Optical Fiber Dispersion Characterization

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OPTICAL FIBER DISPERSION CHARACTERIZATION

By

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B.S.E., Florida Technological University, 1978

THESIS
Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Graduate Studies Program of the College of Engineering at the University of Central Florida; Orlando, Florida

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ALAN EDWARD GEESLIN

ABSTRACT

This thesis discusses the dispersion of optical pulses in fiber waveguides. Procedures for determining the transfer function of an optical fiber using either time domain measurements or frequency domain measurements are given. A test set is described which uses time domain measurements for dispersion characterization. Complex transfer function data are presented for various fiber lengths as well as optical connectors. Prediction of bandwidths of long fibers from bandwidth/measurements taken on shorter length fibers is discussed. A relation between the bandwidth of cascaded connectors in terms of the bandwidth of a single connector is obtained.

Approved by: Aida A. R. Riad
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CHAPTER I

INTRODUCTION

This thesis is concerned with the pulse dispersion evaluation of an optical fiber. Optical fiber waveguides have several advantages over other means of communication, such as greater information handling capacity, light weight, small size and reduced losses. They are now becoming more important in the communications industry, because of requirements for systems with greater information handling capacity, as well as increasing costs of many alternate systems.

To properly evaluate optical waveguides, it is necessary to be able to determine several important parameters about them, such as attenuation, numerical aperture, pulse dispersion, bandwidth and mechanical strength. Pulse dispersion testing is used to determine a fiber's bandwidth and is the topic of this thesis.

It is also necessary to evaluate connectors which may be placed in the communication link, in order to predict the dispersion properties of a fiber link built with these components.

The effects of pulse dispersion are seen in the broadening and rounding of an input pulse, and has the overall effect of reducing bandwidth. The insertion of connectors in an optical fiber link will cause a further reduction of bandwidth. Although extensive studies have been given to attenuation due to connectors, none have been found addressing their dynamic performance.
This thesis will study the effects of connectors on the fiber bandwidth, determine the bandwidths of several lengths of fiber, and attempt to determine a relation between the measurements of shorter lengths and longer ones, thus allowing prediction of long fiber bandwidths from shorter fiber measurements.

Chapter II covers pulse dispersion aspects in greater detail. A discussion of time domain measurements vs. frequency domain measurements for measuring fiber bandwidths and determining the transfer function is conducted.

Chapter III describes the experimental set up used in pulse dispersion testing.

Chapter IV describes the experiment performed to determine the relationship between a fiber's bandwidth and its length, and discusses the results.

Chapter V describes the experiment performed to determine the effects of connectors on the fiber's bandwidth and discusses the results.

Chapter VI presents a summary of the work done and suggests additional research.
CHAPTER II

PULSE DISPERSION

Introduction

This chapter will begin by presenting pulse dispersion as a physical phenomenon in optical fibers. Then, a comparison between different types of fibers regarding their dispersion characteristics will be presented. Finally, methods of fiber dispersion evaluation will be discussed and analyzed.

Pulse Dispersion Phenomenon

Pulse dispersion may be thought of as the spreading or rounding of an input pulse during its passage (transmission) through a system, fig. 2.1. In optical fibers, there are two types of pulse dispersion: material dispersion and modal dispersion.

Material dispersion occurs because of the dependence of the material's index of refraction on the optical wavelength of the transmitted light (Howell 1978). Fig. 2.2 shows a typical dependence. This dependence results in a variation in the velocity of propagation of various wavelength components which make up the optical pulse. Components with longer wavelength travel with greater velocity than shorter ones. Thus the amount of material dispersion in a given material is a function of both the optical spectrum and material properties. Material dispersion can be reduced by proper selection
of glass dopants, and by using sources with narrow spectrums (Gallawa 1979).

Modal dispersion is caused by the different path lengths taken by different light rays in a multi-mode fiber, fig. 2.3. Modes of higher order travel a greater distance, per unit length of fiber, than lower ones. This results in a variation in the velocity of propagation of various modal components making up the optical pulse. Higher order modes travel slower than lower order modes. Thus, the amount of modal dispersion in a given fiber is a function of both the number and order of modes launched onto the fiber, and the difference in path lengths taken by the modes. Modal dispersion may be minimized by proper design of the index profile; typically one whose refractive index decreases as the square of the guide radius (Kawakami 1968), as will be seen in the following section.

Types of Optical Fibers

There are three main types of fibers in common usage; single mode fibers, step-index multimode fibers, and graded-index multimode fibers.

Single Mode Fibers

Single mode fibers are fabricated to allow propagation of only a single mode. A step-index fiber is used, which consists of a rod of dielectric with index of refraction \( n_1 \), called the core, surrounded by a medium with index of refraction \( n_2 \), called the cladding, \((n_1 > n_2)\), fig. 2.4. It has been shown that if

\[
\frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2} < 2.405
\]  

(2.1)
only a single mode, designated the HE\textsubscript{11} mode, will propagate (Barnoski 1976).

By allowing only a single mode to propagate, modal dispersion is avoided, leaving only material dispersion. Thus, both low dispersion and high bandwidth are achieved. To achieve propagation in one mode, however, the diameter of the core is around 2 to 4\textmu m (Howell 1978). Since present optical sources have emitting surfaces which are much larger than this, (in the order of 63\textmu m), it is not practical to couple large amounts of power onto these fibers.

**Step-Index Multimode Fibers**

Step-index multimode fibers are fabricated to allow propagation of more than one mode. A step-index fiber with

\[
\frac{2a}{\lambda} \sqrt{n_1^2 - n_2^2} > 2.405
\]

is classified as a multimode fiber (Barnoski 1976). This increase is usually done by increasing the diameter of the core. The larger core area allows more energy to be coupled into the fiber from the source. Modal dispersion occurs, however, because of the different path lengths between high and low order modes.

**Graded Index Multimode Fibers**

A graded-index multimode fiber is one in which the core index decreases parabolically from the center outward, as described by

\[
n(r) = n_1 \sqrt{1 - 2(n_1 - n_2/n_1)(r/a)^2}
\]

where \(n_1\) is the refractive index at \(r = 0\), \(n_2\) is the cladding index, \(r\) the fiber radius (125\textmu m) and \(a\) the core radius (50\textmu m), fig. 2.5.
In these fibers, the light rays are bent in a sinusoid-like curve about the fiber axis, fig. 2.6. The increased velocity of the rays away from the axis (in the lower index region) compensates for the increased path length resulting in lower dispersion. Core diameters of around 63 μm allow efficient coupling with available sources, allowing more energy to be placed on the fiber.

This thesis will deal only with graded-index multimode fibers, because of their ability to accept energy from sources and because of their reduced dispersion. For these reasons, graded-index multimode fibers have become the most common type of fiber used for wide-band communication systems.

In the section to follow, methods of pulse dispersion evaluation in fibers will be discussed and analyzed.

Pulse Dispersion Evaluation

In the discussion that follows, pulse dispersion refers to the total dispersion, which is the combination of both material and modal dispersion. There are two main methods of pulse dispersion evaluation: direct estimate using pulse spreading and determination of the impulse response and/or complex transfer function.

Pulse Spreading Estimate

If an input pulse $v_i(t)$ is applied to a system, the output $v_o(t)$ will be altered due to the transmission medium, fig. 2.1. Pulses of this type are usually described by their full width measured
at half of their maximum value, or full duration-half maximum, (FDHM). The amount of pulse spreading may be determined by determining the difference between input and output pulse widths.

The pulse spreading due to modal dispersion is given by

$$\Delta t = L \left[ \frac{1}{(v_g)_{1_{\text{max}^{+}},m_{\text{max}^{-}}}} - \frac{1}{v_g(0,0)} \right]$$

(2.4)

where \((v_g)_{1,m}\) is the group velocity for a mode of order \((1,m)\) and \(L\) is the length of the fiber, or

$$\Delta t = \frac{nL}{c} \left[ \frac{n^2}{2nk^2} \left( \frac{1}{m_{\text{max}^{+}}} + \frac{n_{\text{max}^{-}}}{n_{\text{max}^{+}}} + 1 \right)^2 \right]$$

(2.5)

where \(n\) is the index of refraction at the center of the waveguide, \(c\) is the speed of light in free space, \(n_2\) is the rate of change of \(n\) with radius, and \(k\) is \(\frac{\lambda}{2\pi}, N = 1, 2, 3, \ldots\).

In the effects of material dispersion are also included, the relation becomes

$$\Delta t = \frac{2L}{c} \left[ \frac{nn^2}{ck^3} \left( 1 = m = 1 \right)^2 - \frac{dn}{dw} \right]$$

(2.6)

where \(dn/dw\) is the change in \(n\) with the change in the frequency of the optical source, and \(\Delta w\) is the width of the frequency spread of the source (Yariv 1976).

Once the pulse spreading is determined, the maximum frequency which the system will pass is determined from the relation

$$f_{\text{max}} = \frac{1}{\Delta t}$$

(2.7)

This method, while it does give an idea of the system bandwidth, provides very little information about the transfer function.
Advantages of this method are that little time is required for the measurement, and there is no need for signal acquisition or processing. A disadvantage of this method is that the result is often inaccurate since the result is highly dependent on the shape of the input pulse.

Impulse Response/Complex Transfer Function

As will be seen in this section, the determination of the Impulse Response/Complex Transfer Function yields complete information about a fiber's response to various types of inputs, independent of the input waveform.

A fiber may be characterized by either its impulse response waveform, \( h(t) \), or its complex transfer function, \( H(e^{j\omega}) \). The impulse response is the output of a system when excited by an ideal Dirac delta impulse. It is presented in the time domain, and the output \( y(t) \) for a known input \( x(t) \) is found using the relation

\[
y(t) = x(t) * h(t)
\]

(2.8)

where \( * \) denotes the convolution operation. Obtaining \( h(t) \) from this relation requires deconvolution in the time domain.

The complex transfer function, \( H(e^{j\omega}) \) is presented in the frequency domain, and is the complex ratio between the harmonic output, \( Y(e^{j\omega}) \) and the harmonic input \( X(e^{j\omega}) \). Since \( H(e^{j\omega}) \) is presented in the frequency domain, it provides a clear picture of frequency and phase distortion, as well as the usable bandwidth of the system. The output of a system \( Y(e^{-j\omega}) \) is found using the relation, fig. 2.7,
Obtaining $H(e^{j\omega})$ from this relation involves division in the frequency domain, or

$$H(e^{j\omega}) = \frac{Y(e^{j\omega})}{X(e^{j\omega})} \quad (2.10)$$

Signals in the time and frequency domain are related by the Fourier transform pair

$$V(e^{j\omega}) = \int_{-\infty}^{\infty} v(t) e^{-j2\pi ft} \, dt \quad (2.11)$$

$$v(t) = \int_{-\infty}^{\infty} V(e^{j\omega}) e^{+j2\pi ft} \, df \quad (2.12)$$

where $V(e^{j\omega})$ is a complex function.

When using frequency domain measurements, the output signal $Y(e^{j\omega})$ is measured and recorded while the input signal $X(e^{j\omega})$ is held at a fixed frequency. The value of the transfer function for that frequency may then be calculated as described above. To obtain the transfer function, the process must be repeated for all frequencies of interest.

This method of testing is very time consuming, since it requires measurement of both the input and output signals over all frequencies of interest.

Using time domain measurements, a single measurement of the input $x(t)$ and the output $y(t)$ are sufficient. Although a true Dirac delta impulse cannot be generated, a duration limited impulse may be used for $x(t)$. The Fourier transform may be used to convert the input $x(t)$ to $X(e^{j\omega})$ in the frequency domain, and $y(t)$ to $Y(e^{j\omega})$. Then, the transfer function $H(e^{j\omega})$ is found using eq. (2.10). If
desired, the impulse response may be obtained by applying the inverse Fourier transform to $H(e^{j\omega})$ to obtain $h(t)$. This is the deconvolution process, fig. 2.8.

**Summary**

In order to determine the transfer function of optical fibers, whose bandwidth may extend beyond 1 GHz, it is necessary to employ time domain measurements. This is because, at present, there are no optical sources capable of being driven at the high frequencies required, and still emit enough energy to be able to evaluate fibers of practical length for communication systems (Howell 1978). Also, time domain testing allows rapid convenient measurements which reduce errors caused by changes in measurement equipment with time. Such testing has become even more attractive in recent years due to the development of low cost computers and A/D converters.

Step-index fibers are no longer of practical importance in most high-bandwidth systems, due to improved performance of graded index fibers. Graded-index multimode fibers, because of their unique combination of adequate source coupling and acceptable pulse dispersion, have become the most common type of fiber to use in wide-bandwidth system.

The experiment, presented in the next chapter, will study the pulse dispersion of graded-index multimode fibers using time domain analysis.
Fig. 2.1. Pulse spreading due to transmission through a system
Fig. 2.2 Dependence of index of refraction (n) on wavelength (μm)
Fig. 2.3. Modal dispersion indicating different path lengths
Fig. 2.4. Step-index fiber index profile
Fig. 2.5. Graded-index fiber index profile
Fig. 2.6. Propagation in a graded-index fiber
Fig. 2.7. Relation between input and output components in the frequency domain
Fig. 2.8. The deconvolution process.
CHAPTER III

EXPERIMENTAL SET UP

Introduction

This chapter will describe the experimental set up and procedure used in pulse dispersion testing. The devices used will be described and reasons for their choice given. Finally, observations made during the experiment regarding alignment sensitivity and launch conditions will be discussed.

Experimental Set Up

The experimental test set up used for pulse dispersion testing is shown in fig. 3.1. The optical link consisted of an injection laser diode (ILD) for an optical source, and an avalanche photodiode (APD) for the optical detector. For accurate test results, the response time of the ILD/APD combination must be at least as fast as that of the fiber being tested.

The optical output from the ILD was focused through a lens and launched onto the fiber. The fiber was held at both ends by vacuum chucks equipped with three-axis positioners, to allow precise alignment of all components for maximum power transfer. When the pulses left the fiber, they were focused onto the surface of the optical detector. The output of the photodetector was then sampled, and signal analysis performed on the acquired signal as mentioned
A sampling oscilloscope was used, because of the requirement for picosecond time resolution. A variable trigger delay unit was also required, in order to compensate for signal delay caused by the test equipment and the fiber being tested. Finally, a mini-computer was required for signal acquisition and processing.

The pulse dispersion test was an insertion type measurement. First, a reference or "input" waveform, \( x(t) \), was obtained using a short (1 to 2m) fiber placed between the ILD and the APD. This was done to allow ease of measurement and account for input and output launch conditions similar to those experienced during the actual testing of the fiber.

The response waveform, \( y(t) \), was then obtained by replacing the short reference fiber by the fiber being tested. Because alignment is extremely critical, three-axis positioners were used in all measurements to maximize the amplitude of the detected waveform.

**Devices**

This section describes the devices used in the test, and reasons for their selection.

**Optical Source**

The optical source chosen was an RCA SG2002 semiconductor injection laser diode, (ILD). It is capable of generating 0.1ns optical pulses, and can generate up to 2 watts of optical power.

To drive this ILD, an impulse generator was required which could generate 4 to 10A pulses of 100ps to 1ns duration. The
impulse generator used in this experiment is shown in fig. 3.2. An avalanche transistor is used to generate the current pulses. The variable capacitor is used to adjust the amplitude of the pulse, and assure that no secondary pulses occur.

A circuit for providing thermal cooling of the avalanche transistor was built and is shown in fig. 3.2. This served to remove excess heat from the transistor, and allowed repetition rates of up to 15kHz. It also maintained the circuit at a constant temperature (20°C) which helped reduce errors due to thermal drift during the waveform acquisition process.

Trigger Circuit

A trigger circuit is required to trigger the impulse generator and the sampling oscilloscope. This circuit must have low jitter, since any jitter it produces will appear in the measured waveform and introduce errors. The circuit used for this purpose is shown in fig. 3.4. This circuit also includes an adjustable delay to compensate for signal delays.

A trigger delay is required because of the delay between the triggering of the IID impulse generator and the arrival of the output signal at the input of the sampling oscilloscope. This delay time is dependent on the length of the fiber being tested.

The delay circuit contained within the sampling oscilloscope provides delays of up to 100ns, which allows testing of fibers up to about 500m in length without additional delay.

For longer lengths of fiber, an external delay circuit was
required. A Berkeley Nucleonics Corporation delay generator, model 7030, was used. This device provides delays of between 75ns and 99.999us, with a maximum of 100ps of jitter.

**Optical Detector**

The optical detector used was a Mitsubishi avalanche photodiode, model PD1002, which is specified by the manufacturer to have a gain-bandwidth product of 800GHz. For this experiment, it was operated at a gain of 1000, indicating a cutoff frequency of 800MHz. The bias and coupling circuit used with this diode is shown in fig. 3.5.

**Sampling Oscilloscope and Minicomputer**

A Tektronic Digital Processing Oscilloscope (DPO) was used for acquiring and digitizing data. The plug-in used with the DPO was an S-2/7S12 sampling unit of the same manufacture, providing a transition duration of 75ps, which is equivalent to a bandwidth (3dB down) of 4.6GHz.

The DPO was interfaced to a Hewlett-Packard 9825 minicomputer, which was used for data acquisition and processing.

The test set as described displayed about 20ps of jitter noise, which was reduced by signal averaging.

**Signal Processing Software**

Signal processing software is used to obtain the desired information, \( H(e^{j\omega}) \) from the information available, \( x(t) \) and \( y(t) \). The concept is to transform both the input \( x(t) \) and the output \( y(t) \)
to the frequency domain using the fast Fourier transform (FFT) and perform complex division to obtain

\[ H(e^{j\omega}) = \frac{Y(e^{j\omega})}{X(e^{j\omega})} \quad (3.1) \]

The actual process is somewhat more involved.

One of the limitations of the test system is the limited number of sample points which the oscilloscope can provide. The oscilloscope can provide a maximum of 512 time domain samples.

The frequency domain resolution of the FFT is related to both the number of data points and the time interval between them by the relation

\[ (\Delta T) \times (\Delta f) = \frac{1}{N} \quad (3.2) \]

where \( T \) is the time between samples in the time domain, \( f \) is the frequency difference between two consecutive samples in the frequency domain, and \( N \) is the number of sample points.

If it can be assumed that the signal has a value of zero outside the time window as seen by the oscilloscope, additional zeros may be added up to the capability of the processing equipment. With the HP9825 system, up to 1024 points may be processed. Therefore, the choice of the time window of the oscilloscope will determine the time and frequency resolution.

The desired time window may be determined by considering the frequency domain relation

\[ BW = \frac{0.35}{t} \quad (3.3) \]

where \( BW \) is the bandwidth, (3dB), and \( t \) is the fastest transition duration to be measured. The time window must be chosen such that the
desired signal does not occur between sample pulses in either the time or frequency domain. Also, it is desirable to have equal resolution in both the time and frequency domains so that conversion between the two will not introduce large errors.

The transition duration in an acquired waveform may be expressed as

\[ t = (N_t) (\Delta T) \]  \hspace{1cm} (3.4)

where \( N_t \) is the number of points in the time domain sample contained within the transition duration, and the corresponding bandwidth in the frequency domain may be expressed as

\[ BW = (N_f) (\Delta f) \]  \hspace{1cm} (3.5)

where \( N_f \) is the number of points in the frequency domain transform contained within the required bandwidth, fig. 3.6.

With the above considerations, it is easily shown that the required acquisition time window is

\[ T = (t) \]  \hspace{1cm} (25)  \hspace{1cm} (3.6)

where \( T \) is the length of the time window (Riad 1979).

For a typical pulse used in the test set, with \( t = 0.733\text{ns} \), the desired time window is 18.3ns. This corresponds to a sweep rate of 18.3ns/10div, or about 2ns/div, which is the range used. Therefore,

\[ \Delta T = 20\text{ns} / 512 = 39\text{ps} \]  \hspace{1cm} (3.7)

and

\[ \Delta f = (1/1024) / (39\text{ps}) = 25\text{MHz} \]  \hspace{1cm} (3.8)

For point to point correspondence, both reference and response pulses must be taken with the same \( T \).
After the waveforms have been converted to the frequency domain, complex division is required to obtain the transfer function. At high frequencies, where signal levels are quite low, errors may result when the reference function $X(e^{j\omega})$ approaches zero. These errors are removed by filtering the transfer function. A seventh order Chebychev filter was used in the experiment.

The frequency domain resolution may be increased by applying the inverse Fourier transform (IFFT) to $M$ sample points out of the original $N$ sample points, fig. 3.7. The value chosen for $M$ must be less than $N$, and must be a power of two. Also, to include the bandwidth of the transfer function in the band processed by the IFFT, it is required that $M/2 > N_f$. As before, the time and frequency domains are related by Eq. (3.2) with $N$ replaced by $M$, or

$$\Delta T_m = \left( \frac{1}{M} \right) \left( \frac{1}{\Delta f} \right)$$  \hspace{1cm} (3.9)

where the subscript "m" refers to the modified function. If additional "zeros" are added until the number of points again equal $N$ (or 512) the FFT will provide a frequency domain transfer function with $N$ sample points with a frequency spacing

$$\Delta f_m = \left( \frac{1}{N} \right) \left( \Delta T \right) = \left( \Delta f \right) \left( \frac{M}{N} \right)$$  \hspace{1cm} (3.10)

Since $M$ is less than $N$, the frequency domain resolution has been increased by a factor of $N/M$.

In this experiment, $M$ was chosen to be 128. This yielded

$$\Delta f_m = \frac{128}{512} \left( \Delta f \right) = (0.25) \left( 25\text{MHz} \right) = 6.25\text{MHz}$$  \hspace{1cm} (3.11)

The transfer function is presented as $1 / H(e^{j\omega})$, or attenuation and phase functions of frequency:

$$\text{ATTEN} = -10 \log_{10} H(e^{j\omega})$$  \hspace{1cm} (3.12)
and

\[ \text{PHASE} = -\arg \left( H(e^{j\omega}) \right) \] (3.13)

where \( \arg(\cdot) \) is the continuous argument function.

The continuous argument function must be reconstructed from the computed argument function which varies from \(-\pi\) to \(+\pi\), fig. 3.8. The computed argument function can be made continuous by adding or subtracting multiples of \( \pi^0 \) as shown in fig. 3.9. This continuous argument will contain a linear phase component which results from differences between the delay generator delay and the signal delay. Its removal allows the phase characteristics due to dispersion to be viewed, but does not affect its information, fig. 3.10.

Software to perform the above functions is shown in a block diagram in the Appendix.

**Experimental Procedure**

This section describes a mode scrambler, the reasons for its use, and the procedure used to acquire data.

**Mode Scrambler**

For accurate results, uniform launch conditions are required for all measurements. A mode scrambler provides a uniform modal distribution for the launch into the test fiber, approximating a steady state condition. For an optical source with a non-ideal intensity distribution as in fig. 3.11, the mode scrambler provides a more uniform optical distribution for launch onto the test fiber, fig. 3.12.
If a fiber were being tested by launching directly from a source with an intensity distribution similar to that shown in fig. 3.11, the measurement would be very sensitive to misalignment. The modal distribution can be changed significantly by very small alignment changes. Since the optical intensity distribution falling on the core is not uniform, the modal distribution cannot be controlled. Launch conditions will vary between measurements, resulting in measurement errors. The use of the mode scrambler significantly increases the accuracy of bandwidth measurement against changes in launch conditions.

A mode scrambler is shown in fig. 3.13. This device consists of three 1m lengths of fiber, a step-graded fiber, followed by a graded-index fiber, followed by another step-graded fiber. This configuration has been shown to have a smoothing and circularization of the optical source near-field pattern by the step index fiber, and an angular mixing of the source far-field pattern by the graded-index fiber (Love 1979).

In bandwidth measurements both with and without the mode scrambler, the source was moved up to \( \pm 1 \) core radius from the center position in the radial direction. Bandwidth measured at these points indicate a measurement difference of \( \pm 1.28\% \) using a mode scrambler and a difference of \( \pm 18.1\% \) without one (Love 1979).

The mode scrambler used in this experiment contained a second 1m length of graded-index fiber to allow use of connectors for ease of fiber measurement, fig. 3.14. This avoided the uncertainty of a step-index/graded-index interface and a connector/connector
interface occurring at the same point. Such an occurrence could cause excessive attenuation or an unknown modal launch condition.

The mode scrambler used had an attenuation of about 2dB.

Fiber Alignment and Connectors

Proper fiber alignment and end preparation is vital to repeatable tests and meaningful results. Losses in excess of 3dB can occur for radial displacements of 0.01mm (Shumacher 1977). Axial misalignment is less critical, but can still cause a 2dB loss for a separation equal to the diameter of the fiber. Because fiber alignment is critical, it is desirable to have an easy, repeatable means of accurate fiber alignment.

To allow ease of fiber measurement, a connector was used between the mode scrambler and the fiber being tested. This connector was in the optical link during all measurements, and was included in all reference measurements. Therefore, it is assumed that its effect was accounted for during signal processing and removed.

The connectors used were manufactured by Deutsch and allow rapid connection and disconnection of the optical fibers, fig. 3.15. A connector set consists of two optical fiber connector plugs and a feedthru connector receptacle. Each fiber to be connected is first terminated in an optical fiber connector plug. This device protects the end of the fiber when it is not connected to another fiber or other device. A protective shield is extended when the connector plug is not in use, protecting the fiber from damage.

Connector plugs are joined using a feedthru connector receptacle,
which depresses the protective shield on both connectors, and brings the fiber connectors into alignment. Index matching fluid is used to reduce the refractive index differences across the connection and reduce losses.

A connector termination tool was provided by the connector manufacturer to install the connector and break the fiber.

The ends of the fiber on the input end (ILD) and the output end (APD) of the fiber link were held in pace by vacuum chucks, fig. 3.16. These devices held the fiber securely during testing, but allowed ease of removal. The fibers were placed in the vacuum chucks such that the end of the fiber was even with the end of the vacuum chuck nearest the source or detector.

Fibers placed in the vacuum chucks were first stripped of their plastic coating, cut with a fiber cutting tool to assure a smooth end, and their end touched to adhesive tape to remove direct or other contamination from the end of the fiber.

Fine adjustments were then made using the three-axis positioners. The adjustments were made to maximize the output amplitude as viewed on the oscilloscope. It was possible to move both the fiber holders and the optical source and detector. Radial displacements were more critical than axial ones. The lenses were fixed, and were not adjusted.

Waveform Acquisition

After alignment was completed, the detected waveform was acquired. For a waveform viewed on an oscilloscope to be meaningful,
it is necessary to know the horizontal and vertical scales, and the point on the screen which is the zero volt or "ground" reference. To obtain this reference, the optical path was interrupted by placing a piece of opaque material between the ILD and the launch end of the fiber. This was done so that any background radiation, radio frequency emission or other noise will be included in the ground reference and thus would be absent in the acquired waveform.

To reduce errors caused by noise and jitter, the ground reference was sampled several times, and the ground reference used was the average of the samples. In this experiment, all waveforms were sampled 50 times. Signal averaging was performed by the computer; the averaged reference was then stored in memory.

Next, the material blocking the optical path was removed, and the waveform obtained using averaging techniques as described above. At the completion of this process, the waveform was subtracted from the ground reference, point-by-point, horizontal and vertical scale factors read from the oscilloscope under computer control, and the values of attenuators, if used, entered from the keyboard. Wideband attenuators were used, and were observed not to have a noticeable effect on the measured waveform.

With this information, the waveform, as seen by the oscilloscope was now fully defined, and was saved in computer memory. The "reference" fiber was then removed from the test set and replaced by the fiber under test, and the process repeated. When the two waveforms have been acquired, the testing proceeds to the signal analysis, which is as described earlier.
Fig. 3.1. Test set up
Fig. 3.2. Impulse generator circuit
Fig. 3.3 Thermoelectric cooling circuit
Fig. 3.4. Trigger circuit
Fig. 3.5. APO bias and coupling circuit
Fig. 3.6. Time and frequency domain resolution
Fig. 3.7. Resolution enhancement
Fig. 3.8. Computed phase
Fig. 3.9. Computed and continuous phase
PHASE

CONTINUOUS PHASE FUNCTION

LINEAR PHASE COMPONENT

PHASE FUNCTION WITH LINEAR PHASE COMPONENT ELIMINATED

Fig. 3.10. Elimination of linear phase
Fig. 3.11. Non-ideal distribution

Fig. 3.12. Uniform distribution
Fig. 3.13. Mode scrambler (typical)

Fig. 3.14. Mode scrambler used
Fig. 3.15. Connector
Fig. 3.16. Vacuum chuck
CHAPTER IV

FIBER BANDWIDTH VS. LENGTH MEASUREMENTS

Introduction

This chapter will describe the experiment performed to determine the relationship between a fiber's length and its bandwidth. The experimental results are compared with theoretical values.

Fiber bandwidth measurements are usually specified as a frequency-length product. This allows the bandwidth measurement to be easily applied to longer or shorter lengths of the same fiber. Tests of this type have been reported by Gallawa (1979), Dannwolf et al. (1976), and Gans et al. (1977), with bandwidths of up to 1.34GHz-km being reported (Riad 1979).

When combining several fibers of known bandwidth to form a longer length fiber, it is desirable to be able to predict the resulting bandwidth of the combined system.

Experiment and Results

To determine the relation between a fiber's length and its bandwidth, ten separate fibers, each of 600m length, were used. The fibers were available in cabled form, with both ends of each fiber accessible.

First, the bandwidth of each fiber was measured, using the procedure outlined in Chapter III. A mode scrambler was used for
all measurements, and a connector was used between the mode scrambler and the fiber being tested. This connector was also used when taking the reference pulse, by using the reference fiber between the mode scrambler and the APD vacuum chuck, fig. 4.1.

The pulse dispersion test involved relative differences between the reference and the response pulse, therefore, this connector, since it was present in both waveforms, is not expected to have been detrimental to the test accuracy.

After placing the fibers in the test set, the output of the detected waveform was maximized by fine adjustment of the three-axis positioners. Because the mode scrambler was used during all measurements, the alignment of the launch end was not disturbed, and did not require adjustment during the course of the test. The launch end alignment was checked periodically during the test and was seen not to vary by a measurable amount.

A possible reason that realignment would be required is a drift in the operating point of the ILD. This would most likely come about because of temperature variation of the transistor and diode in the ILD circuit. The cooling circuit was able to maintain the temperature of the ILD impulse generator to within \( \pm 0.1^\circ\text{C} \). The ILD and avalanche transistor were in close thermal contact with the cooler, so little temperature difference was expected between the two. After an initial warm-up and thermal stabilization period of about 30 minutes, the amplitude and shape of the pulse were observed to remain constant throughout a normal working day.
A single reference pulse was used for several tests. Testing was not begun until the test set, and the ILD impulse generator in particular, was allowed to stabilize.

The variable delay unit was not required to obtain the reference pulse. When testing the 600m fibers, however, a delay of 2900ns was used, to compensate for the signal delay through the fiber. A typical reference pulse is shown in fig. 4.2, and a typical response pulse for a 600m fiber is shown in fig. 4.3.

After signal processing as described in Chapter III, the above waveforms yielded the transfer function shown in fig. 4.4. The bandwidth was defined as the point having 3dB greater attenuation than that of the lowest frequency point in the frequency domain data. The bandwidths of the ten fibers are shown in table 4.1. Another fiber (#1) was not used in the experiment.

Next, alternate 600m lengths were spliced together to obtain five 1.2km lengths of fiber. A fusion splicer was used for all splicing. The splice was located 600m from the detector, thus any high order modes caused by the splice are assumed to have been attenuated to negligible levels prior to the pulses arrival at the detector.

The fibers were connected such that the direction of propagation was always in the same direction, since fiber lengths tested in the opposite direction could have different dispersion characteristics. This could come about due to differences in index profiles, and non-symmetrical properties of the fused splices.

Each 1.2km loop was then evaluated. The response pulse for
Loop 2-3 is shown in fig. 4.5 and the response pulse for loop 4-5 is shown in fig. 4.6. After signal processing, these waveforms yielded the transfer functions of figs. 4.7 and 4.8 respectfully. Another reference pulse was obtained prior to starting the measurements of the 1.2km lengths. The delay unit was set to 5840ns. The 3dB bandwidths were determined as before, and are shown in table 4.2.

Loops 2-3 and 4-5 were then spliced together to obtain a 2.4km loop. Loops 6-7 and 8-9 were also combined to obtain another 2.4km loop. The response pulse for loop 2-5 is shown in fig. 4.9 and the response pulse for loop 6-9 is shown in fig. 4.10. After signal processing, these waveforms yielded the transfer functions of figs. 4.11 and 4.12 respectfully. Bandwidths of 450MHz were found respectfully. During the testing of the 2.4km loops, the delay generator was set to 11720ns.

Finally, the two 2.4km loops were combined to form a single 4.8km loop. Another reference was obtained prior to testing the 4.8km loop. The delay generator was set to 23560ns.

It was noted that the output pulse had spread considerably, relative to the input, fig. 4.13. It was necessary to go to the 5ns/div scale on the oscilloscope to observe the entire waveform within the time window. A measurement was then taken on the 5ns/div scale.

It was thought that perhaps the splice which was joining the two 2.4km loops was defective, and was causing the large amount of dispersion. This splice was broken and repeated, and a second measurement taken. It was still necessary to use the 5ns/div scale to view...
the entire pulse within the time window. The transfer function for the 4.8km loop is shown in fig. 4.14. The bandwidth of the 4.8km loop was found to be 160MHz.

**Discussion of the Results**

It was observed that several of the transfer functions contained a noticeable dip in the value of attenuation at a frequency of around 1300MHz to 1400MHz. This occurred because of the relation between a pulse in the time domain and its frequency transformation. If the input waveform is approximated by a triangular pulse, its frequency transformation is seem to be of the form \( \sin \frac{x}{x} \), as shown in fig. 4.15 (Stremler 1977). The "zeros" of the frequency transformation are determined by the width of the pulse.

The width of a typical reference pulse (measured at the base) is about 1.5ns, fig. 4.2. The value of \( T \) corresponds to half of this quantity, or 0.75ns. This indicates a first "zero" in the frequency domain of 1333MHz.

At points where the magnitude of the frequency transforms approach zero, errors occurred in the division process used to obtain the transfer function. When determining the bandwidth of transfer functions whose 3dB point fell within the disturbance, a smooth curve was graphically placed through the data, neglecting the disturbance. Other undulations which occur on the plots are also due to division errors and were averaged in the same manner.

The data were compared against two possible bandwidth relationships. First, an inverse quadratic relationship was invest-
igated. In such a relation, one can write
\[
\frac{1}{BW^2} = \left( \frac{1}{B_1^2} + \frac{1}{B_2^2} + \ldots + \frac{1}{B_n^2} \right)
\]
(4.1)
where BW is the bandwidth of the overall system, and B_1, B_2, ..., B_n are the individual bandwidths of the subsystems which make up the complete system space (Millman & Halkias 1972).

The other bandwidth relation was an inverse linear one for which
\[
\frac{1}{BW} = \frac{1}{B_1} + \frac{1}{B_2} + \frac{1}{B_3} + \ldots + \frac{1}{B_n}
\]
(4.2)

Predicted bandwidths using the inverse quadratic relationship were calculated for all 1.2km loops, using data obtained from the 600m measurements. Predicted bandwidths for the 2.4km fibers were calculated from both the 600m measurements and the 1.2km measured values. Predicted bandwidths for the 4.8km loop were made from the 600m measured values and the 2.4km measured values. This data, along with measured values and percent error, is presented in table 4.3. Data calculated in a similar manner using the inverse linear relationship is given in table 4.4.

For fiber lengths 1.2km and less, the inverse quadratic relationship was found to be more accurate. For lengths greater than 2.4km, a linear approximation was seen to be more accurate. This suggested that the actual bandwidth relationship might be of the form
\[
\frac{1}{BW^m} = \frac{1}{BW_1^m} + \frac{1}{BW_2^m} + \ldots + \frac{1}{BW_n^m}
\]
(4.3)
where 1 < m < 2. Calculations based on the 600m measurements are shown in table 4.5 for m=1.5 and in table 4.6 for m=1.75.

It is seen that bandwidths calculated using values of m of 1.5
or 1.75 are not in as good agreement as the inverse quadratic relation \( m=2 \) for fibers 1.2km or less in length. For fibers in the range of 2.4km, using \( m=1.5 \) appears to yield the most accurate value while for longer lengths, the inverse linear approximation \( (m=1) \) appears to be a better approximation. This suggests a dependence on \( m \) on fiber length, since the bandwidth of short fibers (1.2km) is most accurately predicted using \( m=2 \), while bandwidths of long fibers (4.8km) are predicted with best accuracy using \( m=1 \).

**Summary and Conclusions**

Using measured bandwidths of short fiber lengths, it was possible to predict to some degree the bandwidths of longer fibers. For fiber lengths up to around 1.2km, usable predictions were possible using an inverse quadratic relation. For fiber lengths greater than 4km, an inverse linear relation was found to be most accurate. For fibers whose length is between these extremes, a modified relation was a better approximation.

A possible cause for the discrepancy is that some of the short lengths of fiber, due to slightly different index profiles, may have responded differently to the light they received from the preceding fiber than to the light they received from the mode scrambler. When all fibers were initially tested using the mode scrambler, the launch conditions were assumed to be uniform. However, during testing of cascaded sections it is possible that fibers which received their light output from preceding fibers may not have received the same modal distribution as they did during initial testing. Depending on
the manner in which the modal distribution was changed by preceding fibers, this resulted in both higher and lower bandwidths for the cascaded system.
### TABLE 4.1

**BANDWIDTH OF 600m FIBERS**

<table>
<thead>
<tr>
<th>FIBER NUMBER</th>
<th>BANDWIDTH (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>1.24</td>
</tr>
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<td>1.4</td>
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<td>1.6</td>
</tr>
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<td>1.1</td>
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</tr>
<tr>
<td>10</td>
<td>1.56</td>
</tr>
<tr>
<td>11</td>
<td>1.48</td>
</tr>
</tbody>
</table>

### TABLE 4.2

**BANDWIDTH OF 1.2Km FIBERS**

<table>
<thead>
<tr>
<th>LOOP</th>
<th>BANDWIDTH (GHz)</th>
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<tbody>
<tr>
<td>2-3</td>
<td>0.88</td>
</tr>
<tr>
<td>4-5</td>
<td>1.64</td>
</tr>
<tr>
<td>6-7</td>
<td>0.93</td>
</tr>
<tr>
<td>8-9</td>
<td>0.92</td>
</tr>
<tr>
<td>10-11</td>
<td>1.39</td>
</tr>
<tr>
<td>INDEX No.</td>
<td>6km</td>
</tr>
<tr>
<td>----------</td>
<td>-----</td>
</tr>
<tr>
<td>1</td>
<td>1.60</td>
</tr>
<tr>
<td>2</td>
<td>1.24</td>
</tr>
<tr>
<td>3</td>
<td>1.44</td>
</tr>
<tr>
<td>4</td>
<td>1.60</td>
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<tr>
<td>5</td>
<td>1.10</td>
</tr>
<tr>
<td>6</td>
<td>1.54</td>
</tr>
<tr>
<td>7</td>
<td>1.15</td>
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<tr>
<td>8</td>
<td>1.66</td>
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<tr>
<td>9</td>
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</tr>
<tr>
<td>10</td>
<td>1.45</td>
</tr>
<tr>
<td>11</td>
<td>1.45</td>
</tr>
</tbody>
</table>
### Table 4.4

**Measured and Calculated Bandwidth Data for Inverse Linear Relationship**

All measurements in GHz.

<table>
<thead>
<tr>
<th>Length (km)</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.10</td>
<td>0.88</td>
<td>0.66</td>
</tr>
<tr>
<td>1.10</td>
<td>1.64</td>
<td>0.75</td>
</tr>
<tr>
<td>1.10</td>
<td>0.93</td>
<td>0.69</td>
</tr>
<tr>
<td>1.10</td>
<td>0.92</td>
<td>0.64</td>
</tr>
<tr>
<td>1.15</td>
<td>1.39</td>
<td>0.76</td>
</tr>
</tbody>
</table>
### Table 4.5

**Measured and Calculated Bandwidth Data for \( m = 1.50 \)**

All bandwidths in Gbit/s

MEAS: Measured  C: Calculated

<table>
<thead>
<tr>
<th>FIBER No.</th>
<th>600m MEAS</th>
<th>1.2km MEAS</th>
<th>( c(600m) ) ERROR</th>
<th>2.4km MEAS</th>
<th>( c(600m) ) ERROR</th>
<th>( 4.8km ) MEAS</th>
<th>( c(600m) ) ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.40</td>
<td>0.88</td>
<td>0.83</td>
<td>-5.68%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.40</td>
<td>1.64</td>
<td>0.94</td>
<td>42.68%</td>
<td>0.45</td>
<td>0.55</td>
<td>22.22%</td>
</tr>
<tr>
<td>5</td>
<td>1.60</td>
<td></td>
<td></td>
<td></td>
<td>0.16</td>
<td>0.34</td>
<td>112.5%</td>
</tr>
<tr>
<td>6</td>
<td>1.10</td>
<td>0.93</td>
<td>0.85</td>
<td>-8.60%</td>
<td>0.45</td>
<td>0.55</td>
<td>22.22%</td>
</tr>
<tr>
<td>7</td>
<td>1.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.15</td>
<td>0.92</td>
<td>0.81</td>
<td>-11.96%</td>
<td>0.45</td>
<td>0.55</td>
<td>22.22%</td>
</tr>
<tr>
<td>9</td>
<td>1.46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 4.6

MEASURED AND CALCULATED BANDWIDTH DATA FOR \( m = 1.75 \)

ALL BANDWIDTHS IN GHz

MEAS: MEASURED  C: CALCULATED

<table>
<thead>
<tr>
<th>FIBER No.</th>
<th>600m MEAS</th>
<th>1,2km MEAS C(600m)</th>
<th>ERROR</th>
<th>2,4km MEAS C(600m)</th>
<th>ERROR</th>
<th>4,8km MEAS C(600m)</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.40</td>
<td>0.88</td>
<td>0.00%</td>
<td>0.45</td>
<td>0.63</td>
<td>0.16</td>
<td>0.41</td>
</tr>
<tr>
<td>3</td>
<td>1.24</td>
<td>0.88</td>
<td>0.00%</td>
<td>0.60</td>
<td>0.45</td>
<td>0.45</td>
<td>0.60</td>
</tr>
<tr>
<td>4</td>
<td>1.40</td>
<td>1.64</td>
<td>-39.02</td>
<td>0.92</td>
<td>0.26</td>
<td>-6.52</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.60</td>
<td>1.00</td>
<td>-6.52</td>
<td>0.45</td>
<td>0.60</td>
<td>33.33</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.10</td>
<td>0.91</td>
<td>-2.15</td>
<td>0.45</td>
<td>0.60</td>
<td>33.33</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.04</td>
<td>0.91</td>
<td>-2.15</td>
<td>0.45</td>
<td>0.60</td>
<td>33.33</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.15</td>
<td>0.92</td>
<td>-6.52</td>
<td>0.45</td>
<td>0.60</td>
<td>33.33</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.46</td>
<td>0.86</td>
<td>-6.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>
Fig. 4.1. Taking of reference and response pulse
Fig. 4.2. Reference pulse
Fig. 4.5. 1.2km response pulse (loop 2-3)
Fig. 4.6. 1.2km response pulse (loop 4-5)
Fig. 4.7. 1.2km transfer function (loop 2-3)
Fig. 4.9. 2.4km response pulse (loop 2-5)
Fig. 4.10. 2.4km response pulse (loop 6-9)
Fig. 4.12. 2.4km transfer function (Loop 6-9)
Fig. 4.13. 4.8km response pulse (loop 2-9)
Fig. 4.15. A triangular pulse and its frequency transformation
CHAPTER V

CONNECTOR TESTING AND EVALUATION

Introduction

This chapter will describe the experiment performed to determine the affect that connectors have on bandwidth. Much work has been done to determine the low frequency attenuation of connectors, but none has been found addressing their dynamic performance. Such knowledge is required if connectors are to be used in wide bandwidth communication systems. Connectors are likely to be used under a variety of conditions, ranging from closely spaced applications such as optical patch panels, to spacing at great distances, such as terminations of long cables. Their performance must be known at both these extremes.

Experiment and Results

The connectors used in this study were manufactured by Deutsch. They are of the wet type, which use an index matching fluid to reduce the refractive index difference across the connection and reduce losses. A connector set consists of two optical fiber connector plugs and a feedthru connector receptacle, fig. 3.16.

Each fiber to be connected is first terminated in an optical fiber connector plug. This device protects the end of the fiber when it is not connected to another fiber or another device. A protective
shield is extended when the connector plug is not in use, protecting the fiber from damage. Connector plugs are joined using a feedthru connector receptacle, which depresses the protective shield on both connectors, and brings the fiber connectors into alignment. These connectors are specified by the manufacturer to have an attenuation of 1dB or less.

To determine the bandwidth affect of connectors, a 6m length of fiber was spliced in the center of two 600m fibers, fig. 5.1. Fused splices were used on the output end to avoid disturbing the APD fiber adjustment. The affect of this connector was expected to be removed during signal processing, since it was present during the acquiring of the reference pulse. The 600m length after the connector test area allowed steady state conditions to be reached after the connector under test, and removed any cladding light which was created by it.

The bandwidth of the entire link was measured four times to determine an average value for the reference bandwidth and to determine the repeatability of the test set. Bandwidths of 810, 830, 770 and 832MHz were obtained, giving an average value of 810.5MHz, with a maximum error of 60MHz. A typical response pulse and transfer function are shown in figs. 5.2 and 5.3 respectfully.

Next, a single connector was installed, about 0.6m from the end of the 6m fiber, on the end closest launch end of the test loop. The test was repeated with the connector in the loop. The response pulse is shown in fig. 5.4.

Additional connectors were added to the previous loop and additional bandwidth measurements taken. Measurements were taken
with 3, 6 and 9 connectors. All connectors were contained within the 6m length, and were spaced at approximately 0.6m intervals, starting from the end closest the launch end. The response pulse obtained with 3 connectors is shown in fig. 5.5. The response pulses for 6 and 9 connectors are shown in figs. 5.6 and 5.7 respectfully.

To determine the bandwidth of the connectors, it was necessary to remove the bandwidth effects of the remainder of the connector loop. This was done by using, as a reference pulse, the pulse obtained when measuring the bandwidth of the connector loop, fig. 5.2. To determine the bandwidths of connectors, response pulses obtained with the required number of connectors in the loop were used.

The signal processing was the same as that used to determine fiber bandwidth except that no filter was used, and resolution enhancement was not performed. The filter was not used because the 3dB bandwidth was within the frequency range which was usually filtered. Because it was not possible to filter the data, it was not possible to enhance the resolution of the frequency domain data. Thus, the frequency resolution for the connector transfer functions is 25MHz.

The transfer functions obtained for the case of 1, 3, 6 and 9 connectors are shown in figs. 5.8, 5.9, 5.10 and 5.11 respectfully. The resulting 3dB bandwidths are shown in table 5.1.

<table>
<thead>
<tr>
<th>Number of Connectors</th>
<th>Bandwidth (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.40</td>
</tr>
<tr>
<td>3</td>
<td>2.72</td>
</tr>
<tr>
<td>6</td>
<td>3.16</td>
</tr>
<tr>
<td>9</td>
<td>3.52</td>
</tr>
</tbody>
</table>
An initial inspection showed that in all cases, the bandwidth was in excess of 2GHz, which was well above the bandwidth limitation of the fiber. The data do not appear to follow any particular trend, and the variation between the measurements are likely the result of "noisy" division.

Because the filter could not be used, erroneous results which occurred at high frequencies, where the response function became extremely small, were not removed from the data. As seen from the transfer functions, the 3dB bandwidths are in the high frequency "noisy" area. As a result, the bandwidth could not be determined with the same degree of accuracy as when the filter is used.

It was noted that cascading several connectors did not significantly reduce the bandwidth.

**Summary and Conclusions**

Connectors were evaluated for bandwidth limitation under conditions simulating both widely spaced (1) and closely spaced (multiple) connectors. In both cases, it was found that the bandwidth of the connectors did not fall below 2.4GHz, even with a cascade system of 9 connectors. This figure is well above the bandwidth of the fibers to which they are attached. This indicates that with present fibers, the connectors do not adversely affect the bandwidth.
Fig. 5.1. Connector test loop
Fig. 5.2. Response pulse with no connectors
Fig. 5.3. Transfer function of connector loop with no connectors. Bandwidth: 810MHz.
Fig. 5.4. Response pulse with one connector
Fig. 5.5. Response pulse with three connectors.
Fig. 5.6. Response pulse with six connectors
Fig. 5.7. Response pulse with nine connectors
Fig. 5.8. Transfer function of connector loop with one connector
Fig. 5.9. Transfer function of connector loop with three connectors
Fig. 5.10. Transfer function of connector loop with six connectors
Fig. 5.11. Transfer function of connector loop with nine connectors
CHAPTER VI

CONCLUSIONS

Introduction

This chapter discusses the results of the experiment and additional research suggested by the results.

Fiber Bandwidth Measurements

It was found that the bandwidths of cascaded fibers follow an inverse quadratic relation for fiber lengths less than 1.2km, and an inverse linear relation for short fiber measurements applied to longer fiber (4.8km). Between these limits, the actual bandwidth was seen to fall between the predictions made by these two relations.

It is felt that additional information is needed about the index profile and the resulting modal distribution of each fiber in order to make a more accurate bandwidth prediction. The mode scrambler provided a normal distribution to each fiber during its initial testing, but this same modal distribution may not have been seen by all fibers during the cascaded system measurements.

Depending on the index profile of the first fiber, a larger or smaller number of higher order modes may have been received by the second fiber. This difference in modal distribution may have resulted in different amounts of pulse dispersion and therefore different bandwidths.
One way which this might be demonstrated would be to include a mode scrambler between each 600m length of fiber. This would cause the modal distribution entering each fiber to be the same as that encountered during single fiber testing. This procedure would, however, introduce additional attenuation, which could be a problem when measuring long lengths of fiber. If necessary, additional gain could be provided by an external wideband amplifier.

**Connector Bandwidth Measurements**

It was found that the bandwidth of optical connectors is much greater than present optical fibers. A series of up to 9 cascaded connectors exhibits essentially the same bandwidth as a single connector. To accurately evaluate the bandwidth of connectors, a test systems with a wider bandwidth than the present one may be required.
APPENDIX
START "RES102"

READ DISK X,Y FOR 
I = 1 TO 513

PRINT "POINTS = M"

DISPLAY REAL WAVEFORM

CALL "FILTER" G(I) = 1

I = I + 1 1.I TO 1.2

Z = Z + 1

G = G(I) = Y(I)

I = 1 TO 1.2

DISPLAY REAL AND IMAGINARY WAVEFORMS

CALL "FFT" ZW = 1

DISPLAY TIME DOMAIN WAVEFORM

CALL "FFT" 1024 = 1

DISPLAY REAL AND IMAGINARY WAVETRAN

BEGIN MAGNITUDE AND PHASE

RESOLUTION ENHANCEMENT PROGRAM
REFERENCES


