N93-19409

1992 NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

JOHN F. KENNEDY SPACE CENTER
UNIVERSITY OF CENTRAL FLORIDA

INVESTIGATION OF THE BANDWIDTH OF MULTIMODE OPTICAL FIBERS USED WITH 1550-nm LED AND LASER SOURCES

PREPARED BY:	Mr. Preston A. White III
ACADEMIC RANK:	Professor
UNIVERSITY AND DEPARTMENT:	Southern College of Technology Department of Electrical and Computer Engineering Technology
NASA/KSC	
DIVISION:	Electronic Systems
BRANCH:	Communications
NASA COLLEAGUE:	Larry J. Hand, Jr. Po T. Huang
DATE:	August 21, 1992
CONTRACT NUMBER:	University of Central Florida NASA-NGT-60002 Supplement: 8

ACKNOWLEDGEMENTS:

There are many people whose help must first be acknowledged, for without their help, which was sought so many times and in so many areas, this research effort would not have been possible.

Special thanks to my NASA colleagues Larry Hand for granting me the opportunity to make a small contribution to the fascinating work done within his Video and Data Section, and to my mentor, Po Huang, for his patient counsel and for generously allowing me to take advantage of his vast personal library.

My gratitude to the Fiberoptic Laboratory's support personnel cannot be overstated. I am indebted to Houston Galloway for his work before my arrival to try to ensure that the laboratory would be ready to support this research and for his design and fabrication skills which resulted in the custom-made E/O modules that made some of our studies possible. To Robert Swindle, who was always there, thank you for all of your help with the instrumentation. And to a ready and willing co-op student, Reginald Campos, thanks for all of the help with fabrication and for your patience helping me sort out the laboratory's computing equipment.

Finally, let me add my thanks to that of all of the other faculty researchers to the NASA and UCF people that administered a wonderful summer research program. Carol Valdes arranged a fascinating series of tours (and a VIP launch pass!) that enabled us to better understand the complexity of the mission of KSC. Loren Anderson oversaw our research efforts and helped draw us together with preprogram correspondence and summer newsletters. And Kari Stiles did a such a great job fielding questions and keeping up with the numerous forms required by NASA and UCF.

It's not enough, but thank you all. It's hoped that our efforts have provided at least a small benefit to America's space program and to KSC. I'm proud to have worked with you.

ABSTRACT:

Multimode optical fibers are not intended to be used with 1550-nm sources; however, it is desirable to utilize 1300/1550-nm wavelength division multiplexing (WDM) on some multimode fibers at Kennedy Space Center (KSC). No information from fiber vendors nor from the literature is available to support this use. Preliminary studies at KSC have suggested that these fibers might be usable at 1550-nm if the fibers possessed enough bandwidth when sourced by LEDs.

Detailed bandwidth studies were made on 12 multimode fibers using 1300- and 1550-nm lasers and LEDs. The results showed that the modal bandwidth at 1550-nm was about 50% of the 1300-nm value and that the chromatic dispersion could be predicted by extrapolating the vendor's specifications for wavelengths outside the 1550-nm region. Utilizing these data, predictions of the fiber's optical bandwidth were accurately made. Problems with launch conditions and possible differential attenuation at connectors was noted at 1300-nm but was less significant at 1550-nm.

It appears that the multimode fibers studied will offer adequate performance in the 1550-nm region for a number of current KSC needs. Studies of additional fibers are encouraged to gain more confidence and better understanding of the 1550-nm bandwidth of KSC's multimode optical fibers before committing to 1300/1550-nm WDM.

SUMMARY:

The Fiberoptic Laboratory at Kennedy Space Center is studying the use wavelength division multiplexing (WDM) on its multimode optical fibers using 1300-nm and 1550-nm sources. This appears to be the first time that 1550-nm sources are to be used with multimode fiber, which is routinely used at 850-nm and 1300-nm. Multimode fiber manufacturers do not publish any information about the performance of their fibers at 1550-nm nor have any published studies regarding this application been found in the literature. Preliminary attenuation measurements have shown that multimode fibers installed within the past five years have attenuation at 1550-nm that is low enough to be useful. More recently, a few fiberoptic video test circuits were modified to operate at 1550-nm and have demonstrated that there may also be enough bandwidth for some applications.

Before committing to WDM it was necessary to perform a detailed study to determine the bandwidth that results when the multimode fibers in use at KSC are sourced by 1550-nm LEDs. The research reported herein is the result of numerous bandwidth tests on twelve Corning LDF fibers patched into six loops. The fibers were tested in the 1300- and 1550-nm regions, utilizing both lasers and LED sources, then the results were compared to gain a better understanding of the response of the fibers in both regions.

By using narrow-spectrum lasers as sources, it was found that the modal bandwidth of the LDF fibers at 1550-nm is approximately 50% of that available at 1300-nm. The modal bandwidth measurements are very sensitive to launch conditions; however, the 1550-nm measurements exhibited much less sensitivity. This launch sensitivity may be an operational issue due to the widespread use of non-keyed biconic connectors in the multimode fiber circuits at KSC.

Custom-made LED sources were used to make optical bandwidth measurements. These measurements showed that the LDF fiber's bandwidth was limited at 1300-nm by modal-distortion but was chromatic-dispersion limited at 1550-nm. The chromatic dispersion information available from the vendor appears be valid in the 1550-nm range, eventhough the vendor's specifications exclude this range. By combining these specifications it was possible to make predictions of the optical bandwidth of the test fibers that were within 6% of the measured data.

The results of these tests on twelve fibers lead to the conclusion that WDM of 1300-nm and 1550-nm information onto the multimode fibers at KSC appears promising. Before committing to this technology, the results of this study should be confirmed by making additional measurements on a wider range of installed multimode fibers at the Center.

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

Kennedy Space Center (KSC) has a long history of utilizing fiberoptic communication technology, beginning when the technology was in its infancy. As the fiberoptics has matured over the past fifteen years, KSC has continued to install even more fiberoptic cables and terminal equipment. Today there are thousands of kilometers of multimode and singlemode optical fibers in multiple-fiber cables that interconnect virtually every facility at the Center. These fibers are used to transport all manner of communication signals including data, video, and voice.

As new advances in fiberoptic technology become available, KSC personnel research the possible uses of these new technologies in support of the Center's present and future communication needs. Those advances that support KSC's mission are quickly put to work. Such is the case with *wavelength division multiplexing* (WDM), a relatively new technology that allows the multiplexing of several independent simultaneous signals onto one fiber by using a different wavelength source for each signal. The use of WDM can allow an immediate increase in information carrying capacity by more efficiently utilizing existing fibers thereby achieving better economy compared to adding more fiberoptic cables. Currently, KSC is gaining experience with WDM to understand how it can be best used to support the various activities conducted at the Center.

1.1 Multimode Fiber Transmission

Optical fibers are categorized as either singlemode or multimode fibers. Singlemode fibers offer the highest performance, having a virtually unlimited bandwidth (information carrying capacity) and the lowest loss. Singlemode fibers allow fiberoptic transmission over distances greater than 100 km or multi-gigahertz bandwidths. The price of this high performance is that singlemode fibers are more difficult to splice or connectorize and usually require laser sources which are themselves fragile and expensive. Therefore, it is attractive to use multimode fibers when these fibers provide adequate performance. For the distances encountered at KSC, many communication applications can be served by multimode fibers sourced by less expensive and easier to maintain LED-based terminal equipment.

Commercial multimode fiber comes in four standard sizes, with the best performance offered by *50/125* fibers (fiber that has a 50-μm diameter core and a 125-μm diameter clad) as shown in Figure 1. These fibers are invariably *graded-index* fibers which are designed to provide excellent optical confinement by continuously refocusing the light toward the fiber centerline. This is done by carefully modifying the glass formulation in the fiber's core so that the index of refraction is reduced away from the centerline. The multimode fibers currently installed at KSC are 50/125 graded-index fibers. The light rays confined in the core travel curved paths which can be called *modes*. There are several hundred modes in 50/125 fiber. Modes close to the center (for example *(a)* in Figure 1) are *low-order modes* and those far from the center (*(c)* in the Figure) are *high-order modes*. The high-order modes are the least strongly confined and often are lost in poor quality fibers or in fiber paths that have poor connectors, splices, stressful installation or other quality problems.

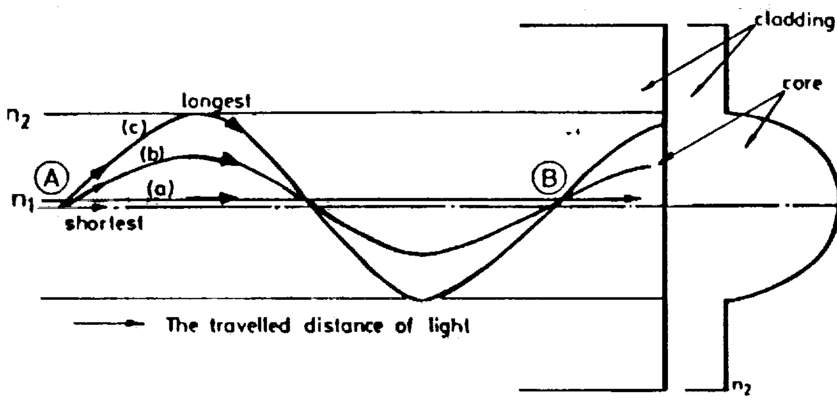

Figure 1. Multimode Optical Fiber

Commercial multimode graded-index fibers have been designed to take advantage of two areas of low attenuation in glass, that naturally occur for light that has wavelengths around 850-nm and around 1300-nm. These areas of high transparency are called *first-window* and *second-window* respectively. Due to the nature of glass, first-window operation is too lossy to be of use over the distances routinely encountered at KSC; therefore, the Center's multimode fibers are sourced by LEDs and lasers that have wavelengths around 1300-nm; that is, by second-window sources.

1.2 Utilization of the Third Window

There is a third window, centered around 1550-nm, which is often used in singlemode fiber systems. However, no fiber vendor offers information on the performance of its 50/125 multimode fibers at this wavelength. Today's WDM devices routinely combine 850- and 1300-nm operation on multimode fibers and 1300- and 1550-nm operation on singlemode fibers.

Since WDM appeared attractive for some applications at KSC and since 850-nm operation was too lossy, some preliminary tests were performed to see if a usable third window existed in KSC's installed multimode fiber. Attenuation tests showed that older fibers were very lossy but fibers less than five years old exhibited a low attenuation window around 1550 nm. This led to the belief that it might be possible to use KSC's 50/125 fibers at both 1300 and 1550 nm, and therefore, WDM might be possible at these wavelengths.

1.3 Necessity of Bandwidth Studies

Given that the multimode fibers exhibited low loss at 1550-nm it is still possible that the bandwidth available in this window might be too low to be practical. The fiber vendors offer little information on this subject; therefore, tests would need to be made on some installed fiber at KSC to try to understand whether sufficient bandwidth might be available in this window.

A preliminary test was performed by replacing the some of the 1300-nm LEDs with third window LEDs in some of the single-channel video on fiber terminal equipment common at KSC. It was found that most of these modified units still functioned acceptably in third-window operation.

Those encouraging results led to the work reported herein. This research effort seeks to determine the bandwidth that is available in KSC's 50/125 multimode fibers when third window sources are used and to understand the factors that affect third-window bandwidth.

2. FACTORS AFFECTING MULTIMODE FIBER BANDWIDTH

While the 50/125 fiber that is installed at KSC has come from several vendors, the majority of the fiber is from Corning and carries Corning's trade name *Long Distance Fiber* abbreviated LDF. It is this fiber that will be the subject of these studies.

2.1 Modal Distortion

The 50/125 multimode optical fiber common at KSC, allows the propagation of several hundred individual electromagnetic modes as information is guided down the waveguide. Each mode has its own discrete properties including power distribution profile, ray path and propagation delay. The differences between modal propagation delays lead to undesirable distortion manifested as optical pulse broadening, or equivalently, modulation bandwidth limitations. Bandwidth limitations due to this effect are known as *Modal Bandwidth.* Only singlemode fibers are immune to modal bandwidth limitations which is the primary reason that these fibers offer the highest performance.

System designers request one bandwidth parameter that will allow prediction of system performance; however modal bandwidth must be treated as an approximation since it results from a complex interaction of the modes which is influenced by many factors including:

1) the chemical composition and purity of the glass,
2) the indices of refraction of the core and clad and
3) the index of refraction profile

Furthermore, any event that changes the power distribution among the modes will alter the modal bandwidth. Even the small random variations of these parameters, which are inevitable in today's mass-produced fibers, will substantially affect modal bandwidth. Therefore, to be useful in system design, modal bandwidth parameter must be conservatively and cautiously applied.

Graded-index multimode fibers are designed to minimize the modal distortion by differential doping of the host glass to give radial reduction of the core's index as shown in Figure 2. One mathematical parameter can describe the index of refraction reduction function and is called the fiber's *index profile parameter*, α. The figure exemplifies the variation of actual profile of a practical fiber from the design profile.

Dielectric waveguide theory shows that for any one wavelength of light there is one discrete α that causes modal pulse distortion to become negligible. However, since it is not possible to operate a fiber at one wavelength (no monochrome sources exist) and since real fibers have random variations in their profile parameter, practical graded-index fibers always have some significant modal distortion. For today's multimode fibers, α is chosen either to optimize the fiber's modal bandwidth for one window or to give moderately good performance in both first and second windows. Generally, manufacturers optimize 50/125 multimode fiber for second window operation so that the bandwidth is highest in this region. Fiber manufacturers test the modal bandwidth of their multimode products and publish a specification called the *bandwidth•length product* that gives the typical modal bandwidth for a one-kilometer continuous length of fiber. Bandwidth•length products are given for first and second window operation but no information is available for third window operation.

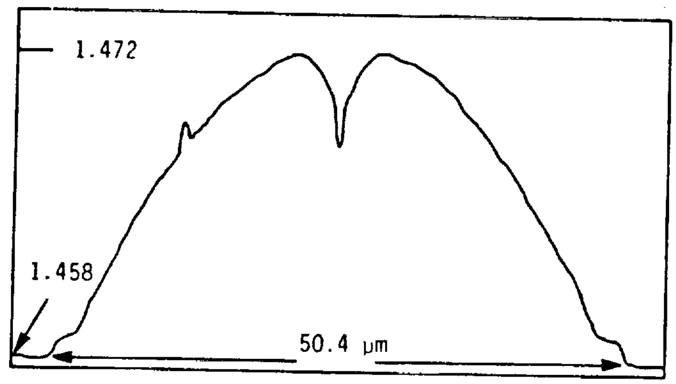

Figure 2 - Index of Refraction Profile

If the fiber's modal bandwidth properties are specified for one kilometer of fiber, it is necessary to know how to scale this specification to the actual lengths of installed fiber; especially, when fiber paths usually consist of a concatenation of several shorter fiber sections. This scaling is usually summarized using the following equation:

$$BW_M = BW_{(l)}/L^{\gamma} \quad (1)$$

where $BW_{(l)}$the bandwidth•length specification, BW_M is the modal bandwidth of length L (kilometers) of fiber and γ is the *concatenation factor*.

The publishing of a bandwidth•length product should not be interpreted as meaning that the bandwidth is inversely proportional to the length; that is, that $\gamma = 1$. Experiment has shown that γ depends on the axial variability of the optical properties of the fiber which cause an increase of power mixing among the modes. Generally, γ is in the range $0.7 \leq \gamma \leq 1$. Fibers with a lot of variability will have a high degree of mode mixing which leads to a lower γ but high-quality fibers with less variability will have a γ closer to unity. However this analysis is only true for continuous lengths of fiber. Fiber-to-fiber joints (connectors or splices) can cause a very large disruption in the power distribution among the several hundred propagating modes which in turn may cause large variations in modal distortion. For concatenated fiber paths containing many fiber joints, the modal distortion could be quite different from the bandwidth for the same length of continuous fiber. Usually, when concatenated into long paths, even high quality fibers will have a γ less than unity[1].

2.2 Chromatic Dispersion

Except for free-space, all transparent media propagate light waves at speeds that are somewhat dependent on the wavelength of the light. Therefore, different wavelengths of light travel at different speeds and possess different indices of refraction. Transparent materials that exhibit this effect are know as *dispersive materials*. The glass used in all optical fibers is dispersive. Figure 3 shows the dependence of index of refraction on wavelength for Corning's 50/125 LDF fiber[2].

Since fiberoptic sources are not monochromatic, a pulse of light propagating down a fiber will always consist of a group of wavelengths which will possess a range of propagation delays. Mathematically, it is convenient to define the *group index*, N, which is related to the speed at which the wavelength group will conduct information down the waveguide. Group index is related to index of refraction, n, by the following relation:

$$N = n - \lambda(dn/d\lambda) \qquad (2)$$

The group index for Corning 50/125μm LDF is included in Figure 3.

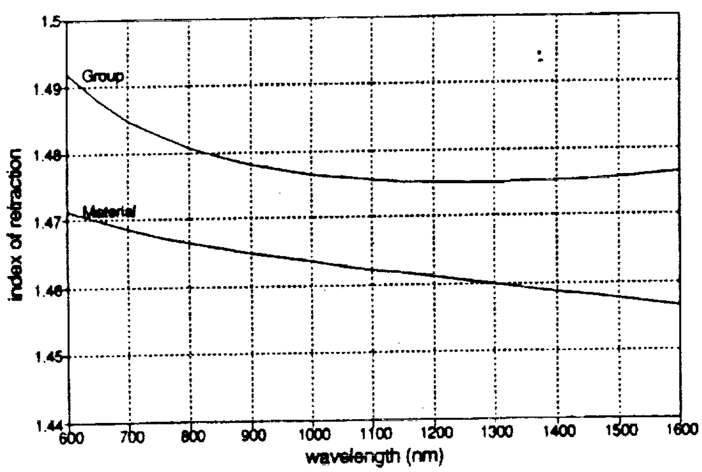

Figure 3. Index of Refraction for Corning LDF

The range of delays in the optical group will broaden optical pulses as they propagate along the fiber. The amount of pulse broadening will be determined by the fiber's material dispersion and the range of wavelengths emitted by the source. It must be reemphasized that since optical fibers are made from a dispersive material, all fibers, singlemode and multimode, exhibit dispersive pulse broadening.

In addition to material dispersion, there is an additional pulse broadening effect due to the confinement of light within a fiber waveguide. This effect is denoted as *waveguide dispersion*. Fiber vendors, knowledgeable of their product's performance and understanding the needs of the customers publish the *chromatic dispersion*, D, which is the combined effect of material and waveguide dispersions.[3]

Group delay, τ, group index, N, fiber length, L, and chromatic dispersion, D, are related as follows:

$$\tau = LN/c \qquad (3)$$

$$d\tau/d\lambda = L/c \cdot (dN/d\lambda) = L \cdot D \qquad (4)$$

Figure 4 depicts these relations, for one kilometer of typical Corning 50/125 LDF.

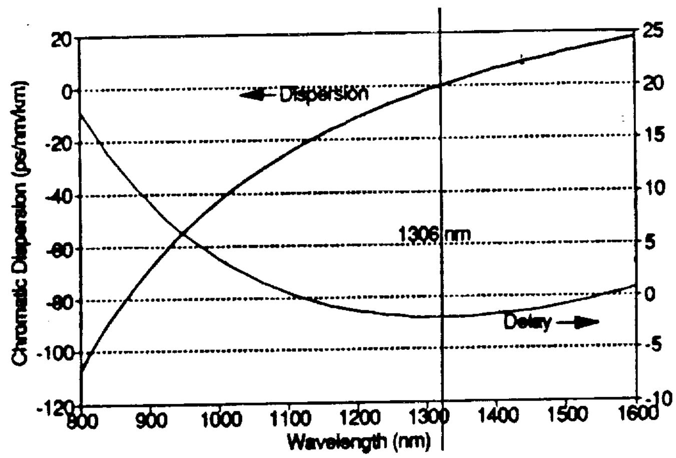

Figure 4. Chromatic Properties of Corning LDF

One standout feature of Figure 4 is that at λ = 1306 nm chromatic dispersion is zero. This is the *zero-dispersion wavelength*, λ_o, for Corning LDF; however, all ordinary (not dispersion-shifted) fibers have a dispersion graph very similar to the one shown and have a zero-dispersion wavelength in the range $1250 \le \lambda_o \le 1350$ nm. It is standard practice for fiber vendors to specify the chromatic properties of their products by giving two specifications: λ_o and S_o which are respectively, the zero-dispersion wavelength and the slope of the dispersion graph at λ_o.

These specifications can be used with the standard mathematical model that adequately describes ordinary fibers to give pulse delay characteristics as follows:[8]

$$\tau = \tau_o + S_o \cdot [\lambda - \lambda_o^2/\lambda]^2/8 \qquad (5)$$

$$D = S_o \cdot \lambda \cdot [1 - (\lambda_o/\lambda)^4]/4 \qquad (6)$$

Ultimately, system designers require a means to determine the effect of chromatic dispersion on the information carrying capability of installed optical fibers. This is usually done by determining the pulse broadening, $\Delta\tau$, and the chromatic dispersion bandwidth, BW_D, using the following relationships ($\Delta\lambda$ is the FWHM spectral width of the optical source). For first- and third-window sources

$$\Delta\tau \cong L \cdot \Delta\lambda \cdot D \tag{7a}$$

for second-window sources:

$$\Delta\tau^2 \cong L^2 \cdot [(\Delta\lambda \cdot D)^2 + (\Delta\lambda^2 \cdot S_o/2)^2] \tag{7b}$$

and finally:

$$BW_D = 0.441/\Delta\tau \tag{8}$$

Unlike modal distortion, chromatic dispersion is not affected by launch conditions or fiber joints; therefore, chromatic dispersion bandwidth is inversely proportional to the length of the fiberoptic path. However, as the above relations show, dispersion bandwidth is critically dependent on the spectral characteristics of the fiberoptic source.

2.3 Expected Results:

The specification sheets for the Corning 50/125 LDF include the following information:[4]

Table 1. Properties of Corning LDF

1300-nm:	attenuation:	0.5 to 1.2 dB/km (KSC requires $\leq$1.0 dB/km)
	modal bandwidth:	400 to 1500 MHz•km (KSC requires $\geq$1000 MHz•km)
Chromatic Dispersion:		
	zero-dispersion wavelength, λ_o:	1297 to 1316 nm
	zero-dispersion slope, $S_o < 0.101$ ps/km/nm^2	
	dispersion function:	equation (6), $750 < \lambda < 1450$ nm
Index of refraction:	at 850-nm = 1.4655	
	at 1300-nm = 1.4598	

It is expected that the modal bandwidth of the Corning LDF test fibers will be quite high in the second window, since it's optimized for that operation, and somewhat reduced when third-window sources are used. Based upon KSC requirements and Corning specifications, the modal bandwidth•length product should be greater than the KSC minimum 1000 MHz•km when tested close to 1300-nm.

Also, modal bandwidth measurements may be difficult due to modal noise which is present in multimode fiber joints when narrowline lasers are used as sources. It will be important to use a tightly constrained and overfilled launch condition to fully stimulate all of the modes when testing multimode fibers.[2]

When concatenated links are tested, the modal tests should produce a concatenation factor that is somewhat less than one. It is not known whether this factor will be different for 1300- and 1550-nm operation. The attenuation of the fiber paths under test should be less that 1.0 dB/km in second window operation and slightly lower in third window tests. There may be a relationship between attenuation and modal bandwidth if the fiber joints in the paths under test are subject to differential mode attenuation. In this case, higher loss links may have a higher apparent bandwidth.

Chromatic dispersion effects should be much larger for third window operation than for second. It is expected that the information bandwidth of the 50/125 LDF fibers will be dispersion-limited for third window operation; but dispersion and modal distortion may be equally important for second window tests.

Based upon the Corning's chromatic specifications and assuming an LED source with a FWHM of 65-nm the dispersion bandwidth of one kilometer of fiber should be as shown in Figure 5.

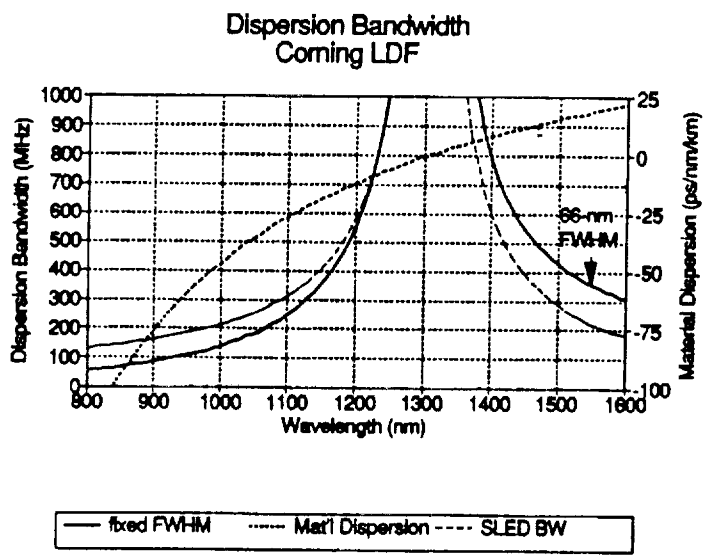

Figure 5. Dispersion Bandwidth for Corning LDF

3. INSTRUMENTATION AND RESEARCH DESIGN

There are twelve Corning LDF fibers that connect the Engineering Development Laboratory (EDL) with the Communication Distribution and Switching Center (CDSC). These fibers are reserved for tests and terminate in the EDL's Fiberoptic Laboratory in biconic connector ports labelled *1* through *12*. In order to allow reliable measurement of a wide range of fiber paths, these 12 fibers were patched into 6 test loops. Four test loops consisted of 4.8-km of fiber looped back at the CDSC. Two test loops consisted of a total of 12.8-km of fiber patched through at the CDSC and looping back at the Banana River Repeater Station (BRRS). Measurements included up to three concatenated CDSC loops. Figure 6 depicts the test loops.

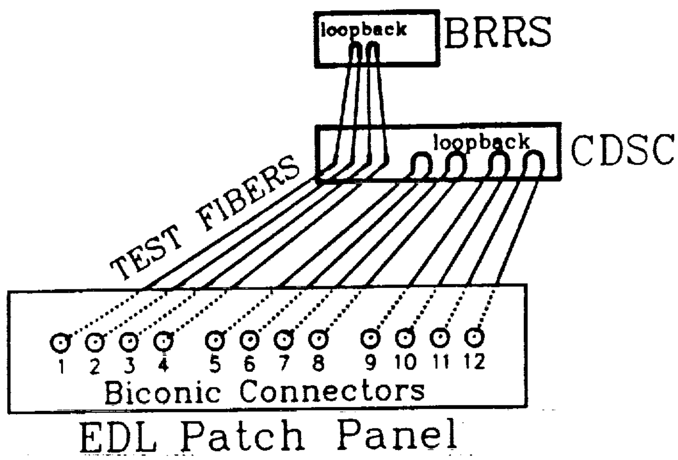

Figure 6. EDL Test Fiber Loops

In support of the wide utilization of fiberoptic technology at KSC, the Fiberoptic Laboratory houses an impressive collection of fiberoptic test instrumentation which allows a complete range of testing of both singlemode and multimode fibers and entire fiberoptic systems. The laboratory's support personnel possess a praiseworthy range of expertize and their aid and counsel made the investigations described herein possible.

Table 2. Test Loop Characteristics

EDL Fiber Numbers	Loop-back Point	total distance (km)	Attenuation (dB)			
			1299-nm		1549-nm	
			forward	reverse	forward	reverse
1-2	BRRS	12.8	16.7	15.8	20.5	19.6
3-4	BRRS	12.8	19.5	18.4	24.6	22.6
5-6	CDSC	4.8	14.7	14.6	15.3	15.8
7-8	CDSC	4.8	8.6	9.7	9.5	10.4
9-10	CDSC	4.8	7.7	6.7	8.5	8.3
11-12	CDSC	4.8	7.4	6.1	7.3	8.9

3.1 Attenuation Measurements

The attenuation of each loop was recorded at 1298-nm and 1549-nm using an EXFO FOT-90 Fiberoptic Test Set. Table 2 summarizes the results of the attenuation tests.

To gain more information on the test loops, each loop was scanned using a Laser Precision TD-9960 OTDR with a TD-861 1300-nm Multimode Optical Module. Figure 7 is an example of one of the OTDR traces.

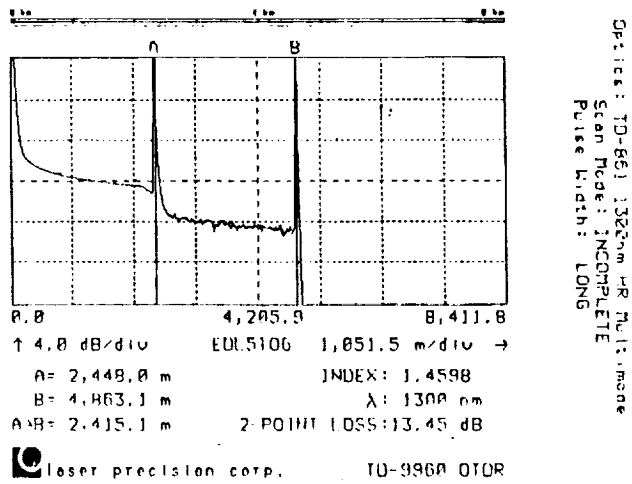

Figure 7. OTDR Trace of Loop 5-6

3.2 Modal Bandwidth Studies

A recently acquired Hewlett-Packard HP-8702B Lightwave Component Analyzer was used to measure the modal bandwidth of the multimode test fibers. As the block diagram in Figure 8 shows, the HP-8702B is essentially a 300-kHz to 3-GHz microwave network analyzer. By utilizing the calibrated E/O and O/E converters the HP-8702B can make swept-frequency measurements of optical fibers. As the first two rows of Table 3 show, the two Hewlett-Packard laser-based E/O modules had wavelengths of 1309 nm and 1533 nm, chosen to allow fiber measurements in the second and third windows.

Table 3 - E/O Source Modules

E/O Module		Optical Spectrum		Coupled Power
Name	maker	peak (nm)	FWHM (nm)	(dBm)
83402A	HP	1309	3	+0.4
83403A	HP	1533	5	-1.6
LED-2	custom	1314	65	-12.0
LED-3	custom	1504	62	-14.3

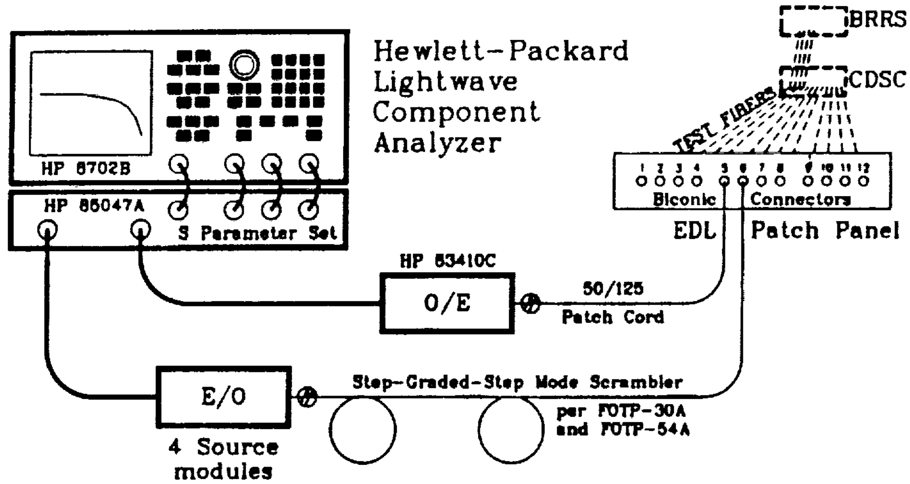

Figure 8. Lightwave Component Analyzer

Modal bandwidth measurements were made in accordance with FOTP-30A[5]. Due to the lengths of the test loops, cladding mode strippers were deemed unnecessary and were not used. In order to enhance measurement reliability, an Anritsu step-graded-step mode scrambler was used at the test fiber loop launch aperture to create a uniformly overfilled launch condition; thus meeting the criteria specified in FOTP-54A[6]. The spectral widths of the Hewlett-Packard E/O lasers were narrow enough so that, according to FOTP-30A, chromatic dispersion effects could be considered insignificant. Thus, the bandwidth measurements made using these E/Os would represent modal distortion bandwidths.

3.3 Chromatic Dispersion Effects

Direct measurements of chromatic dispersion and/or chromatic dispersion bandwidth were not possible with the instrumentation available in the Fiberoptic Laboratory. However, chromatic bandwidth information could be indirectly obtained if bandwidth measurements of the test fibers could be made using a broad-linewidth, LED-based, E/O converter connected to the HP-8702B. Hewlett-Packard does not offer such converters; therefore, the Fiberoptic Laboratory's support personnel designed and fabricated two such modules, one for second-window and one for third-window measurements. The LEDs included in these modules were carefully selected from those available in the laboratory, for high output power, reasonable spectral width and fast risetime. The optical characteristics of these custom-made E/O modules are given in the last two rows of Table 3.

Using the custom E/O modules, swept-frequency response measurements of all of the test loops would be attempted. It was expected that the dynamic range of the Lightwave Component Analyzer would be sufficient to reliably measure the response of two concatenated CDSC loops; however, it was not clear if measurements on three concatenated loops would be possible.

The modal bandwidth measurements obtained from laser E/O modules could be combined with computed dispersion bandwidths obtained using the chromatic specifications published by Corning to obtain an *expected* optical bandwidth. This expected optical bandwidth could then be compared to the measured optical bandwidths obtained using the custom LED E/O modules. It was hoped that a better understanding of factors affecting the third-window bandwidth of the CDSC fibers would result.

Theory suggests that chromatic effects should play a relatively minor role in the second window bandwidth; however, these effects should be a major factor in determining the useful bandwidth limitations when multimode fibers are used with third-window sources.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Using the HP-8702B configured for optical measurements, frequency response plots were obtained for each of the multimode fiber test loops and for as many concatenated paths as possible. The frequency response of each fiber loop was recorded using each E/O source module. All tests were made in both directions. When making optical measurements with the HP-8702B, the electroptical characteristics of the stimulus and response elements (the E/O and O/E module pair and the mode scrambler and patch cord) are stored in the instrument's memory and are used to correct the end-to-end response of the fiberoptic circuit under test so that the display represents the optical performance of the test fiber. Therefore, the fiber's modal optical bandwidth is represented by the -3 dB response point on the plots[7]. A typical set of test plots is shown in Figure 9. As is seen in the Figure, the -3-dB bandwidth of each plot was recorded on the traces.

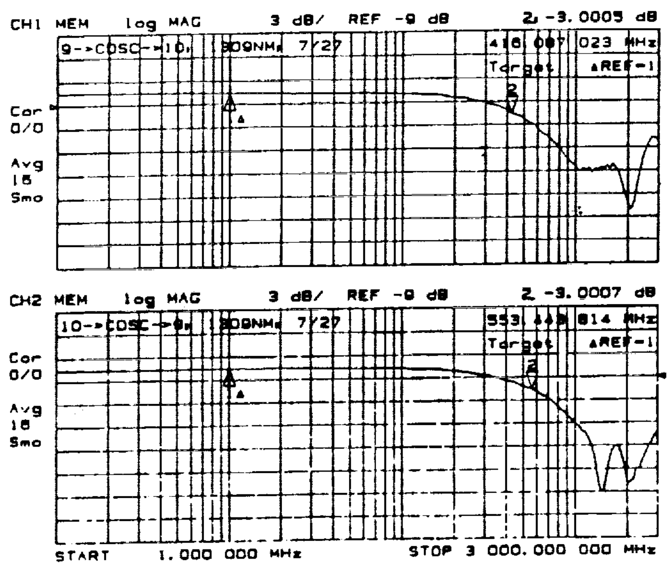

Figure 9. Typical Frequency Response Plot of Test Fibers

4.1 Modal Bandwidth Results:

While performing the modal bandwidth measurements several important observations were made. First, the second-window bandwidth measurements were very sensitive to launch conditions. Since non-keyed biconic connectors were used to interconnect the test equipment and the fiber test loops, the launch conditions could be easily changed. By simply rotating the launch connector a wide range of frequency plots for the same test path could be recorded. Bandwidth differences of as much as 25% were not uncommon. Figure 10 demonstrates this effect by showing two frequency response traces for the same test, where the only difference was that the biconic launch connector was rotated by approximately 60°. As the figure shows, an increase in coupling loss is generally accompanied by an apparent increase in the modal bandwidth. A reasonable explanation of this effect is that when the launch conditions are changed so that less light is coupled into the fiber, the coupling efficiency of the weakly guided high-order modes is reduced more than the strongly guided low-order modes. Therefore, the higher-loss optical signal consists mostly of low-order modes which have a smaller range of propagation delays resulting in a higher apparent bandwidth.

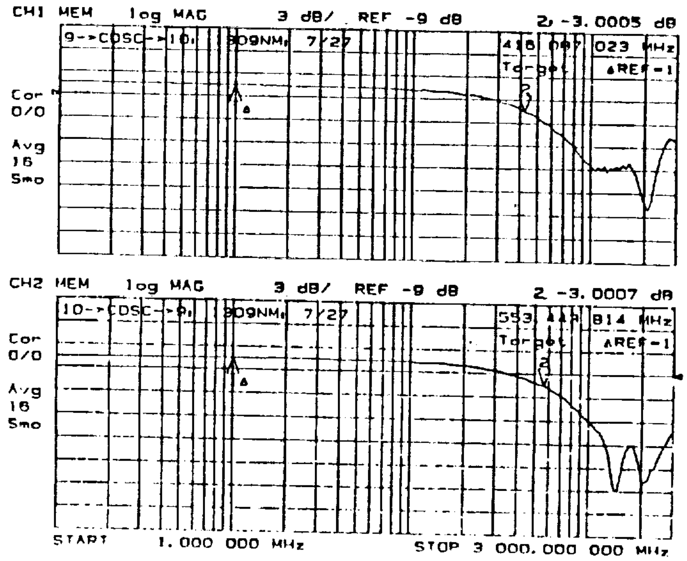

Figure 10. Effect of Launch Connector Rotation on Bandwidth

The third window tests exhibited far less of this launch-condition variability than the second window measurements. This is probably due to the fact that the optical properties of the multimode fiber were tuned to reduce the differential mode delays for second window operation when those fibers have all guided modes stimulated. On the other hand, using the fiber at other than the optimized wavelength produces a bandwidth that is predictably reduced in magnitude but is also reduced in sensitivity to optical path perturbations.

In an attempt to obtain a bandwidth data set that was least corrupted by launch condition variability, two additional steps were included in the test procedure: 1) 1309-nm bandwidth was measured after manipulating the launch connector to give maximum coupling efficiency, and 2) the 1533-nm measurement was then made without disturbing the launch connector.

Figure 11a depicts the results of the modal bandwidth measurements for all four EDL to CDSC test loops. Modal bandwidths are shown using bars and the primary ordinate; and the line and secondary ordinate express the 1533-nm modal bandwidth as a percent of the 1309-nm data. The average data, shown on the right of the figure, were computed without including the 5-6 loop (for reasons described below). As can be seen, the third window modal bandwidth averages 46% of the second window bandwidth; confirming the expectation of a reduction in modal bandwidth for wavelengths away from the optimized second window.

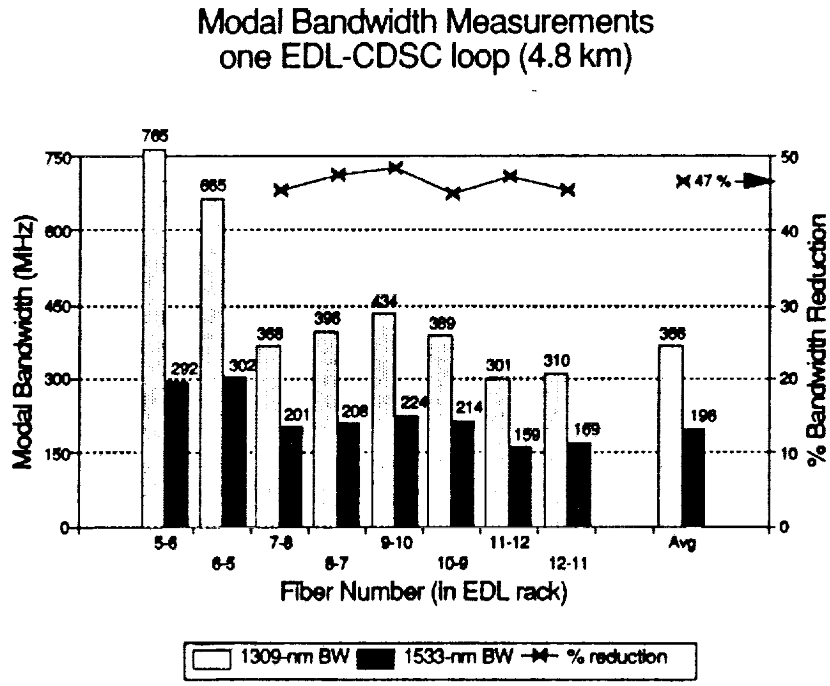

Figure 11a. Measured Modal Bandwidth, Single CDSC Fiber Loops

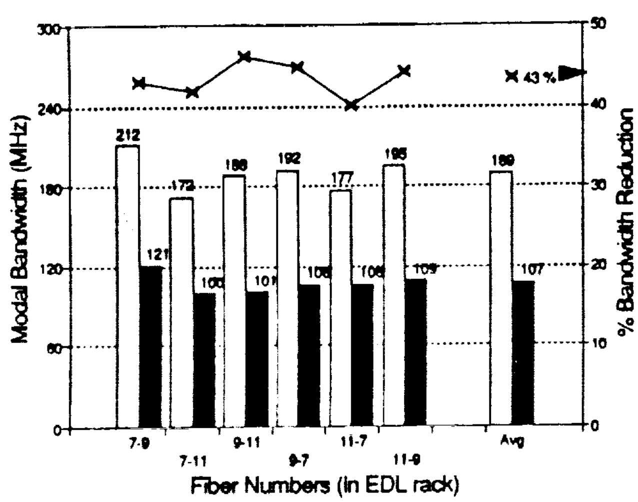

Figure 11b. Measured Modal BW two concatenated CDSC loops

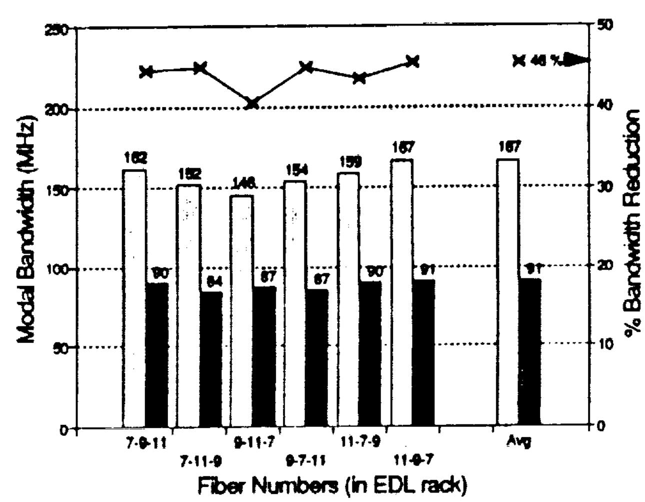

Figure 11c. Measured Modal BW three concatenated CDSC loops

Reviewing the data of the four CDSC test loops (Figure 11a and Table 2) shows that the loop comprised of fibers *5* & *6* had both a considerably higher bandwidth and attenuation than the other three loops. The bandwidth difference is substantially more pronounced at 1300-nm (95% higher) than in the 1550-nm window (51% higher). This is thought to be another manifestation of the effect of differential attenuation of the higher order modes at one or several connectors along the loops. Also, of the three other loops, loop *11-12* had the lowest attenuation and the lowest bandwidth; possible further evidence supporting this conclusion. Since the transmission characteristics of loop *5-6* were so different from the other three, this loop was excluded from the average comparisons shown on Figure 11a and from the concatenation studies.

Figures 11b and 11c depict the bandwidth and bandwidth reduction information for two and three concatenated CDSC loops. These data compare favorably to the data for the single CDSC loops showing that the third-window modal bandwidth is approximately 45% of that obtained in the superior second-window.

The CDSC loop data for 1309-nm and 1533-nm was subjected to a linear regression analysis in order to find the modal bandwidth-length product and the concatenation factor, γ. Figure 12 shows the results of these analyses.

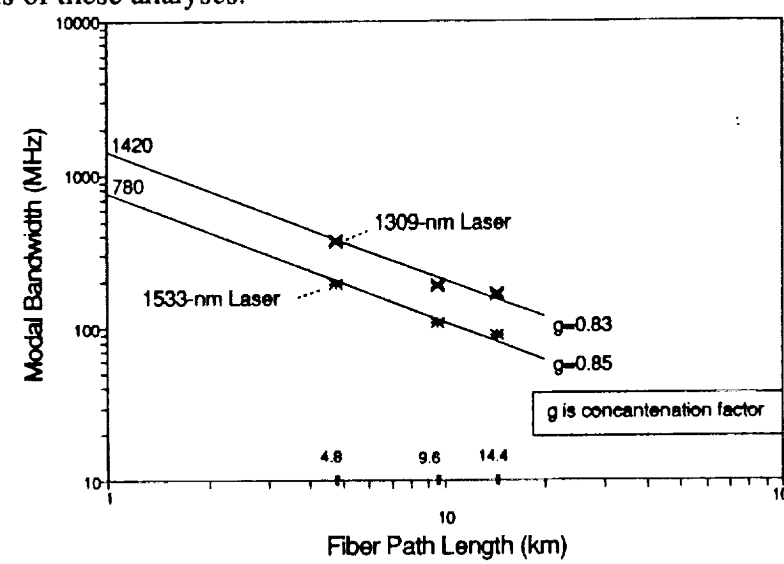

Figure 12. Modal Bandwidth (CDSC Loops) Linear Regression Fit

Figure 13 shows the results of the measurements on the two BRRS test loops using the same format as previously described. An attempt was made to analyze the data from the EDL-BRRS loops similarly; but this was prevented by three additional problems. First, there were only two loops, a very restrictive sample. Second, the test equipment did not have enough dynamic range to allow concatenated measurements on the BRRS loops. Third, these paths contain fibers in two different cables. It is not clear at this time how different these fibers are in modal characteristics or how these differences would affect the measurements. Limited time caused this study to concentrate on the CDSC loops.

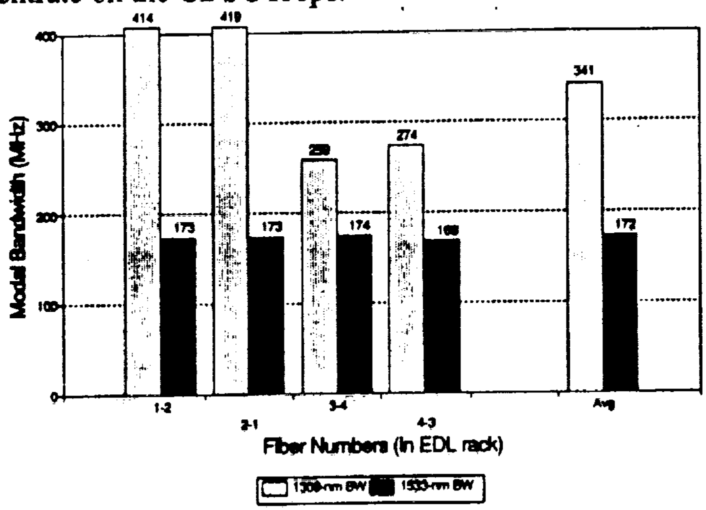

Figure 13 - Modal Bandwidth of Single EDL to BRRS Test Loops

4.2 Dispersion Bandwidth Results:

It was found that the custom made LED-based E/O modules performed admirably making optical bandwidth measurements possible. Using the custom E/O modules, the swept-frequency response measurements of all of the test loops was repeated. The step-graded-step mode scrambler was used on all measurements except those for three CDSC links concatenated. It was determined that, when using the LED-based custom E/O modules, there was very little sensitivity to launch connector alignment, even when the mode scrambler was removed and replaced with a patch cord. Therefore, it was assumed that complete mode excitation was possible without the scrambler when using the LED modules. By removing the scrambler, and its inherent 3.8-dB loss, it was possible to measure bandwidth data for three concatenated CDSC loops.

The results of these bandwidth measurements are shown in Figures 14 and 15. Since the LEDs had spectral widths which were at least twenty times those of the laser modules, these bandwidth measurements would be the result of a combination of both modal distortion and chromatic dispersion effects; that is, the data would represent the *optical* bandwidth. Little chromatic effect was expected for operation close to 1300-nm and this study's data support this expectation. Comparing the second-window bandwidth data for the narrow line laser with the broad spectrum LED data (Figures 11a and 14a) shows that, on average, the LED's optical bandwidth is 10% lower than the laser's modal bandwidth for the single CDSC loops. Since the concatenation factor for the modal bandwidth is less than unity and the factor for dispersion effects is unity, then it would be expected that longer fiber paths would exhibit a larger percent modal bandwidth reduction due to dispersion. It is noted that the data (Figures 11b, 11c, 14b and 14c) support this conclusion.

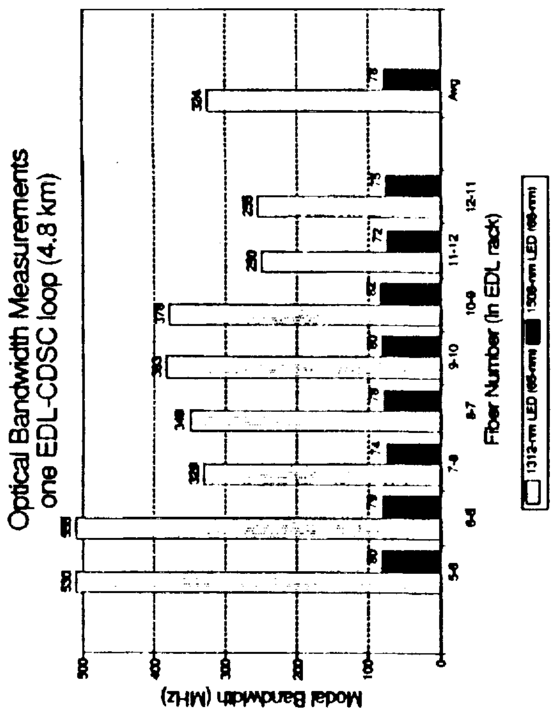

Figure 14a. Optical Bandwidth
Single CDSC Loops

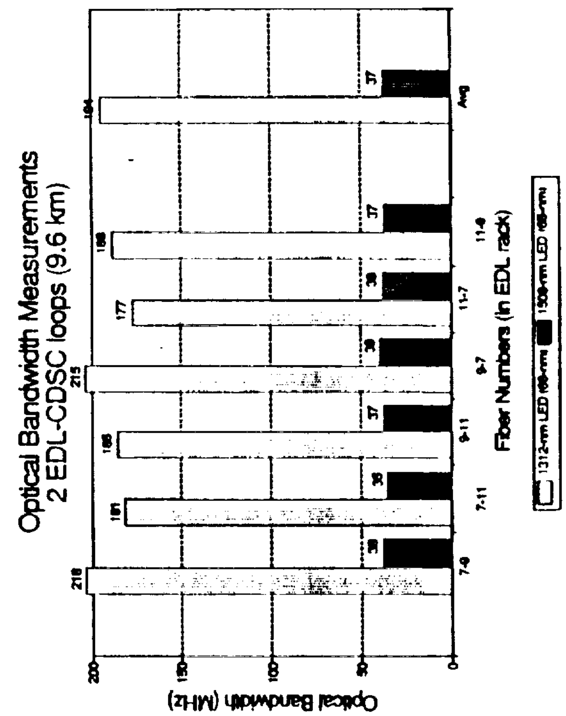

Figure 14b. Optical Bandwidth
Two Concatenated CDSC Loops

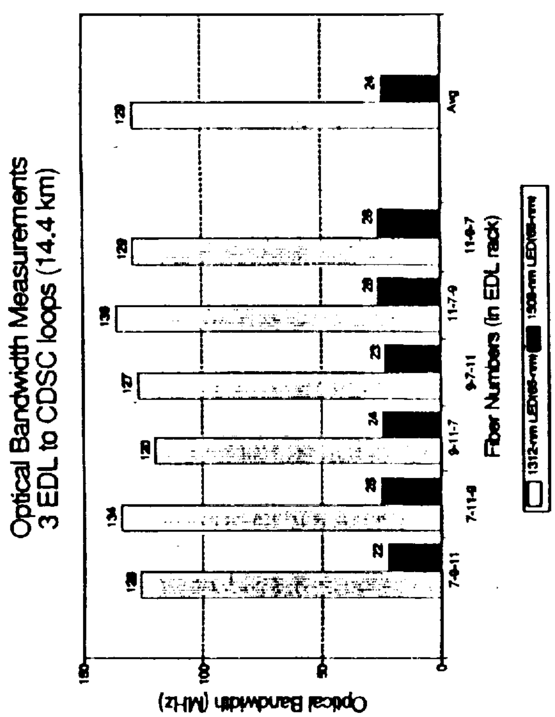

Figure 14c. Optical Bandwidth
Three Concatenated CDSC Loops

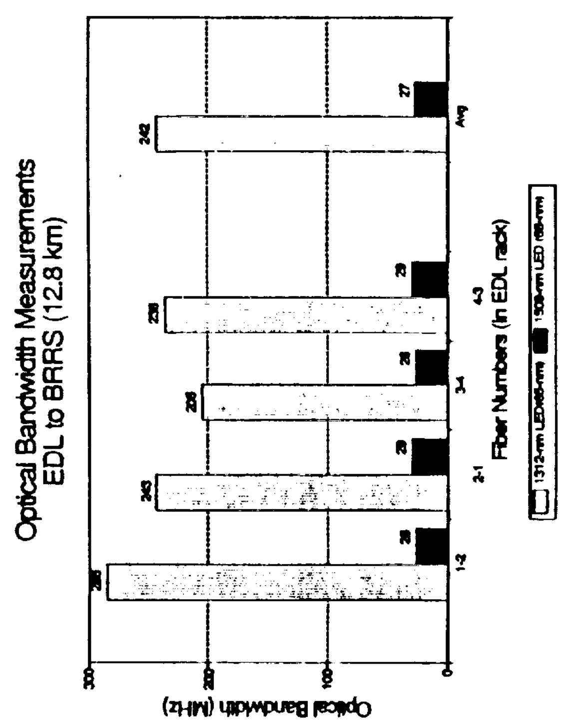

Figure 15. Optical Bandwidth
BRRS Loops

When used with a third-window LED, however, the dispersion effects due to the wide spectral width and the significant chromatic dispersion of the fiber were expected to be comparable to the modal effects. As Figures 11 and 14 show, the third window optical bandwidth of the fibers is approximately one-third of the modal bandwidth and the dispersion effects become even more pronounced at longer distances, as was true with the second-window tests. Therefore, when sourced by a third-window LED, these fibers exhibited a dispersion-limited information transmission capability.

By combining the average measured modal bandwidths with dispersion bandwidth obtained by computation using the Corning chromatic specifications and the spectral characteristics of the LEDs (Table 3) an *expected* optical bandwidth was obtained. Figures 16a, 16b and 16c compare the expected and measured optical bandwidths for all combinations of CDSC fiber loops. It is noted that the relative difference between these two optical bandwidths was 6% or less.. This agreement is quite good especially when the variability of the modal bandwidth measurements and the inherent variability of the fibers themselves are recalled.

4.3 Discussion

As expected, the third window modal bandwidth of the EDL multimode test fibers was reduced to slightly less than 50% of the 1300-nm (optimum) modal bandwidth; that is, from 1400 to 780 MHz•km. At 1300-nm the modal bandwidth measurements were highly dependent on launch conditions; however, the third-window measurements showed much less dependence on launch conditions. The concatenation factor for each window was approximately $\gamma = 0.84$.

While the second-window optical bandwidths were modal-distortion limited, the third-window tests exhibited strong dependence on chromatic dispersion. The expected optical bandwidth, in part based upon manufacturer's chromatic dispersion specifications (λ_o, S_o), agreed nicely with the optical bandwidth measurements made using the LED-based custom-made E/O modules, eventhough the manufacturer did not claim that the dispersion specifications were applicable beyond 1450-nm.

Figure 17 is based upon the average measured modal bandwidth for the CDSC test fibers and Corning's chromatic specifications and shows the expected optical bandwidth for various lengths of EDL test fiber when sourced by 1550-nm LEDs with various spectral widths and by a narrowline laser.

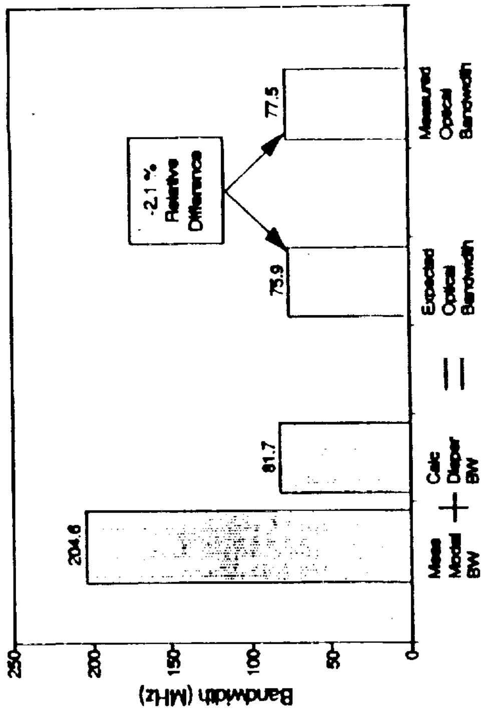

Figure 16a. Expected vs. Measured BW
Single CDSC Loop

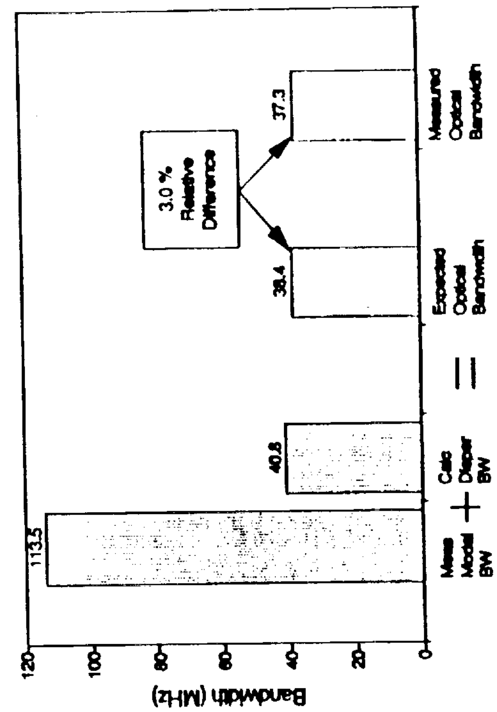

Figure 16b. Expected vs. Measured BW
Two Concatenated CDSC Loops

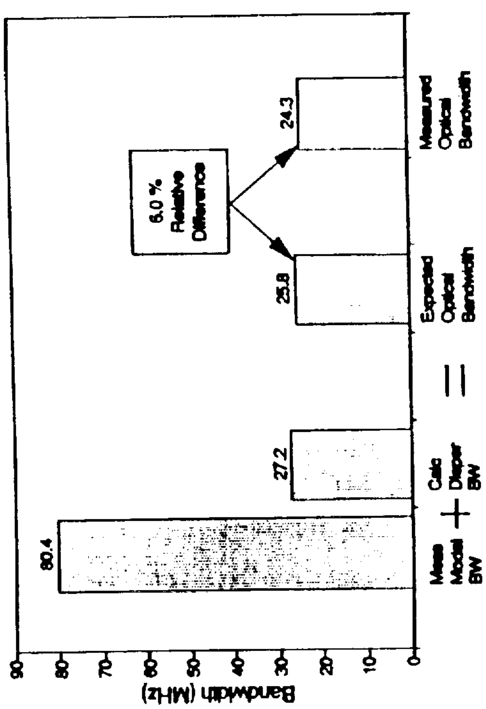

Figure 16c. Expected vs. Measured BW
Three Concatenated CDSC Loops

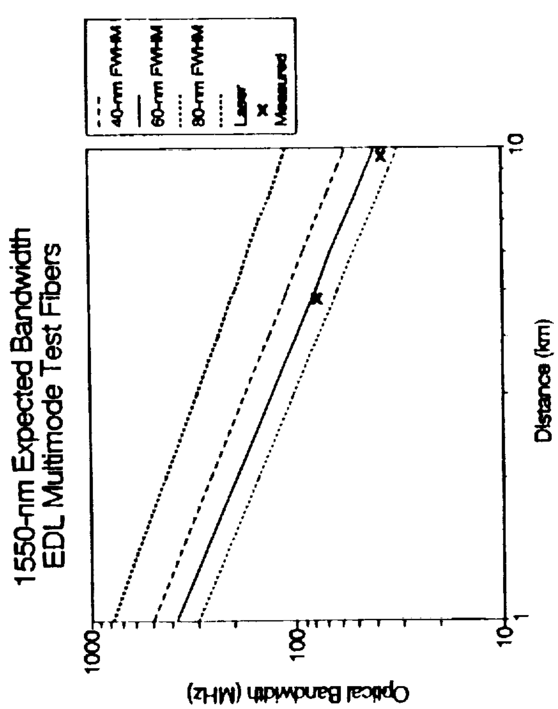

Figure 17. Expected BW
LDF Test Fiber

5. CONCLUSIONS AND RECOMMENDATIONS

The results of this study show that the twelve Corning LDF multimode fiber tested have a usable and predictable bandwidth when used with sources in the 1550-nm third window. If the fibers tested are representative of the multimode fibers that have been installed at KSC during the past five years, then WDM on these fibers at 1300- and 1550-nm is an attractive possibility.

The modal bandwidth of these test fibers when used with 1550-nm sources was about 45% of the modal bandwidth expected when 1300-nm sources are used. This bandwidth reduction was true for one 4.8-km test loop but also was valid when or two or three of these loops were concatenated. The tests confirmed that launch conditions can affect the measured bandwidth to a very large degree when 1300-nm sources are used; however, the third-window bandwidth exhibited much less sensitivity.

The bandwidth of these fibers was modal-distortion limited in the second window; but was chromatic dispersion limited when third window LEDs were used. The chromatic dispersion specifications published by the vendor appear to be applicable when extrapolated to third window operation eventhough the vendor excludes wavelengths beyond 1450-nm from these specifications. By utilizing the measured modal bandwidth and the chromatic dispersion specifications, good predictions of the fiber's optical bandwidth were possible.

Before committing to 1550-nm operation, it is recommended that tests similar to those made in this study be performed on a larger sample and a wider range of the installed multimode fibers at KSC. These tests should include fibers of various ages and of various manufacturers. Only by additional testing can it be verified that the 1550-nm window is routinely available on all of the Center's multimode fibers.

If the 1550-nm window is to be used at KSC it is further recommended that, for new fiber cables, the vendors be required to provide chromatic-dispersion information that is valid in the second and third windows. This is especially important since it was confirmed that the optical bandwidth in the 1550-nm window is dispersion-limited.

REFERENCES

1. Refi, J. J. "LED Bandwidth of Multimode Fibers as a Function of Laser Bandwidth and LED Spectral Characteristics." Journal of Lightwave Technology. 4:3, 3/86, p265.

2. Hackert, M. J. "Explanation of Launch Condition Choice for GRIN Multimode fiber Attenuation and Bandwidth Measurements" Journal of Lightwave Technology. 10:2, 2/92, p125.

3. Corning, Inc. "Multimode Chromatic Dispersion". Measruement Method MM-110. 8/90.

4. Corning, Inc. "Corning 50/125 CPC3 Multimode Optical Fiber". Corning Product Information, 7/90.

5. EIA Standard FOTP-30A, "Frequency Domain Measurement of Multimode Optical Fiber Information Transmission Capacity". Electronic Industries Association, Washington, DC, 8/88.

6. EIA Standard FOTP-54A, " Mode Scrambler Launch Requirements for Information Transmission Capacity Measurements". Electronic Industries Association, Washington, DC, 6/85.

7. Verified in a telephone conversation with Sandy Walker of Hewlett-Packard, 7/23/92.

8. EIA Standard FOTP 168, "Chromatic Dispersion Measurement of Multimode Graded-Index and Single-mode Optical Fibers by Spectral Group Delay Measurement in the Time Domain", Appendix A, Electronic Industries Association, Washington, DC, 7/87.