensity is believed to be adequate when the spectral width of the source is large compared to the highest frequency components of the modulating signal [1]. As a point of reference, a 1 nm spectral width at 850 nm corresponds to a frequency range of 415 GHz.

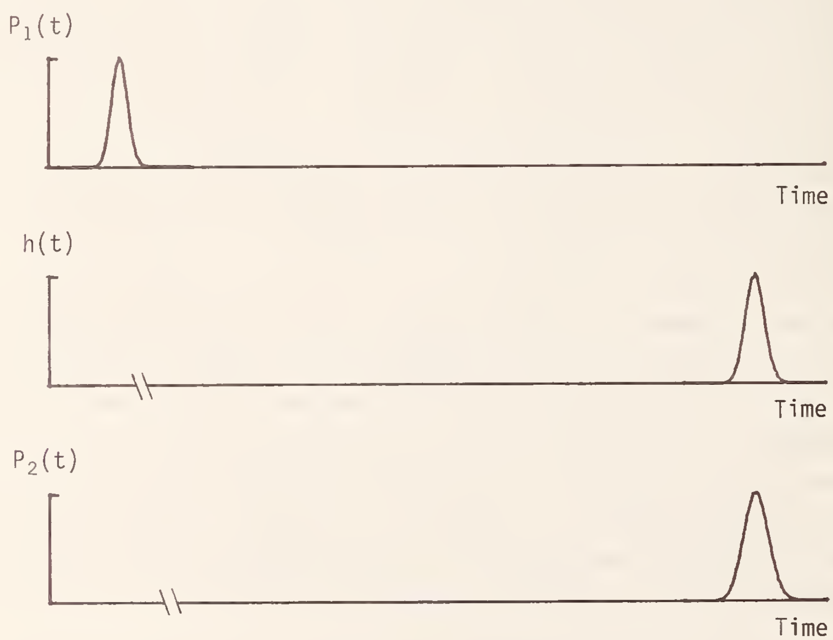


Figure 2-1. The output waveform of a linear system, $p_2(t)$, can be described as the convolution of the input waveform, $P_1(t)$ and the impulse response, $h(t)$, of the system. In a transmission medium the impulse response, that is the response to an impulse at t=0, is characterized by a delay corresponding to the propagation time and distortion.

2.1 Time Domain Concepts

With the assumption of linearity and time invariance, we can relate the time dependence of the modulating signal at the output to that at the input through the convolution integral. We write

$$p_2(t) = \int_{-\infty}^{\infty} p_1(t)\ h(u-t)\ du \equiv p_1(t) * h(t), \tag{2-1}$$

where $p_1(t)$ is the modulating signal applied at the input, $p_2(t)$ is the modulation observed at the output, and h(t) is the modulation waveform that would appear at the output when a modulation waveform that was sufficiently brief that it could be considered to be a true impulse was applied at the input (fig. 2-1). The effect of propagation through the fiber is thus completely specified through a knowledge of h(t), which is known as the impulse response of the fiber. If h(t) could be reliably determined it would therefore be a particularly well suited parameter for measurement.

As a practical matter, it is often not feasible to provide an input waveform that is of sufficiently brief duration to be considered an impulse, nor may it be possible to solve eq (2-1) accurately for h(t) given $p_1(t)$ and $p_2(t)$. Therefore one commonly resorts to approximate methods of describing h(t).

One common but in general highly approximate method is to use the concept of full-duration-half-maximum (FDHM) pulse-broadening. If the measured input waveform is a pulse with a FDHM of D_1, and the measured FDHM of the output waveform is D_2, then the FDHM of h(t), D_h, may be estimated by

$$D_h \sim \left(D_2^2 - D_1^2\right)^{1/2} . \tag{2-2}$$

The attractiveness of this approximation results from the ease with which it may be applied. Its usefulness depends on the shape of $p_1(t)$ and h(t), (and therefore on $p_2(t)$) and on their relative durations.

The approximation in equation (2-2) becomes an equality when $p_1(t)$ and h(t) have Gaussian time dependences. For high quality graded index fibers, h(t) frequently resembles a Gaussian shape. Therefore, if $p_1(t)$ also resembles a Gaussian, as it does in many cases of interest, the approximation may be useful, improving, of course, as D_1 is made smaller. When h(t) assumes other shapes, as for example in a step index fiber, the approximation becomes rather poor.

A better approximate method of characterizing h(t) is through an examination of its moments. The moments of a time varying function f(t) are defined as [2]

$$M_n = \int_{-\infty}^{\infty} t^n f(t)\ dt, \tag{2-3}$$

where n is an integer. The zeroth moment, M_0, is a simply the area under f(t). The first moment, when normalized to M_0, is known as the central time,

$$T = M_1/M_o. \qquad (2\text{-}4)$$

The variance, which is related to the first three moments, turns out to be a particularly useful analytic tool in characterizing the impulse response approximately with a single number. It is given by

$$\sigma^2 = \frac{1}{M_o} \int_{-\infty}^{\infty} (t-T)^2 f(t)dt \qquad (2\text{-}5)$$

$$= \frac{M_2}{M_o} - T^2. \qquad (2\text{-}6)$$

The square root of the variance of h(t), σ_h, is known as the rms pulse broadening.

The variance possesses a very useful attribute related to the operation of convolution. It is that the variance of f(t) convolved with g(t) is exactly equal to the sum of the variances of f(t) and g(t) [2]. That is, since (eq (2-1))

$$p_2(t) = p_1(t) * h(t)$$

then

$$\sigma_{p_2}^2 = \sigma_{p_1}^2 + \sigma_h^2. \qquad (2\text{-}7)$$

Thus, if we could accurately measure σ_{p_1} and σ_{p_2} we could obtain σ_h. The usefulness of σ_h in system design has been discussed by Personick [3].

Unfortunately, for technical reasons, it is difficult to measure directly σ_{p_1} and σ_{p_2}. The variance of the impulse response and the rms pulse broadening are thus less useful means of experimentally characterizing a fiber than one might like or suppose.

Another measure of the duration of the impulse response that may be useful is its equivalent duration defined as

$$D_{eq} = \frac{\int_{-\infty}^{\infty} h\ (t)\ dt}{h(T)}. \qquad (2\text{-}8)$$

D_{eq} is thus the duration of a rectangular waveform that has the same "height" as h(t) and encompasses the same area as h(t). The usefulness of D_{eq} arises primarily from a correspondence relation described in section 2.2.3 below; it is most useful when h(t) is even, that is symmetric, about its central time.

The relationship among σ_h, D_h, and D_{eq} for a Gaussian impulse response is shown in figure 2-2.

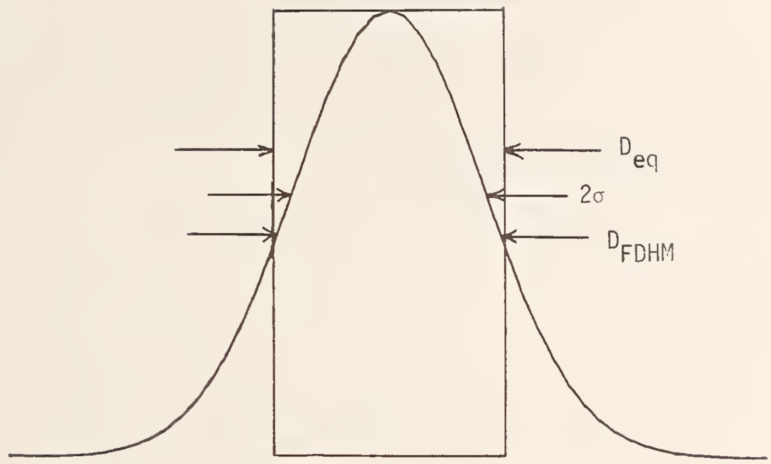


Figure 2-2. The relationship between three methods of characterizing a Gaussian impulse response. $D_{FDHM} = 2.33\ \sigma$; $D_{eq} = 2.48\ \sigma$.

2.2 Frequency Domain Concepts

The same conditions that allow the use of the convolution integral (eq (2-1)) to relate input and output waveforms allow us to develop equivalent relations in the frequency domain through the use of the Fourier transformation, or if the integrals of the waveforms are unbounded, through the Laplace transform. For this work we choose the symmetrical form of the Fourier transform pair:

$$F(f) = \int_{-\infty}^{\infty} f(t)\, e^{i2\pi ft} dt$$

$$\tag{2-9}$$

$$f(t) = \int_{-\infty}^{\infty} F(f)\, e^{-i2\pi ft} df.$$

We use the convention that frequency domain functions are identified by upper case symbols with the corresponding lower case symbols for the corresponding time domain function.

F(f) is, in general, a complex function,

$$F(f) = \mathrm{Re}\,[F(f)] + i\mathrm{Im}\,[F(f)]. \tag{2-10}$$

Since f(t) is a real function, certain things can be said about the real and imaginary parts of F(f). In particular, F(f) is Hermitian; that is the real part is even with respect to f = 0 and the imaginary part is odd with respect to f = 0. Furthermore, if f(t) is even about t = 0, $\mathrm{Im}[F(f)] \equiv 0$.

It is frequently convenient to write F(f) in polar form,

$$F(f) = |F(f)|\, e^{i\phi_F(f)} \tag{2-11}$$

which is related to the rectangular form through

$$|F(f)|^2 = (\mathrm{Re}[F(f)])^2 + (\mathrm{Im}[F(f)])^2 \tag{2-12}$$

and

$$\phi_F(f) = \tan^{-1} (\mathrm{Im}[F(f)]/\mathrm{Re}[F(f)]). \tag{2-13}$$

The usefulness of these representations comes largely from the frequency domain analog of convolution. Specifically if eq (2-1) holds, then it is easy to show that

$$P_2(f) = P_1(f)\ H(f). \tag{2-14}$$

H(f), the Fourier transform of h(t), is generally known as the transfer function of the fiber. It is sometimes also called the frequency response, or to emphasize that $p_1(t)$ and $p_2(t)$ are modulation functions it may be called the modulation transfer function. |H(f)| is known as the magnitude of the transfer function and represents the diminution that each spectral component of the input waveform suffers during propagation. $\phi_H(f)$ is known as the phase of the transfer function and represents the shift in phase angle that each spectral component incurs. With respect to $\phi_H(f)$ it is useful to define the group (or envelope) delay as

$$\tau_g(f) = -\frac{1}{2\pi}\frac{d\phi_H(f)}{df} \tag{2-15}$$

which represents the delay that the spectral components at frequency f of the envelope of p_1 incur (fig. 2-3). This is distinguished from the delay that individual components suffer which is known as the phase delay given by

$$\tau_p(f) = -\frac{1}{2\pi}\frac{\phi_H(f)}{f}. \tag{2-16}$$

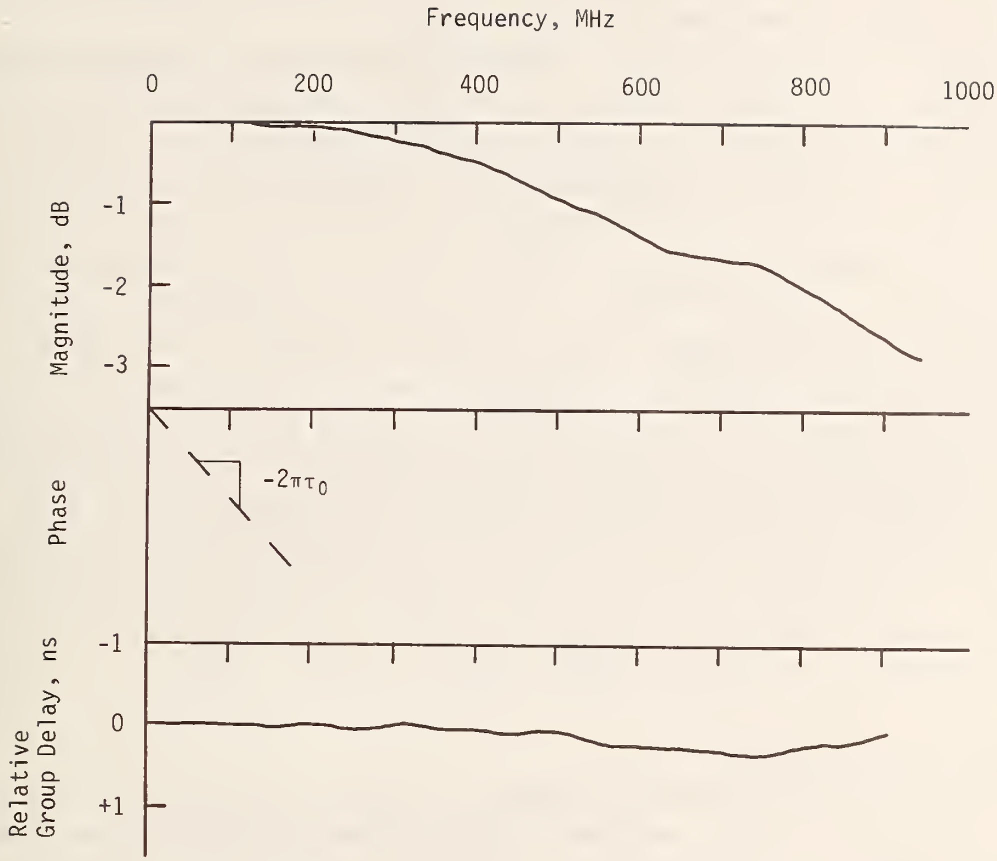


Figure 2-3. Characteristics of a high bandwidth fiber having an approximately Gaussian impulse response. The magnitude, if plotted linearly, would be approximately Gaussian, as well. The phase, if measured, would be nearly linear with a slope of $-2\pi\tau_0$ rad/Hz, where τ_0 is the propagation time. The group delay is nearly independent of frequency. These measurements were taken with a developmental system similar to that shown in figure 4-2.

The shift theorem states that if F(f) is the transform of f(t) then $F(f)e^{-2\pi ifT}$ is the transform of f(t-T). Therefore, when the impulse response is characterized in part by a time delay, as in the case of a fiber or other transmission medium, the phase of the transfer function contains a term linear in frequency which accounts for the distortion-free delay plus a term that represents phase distortion,

$$\Phi_H(f) = -(2\pi\ \tau_0 f + 2\pi\ \gamma(f)) \tag{2-17}$$

Thus the group delay in this case consists of a constant, τ_0, plus a frequency dependent term, $d\gamma(f)/df$. It is this latter term, together with $|H(f)|$, which represents the total distortion and which therefore determines the highest rates at which information can be transmitted. It may be useful to think of $|H(f)|$ as contributing a symmetric distortion and $\gamma(f)$ as contributing an antisymmetrical distortion [4].

In the time domain representation, it was noted that h(t) was a complete representation of the system. In the frequency domain it can be shown that since the system is causal (output does not begin before input) that either Re[H(f)] or Im[H(f)] is a complete representation and in fact one can be computed from the other through the Hilbert transform [2]. However, neither $|H(f)|$ nor $\gamma(f)$ is a complete representation of a system, except for those systems known as minimum phase systems. Fibers are not, in general, minimum phase systems [5].

In spite of its incompleteness, $|H(f)|$, typically normalized to its value at f = 0, is often used as the principal means of specifying a fiber. To futher reduce the characterization to a single number rather than a function it is common to indicate the -3 dB bandwidth, that is the lowest frequency at which $|H(f)| = 0.5$ or $|H(f)|_{db} = -3$ dB. Alternatively, one might choose a specification of bandwidth at another level, say -6 dB, or -1.5 dB. The latter value may be attractive since in a detector or source an electrical quantity, current or voltage, is proportional to optical power. Electrical power is thus proportional to optical power squared and $|H(f)|_{db} = -1.5$ dB corresponds to a -3 dB specification in terms of electrical power.

2.3 Correspondence Relations

In addition to the correspondence between convolution in the time domain and multiplication in the frequency domain, many other relations between time and frequency domain quantities can be derived. Some are useful for component characterization; others are not.

The similarity theorem [2] states that if f(t) has the Fourier transform F(f) then f(at) has the transform $|1/a|\, F(f/a)$. Thus, when comparing two impulse responses of identical shape, the ratio of durations at any arbitrarily defined points, say the 50 percent points, is inversely proportional to the ratio of bandwidths at an independently chosen level, say -6 dB.

The moments of h(t) can be expressed in terms of frequency domain quantities through [2]

$$M_n = \int_{-\infty}^{\infty} t^n h(t)dt = \frac{H^n(o)}{(-2\pi i)^n}, \qquad (2\text{-}18)$$

where $H^n(0)$ is the value of the nth derivitive of H(f) evaluated f = 0. These relations are probably not directly useful in metrology because of the difficulty in reliably evaluating $H^n(0)$. However, they do lead to what may be useful approximations.

From eq (2-18) and the reciprocal nature of the transform we can relate the equivalent width of the impulse response to the equivalent width of the transfer function, as follows:

$$\frac{\int_{-\infty}^{\infty} h(t)dt}{h(0)} = \frac{H(0)}{\int_{-\infty}^{\infty} H(f)\, df}, \tag{2-19}$$

or somewhat more generally using the shift theorem

$$\frac{\int_{-\infty}^{\infty} h(t)dt}{h(T)} = \frac{H(0)}{\int_{-\infty}^{\infty} H(f)e^{ia\pi fT}df}. \tag{2-20}$$

This expression is probably most useful where f(t) is symmetrical about T, for then the argument of the integral on the right side of eq (2-20) is real and equal to the transform of h(t-T).

Because of the additive property of the variance in convolution it would be desirable to usefully relate the variance to frequency domain quantities. The relation that arises from eq (2-18) is probably not useful for the reasons noted before. An alternate approach might be to express the transform in terms of the moments of h(t) by writing $e^{i2\pi ft}$ as a power series

$$H(f) = \int h(t)\ (1 + \frac{i2\pi ft}{1!} + \frac{(i2\pi ft)^2}{2!} + \ldots)dt.$$

Then

$$H(f) = M_0 + i2\pi M_1 f - \frac{(2\pi)^2}{2} M_2 f^2 + \ldots$$

and

$$|H(f)|^2 = H(f)\ H^*(f)$$

$$= M_0^2(1-(2\pi)^2\sigma_h^2 f^2 + \ldots). \tag{2-21}$$

Thus one may, at least in principal, obtain σ_h by fitting $|H(f)|^2$ to a power series in f and isolating the coefficient of f^2. The practical usefulness of this approach has not as yet been explored.

2.4 Specification Choices

Given the array of parameters outlined in the above sections, it is often not clear how best to specify the information carrying capacity of a fiber. The choice undoubtedly depends on the type of fiber, the characteristics of the system in which it will be used, measurement considerations, and the experience and preference of the designer.

It is sometimes suggested that time domain specifications should be used for digital systems and frequency domain specifications for analog systems. Since the larger fraction of fiber systems will be digital, one might expect time domain specifications to dominate. Such has not been the case in industry.

In the U.S., the majority of manufacturers use time domain measurement methods but specify their product by the -3 dB bandwidth. The reasons are several. Early in the development of fiber systems it was easier to obtain suitable sources for pulsed measurements than for cw measurements. However, it is difficult, for technical reasons, to obtain an accurate impulse response or an accurate value for rms pulse broadening; hence frequency domain computations. And, perhaps more importantly, it seems to be the preference of most designers to use bandwidth specifications. In Japan, a different situation has evolved in that many manufacturers use both frequency domain specifications and frequency domain measurement techniques.

If frequency domain specifications continue to dominate, it seems likely that frequency domain measurements will grow in popularity. With presently available components, frequency domain systems are easier to construct, simpler to operate, and more direct in computation. Their precision is comparable to time domain systems on short fibers; for long fibers they offer easier signal averaging.

3. Bandwidth Limitations in Multimode Fibers

3.1 Distortion Mechanisms

Regardless of general preferences for time domain or frequency domain representations, it turns out to be more convenient to consider the limiting mechanisms in the time domain, specifically as sources of variation in propagation time. These variations, which lead to waveform distortion, arise in two separable categories. One comes from differences in propagation constants between individual modes or mode groups, and is called <u>intermodal distortion</u>. The other comes from the variation in the propagation constant of individual modes with wavelength, called <u>intramodal dispersion</u>. For a non-zero source spectral width, intramodal dispersion results in additional waveform distortion.

3.1.1 Intermodal Distortion

In a step index fiber, if one assumes that the angle that a light ray makes with the axis corresponds to a particular mode designation it is intuitive that high order modes (high angle rays) will propagate more slowly than low order modes. Thus a propagating pulse will be broadened. It has long been known that by properly tailoring the refractive index distribution these intermodal differences can be minimized.

For a optical waveguide in which the maximum difference in refractive index between the core and cladding is about a percent, Gloge and Marcatilli [6] have shown how the refractive index profile may be optimized. They considered a class of profiles given by

$$
n(r) \equiv \begin{cases} n_1 \left[1-2\Delta(r/a)^g \right]^{1/2} & \text{for } r<a \\ n_1[1-2\Delta]^{1/2} \equiv n_2 & \text{for } r>a \end{cases} , \tag{3-1}
$$

where $n(r)$ represents the refractive index as a function of radius, n_1 is the refractive index on axis, a is the core radius, n_2 is the refractive index in the cladding and Δ is a parameter related to the difference between n_1 and n_2 given by

$$
\Delta \equiv \frac{n_1^2 - n_2^2}{2\, n_1^2} \approx (n_1 - n_2)/n_1 .
$$

The parameter g, known as the profile parameter, takes on values between 1 and ∞. As it does so one may consider a broad range of profiles from triangular (g=1) to parabolic (g=2) to step (g=∞).

Analysis of these profiles shows that the duration of the impulse response is a function of g and Δ. In particular, under the assumption that $n(r)$ is independent of wavelength, it was shown [6] that for a particular value of g given by

$$
g_{opt} = 2-2\Delta \tag{3-3}
$$

the duration of the impulse response goes to zero.

Olshansky and Keck [7] have extended the work of [6] to include the variation in refractive index with wavelength. They give an approximate expression for the rms duration of the impulse response due to intermodal effects as follows:

$$
\sigma_{INTER} \approx \frac{LN_1\Delta}{2C} \quad \frac{g}{g+1} \quad \frac{g+2}{3g+2} \left| \frac{g-2-P}{g+2} \right| , \tag{3-4}
$$

where

$$
N_1 \equiv n_1 - \lambda \frac{dn_1}{d\lambda} \tag{3-5}
$$

is known as the <u>material group index</u> and P, sometimes known as the <u>profile dispersion parameter,</u> is given by

$$
P = -2 \frac{n_1}{N_1} \frac{\lambda}{\Delta} \frac{d\Delta}{d\lambda}. \tag{3-6}
$$

From eq (3-4), g_{opt} is seen to be

$$
g_{opt} = 2 + P \tag{3-7}
$$

or, from a more exact version of eq (3-4) [7],

$$
g_{opt} = 2 + P - \Delta \frac{(4+P)(3+P)}{(5+2P)}. \tag{3-8}
$$

For P = 0, eq (3-8) is approximately equal to eq (3-3).

In any case, it is apparent from eq (3-4) and (3-8) that even though P is small, its effect can be to make σ_{INTER} and hence the fiber bandwidth a strong function of wavelength, particularly when the fabrication of the fiber is such that $g \approx g_{opt}$. Several authors [8] have studied the variation in the intermodal distortion with wavelength experimentally and have observed large variations.

3.1.2 Intramodal Dispersion

To understand the broadening that occurs within a single mode it is necessary to identify those parameters that determine the velocity of propagation of a mode. Consider the effective phase index of a mode, $n_{\mu\nu}$, which is the ratio of the speed of light in vacuum to the phase velocity of the mode. For each mode $n_{\mu\nu}$ varies between n_1 at short wavelengths (far above cutoff) where the power is confined near the axis to n_2 at cut-off where the power propagates through the cladding. For a specific mode, $n_{\mu\nu}$ depends on the core radius, the wavelength explicitly, and on $n_1(\lambda)$, $\Delta(\lambda)$, and $g(\lambda)$. That is,

$$n_{\mu\nu} = f(a, \lambda, n_1, \Delta, g). \tag{3-9}$$

It should not be inferred from this relation that the dependence of $n_{\mu\nu}$ on these parameters is separable. However, it is usual to identify the dependence on a/λ, which would be present even if the waveguide were composed of dispersion-free glass, as <u>waveguide dispersion.</u> Then $n_1(\lambda)$ is said to give rise to <u>material dispersion</u>, $\Delta(\lambda)$ to <u>profile dispersion</u>, and $g(\lambda)$ to what might be called <u>profile parameter dispersion.</u>

For those modes farthest from cut-off

$$n_{\mu\nu} \to n_1(\lambda). \tag{3-10}$$

We therefore expect that material dispersion will be the dominant contributor to intramodal dispersion except perhaps near where $dn_1/d\lambda = 0$.

In the limit of expression (3-10) the velocity of propagation (both phase and group) approaches that of a plane wave in a medium of refractive index $n_1(\lambda)$. The propagation constant in that case is $\beta = 2\pi n_1(\lambda)/\lambda$. The time for a pulse to propagate a distance L is

$$\tau_{\mu\nu} = \frac{L}{v_g} = L\frac{d\beta}{d\omega} = \frac{L}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \equiv \frac{L}{c} N_1, \tag{3-11}$$

where v_g is the group velocity and N_1 is the material group index as stated earlier.

The intramodal pulse broadening then becomes

$$\sigma_{INTRA} \approx \sigma_{Material} = \sigma_s \frac{d\tau_{\mu\nu}}{d\lambda} = \sigma_s \frac{L}{c} \frac{dN_1}{d\lambda}$$

$$= -\sigma_s \frac{L}{c} \frac{d^2 n_1}{d\lambda^2} \equiv -\sigma_s LM, \qquad (3\text{-}12)$$

where $\sigma_{material}$ is the rms pulse broadening due to material dispersion, σ_s is the rms spectral width of the source, and M is known as the material dispersion parameter.

For most glasses M is zero at a wavelength near 1.3 μm. At shorter wavelengths it is positive and at longer wavelengths negative. M is not a strong function of glass composition. At 800 nm its value for most glasses falls in the range of 120-150 ps/nm·km and at 900 nm, 70-90 ps/nm·km.

3.2 Separation of Chromatic and Monochromatic Distortion

With regard to measurements, the most important aspect of the above discussion is the extent to which the total distortion or bandwidth depends on the spectral characteristics of the source. Because the material of which the fiber is composed is dispersive, both σ_{INTRA} and σ_{INTER} depend on wavelength. Further, σ_{INTRA} is proportional to the spectral width of the source (σ_s). Within the limits of the analysis σ_{INTER} is independent of σ_s. The problem, then, is in interpreting measurement results.

The variation of intermodal pulse broadening with wavelength is not readily predictable. It is thus difficult to use measurements at one wavelength to design a system that will operate at another wavelength. Appropriate sources are available over most of the range at which systems are likely to operate but economic considerations generally preclude routine spectral bandwidth measurements.

The dependence of bandwidth on source spectral width generally causes greater difficulty in measurements. It is usually not possible to choose a source for measurement that will have the same spectral line shape as will be found in the system in which the fiber will ultimately be used. It is also difficult to accurately separate chromatic and monochromatic effects in a measurement result that depends significantly on both.

Usual practice therefore is to set limits on the spectral width of the source used for measurements so that one or the other effect dominates. The focus is usually on intermodal effects since they vary much more between fibers and since in most systems they represent the limitation.

If the total distortion can be written as the convolution of the "intermodal impulse response" with the "intramodal impulse response" we can write

$$\sigma_h^2 = \sigma_{INTER}^2 + \sigma_{INTRA}^2. \qquad (3\text{-}13)$$

We may decide arbitrarily that intermodal effects dominate whenever

$$\sigma_{INTRA}^2 \equiv \sigma_s^2 M^2 L^2 < 0.21\, \sigma_h^2, \qquad (3\text{-}14)$$

Table 3-1.
Values of the parameter 0.2/|M| for a germanium-phosphorus-doped silica fiber [10]. Gaussian impulse response shapes and Gaussian pulse shapes were assumed to generate these data.

λ(nm)	0.2/|M| (GHz km nm)	λ(nm)	0.2/|M| (GHz km nm)
800	1.6	1200	18.
820	1.7	1250	42.
840	1.9	1300	220.
860	2.1	1340	40.
880	2.3	1510	11.
900	2.5		

that is, whenever intramodal effects account for no more than ten percent of a measured σ_h. This leads to

$$\sigma_s^2 \leqslant \frac{0.21\ \sigma_h^2}{M^2\ L^2} . \tag{3-15}$$

If the source line shape and the impulse response are both reasonably modelled as Gaussians, eq (3-15) may be rewritten as

$$\Delta\lambda \leqslant \frac{0.2\ f_{-3dB}}{|M|\ L}, \tag{3-16}$$

where $\Delta\lambda$ is the full-width-half-maximum (FWHM) of the source spectrum and f_{-3dB} is the frequency at which the measured transfer function equals -3 dB.

Equation (3-16) has been used by standards committees [9] as a necessary condition for a valid measurement of "intermodal bandwidth". As indicated in section 3.1.2, M is a fairly weak function of glass composition but a strong function of wavelength. Table 3-1 gives the quantity 0.2/|M| for a germanium-phosphorus-doped silica fiber [10]. From this data one concludes, for example, that to measure a 1 km-long fiber having a 1 GHz bandwidth at 850 nm a source spectral width of less than 2 nm is required. In the longer wavelength region a much greater source spectral width could be used.

3.3 Length Dependent Effects and Launching Conditions

In multimode fibers several mechanisms act to render the fiber bandwidth a nonlinear function of length. These effects can make the interpretation of data very difficult.

Certain non-ideal characteristics of a fiber result in power being coupled between modes, an effect known as mode coupling or mode mixing. The transfer of power from modes with low group velocities to those with high group velocities and vice versa means that fiber bandwidth will decrease more slowly with length than would otherwise be the case. The actual functional dependence frequently falls in the range of $L^{-1/2}$ to L^{-1}, depending on the degree of mode coupling present [11].

Mode coupling may arise from defects introduced during manufacturing; for example, variations in diameter or index profile with length. Mode mixing also arises from bending of the fiber, particularly from bends that have spatial periods of the order of a millimeter. This means that the manner in which a fiber is cabled or handled can have a major effect on a bandwidth measurement. Particular care is required in the measurement of unbuffered fiber wound tightly on a spool.

Differential modal attenuation can also cause fiber bandwidth to be a nonlinear function of length. If high order modes of the fiber are excited and if, as is frequently the case, these modes suffer from higher attenuation than low order modes, then the rate at which bandwidth decreases with length is likely to be greatest near the input, where the complete range of mode groups is encountered.

The combined effects of mode coupling and differential modal attenuation may result in a complex functional dependence of bandwidth on length. For example, when both effects are important the bandwidth has been observed to decrease as L^{-1} near the input, progressing gradually to perhaps $L^{-1/2}$ after a substantial distance [12], and stabilizing at that value. Such a condition, where the functional dependence of bandwidth on length is stable, is sometimes known as modal equilibrium because it occurs when the distribution of power among the modes changes no further with length. The attenuation coefficient presumably becomes independent of length in this case, as well.

Another factor that effects the dependence of bandwidth on length is variations in index profile. If, in attempting to produce a fiber in which the group velocities of all modes are equal, some parts of the fiber are overcompensated* and other parts are undercompensated, equilization occurs.

This leads to a higher bandwidth than would otherwise be expected and to a very complex variation of bandwidth with length. Such variations in the degree of compensation frequently appear between fibers joined together in a link, and make the prediction of system performance difficult.

All of the problems described above make the choice of launching conditions for bandwidth measurements very difficult. Until such time as better methods of describing the variation of bandwidth with length are found it is probably wisest to simply choose measurement (launching) conditions that are well defined and easy to verify and which therefore may be expected to yield reproducible results. Certain standards groups [9] have therefore suggested that bandwidth measurements be made in such a way that all the modes of the fiber are excited. This means that light should be coupled into the fiber over the full area of the core and over a range of angles as large as the acceptance angle of the fiber. These are the criteria generally adopted in this Technical Note.

*A properly compensated fiber is one in which the group velocities of all modes are the same. Overcompensation is the case where low order modes propagate more slowly than higher order modes (in the power law representation, $g<g_{opt}$). Undercompensation is the opposite case.

4. Frequency Domain Techniques and Systems

Many techniques have been developed for the characterization of rf components in the frequency domain and instruments and devices for use in these measurement systems are widely available. With care, much of this same technology can be applied to the characterization of optical fibers. This section provides a survey of several potentially appropriate measurement methods, one of which has been extensively evaluated and is described in detail in subsequent sections.

4.1 Systems

It may be useful to separate frequency domain techniques into two groups: those that use wideband rf detection and those that use narrowband rf detection. Wideband detection generally leads to a simpler and less expensive measurement system but suffers from a lack of harmonic rejection and may give inferior noise performance. Narrowband detection is more complex but provides freedom from distortion, an important consideration when the system includes lasers or LEDs.

4.1.1 Systems Using Wideband Detection

One of the simplest systems that might be used is shown in the block diagram of figure 4-1. An rf sweep generator provides a controlled input signal, the frequency of which can be varied or swept over the range of interest. This signal is applied to the system under test, which in the case of a fiber would include the optical source and detector. The output rf signal is detected by a wideband, linear (in power) rf detector. If the signal-to-noise ratio is not an important consideration this arrangement may be sufficient to determine the magnitude of the transfer function by comparing the ratio of output-to-input signal level as a function of frequency with the test system in place to the same ratio with it removed. If the losses in the test system are large, the signal-to-noise ratio can be improved by amplitude modulating the input at a low frequency and using a lock-in amplifier as shown.

Probably the greatest difficulty in using this system for fiber measurements is that most suitable optical sources introduce harmonic distortion to the signal. With typical sources this problem may be sufficient to result in a several percent error in the transfer function (see section 5.1).

A variation of the system shown in figure 4-1 that allows the determination of group delay as well as transfer function magnitude [13] is shown in figure 4-2. In this case, the input is amplitude modulated at a relatively high frequency--perhaps 10 MHz for a sweep range from 30 MHz to 1.5 GHz. The output of the rf detector then goes into a vector voltmeter which gives the ratio of the output (envelope) magnitude to input magnitude and the phase shift in the envelope. The group delay (section 2.2) is related to this phase shift by the relation [13]

$$\tau_g = \frac{\phi_e}{360\ f_m},$$

where ϕ_e is the phase shift in the envelope, in degrees, and f_m is the modulation frequency.

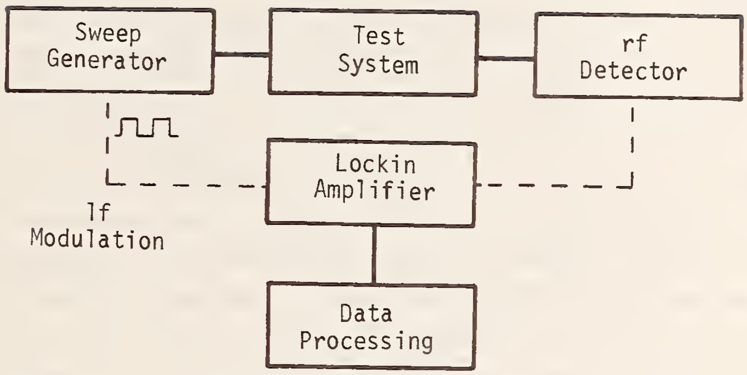


Figure 4-1. Block diagram of a simplified frequency domain measurement system. When the signal-to-noise ratio is high, the lock-in amplifier may not be necessary.

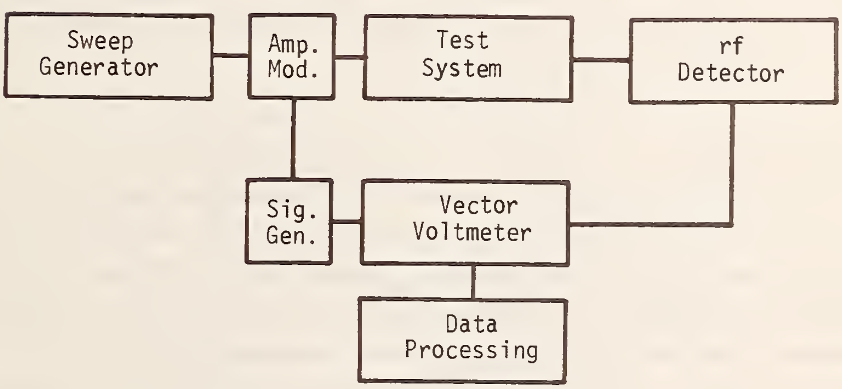


Figure 4-2. A modification of the system of figure 4-1 which allows both magnitude and group delay measurements. The signal generator operates at a relatively high frequency and the vector voltmeter determines both the magnitude and phase of the input and output modulation envelopes.

This is probably the simplest method of obtaining phase data on a fiber. It has been used by the author to evaluate several fibers and except for the problem of harmonic distortion works quite well.

4.1.2 Systems Using Narrowband Detection

The wide choice of detection bandwidth, gain, sweep rate, averaging, etc. generally available in commercial rf spectrum analyzers make that instrument a good choice for the detector in systems using narrowband detection (fig. 4-3). To fully exploit its capability, however, it must be used with a signal source that is frequency locked to the local oscillator of the spectrum analyzer. Thus, the source output frequency will vary coincidentally with the sweep of the spectrum analyzer. Such sources, known as tracking generators, and designed for use with specific spectrum analyzers are available from several manufacturers. The system bandwidth is generally limited by the degree to which the lock between the tracking generator and spectrum analyzer can be maintained. The simplicity of construction and operation of this system probably make it the best choice for fiber measurements whenever magnitude information is sufficient.

In the testing of discrete rf components, a vector voltmeter is frequently used to obtain both magnitude and phase information. It is not generally used in the testing of systems characterized by long propagation delays because of the difficulty in separating the phase distortion information from the large linear phase shift associated with the delay. Two techniques shown in figure 4-4 allow one to avoid these difficulties to a degree. One approach is to use a frequency synthesizer instead of a conventional sweep generator [14]. The synthesizer provides a discretely variable source frequency that can be varied arbitrarily slowly over the range of interest allowing more accurate phase measurements to be made. The other approach is to insert a system characterized by a similar delay but much smaller distortion in the reference line [15]. The phase distortion is then a much larger portion of the total phase shift. A single mode fiber would be a suitable choice for a system designed to characterize multimode fibers.

4.1.3 Network Analyzers

The four measurement systems described above are fundamentally similar in function and form to more elaborate rf measurement systems known as network analyzers which measure the S-parameters of microwave devices and circuits. Commercially available network analyzers can also be grouped into wide and narrowband detection types. They will measure the magnitude of the transfer function (i.e., S_{12}, S_{21}) and, depending on type, will provide some form of phase characterization. Generally, they are also designed to measure other parameters important in rf circuit design (e.g., impedance, S_{11}, S_{22}). Thus, a network analyzer suitable for carrying out fiber transfer function measurements is generally an expensive alternative to the limited purpose systems described.

4.2 Choosing a System and the Matter of Phase

Performance, convenience, and cost together determine the choice of measurement system. Several of the methods described in section 4.1, above, have been used at NBS and of

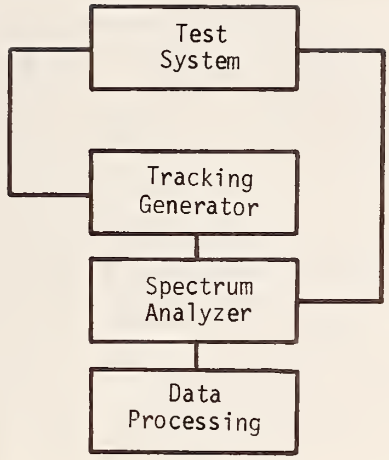


Figure 4-3. A simplified frequency domain system using narrowband detection. This arrangement forms the basis of the system described in detail in section 5.

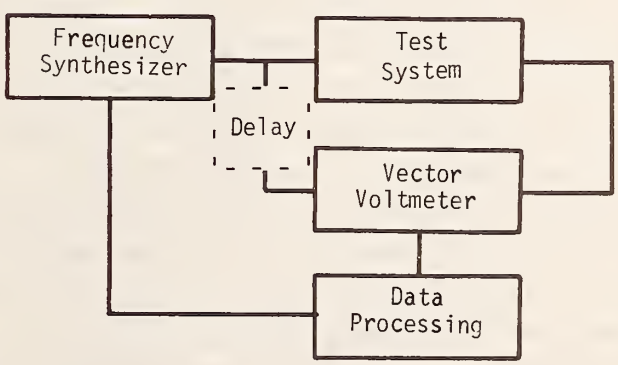


Figure 4-4. A narrowband system that can provide phase information. The system works best if a compensating delay is inserted in the reference channel of the vector voltmeter.

them, provided that only magnitude information is needed, the system shown in figure 4-3 seems to be the most appropriate choice. This brings us again to the question of whether the incomplete characterization of the information carrying capacity by $|H(f)|$ is sufficient.

Most high quality graded-index fibers designed for telecommunications applications have an impulse response that is nearly symmetrical about its central time and therefore show very little variation of group delay with frequency. The phase distortion that is present is therefore probably of little consequence as long as the problems noted in section 3.3 continue to complicate the interpretation of bandwidth measurements.

Step-index and other non-optimum profiles generally do not have symmetric impulse responses. It is conceivable that in certain systems using such fibers or in other special purpose systems phase distortion may be important. However, it appears that at this time these cases arise infrequently and most of the needs of the industry can be met with magnitude data alone.

The system of figure 4-3 was therefore chosen for further evaluation and use. The design and performance details of the version now in use at NBS are given in the following sections.

5. Description of the Measurement System

Figure 5-1 shows a block diagram of the system. The optical design is similar to that of a time domain system described elsewhere [16], though certain refinements have been incorporated. Almost all of the components are commercially available; their important characteristics are described below along with the basic system design.

5.1 Source

The source normally used in this system is a commercially available "laser transmitter". It consists of a single-transverse, multi-longitudinal mode GaAlAs laser diode coupled directly to a 2 m length of 50/125 μm core/cladding diameter, graded-index fiber. The laser is mounted on a temperature controlled substrate. Output from the laser is further stabilized by using the detected light from the back face of the laser to control the bias current. Radio frequency signals may be superimposed upon the bias current using a single R-C network, thus providing wide-bandwidth amplitude modulation. The entire unit, excluding power supply, measures about 3.5 by 7 by 4 cm (fig. 5-2).

The specified output power at the laser is 2.5 mW with an amplitude stability of 0.1 percent. Measured power at the fiber output is about 1.25 mW, where a long term drift of 1 to 2 percent is noted. This drift probably results from changes in optical feedback (reflections from the fiber ends) with temperature.

Figure 5-3 shows the spectrum of the source as measured with a 0.5 m Ebert-type spectrometer, with a resolution indicated by the width of individual longitudinal modes. The relative power of the modes varies somewhat with time with the result that a specificiation of spectral linewidth based on the full-width-half-maximum (FWHM) of the envelope becomes uncertain. However, for purposes of estimating the frequency at which chromatic effects begin to effect a bandwidth measurement (section 3.2) we choose $\Delta\lambda = 0.9 \pm 0.15$ nm. This

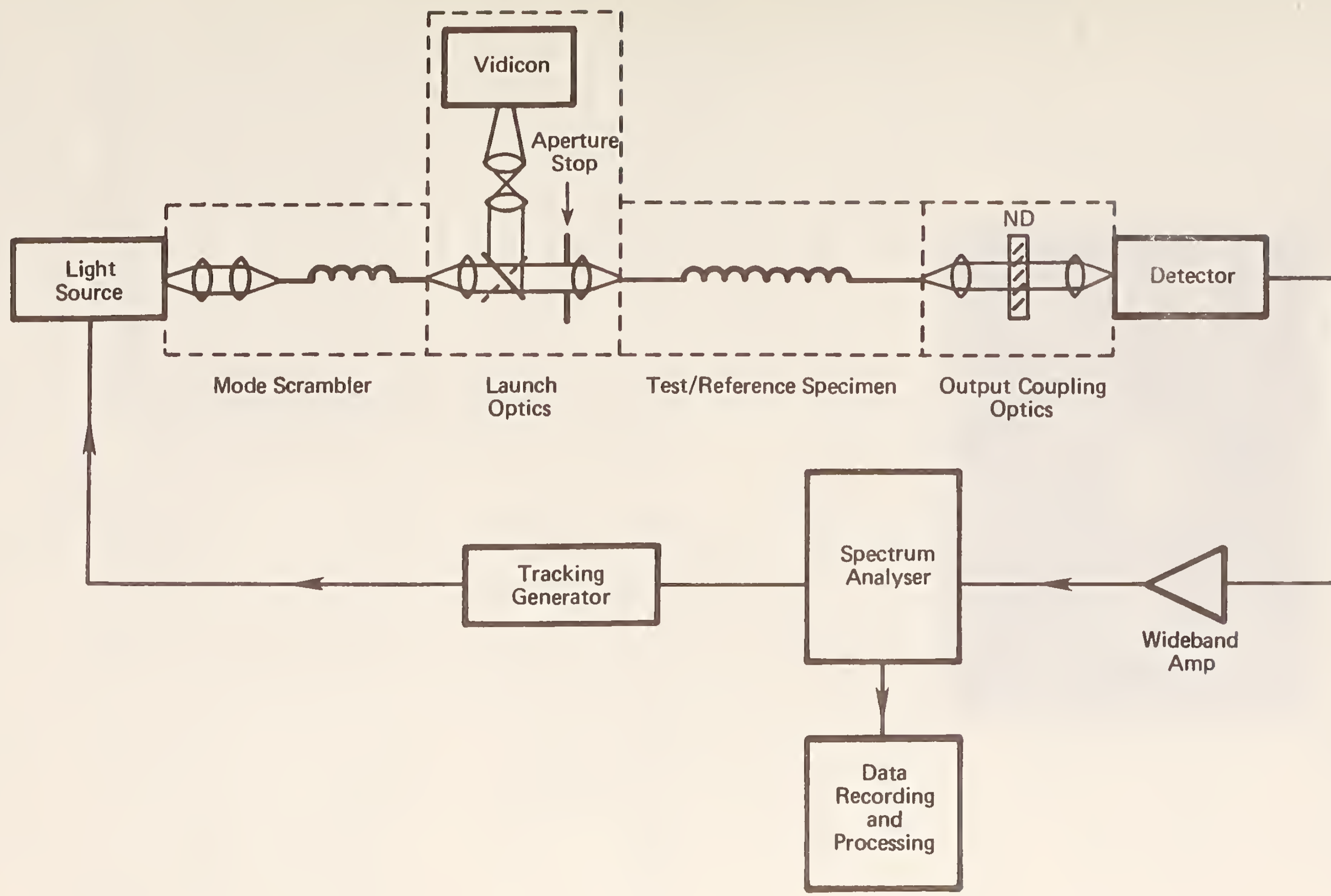


Figure 5-1. Block diagram of frequency domain fiber bandwidth measurement system.

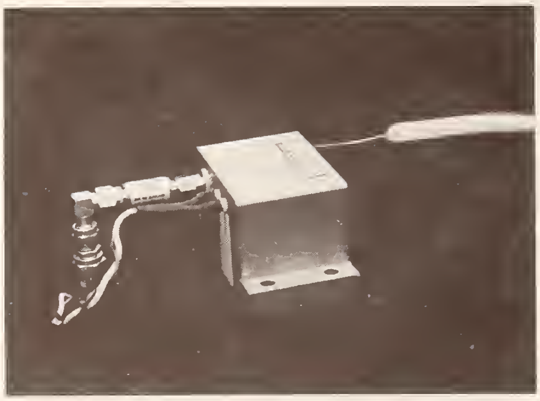


Figure 5-2. Photograph of "laser transmitter" used as the source.

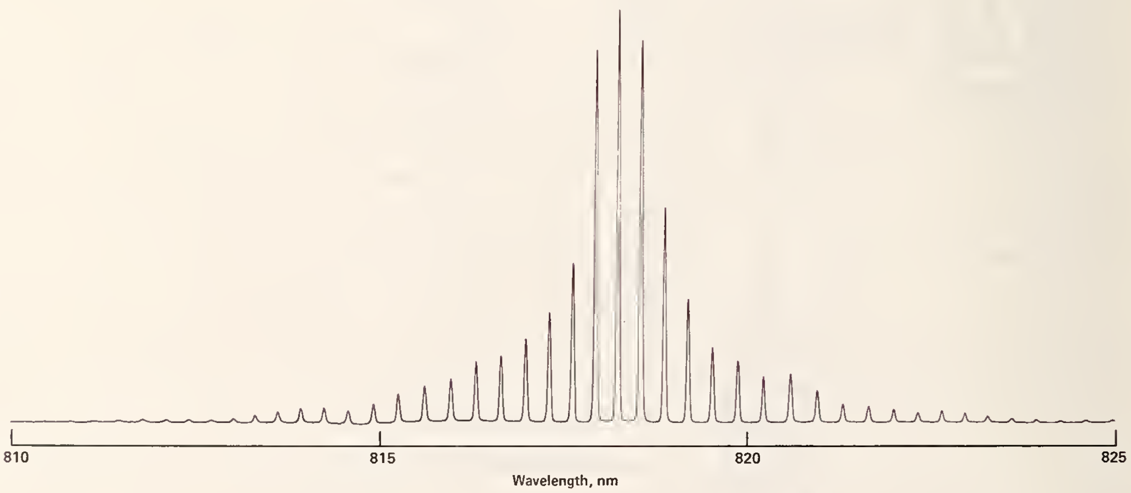


Figure 5-3. Output spectrum of source obtained with a 0.5 m Ebert-type spectrometer.

suggests that for a typical germanium-phosphorus doped silica fiber material dispersion does not become a contributor to the measurement below 1.9 GHz which is outside of the operating range of the system.

Figure 5-4 shows the variation in modulation index (optical power modulation/rf drive) versus frequency. The modulation index is essentially independent of frequency from a few tens of hertz to 600 MHz (specified bandwidth is 500 MHz). The index decreases by about 2.5 dB (optical) between 600 and 680 MHz and then increases gradually to a value about 4 dB (optical) above its low frequency value at 1430 MHz near the limit of the system. Independent tests on the detector used in this measurement indicate that the variations in modulation index are not measurably affected by the detector. The increase at the highest frequencies may be related to self pulsing in the laser because the noise spectrum of the laser output shows a similar increase. The dip at 680 MHz is of unknown origin.

Harmonic distortion in the source output can, as noted in section 4, cause difficulties when broadband detection is used. Figure 5-5 shows the distortion produced by this source. At a drive frequency of 100 MHz and an rf signal level of 0 dBm, the second harmonic is about 38 dB below the fundamental (manufacturer's specification: 40 dB). However, as the drive frequency is increased the harmonic distortion increases until at a fundamental frequency of 500 MHz both the second and third harmonics are only about 20 dB down. This would be unacceptable for broadband detection.

5.2 Mode Scrambler

Since the results of a fiber bandwidth measurement depend rather strongly on the spatial and angular characteristics of the input light, that is to say the input mode volume, it becomes necessary to minimize the effects of such changes in the source. This problem is somewhat less severe in the frequency domain system than in the time domain system [16] since the cw laser diodes are inherently more stable spatially than those used in time domain systems.

The usual way of maintaining launch stability is to couple the output of the source through a specially designed spatial filter. The spatial filter has the properties that the spatial and angular characteristics of its output are independent of those of the input. In practice, the spatial filter usually consists of a piece or pieces of suitably chosen fiber [16,17]. For this reason it has come to be known as a <u>mode scrambler</u>.

The mode scrambler used in this system consists of two pieces of fiber. The first is the 2 m section of 50/125 μm core/cladding diameter, graded-index fiber directly coupled to the laser by the manufacturer. The second is a similar length of 80/125 μm core/cladding diameter, step-index fiber spliced onto the first fiber in a loose tube. The radiation angle of each fiber is nominally 0.2 rad.

Figure 5-6 shows the characteristics of the device. The near-field profiles are obtained by imaging the output face of the fiber onto a silicon target vidicon. The video signal is processed with commercial equipment in such a way that the intensity of the image along a line normal to the raster is determined and plotted on the monitor screen.

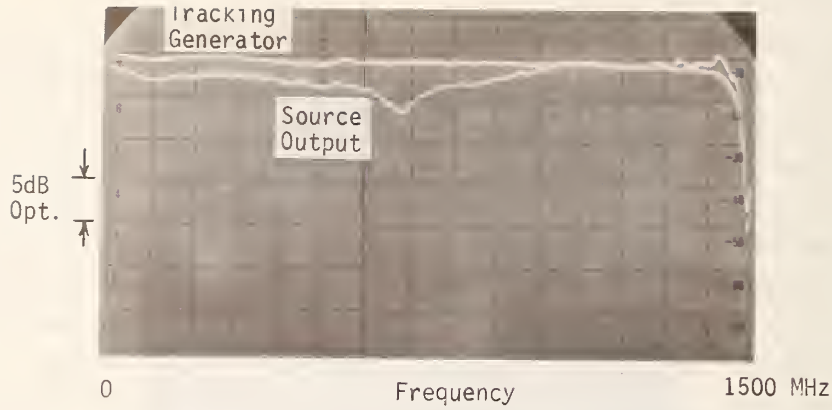


Figure 5-4. Modulation index of source as a function of frequency. The output of the tracking generator was applied to the source and the output of the graded-index pigtail from the source focused onto the detector.

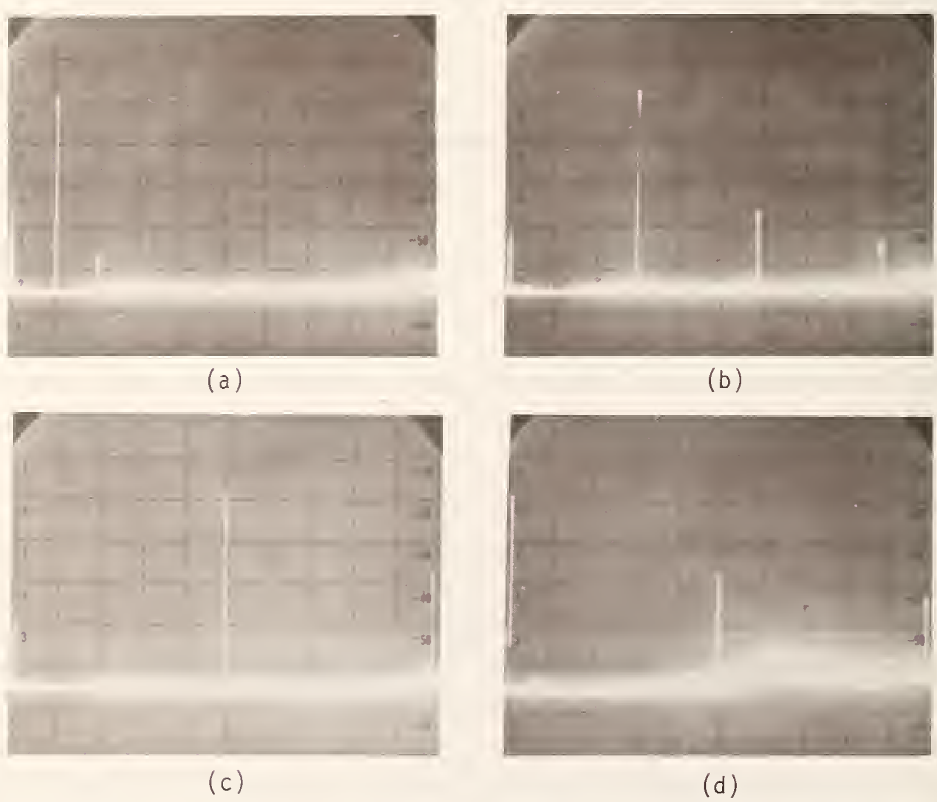


Figure 5-5. Distortion in source output. Drive level was approximately 0 dBm and the vertical scale 10 dB (electrical)/div in each case. (a) Drive: 100 MHz, Scale: 0-1000 MHz; (b) Drive: 300 MHz, Scale: 0-1000 MHz; (c) Drive: 500 MHz, Scale: 0-1000 MHz; (d) Drive: 500 MHz, Scale: 500-1000 MHz.

The near field of the output from the graded-index fiber shows a rounded profile as expected, with a great deal of variation due to speckle. At the output of the step fiber the core is completely filled and the variations due to speckle appear somewhat reduced.

The far-field pattern from the step fiber was obtained by scanning a detector along a circular arc about 10 cm from the fiber end [18]. The far-field radiation angle is about 0.19 at the 90 percent irradiance points.

The speckle evident in all the data of figure 5-6 represents a fundamental difficulty in controlling the launching conditions for bandwidth measurements. It results from constructive and destructive interference in the superposition of fields from the modes of the fiber and appears whenever the coherence time of the source is long compared to the differences in group delay among the modes. The details of the speckle pattern vary with the relative phase of the modes. Very slight movement or distortion of the fiber will produce such phase shifts as will a change in temperature. These effects make it difficult to precisely define launching conditions. Further, when the speckle pattern shifts with time in a system where mode sensitive devices, such as couplers, are present or where there is significant differential mode attenuation, noise, generally known as modal noise results [19].

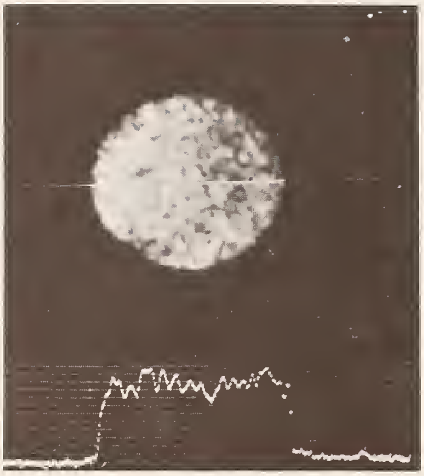
One solution to the problem of speckle is to use a less coherent (broader spectral linewidth) source. However, as noted earlier (section 3.2) that can result in additional limitations to the bandwidth from the material dispersion. As a practical compromise, source spectral widths of about 1 nm are reasonable.

Another possible solution for measurement systems might be to deliberately introduce periodic phase shifts, through for example, mechanical distortion by a piezoelectric transducer. This should have the effect of smearing the speckle pattern. This approach has not been seriously pursued, as yet.

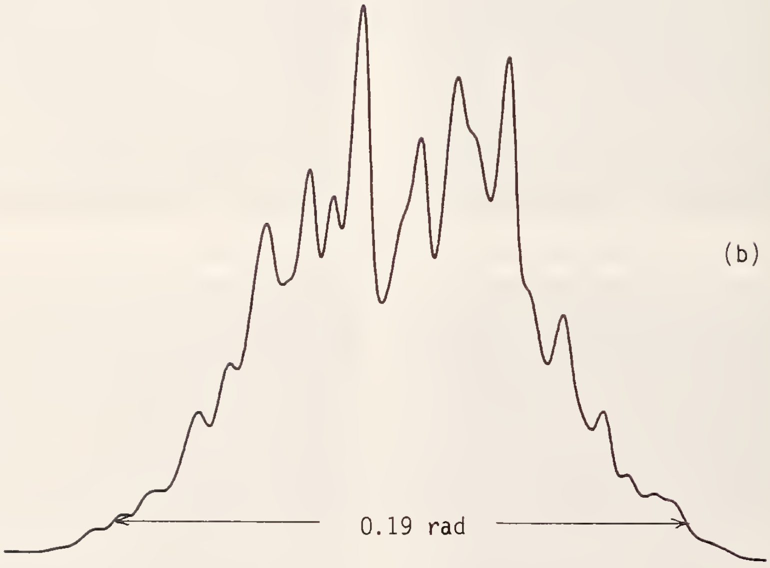
5.3 Launching Optics

The section of figure 5-1 labeled launching optics is designed to image the output of the mode scrambler onto a fiber specimen in a well defined and reproducible fashion. The launching parameters of interest are the size of the image (the "spot size") on the input end of the fiber specimen and the angular extent of the bundle of rays that converge to form the image (the "launch numerical aperture", LNA). With this system (fig. 5-7) it is possible to control these parameters independently, though rather less conveniently than is necessary in an attenuation measurement system [20]. However, as noted in 3.3.3, the greatest interest at present is in measurements made with full excitation of the fiber.

Two microscope objectives form the image. The first, usually a 10X, 0.25 NA lens, collimates the output of the mode scrambler. The second, in most cases identical to the first, focuses the collimated beam onto the specimen. The ratio of the spot size on the end of the test specimen to the spot size at the output of the mode scrambler is equal to the ratio of the focal length of the second objective to that of the first. This is perhaps the easiest way to control the spot size. The launch numerical aperture is somewhat more complicated to predict. If the objectives are identical, the LNA should be the lesser of the sine of the radiation angle of the mode scrambler or the effective NA of the objective. If the objectives are different, a more specific analysis is necessary to predict the



(a)



(b)

Figure 5-6. Characteristics of mode scrambler. (a) Near-field pattern, nominal diameter, 83 μm. Plot at bottom is of intensity along line through image. (b) Scan of far field of mode scrambler.

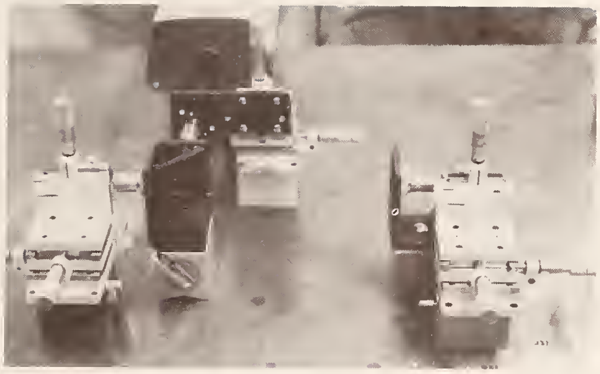
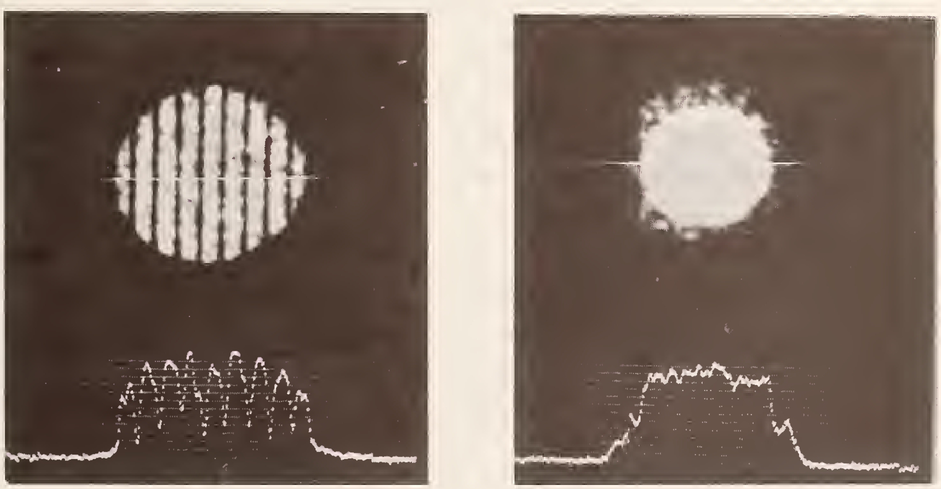


Figure 5-7. Photograph of launching optics. Output of mode scrambler is on manipulator at right, specimen input on manipulator at left. Pellicle at left of center can be rotated 90° to direct the image of either the mode scrambler output or the specimen input onto vidicon at top of photo (see fig. 5-1).



(a) (b)

Figure 5-8. (a) Image of stage micrometer placed where specimen input would normally be placed, to verify size of launch spot. Line spacing is 10 μm. (b) Image of short step-index specimen. The core appears brighter because of reflected light from output end of fiber.

LNA. The LNA may be limited beyond that determined by the mode scrambler or lenses by placing an aperture in the collimated portion of the beam.

For purposes of system alignment and evaluation it is convenient to place a pellicle beam splitter in the collimated beam and to thereby image, with some additional magnification, the input end of the fiber specimen as illuminated by the source. Figure 5-8a shows the image produced on a stage micrometer placed at the image point; verification of the launched spot size is thus obtained from the 10 μm line spacing on the micrometer. Figure 5-8b shows the image of a short (~ 2m) fiber specimen similarly obtained. The core appears brighter than the cladding due to light reflected back from the output end of the fiber. With a long fiber or with the output end index matched there is little difference in appearance between the core and cladding.

The launch numerical aperture could be verified by scanning a small detector through the diverging beam beyond the image point. An alternate method is to determine the far-field radiation angle from a short piece of fiber (fig. 5-9).

5.4 Specimens

In most cases, the test specimen is a known length (typically 1 km) of multimode graded-index fiber. A separate reference specimen representative of the test specimen, generally a piece cut from one end of the test specimen, is chosen. The length of the reference specimen must be such that the magnitude of its transfer function is essentially unity over the frequency range of interest. As a practical matter, it is usually sufficient to limit the length of the reference specimen to 1 percent of the length of the test specimen.

Both ends of each specimen are prepared by cleaving and are inspected with a 400 power microscope for flatness and perpendicularity. Illumination is either collinear with the microscope axis or from the far end of the fiber. Ends with perceptable hackle or breakout within the core region are rejected as are ends on which the entire outer surface of the cladding can not be brought into sharp focus at the same time. The theoretical depth of focus of the microscope is about 3 μm which means that for a 125 μm fiber diameter angles smaller than 1 to 1.5 degree are accepted.

Cladding mode strippers are not used in this system. Unlike the case with attenuation measurements, light that remains trapped within the cladding for the full length of the reference fiber should not affect the measurement.

It is important that the test specimen be handled in such a way that no excess microbending is applied to the fiber. This consideration can be very important when testing uncabled fiber that has a very thin buffer.

5.5 Detection

A suitable detector must have a sufficient frequency response, linearity of response over the range of operating levels, and a uniformity of response over the active area. The detector chosen for this system is a 200 μm diameter Si APD. The characteristics of this detector were described previously [16] and are briefly summarized here. The impulse response duration is about 200 ps which gives a more than adequate frequency response for

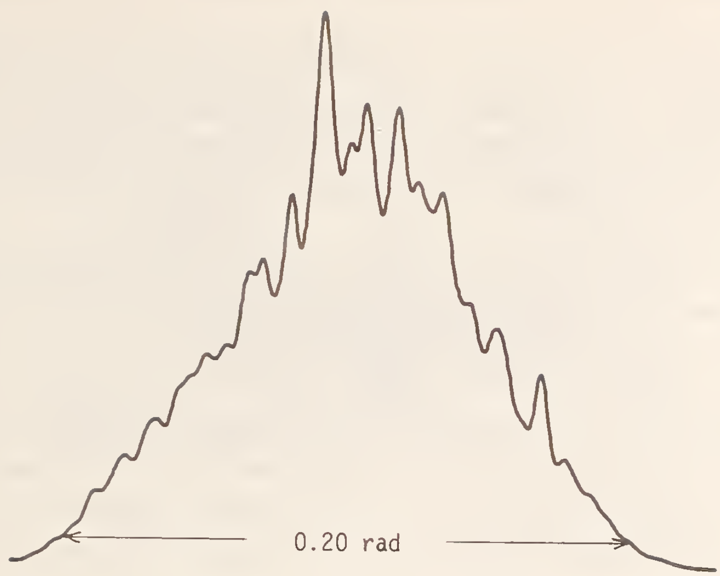
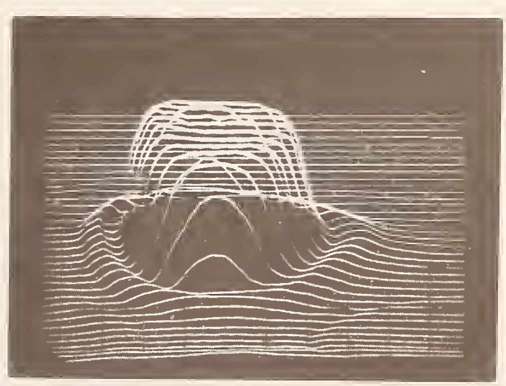


Figure 5-9. Far-field radiation pattern from a short piece of large acceptance angle fiber placed in test system to verify launch numerical aperture. Fiber specifications: 100 μm core diameter, quasi-step index profile, 0.3 NA.

(a)



(b)

Figure 5-10. (a) Photograph of Si APD detector used. Active area is 200 μm diameter. (b) Plot of spatial response uniformity. Detector is uniform to about 5 percent peak to peak.

this system (see also fig. 5-3). The uniformity of response (fig. 5-10) is about 5 percent peak to peak.

The pulse linearity is good [16]. At the higher average currents (50-100 μA) used in this system perceptable heating occurs. This is sufficient to cause a few percent change in detector gain but allowing the detector to stabilize before measurements eliminates most of the difficulty. Further compensation for temperature changes by the method described below fully eliminates the problem.

The detector is mounted in a coaxial mount similar to one described by Green [21] (fig. 5-11) and biased with the circuit of figure 5-12, which differs somewhat from the bias circuit used with the time domain system [16].

The detector is normally biased at a point (typically 140 V) where the gain is between 5 and 10. To compensate for any temperature induced change in gain or change in laser output the dc current is monitored with a 10 Ω sensing resistor. The slopes of the dc and rf load lines being nearly equal (1/60 versus 1/50 Ω^{-1} when the ammeter is shorted) a change in this reference voltage is proportional to any laser output or detector gain induced changes in detected rf level.

It is necessary that the outputs of the test and reference fibers are completely coupled to the uniform detector to insure that all mode groups are equally detected. This is done with two microscope objectives, as shown in figures 5-1 and 5-13. Usually the objective nearest the fiber output is a 10 X, 0.25 NA while the second is a 5 X, 0.1 NA to provide a larger spot on the detector and thus average over spatial nonuniformities.

Neutral density filters (fixed and circularly variable) are placed in the collimated region to set the signal levels for test and reference specimens equal, minimizing the effect of detection nonlinearities.

5.6 Electronics

A more detailed block diagram of the electronic part of the system is shown in figure 5-14. The detector output passes through a wide-band (0.1 to 1400 MHz) high gain amplifier (+26 dB) and into the input of the spectrum analyzer. A ramp generator controls the sweep of the spectrum analyzer and hence the output of the tracking generator which is fed to the laser source. The vertical output of the spectrum analyzer is amplified and along with the ramp voltage and the amplified current reference signal is processed with a data logging apparatus. This unit includes A/D conversion, timing and control circuitry, and parallel to serial conversion. The data is then recorded on magnetic tape cassettes for subsequent computer processing.

Typically, the frequency sweep covers 10 MHz to 1200-1300 MHz in about 2 minutes. About 250 data points are recorded with a frequency resolution of about 5 MHz. Increased resolution or reduced sweep range can be used when required.

Calibration of the sweep is provided by substituting a step variable precision power supply for the ramp generator and measuring the output frequency of the tracking generator with a counter. About 100 calibration points at equally spaced frequencies are obtained. Some slight hysteresis (~ 0.2 MHz) is observed. The reproducibility of the calibration curve depends on tracking generator adjustment as well as other factors but measurements

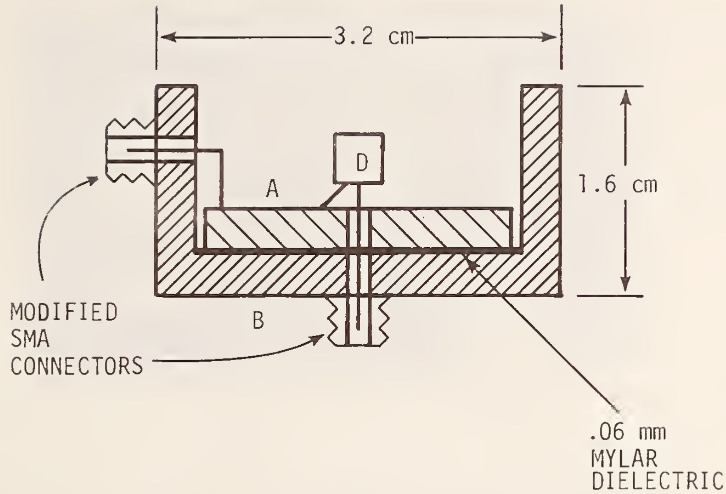


Figure 5-11. Diagram of detector mount.

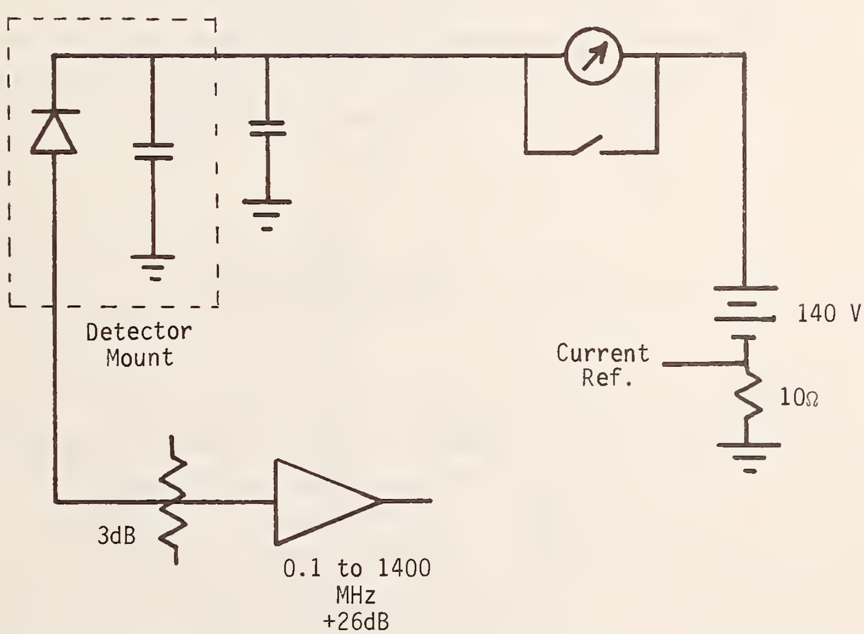


Figure 5-12. Detector bias circuitry.

Figure 5-13. Photograph of output coupling optics. Specimen output is on manipulator at right. Fixed and circular-variable neutral density filters are placed between microscope objectives. Detector is in cylindrical mount at left (see fig. 5-1).

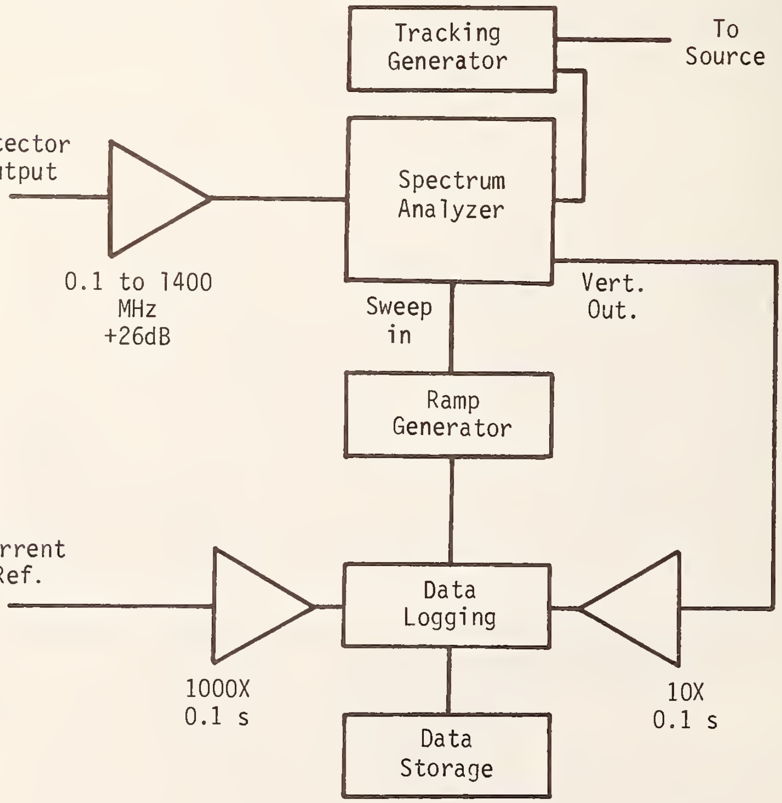


Figure 5-14. Block diagram of electronics.

over several months indicate that ± 0.5 MHz is readily obtained. Frequency calibration data are plotted in figure 5-15 along with a linear least-squares fit.

The vertical output of the spectrum analyzer is calibrated using a signal generator and a set of precision attenuators. Calibration points are taken at 1 dB electrical (0.5 dB optical) intervals. The attenuators were chosen for their reproducibility and frequency independence. The specified values were verified or adjusted using a bolometer-type rf-microwave power meter accurate to 1 percent. This power meter thus becomes the magnitude reference standard for the system. Calibration at several frequencies indicates that single frequency calibration is sufficient. Vertical calibration data relative to a suitably chosen reference level are shown in figure 5-16, along with a linear least-squares fit.

5.7 Computation

For each data point there is one value related to the signal level in dB, one related to frequency, and one related to the linear value of the current reference. The first two of these are converted to dB and frequency, respectively, by linear interpolation using the data described in section 5.6. The vertical signal is then adjusted for changes in the current reference by subtracting 5 times the latter (normalized) from the former. This procedure is followed for data from both a test and a reference specimen.

The result of these manipulations is two arrays of data, magnitude versus frequency; one for the test specimen and one for the reference specimen (fig. 5-17). Unfortunately, the operation of the system does not insure that frequency values in the two arrays coincide so further interpolation is required, as shown.

Verification of the computations was obtained by inserting the precision attenuator set between the tracking generator and spectrum analyzer in place of the usual test apparatus. The attenuators were switched at intervals as the usual speed range was covered (fig. 5-18). Deviations from calibrated values (averaging over several standing wave periods where necessary) are all less than 0.03 dB.

6. System Performance

6.1 Measurement Procedure

Following preparation of the test and reference specimens as indicated in section 5-4, the two fibers are placed into the system. Generally, the test specimen is evaluated first. The alignment procedure consists of observing the fiber end on the monitor and adjusting the end position so that both the end and the spot striking it are in focus and the spot is visually centered within the core circumference. At the fiber output the image of the output end is located on the detector by adjusting the focus for maximum signal and adjusting the transverse position to center the spot on the detector.

The signal level is adjusted with discrete and variable neutral density filters to a satisfactory value not exceeding the limits of the detector. (If a high-loss fiber is measured no ND is used with the test specimen.) The tracking generator is adjusted for proper tracking, the spectrum analyzer is set to scales and conditions on which calibration data is available, the sweep is begun, and data are recorded.

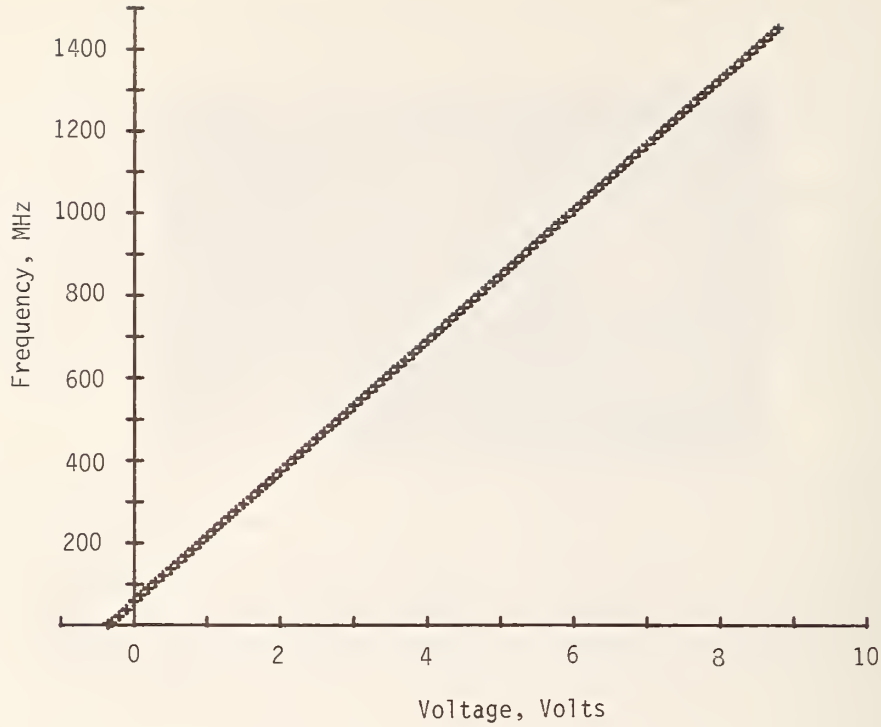


Figure 5-15. Frequency calibration data.

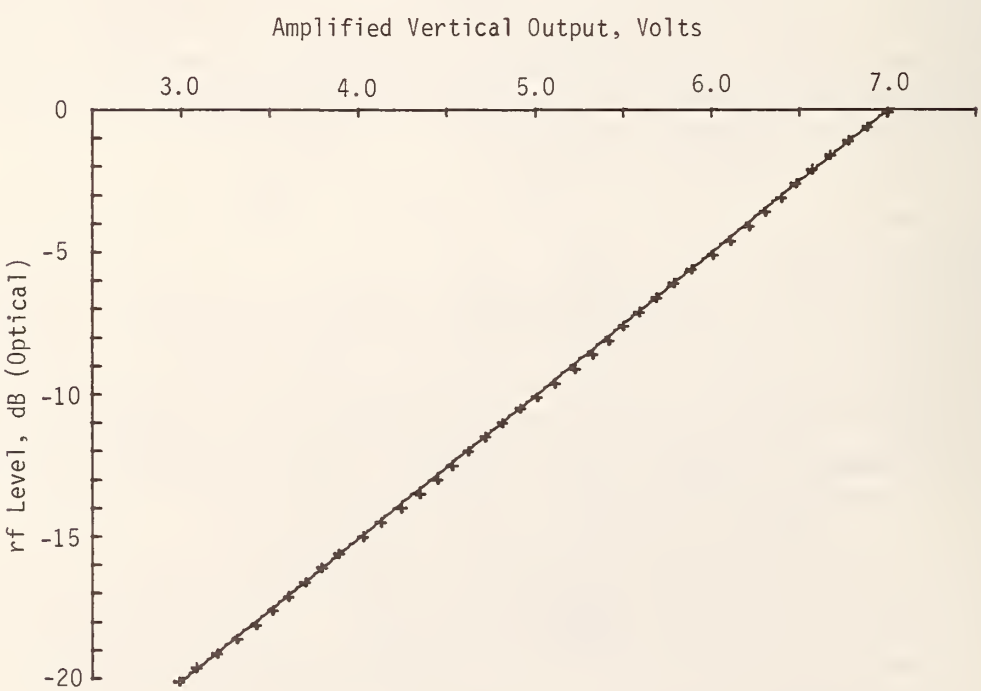


Figure 5-16. Vertical calibration data.

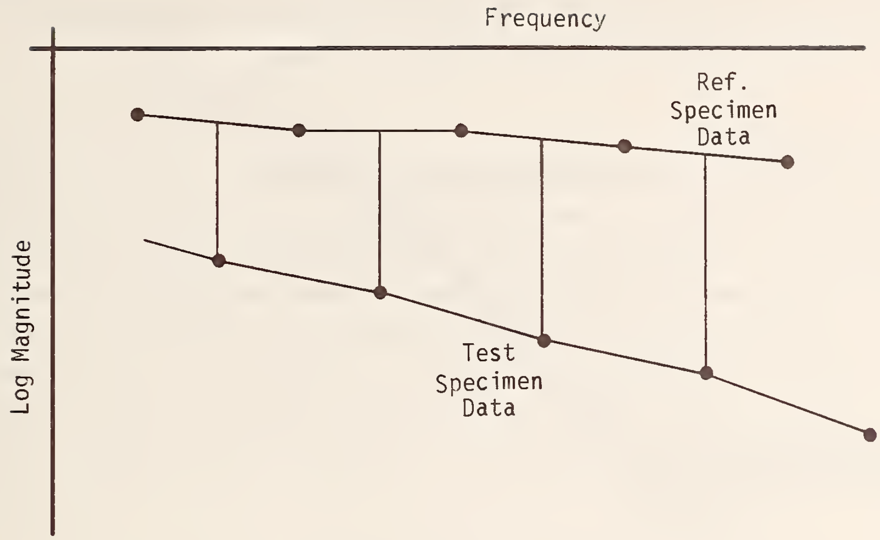


Figure 5-17. The measurement process results in two arrays of data, magnitude versus frequency, one for the test specimen and one for the reference specimen. The frequency points are not necessarily coincident. The reference specimen data is therefore interpolated before the differences in magnitude are obtained.

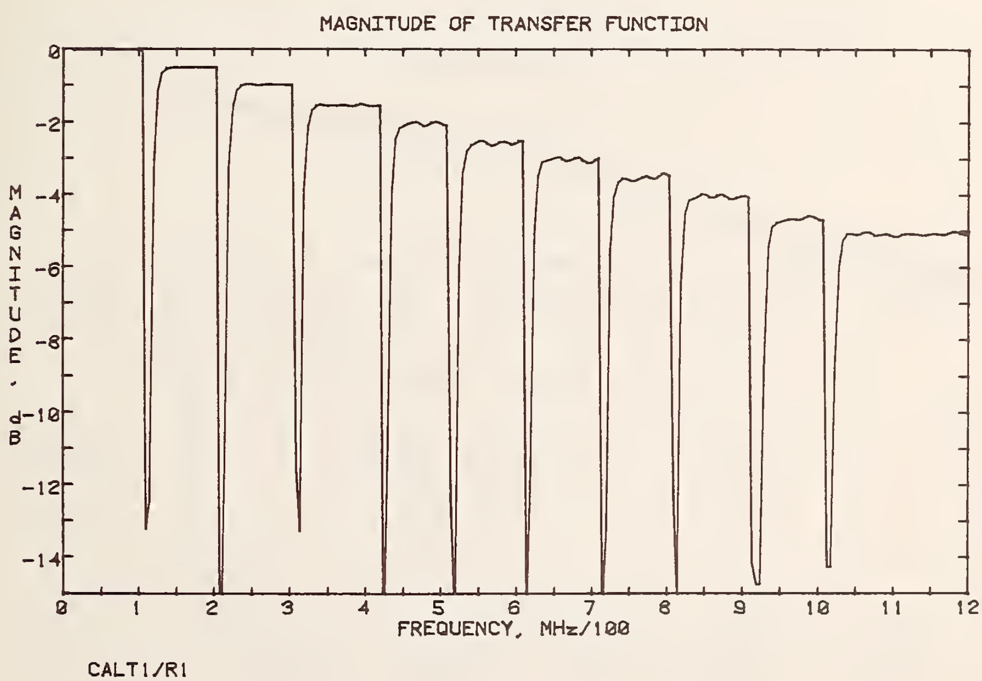


Figure 5-18. Result of replacing test system with a set of precision, step-variable attenuators and switching at intervals during scan.

The procedure is repeated for the reference specimen. In this case, the average current level at the detection is set equal to that with the test specimen and care is taken to ensure that the same spectrum analyzer parameters are chosen.

6.2 Precision and Accuracy

Given the difficulty of interpreting bandwidth measurements, the most important aspect of bandwidth measurement quality at the present time is the precision, or reproducibility. To test the precision of this system repeated measurements were made on each of two selected fibers, using the procedure of section 6.1. The two fibers were chosen because in each case a substantial history of both bandwidth and attenuation measurements was available [16,22] indicating stability of characteristics. The nominal characteristics of the fibers are summarized in table 6-1. Each measurement consisted of separate test and reference data with a completely new alignment and resetting of levels for each specimen. The results are shown in figure 6-1 and 6-2.

Table 6-1.
Characteristics of fiber used in precision determinations

Fiber	I308	I223
Length	1.3 km	1.1 km
Size	50/125 μm	50/125 μm
NA	0.25	0.25
Attenuation	6.0 dB/km @ 850	6.0 dB/km @ 850

Table 6-2.
Comparison in precision between a time domain system [16] and the frequency domain system described here. The variation in FD precision on I308 at the -3, -6, and -9 dB levels probably results from the different slopes of the transfer at these points.

Fiber	Level (dB)	TD-Precision (%)	FD-Precision (%)
I308	-3	0.6	1.7
I308	-6	1.	0.06
I308	-9	1.	0.06
I223	-3	4.	3.4
I223	-6	3.	3.3

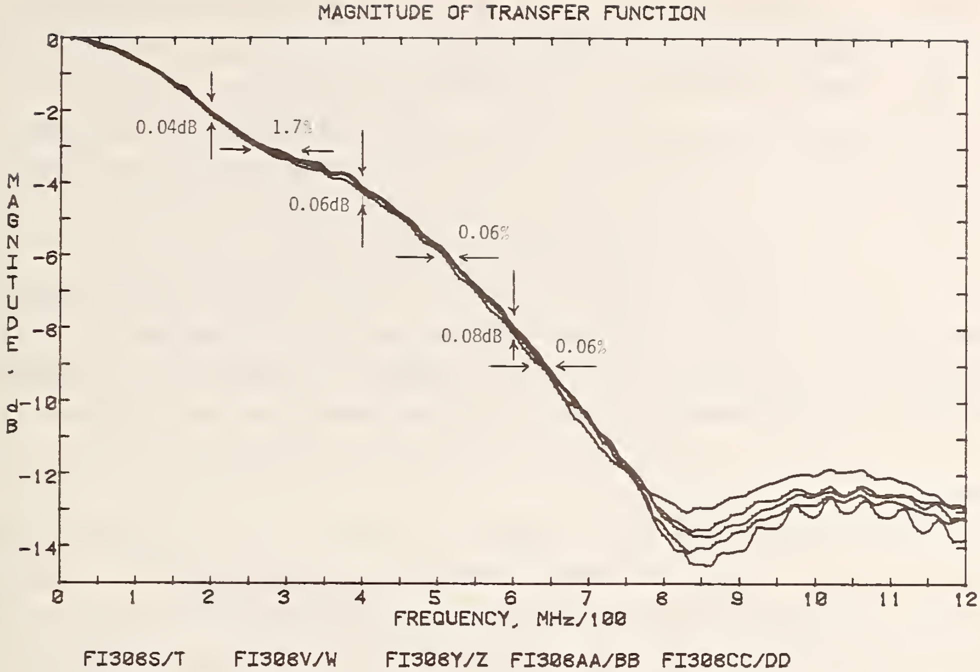


Figure 6-1. Superposition of the results of five independent measurements on fiber I308. Arrows indicate the one standard deviation imprecision at the -3, -6, and -9 dB levels in percent and at frequencies of 200, 400, and 600 MHz in dB.

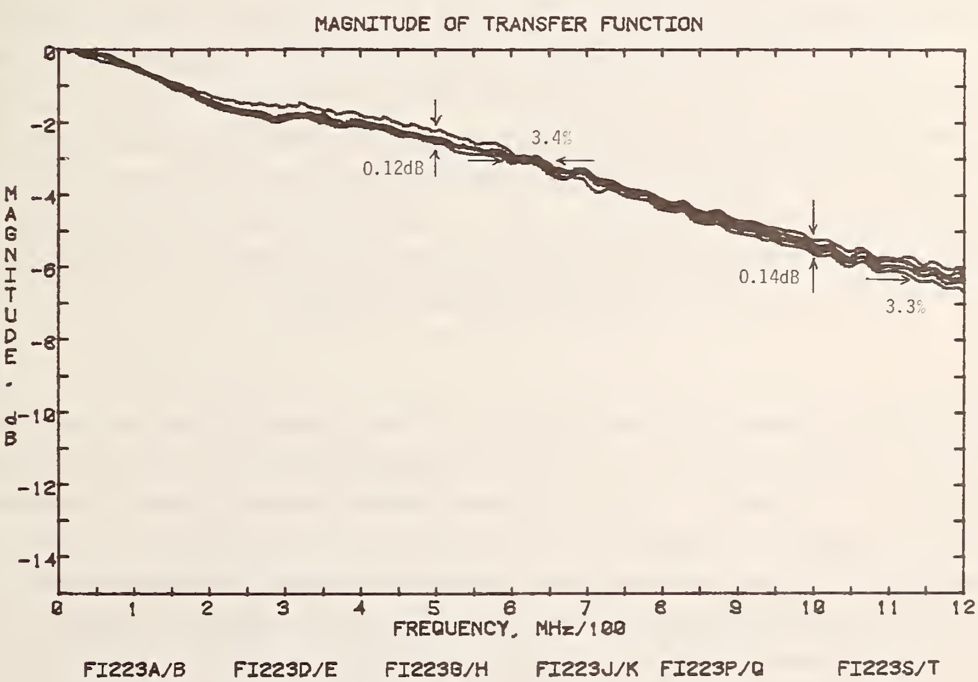


Figure 6-2. Superposition of the results of five independent measurements on fiber I223. Arrows indicate the one standard deviation imprecision at the -3, and -6, dB levels in percent and at the frequencies of 500, and 1000 MHz in dB.

It is useful to specify precision in two ways. One is reproducibility in determining the frequency at which the magnitude reaches a specified level, say -3 dB, -6 dB, -9 dB, etc. The other is the reproducibility in magnitude at a specified frequency. In figures 6-1 and 6-2 a one standard deviation precision at several levels and frequencies is indicated. Note that the precision on fiber I308 is significantly better than for fiber I223. This difference appears to be related to the fiber characteristics--presumably differences in mode coupling and differential attenuation--and was noted in previous work. (I308 was identified as fiber A and I223 as fiber B in [16].) In fact, the precision obtained in that previous work is very similar in both cases to the precision obtained here (table 6-2). This is not at all surprising since the optical part of the system in all probability determines the system precision and the optics in the two systems are very similar.

6.3 Limitations

The frequency range over which this system is operated, 10 to ~ 1200 MHz is sufficient to test most commercial fibers--the highest commercial specification at this time appears to be 1000 MHz·km. However, experimental fibers with a bandwidth of 2 to 3 GHz·km and higher have been reported, and it would be desirable to extend the range of the system.

Several factors limit the upper frequency of the system as it now exists. The presently used wideband amplifier and the tracking generator/spectrum analyzer all have limitations in the 1400 MHz region. Each could be upgraded somewhat, though material dispersion due to source linewidth becomes a significant factor somewhat near 2 GHz. Using a more coherent source will decrease material dispersion contributions but will increase problems in specifying launching conditions due to speckle. Unless the speckle problem can be eliminated by other means, 2 GHz is probably the maximum useful frequency for a system of this sort at this wavelength.

It is becoming increasingly important to be able to measure long systems with substantial loss. The dynamic range of this system has not been carefully studied, but is clearly limited, at present, to roughly 20 dB loss as a result of direct electrical coupling from input to output. Signal-to-noise measurements indicate that when this problem is eliminated fibers with a loss of at least 30 to 40 dB could be measured.

7. Summary

Based on data and experience obtained to date and reported in previous sections, the frequency domain system described in this Technical Note seems well suited for the routine measurement of fiber bandwidth. It is relatively simple to construct using components that are almost all commercially available. It is easy to use and requires fewer and less complex computations than time domain systems. The precision obtained is comparable to that obtained in the time domain and well within the uncertainties observed between laboratories [23]. Certain improvements in the system and an extension to the 1.3 or 1.55 μm region would allow it to perform most of the multimode fiber bandwidth measurements required in the foreseeable future.

While this and other work suggest that the measurement of bandwidth on a specific length of fiber is well in hand, a great deal of work needs to be done on the length dependence of fiber bandwidth. Until new approaches to this problem are developed it is likely that the most appropriate measurement conditions for bandwidth measurements will continue to be a full excitation of the fiber modes.

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8. References

[1] (a) Personick, S. D., Hubbard, W. M., and Holden, W. S. Measurement of the baseband frequency response of a 1 Km fiber. Appl. Opt. 13:266-268; 1974.

(b) Personick, S. D. Baseband linearity and equilization in fiber optic digital communications systems. Bell Sys. Tech. J. 52:1175-1195; 1973.

(c) Vassallo, Charles. Linear power responses of an optical fiber. IEEE Trans. Microwave Theory Tech. MTT-25:572-576; 1977.

[2] Bracewell, Ron. The Fourier transform and its applications. McGraw-Hill; 1965.

[3] Personick, S. D. Design of repeaters for fiber systems, in Fundamentals of optical fiber communications. Barnoski, Michael K., ed. Academic Press; 1976.

[4] Goldman, Stanford. Frequency analysis, modulation, and noise. McGraw-Hill; 1948.

[5] (a) Sandberg, I. W.; Kaminow, I. P.; Cohen, L. G.; and Mammel, W. L. . On the phase of the modulation transfer function of a multimode optical-fiber guide. Bell Sys. Tech. J. 57:99-109; 1978.

(b) Sandberg, I. W. A note concerning optical-waveguide modulation transfer functions. Bell Sys. Tech. J. 57:3047-3057; 1978.

[6] Gloge, D. and Marcatili, E. A. J. Multimode theory of graded-core fibers. Bell Syst. Tech. J. 52:1563-1578; 1973.

[7] Olshansky, Robert and Keck, Donald B. Pulse broadening in graded-index optical fibers. Appl. Opt. 15:483-492; 1976.

[8] (a) Cohen, Leonard G.; Kaminow, Ivan P.; Astle, Harry W.; and Stulz, Lawrence W. Profile dispersion effects on transmission bandwidths in graded index optical fibers. IEEE J. Quantum Electron. QE-14:47-41; 1978.

(b) Horiguchi, M.; Ohmori, Y.; and Takata, H. Profile dispersion characteristics in high bandwidth graded-index optical fibers. Appl. Opt. 19:3159-3167; 1980.

[9] Procedures now under consideration by EIA Committee P6.6--Working Group on Fibers and Materials (Electronic Industries Association, 2001 Eye St., Washington, DC 20006).

[10] Data supplied by P. Reitz, Corning Glass Works, Corning, NY.

[11] (a) Suzuki, S.; Kawahara, T.; Tanaka, G; Yoshida, M.; Kyoto, M.; Nakahara, T.; Kumamaru, H.; Takada, H.; Inagaki, N.; and Kitayama, K. Characteristics of graded-index fiber by VAD method. Proc. Optical Comm. Conf., Amsterdam, 12.6-1--12.6-4; 1979.

(b) Kapron, F. P.; Sladen, F. M. E.; Garel-Jones, P. M.; and Kneller, D. G. Attenuation and pulse broadening along concatenated fiber links. Tech. Digest, Symp. Opt. Fiber Meas.-1980, Boulder, 63-66; 1980. U.S. Govt. Printing Office, Washington, DC 20402.

[12] Cohen, L. G. Shuttle pulse measurements of pulse spreading in an optical fiber. Appl. Opt. 14:1351-1360; 1975.

[13] Swept-frequency group delay measurements. Applications Note 77-4, Hewlett-Packard, Palo Alto, CA 94304.

[14] Kobayashi, Ikutaro. Bandwidth measurement in multimode optical fibers. Tech. Digest, Symp. Opt. Fiber Meas.-1980, Boulder, 49-54; 1980. U.S. Govt. Printing Office, Washington, DC 20402.

[15] Okoshi, T.; Chang, J. C.; and Saito, S. Measuring the complex frequency response of multimode optical fibers. Appl. Opt. 20:1414-1417; 1981.

[16] Franzen, Douglas L. and Day, G. W. Measurement of optical fiber bandwidth in the time domain. Nat. Bur. Stand. (U.S.) Tech. Note 1019; 1980.

[17] Love, W. F. Novel mode scrambler for use in optical-fiber bandwidth measurements. Tech. Digest, Opt. Fiber Commun., Washington, 118-120; 1979. Optical Society of America.

[18] Kim, Ernest M. and Franzen, Douglas L. Measurement of far-field and near-field radiation patterns from optical fibers. Nat. Bur. Stand. (U.S.) Tech. Note 1032; 1978.

[19] Epworth, R. E. The phenomenon of modal noise in analog and digital systems. Digest, Fourth Eur. Conf. Opt. Comm., Genova, 492-501; 1978.

[20] Chamberlain, G. E.; Day, G. W.; Franzen, D. L.; Gallawa, R. L.; and Young, M. Attenuation measurements on multimode optical fibers. Nat. Bur. Stand. (U.S.) Tech. Note (in preparation).

[21] Green, S. I. 50 picosecond detector pulse monitor. Rev. Sci. Instrum. 47:1083-1085; 1976.

[22] Day, G. W. and Chamberlain, G. E. Attenuation measurements on optical fiber waveguides: an interlaboratory comparison among manufacturers. Nat. Bur. Stand. (U.S.) NBSIR 79-1608; 1979.

[23] Franzen, Douglas L.; Day, G. W., Danielson, Bruce L.; Chamberlain, George E.; and Kim, Ernest M. Interlaboratory measurement comparison to determine the attenuation and bandwidth of graded-index optical fibers. Appl. Opt. 15:2412-2419; 1981.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The design, evaluation, and performance of a system for determining the magnitude of the transfer function(hence, bandwidth) of a multimode optical fiber are presented. The system operates to about 1450 MHz using a tracking generator/spectrum analyzer combination for narrowband detection. It is constructed, almost entirely, from commercially available components. The system is less complex and easier to use than an equivalent time domain system and the measurement precision is comparable. Background information on time and frequency domain specifications, fiber bandwidth limitations, and alternate frequency domain techniques is also presented.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

fiber optics; optical communications; optical fiber bandwidth; optical fiber distortion; optical fibers.

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