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STUDY OF WAVELENGTH DIVISION MULTIPLEXING AS A MEANS OF INCREASING THE NUMBER OF CHANNELS IN MULTIMODE FIBER OPTIC COMMUNICATION LINKS

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ABSTRACT

A number of optical communication lines are now in use at the Kennedy Space Center (KSC) for the transmission of voice, computer data and video signals. At the present time all of these channels utilize a single carrier wavelength centered near 1300 nm. The theoretical bandwidth of the fiber far exceeds the utilized capacity. Yet practical considerations limit the usable bandwidth. The fibers have the capability of transmitting a multiplicity of signals simultaneously in each of two separate bands (1300nm and 1550 nm). Thus, in principle, the number of transmission channels can be increased without installing new cable if some means of wavelength division multiplexing (WDM) can be utilized. The main goal of these experiments was to demonstrate that a factor of 2 increase in bandwidth utilization can be achieved by proving that video and data signals can share the same fiber in both a unidirectional configuration and a bidirectional mode of operation. Both single and multimode fiber is installed at the Space Center. The great majority is multimode. Therefore this effort concentrated on multimode systems.

SUMMARY

Many optical communication links are now in use at the Kennedy Space Center (KSC) for the transmission of voice, computer data and video signals. At the present time all of these channels utilize a single carrier wavelength centered near 1300 nm. The theoretical bandwidth of the fiber far exceeds the utilized capacity. Yet practical considerations limit the usable bandwidth.

The main goal of this experimental program was to demonstrate that a factor of 2 increase in bandwidth utilization can be achieved by proving that video/digital data and digital data/digital data signals can share the same fiber in both a unidirectional configuration and a bidirectional mode of operation. This effort concentrated on multimode fiber systems.

During the project, a spectroscopic system was interfaced to a Macintosh computer. The system was used to characterize a number of WDM systems as well as a small number of components of the fiber optics communications systems at KSC.

A demonstration WDM 1300 nm /1550 nm link was demonstrated to work successfully with both video and digital data signals.

An experiment was performed to determine the susceptibility of the PCO receivers to crosstalk.

No tests were performed to establish nonlinearity limits in fibers nor were sufficient observations made to fully characterize the installed fiber optic system at KSC.

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ABBREVIATIONS AND ACRONYMS LIST

CDSC	Communications Distribution and Switching Center
OSA	Optical Spectrum Analyzer
LED	Light Emitting Diode
KSC	Kennedy Space Center
WDM	Wavelength Division Multiplexer or Demultiplexer
TX	Transmitter
RX	Receiver
LID	Laser Diode

I. INTRODUCTION

A number of optical communication lines are now in use at the Kennedy Space Center (KSC) for the transmission of voice, computer data and video signals. At the present time all of these channels utilize a single carrier wavelength centered near 1300 nm. The theoretical bandwidth of the fiber far exceeds its capacity. The 1300 nm window has about 10,000 GHz of available bandwidth and only 0.01 GHz is utilized.

Practical considerations such as multimode dispersion, material dispersion, detector rise time, modulation limits of the receiver...etc. limit the usable bandwidth.[1] The fibers have the capability of transmitting a multiplicity of signals simultaneously in each of two separate bands (1300nm and 1550 nm)[2,3]. Thus, in principle, the number of transmission channels can be increased without installing new cable if wavelength division multiplexing (WDM) can be utilized. The main goal of these experiments was to demonstrate that at least a factor of 2 increase in bandwidth utilization can be achieved by proving that video and data signals can share the same fiber in both a unidirectional configuration and a bidirectional mode of operation. Both single and multimode fiber is installed at the Space Center. The great majority is multimode. Therefore this effort concentrated on multimode systems.

This experimental effort has not only been aimed at a demonstration of the WDM concept within the constraints of the KSC system, but also to understand the parameters of the system so as to provide the system engineer with information needed to make decisions on future systems. Thus, part of this effort has been an effort to do spectroscopic studies on a small number of LED and laser sources, optical fiber links and WDM devices.

It is important to mention some of the questions that this work did not answer. One fundamental limitation in any WDM system as link lengths are increased should be nonlinear effects in the fiber that would mix the two channels and produce nonlinear crosstalk. [4] In addition, a good statistical sample of spectra of sources, fibers and detectors has not been made. Only items in the EDL were subjected to test. This study has not determined the properties of the overall fiber optic plant with any great statistical certainty.

II. LABORATORY SPECTRAL ANALYSIS SYSTEM

2.1 OPTICAL SPECTRUM ANALYZER

An Anaritsu optical spectrum analyzer was available in the laboratory to be used to perform spectral analysis of coherent and incoherent sources. This piece of test equipment was equipped with an IEEE 488 computer interface which provides for bidirectional computer communication. A portion of the work done under this research effort was to interface the OSA with a Macintosh IIx computer to enable the efficient collection of spectral data in machine readable form. It was envisioned that the operator would manually set up the spectrum analyzer for any given experiment and when a spectrum was collected, activate the computer interface system and acquire a sequential data file containing the maximum wavelength, the minimum wavelength of the scan and 500 data points of optical spectral power density expressed in dBm or milliwatts evenly distributed over the spectral interval.

2.2 THE MACINTOSH IIX COMPUTER

A Macintosh IIx Computer was available for use in data analysis in the laboratory. A IEEE-488 National Instruments interface board was obtained on loan to be used in an attempt to connect the Macintosh with the optical spectrum analyzer. This was accomplished through the use of Hypercard, an object oriented computer language system supplied with all Macintoshes.

The Hypercard stack (program)[5] created to connect the Macintosh with the optical spectrum analyzer is based on three cards or windows. Each has a specific function. The first appears when the stack is activated by double clicking the OSA control icon located on the main directory of the MACFIBER hard disk on the computer. (Note: a backup copy of this program is located on the floppy disk labeled "OSA control".) This first window or card contains the Hypertalk script necessary to link the Macintosh to the optical spectrum analyzer.

A second card shows a display of a subset of the optical spectrum analyzer controls as well as buttons for acquiring a spectrum or transmission data. If the single spectrum button is activated, the program will acquire 500 data points from one of the three data files available from the optical spectrum analyzer. These files will be saved as "Name".spec in the MACFIBER main directory. Where the "Name" is taken from a text field at the bottom of the card.

If the transmission button is activated, the program will collect two sets of points. One from the reference channel and the other from the sample channel. These files will be saved as "Name".ref and "Name".meas.

The third card in the OSA control stack contains information about using the system.

All spectra obtained during this research effort were taken using this system. Data analysis was accomplished using EXCEL and the results plotted using Cricket Graph.

2.3 DESIGN OF WHITE LIGHT SOURCE FROM AVAILABLE MATERIALS

In order to determine the optical transmission as a function of wavelength of components of a WDM communication system, a source of light was required with energy available over a broad band of wavelengths. Such a source was constructed using a projector lamp, lenses, and a precision translation stage to hold an optical fiber. The optical design is shown in the diagram below.

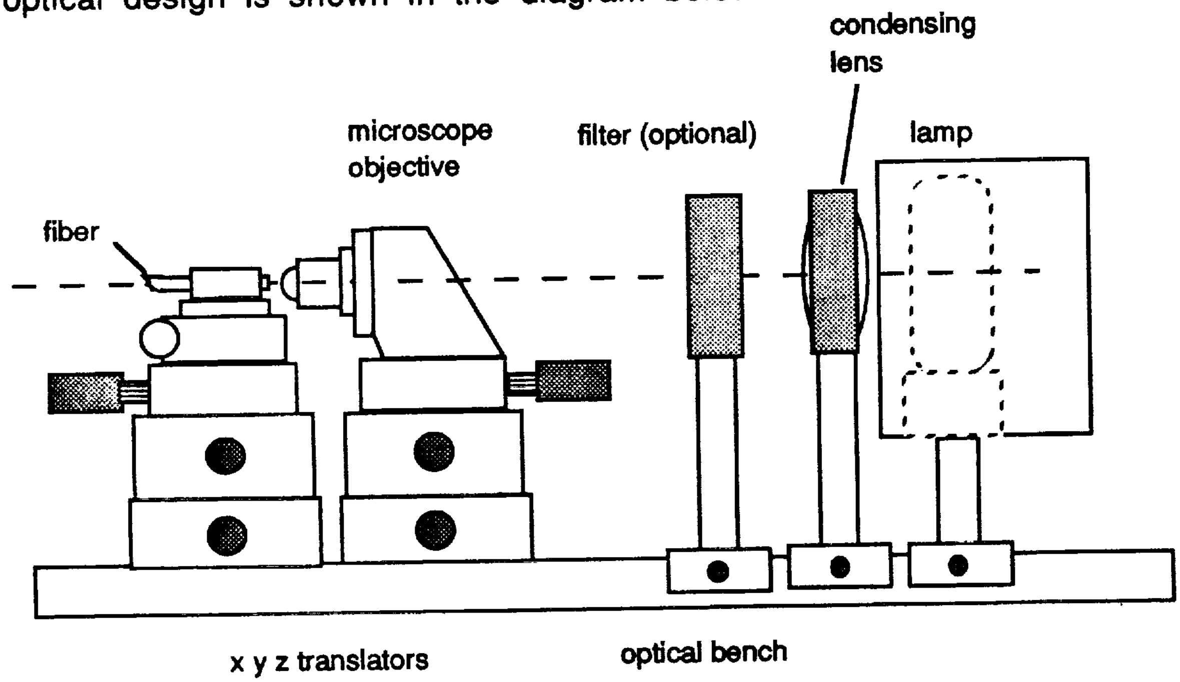

Figure 2-1. Concept Drawing of White Light Source (not to scale)

Experiments were conducted to determine the best microscope objective to use in the system. It was found that a x10 objective having a numerical aperture of 0.25 gave the best results. This closely matches the numerical aperture of the fiber which is 0.20 . The condenser lens was chosen from available stock to have the shortest focal length (2.5 cm) consistent with the physical dimensions of the lamp (GE BXT) and lamp holder. The lamp was rotated to a position so that the filament was oriented about 20 degrees with respect to the optic axis of the bench (looking down at a top view). This gave the most uniform optical field at the microscope objective and maximum power.

The total optical power coupled into the fiber was not only related to the design of the source but was critically related to the alignment of the optics with respect to the fiber. This alignment was accomplished with the x y z translators with the output fiber connected to an optical power meter before each series of tests. The power coupled into a 50 micron-core fiber was measured as a function of lamp power. An optical power of -16 dBm was coupled into the fiber with 10 volts on the lamp and optimum alignment of the system. This proved adequate for all experiments except crosstalk rejection experiments and allowed the lamp to be operated at a reduced voltage for extended life.

2.4 CALIBRATION CHECKS OF THE OPTICAL SPECTRUM ANALYZER

Before conducting spectroscopic experiments on fiber optic communications components, the spectral calibration of the optical spectrum analyzer was cross checked against available filters and a helium neon laser. In addition, saturation and repeatability tests were conducted.

2.4.1 CALIBRATIONS. The HeNe laser was coupled into the optical spectrum analyzer through a multimode fiber using a microscope objective. A high resolution spectrum was collected using the analyzer. This spectrum is shown below.

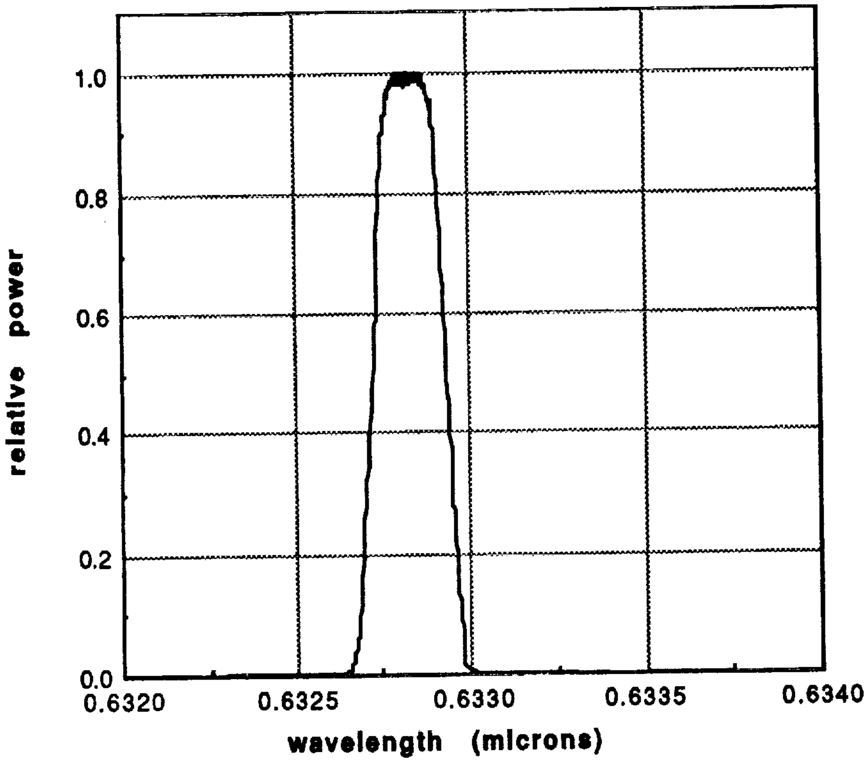

Figure 2-2 Peak Normalized Spectrum of HeNe Laser as Observed With OSA

It should be understood that the HeNe laser spectrum shown in this figure represents the OSA instrument response function and is not an accurate representation of the laser spectrum itself.

A selection of interference filters were inserted into the white light source and the peak of each transmission function measured and compared with the manufacturers values. The filter transmission function data and the HeNe spectral data were summarized and plotted. The graph verifying the spectral calibration of the OSA is shown in Figure 2.-3 below.

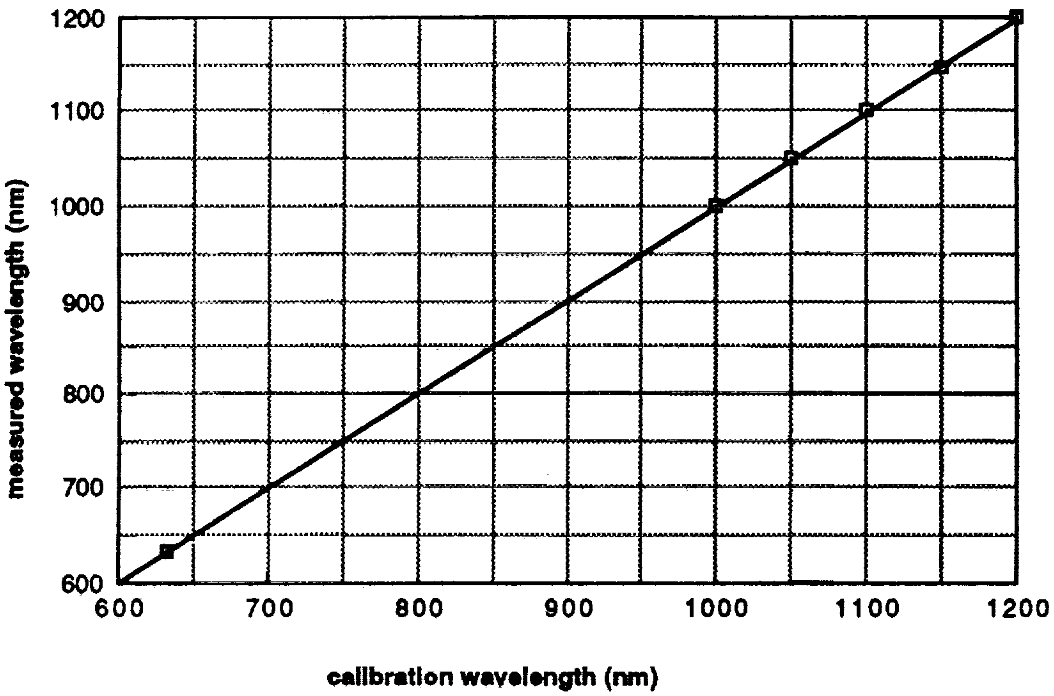

Figure 2-3 OSA Spectral Calibration Summary

2.4.2 OSA DYNAMIC RANGE STUDY. Experiments were conducted to determine the dynamic range of the optical spectrum analyzer operating together with the white light source. A series of spectra were collected each through an optical attenuator which is taken to be the standard. A three dimensional plot of the observed vs actual attenuation values over a range of wavelengths is shown below.

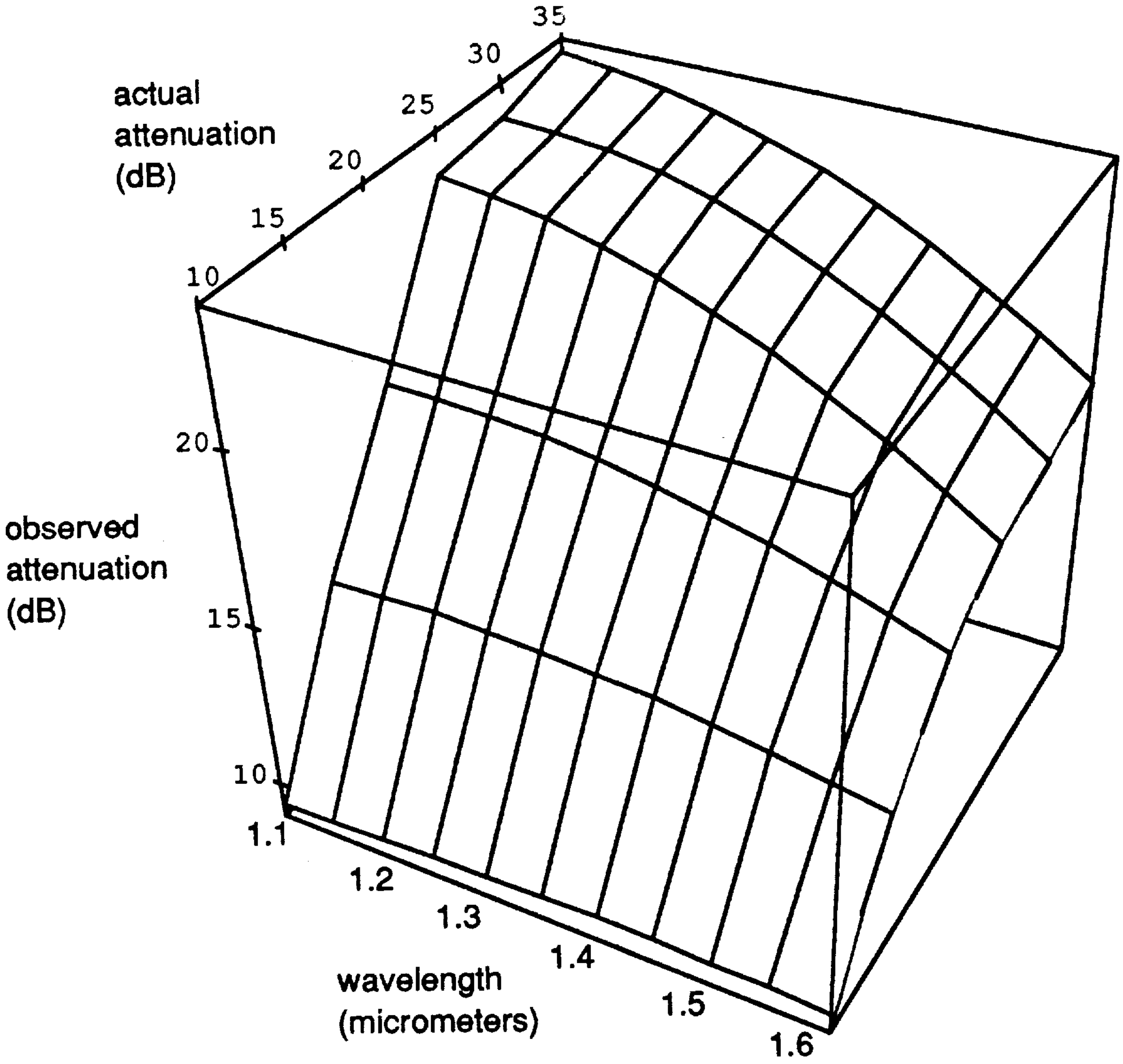

Figure 2-4 Dynamic Range of Optical Spectrum Analyzer White Light Source System

The dynamic range decreases as the system operates at longer wavelengths. Instead of an ideal linear plane, the surface droops as the noise floor is reached at each set of wavelengths plotted. As a result of these observations, no attempt was made to infer the degree of crosstalk in WDM systems using the OSA and white light source. Instead, a single data point was collected using each of the two sources of interest at 1.3 micrometers and 1.55 micrometers respectively.

III. Characterization of KSC Multimode Fiber

3.1 TYPICAL FIBER TEST LINK

The Fiber Optics Laboratory in the EDL building has a series of multimode fiber optic links to the CDSC building. See Figure 6-1 below for a diagram of a typical link. The spectral loss of pairs of these links was measured as a function of wavelength using the white light source and the OSA.

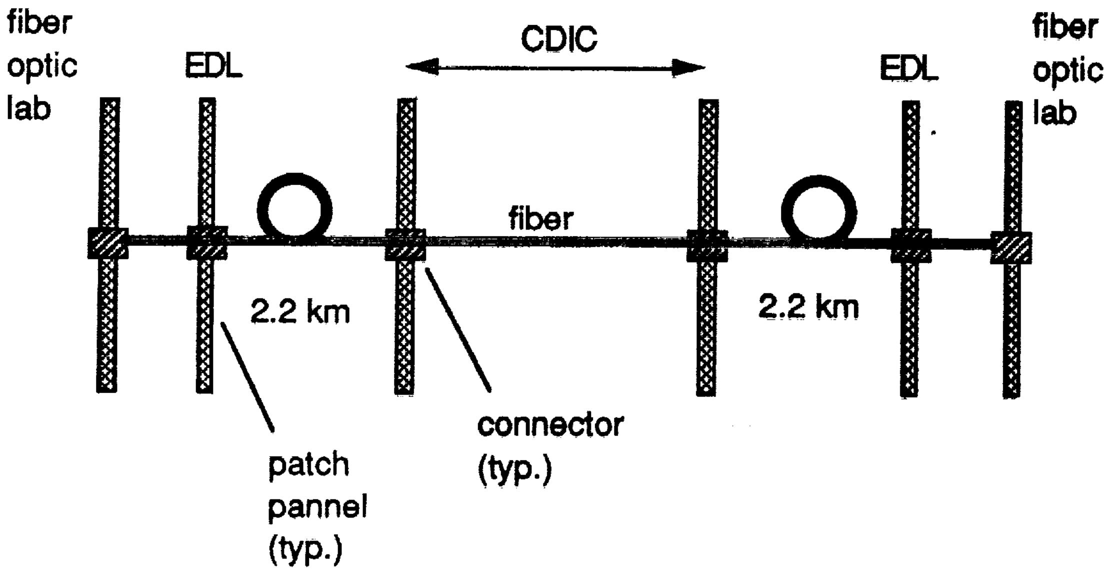

Figure 3-1 Typical Link from Fiber Optic Lab to CDIC and Back

3.2 SPECTROSCOPIC PROPERTIES OF FIBER LINKS IN THE EDL

Measurements were made without using a cladding mode stripper. A cladding mode stripper was constructed and tested. Link 11-12 was remeasured. A linearized loss function due to cladding mode effects was computed and added to the raw data. The resulting loss is plotted as a function of wavelength in a series of graphs that follow (Figures 3-2 through 3-7). The spectra are numbered with the connector numbers located on the patch panel in the Fiber Optic Lab. The average loss of all link pairs was computed and is plotted along with graphs of the average plus and minus one standard deviation in Figure 3-8.

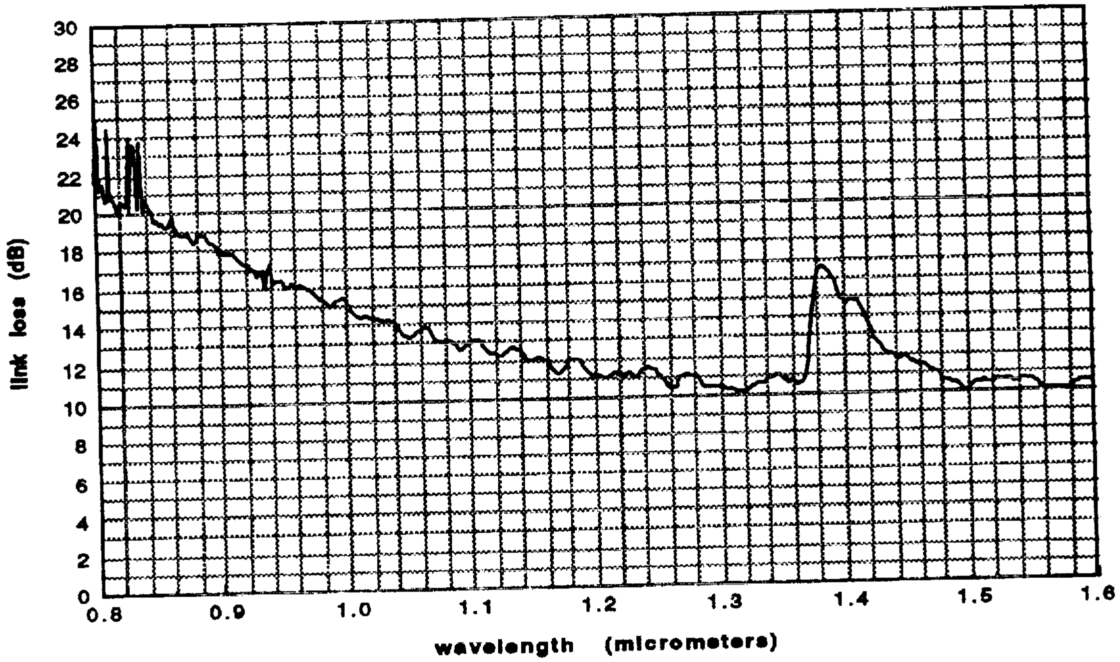

Figure 3-2 Loss in laboratory fiber link 1-2

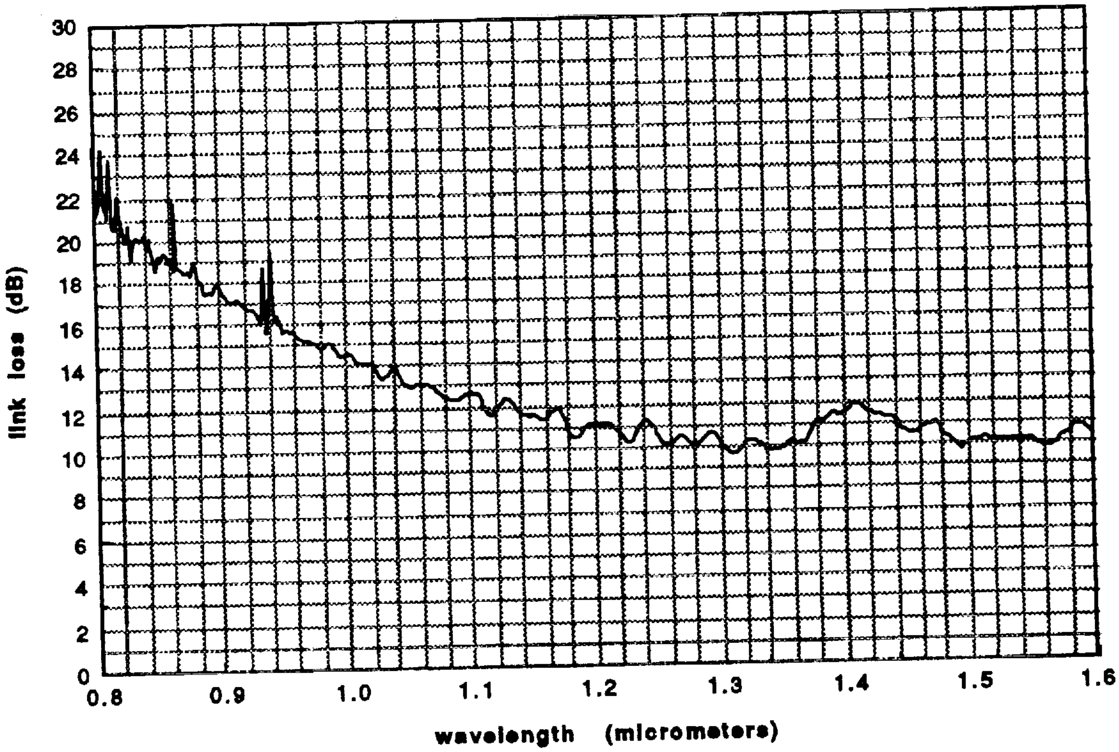

Figure 3-3 Loss in laboratory fiber link 3-4

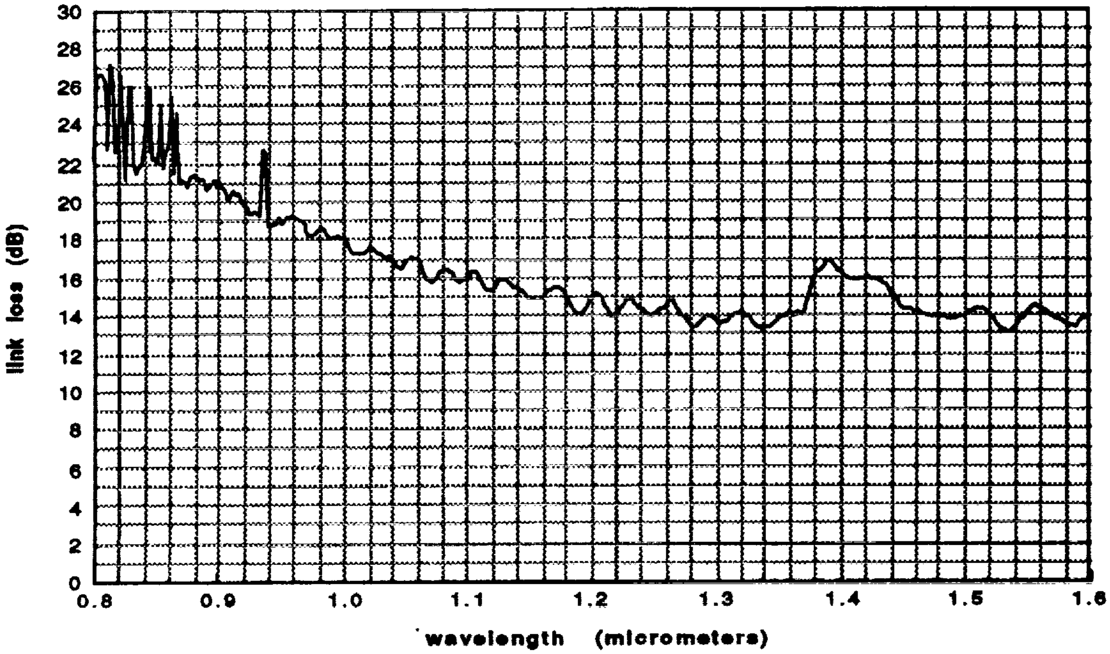

Figure 3-4 Loss in laboratory fiber link 5-6

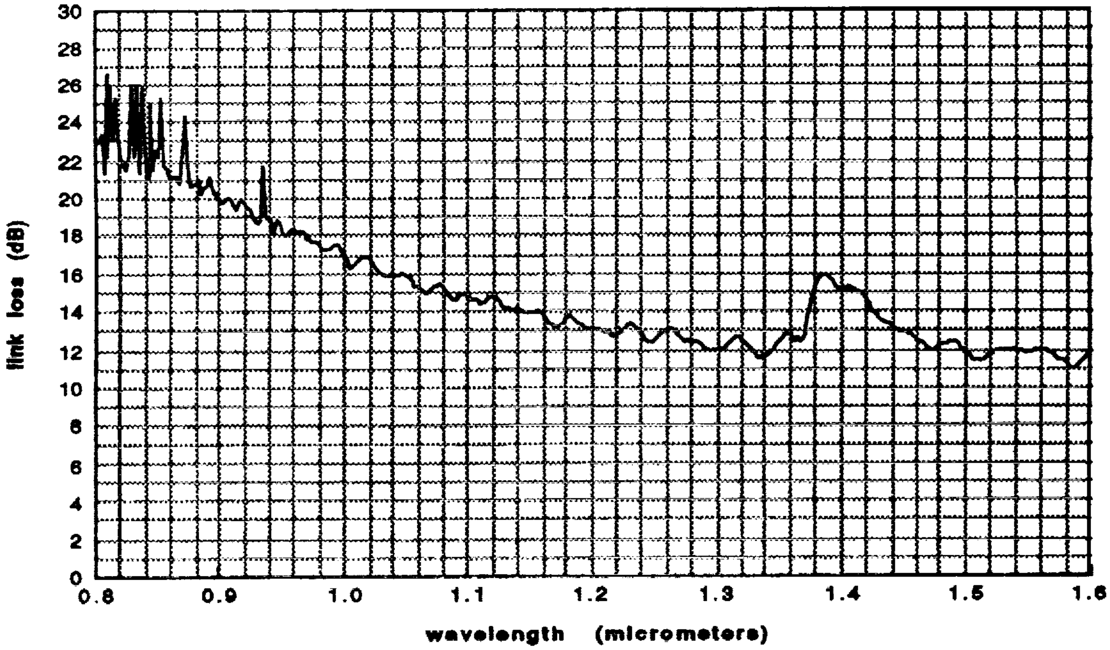

Figure 3-5 Loss in laboratory fiber link 7-8

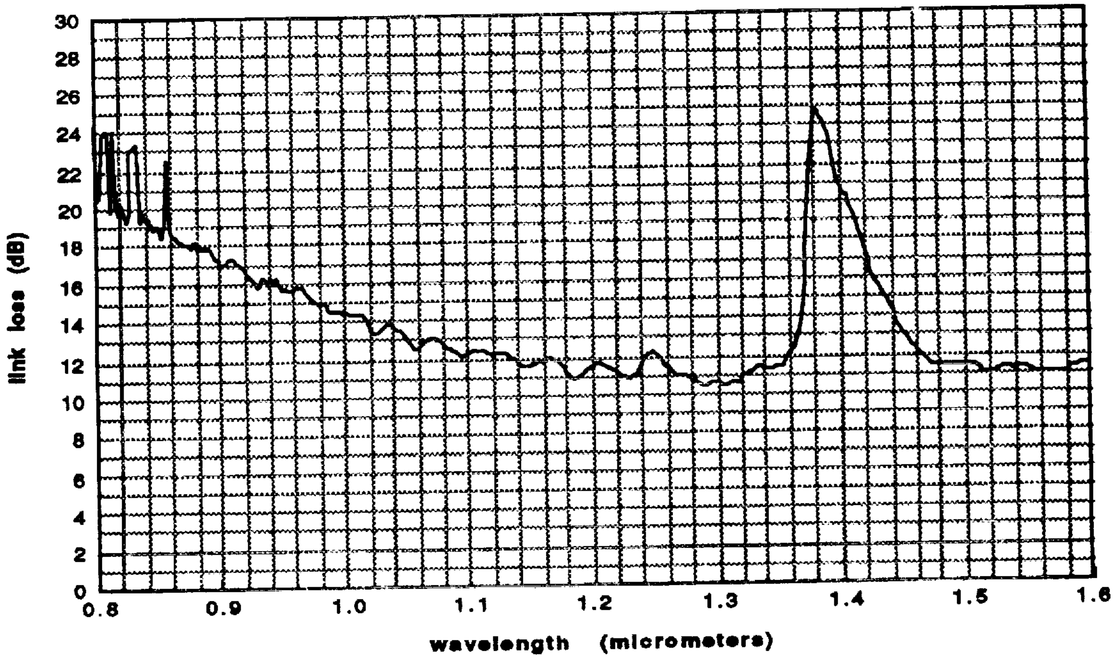

Figure 3-6 Loss in laboratory fiber link 9-10

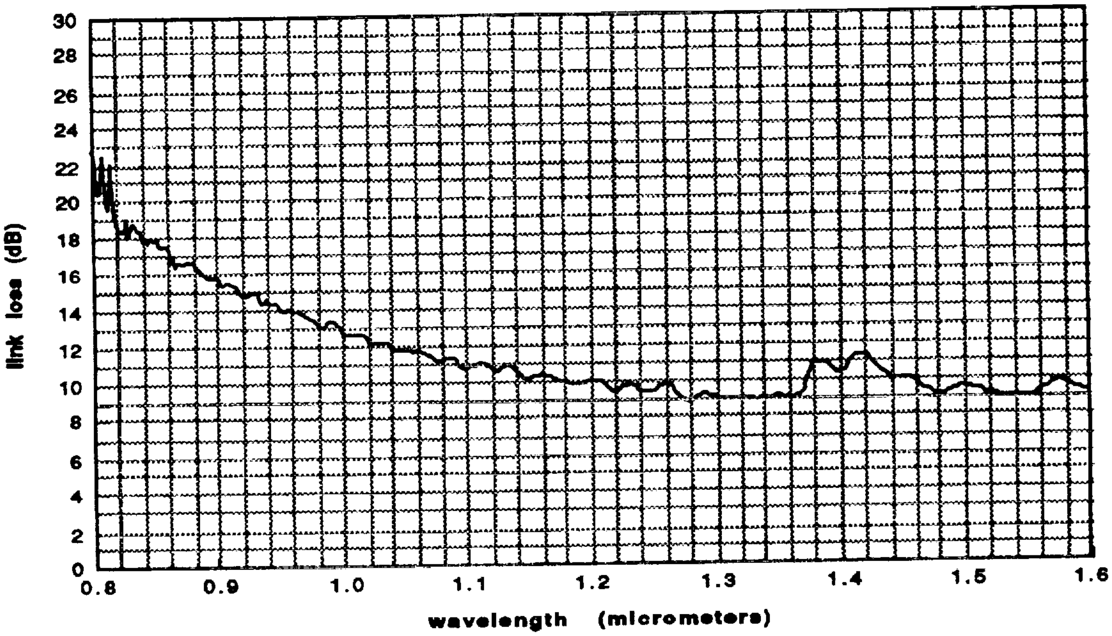

Figure 3-7 Loss in laboratory fiber link 11-12

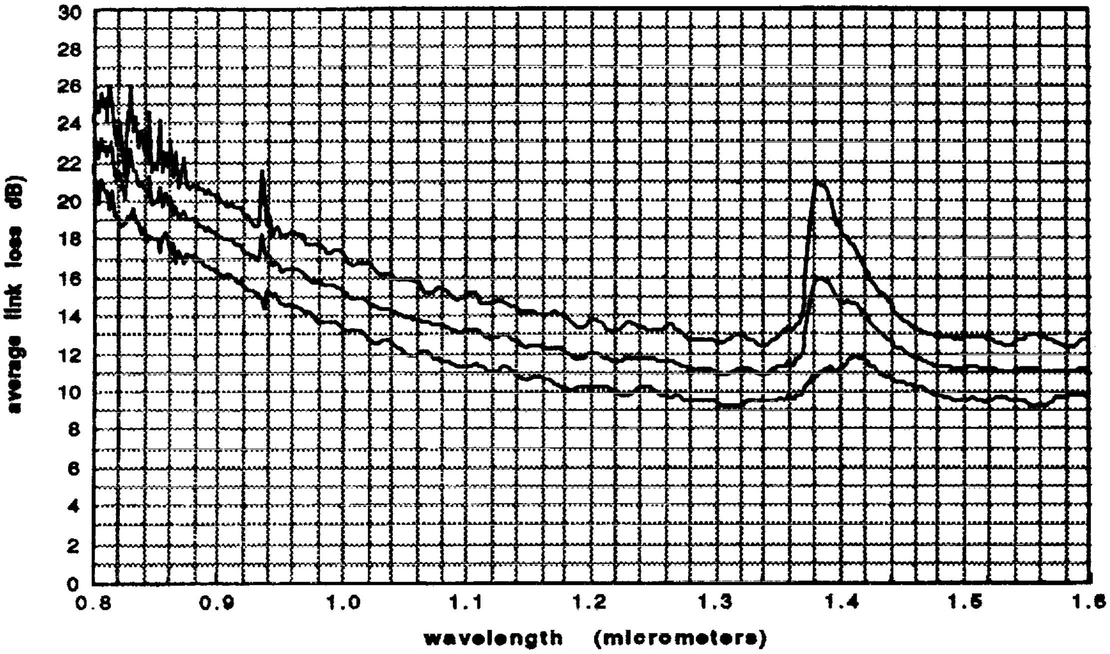

Figure 3-8 Average loss in laboratory fiber links +/- one standard deviation

IV. CHARACTERIZATION OF KSC LEDS AND LASERS

4.1 SPECTROSCOPIC MEASUREMENTS

The OSA was used to collect a selection of spectra of LEDs and laser transmitters. Results of these experimental runs are shown below in Figures 4-1 to 4-3.

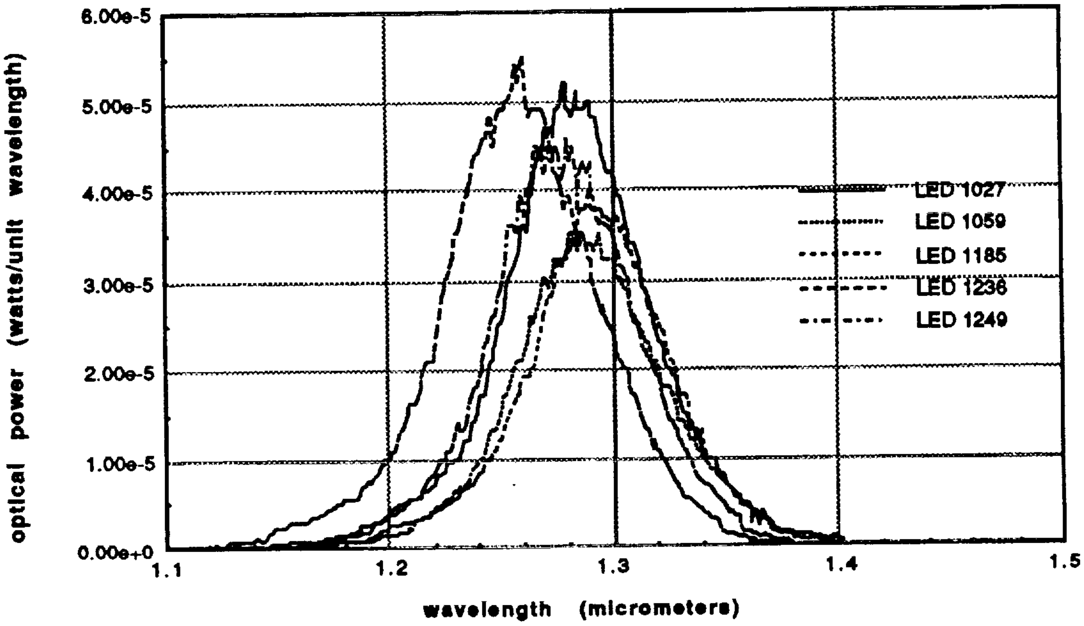

Figure 4-1 Selection of LED Spectra

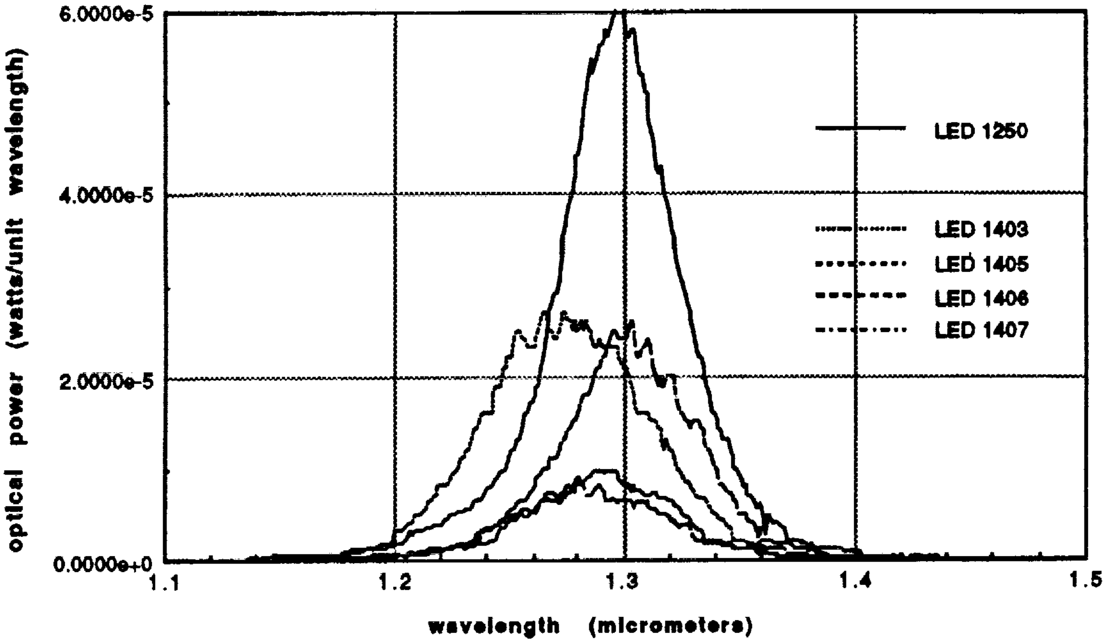

Figure 4-2 Selection of LED Spectra

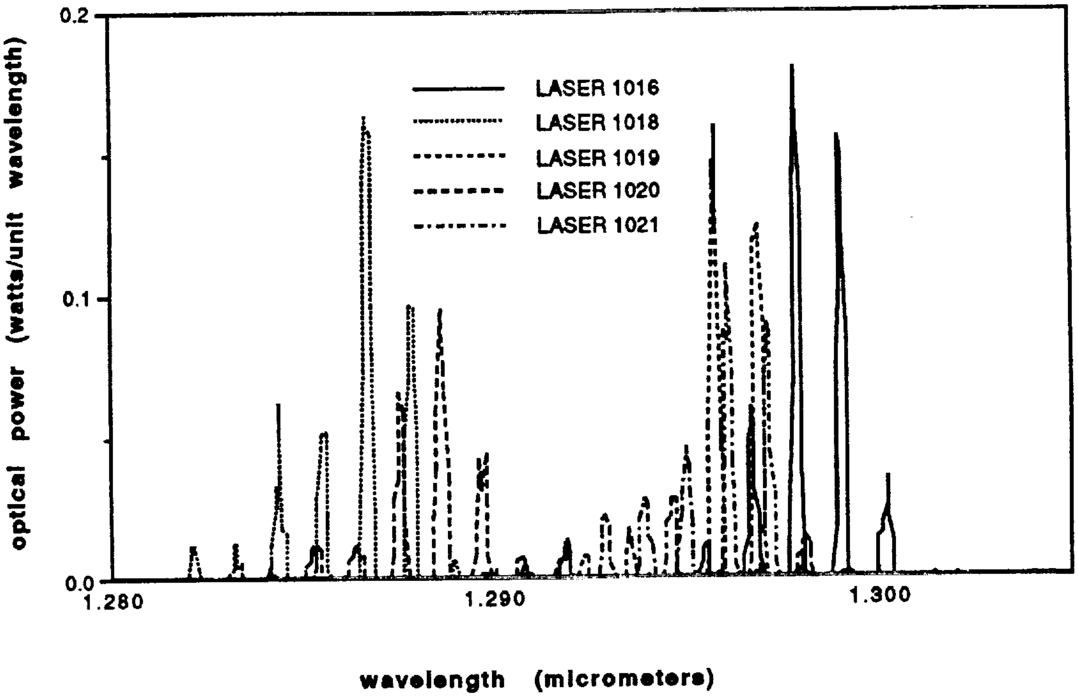

Figure 4-3 Selection of Laser Spectra

It can be seen that each different laser is characterized by a series of simultaneously radiated longitudinal modes. Furthermore, a collection of transmitter modules oscillate at a number of different center wavelengths. This suggests that an experiment to test the ultimate channel density could be performed by carefully selecting pairs of transmitters having specific different wavelength spacings and using these to establish the minimum acceptable channel spacing.

V. CHARACTERIZATION OF A SELECTION OF WDMS

5.1 EXPERIMENTS PERFORMED TO CHARACTERIZE WDMS

Several experiments were performed to characterize the properties of each WDM. The Spectral transmission function of each WDM was measured using the white light source and OSA between each pair of input and output ports. In order to keep the channels consistent between devices, a common numbering system was adopted. Port 1 is designated the common port, port 2 is the 1300 nm input or output port and port 3 is the 1550 nm input or output port. In addition, the insertion loss and crosstalk was measured for each device using a laser source at 1550 nm, a stabilized LED source at 1300 nm and an optical power meter.

5.2 INSERTION LOSS AND CROSSTALK MEASUREMENTS AT SINGLE WAVELENGTHS

These measurements were conducted using a light source, a mode scrambler/cladding mode stripper, the device under study and an optical power meter (Ando AQ 1135E). The input level at the power meter was standardized to 0 dB with the output of the cladding mode stripper directly connected to the meter. The the WDM was inserted in the path and a reading of the loss obtained between the specific pair of ports selected.

Table 5-1 Single Wavelength Insertion Loss and Crosstalk Tests

WDM Tested	Ports (in-out)	1300 nm loss (dB)	1550 nm loss (dB)
Corning M0200061 (1)	1 - 2	4.52	43.4
	1 - 3	33.6	1.48
	2 - 1	4.32	43.5
	3 - 1	34.3	1.87
Corning M0200061 (2)	1 - 2	2.42	43.7
	1 - 3	33.5	4.71
	2 - 1	2.44	40.6
	3 - 1	33.4	4.16
JDS WD13115UC-50 (1)	1 - 2	1.19	43.5
	1 - 3	32.7	0.65
	2 - 1	1.21	43.8
	3 - 1	32.6	0.73
JDS WD13115UC-50 (2)	1 - 2	0.88	43.7
	1 - 3	32.7	0.56
	2 - 1	0.99	43.9
	3 - 1	32.8	0.64
ASTER MWM 12-25-BR (1)	1 - 2	1.90	42.0
	1 - 3	38.2	1.06
	2 - 1	1.68	41.9
	3 - 1	38.1	1.18
ASTER MWM 12-25-BR (2)	1 - 2	2.13	42.2
	1 - 3	38.5	1.39
	2 - 1	2.61	42.4
	3 - 1	39.1	1.59
ALCATEL 7299-C-1 (1)	1 - 2	2.55	42.9
	1 - 3	39.3	1.41
	2 - 1	2.50	42.8
	3 - 1	39.7	1.41
ALCATEL 7299-C-1 (2)	1 - 2	2.23	42.7
	1 - 3	40.0	1.69
	2 - 1	2.06	43.1
	3 - 1	39.1	1.9

In each WDM tested the loss between 2 and 3 and 3 and 2 were measured as well. The result was always greater than 50 dB.

5.2 SPECTRAL TRANSMISSION FUNCTIONS OF WDMS

These measurements were conducted using the white light source, a mode scrambler/cladding mode stripper, the device under study and the OSA. The input level was standardized by collecting a spectrum with the output of the cladding mode stripper directly connected to the OSA. This was stored in memory 1 of the OSA. The the WDM was inserted in the path and a second spectrum was obtained between the specific pair of ports selected. This was stored in memory 2. The OSA control stack was then activated to collect the spectra in a computer data file. A hard copy was also made from the OSA. The following is two samples of the spectra obtained, one of the best WDM systems studied and one having the least transmission. For lack of space, not every spectrum collected is included in this report.

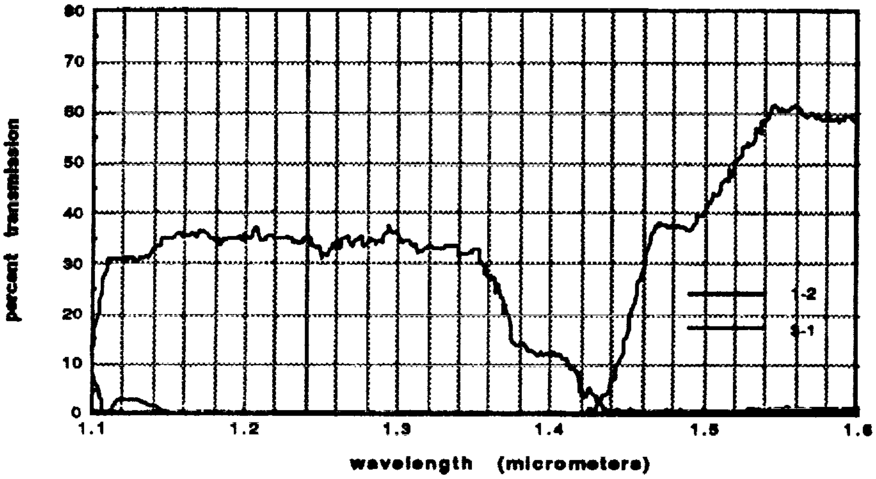

Figure 5-1 Transmission Spectrum of the Corning #1 WDM

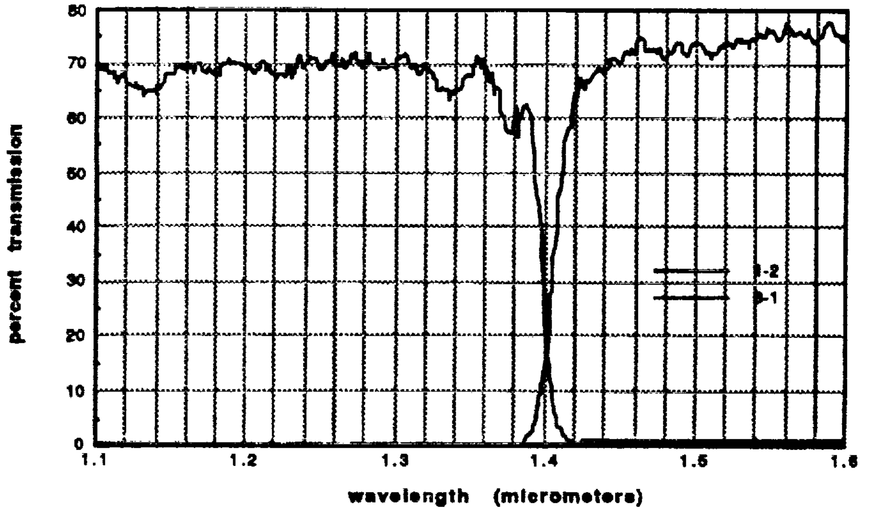

Figure 5-2 Transmission Spectrum of the Aster #1 WDM

VI. THE SIMULTANEOUS TRANSMISSION OF DIGITAL AND VIDEO DATA

6.1 THE SYSTEM TEST

The ultimate test of the two channel WDM concept at KSC was the system test. A complete WDM two channel system was constructed and used to transmit separate signals on a single fiber. The Aster WDM was selected as the best candidate based on tests described in the previous section was used in all of these tests.

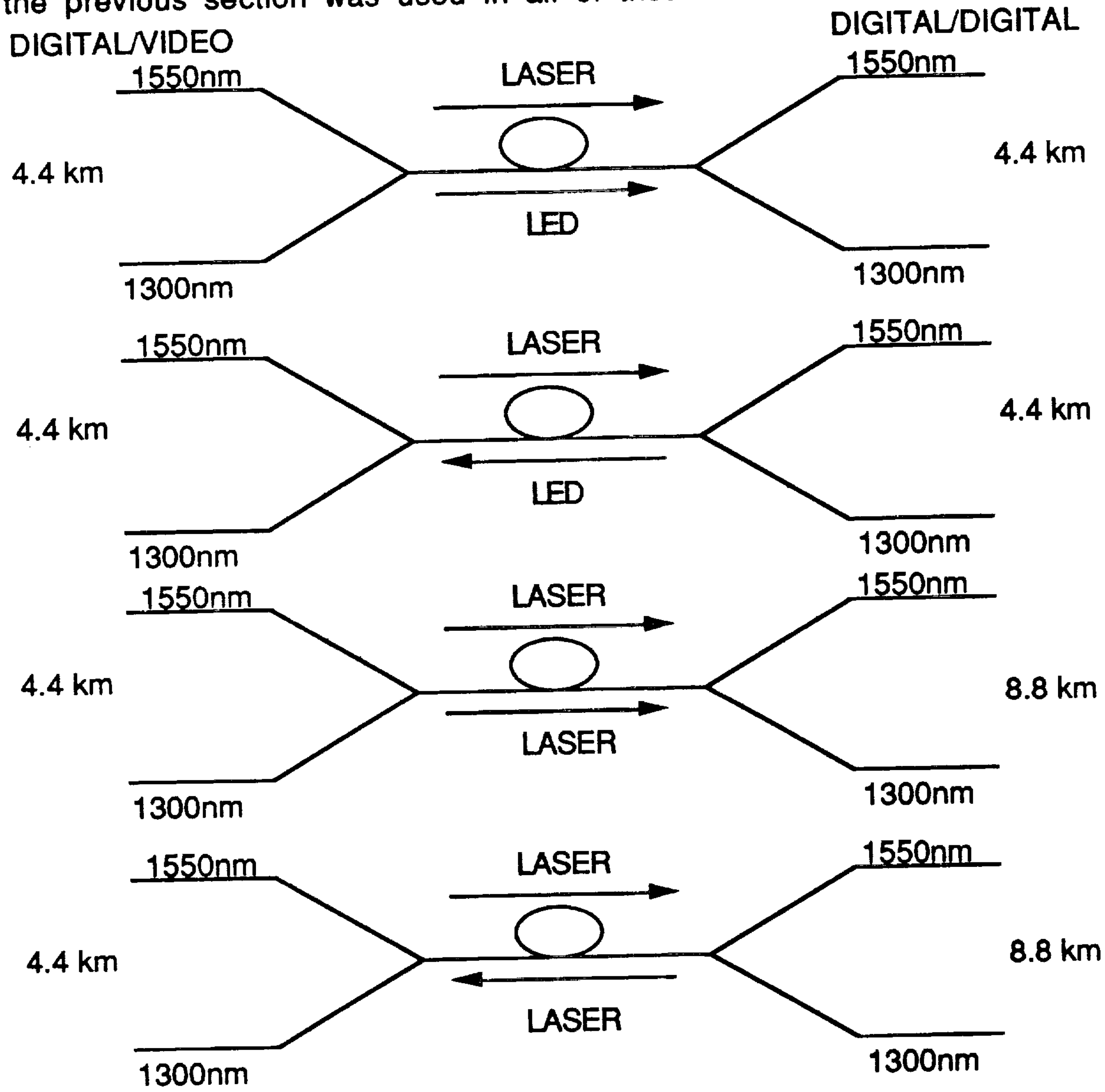

Figure 6-1 WDM System Configurations Tested

A two channel WDM communication system was constructed using these multiplexer/demultiplexer combinations and subjected to rigorous testing in many different configurations. Figure 6-1 shows the different configurations tested. The two vertices in each configuration diagram represent the WDMs. The 4.4 km link is the length of fiber used in a configuration similar to the fiber link described in Figure 3-1 In all cases The 1550 nm source used was a 1550 nm ECL driven laser diode. The 1300 nm channels were lasers or LEDs. neither LEDs nor video signals could be propagated over greater than 4.4 km. Digital signals generated with laser transmitters could be propagated over 8.8 km.

6.2 VIDEO TESTS

Each system configuration was tested with a 1300 nm video signal copropagated with a 1550 nm digital signal. The video signal was checked against the RS 250B short haul standards by transmitting a test pattern using a video generator and analyzing the resulting signal at the receiver end of the link using a Tektronix VM700 test set. The block diagram of a typical test set is shown in Figure 6-2 below.

In all tests, the video channel showed no sensitivity to the presence of the digital data occupying the other wavelength channel. The frequency of the digital data was varied from 1 to 59 MHz. If the video channel could be setup to operate without the 1550 nm channel, It would operate with the potentially interfering signal. Furthermore, the digital data (in the form of a random bit pattern) showed no degradation due to the simultaneous presence of the video signal. Table 6-1 below lists the video parameters checked in these tests.

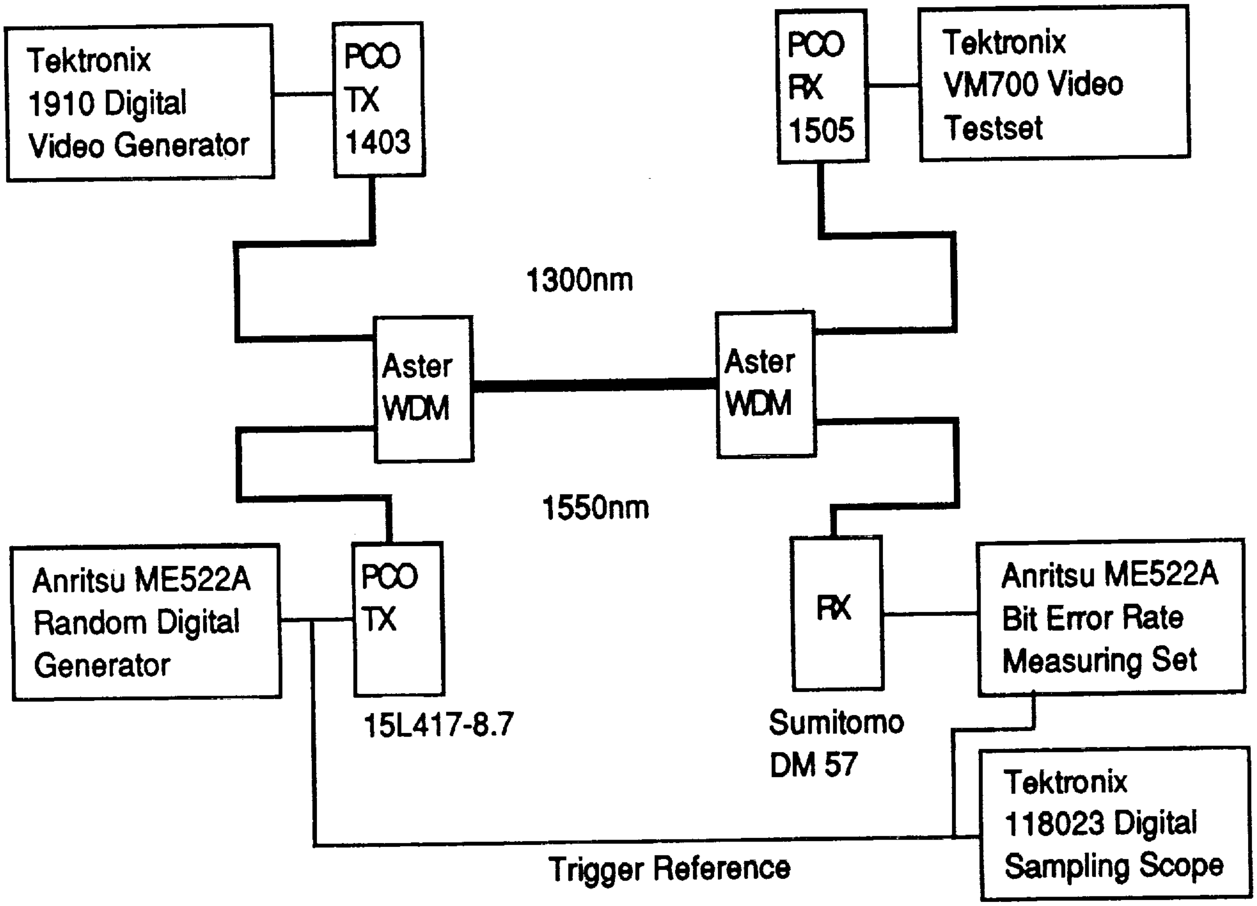

Figure 6-2 Block Diagram of Video/Digital Test Setup

Table 6-1 RS 250B Parameters Checked in System Tests

Avg. Picture Level	51.3 %	S/N Unweighted	58.7 dB
Bar Amplitude	100.6 IRE	S/N Lum-Weighted	68.1 dB
Sync Amplitude (Bar)	40.4 %	S/N Periodic	53.1 dB
Burst Amplitude (Sync)	100.2 %		
		Chroma-Lum Delay	4.1 ns
Sync Risetime	142 ns	Chroma-Lum Gain	100.6 %
Sync Falltime	145 ns		
		Differential Gain	1.98 %
VIRS Chroma Ampl	97.6 %	Differential Phase	0.66 Deg
VIRS Chroma Ampl	39.4 %	Lum Non-Linearity	0.77 %
VIRS Chroma Phase	-0.8 °		
		Relative Burst Gain	-0.06 %
Line Time Distortion	0.4 %	Relative Burst Phase	-0.10 Deg
Pulse/Bar Ratio	97.6 %		
2T Pulse K-Factor	0.3 % Kf		

6.2 DATA/DATA TESTS

Digital data was propagated in all possible combinations along the optical link. One channel would be setup to transmit a random bit pattern and the other would be setup to transmit a clock at the same fundamental frequency. The clock signal along the 1550 nm channel was also be set to the FM signal frequency of the 1300 nm PCO equipment. A bit error rate of better than 1 x 10^{-9} was maintained over links as long as 8.8 km with no descernible cross-channel interference.

6.3 CROSSTALK SENSITIVITY TESTS

Since no channel failure could be induced in the WDM system tests, it was decided to conduct crosstalk sensitivity tests by feeding both 1300 nm video and 1550 nm interfering light into a PCO receiver. The test setup used is shown below in Figure 6-3.

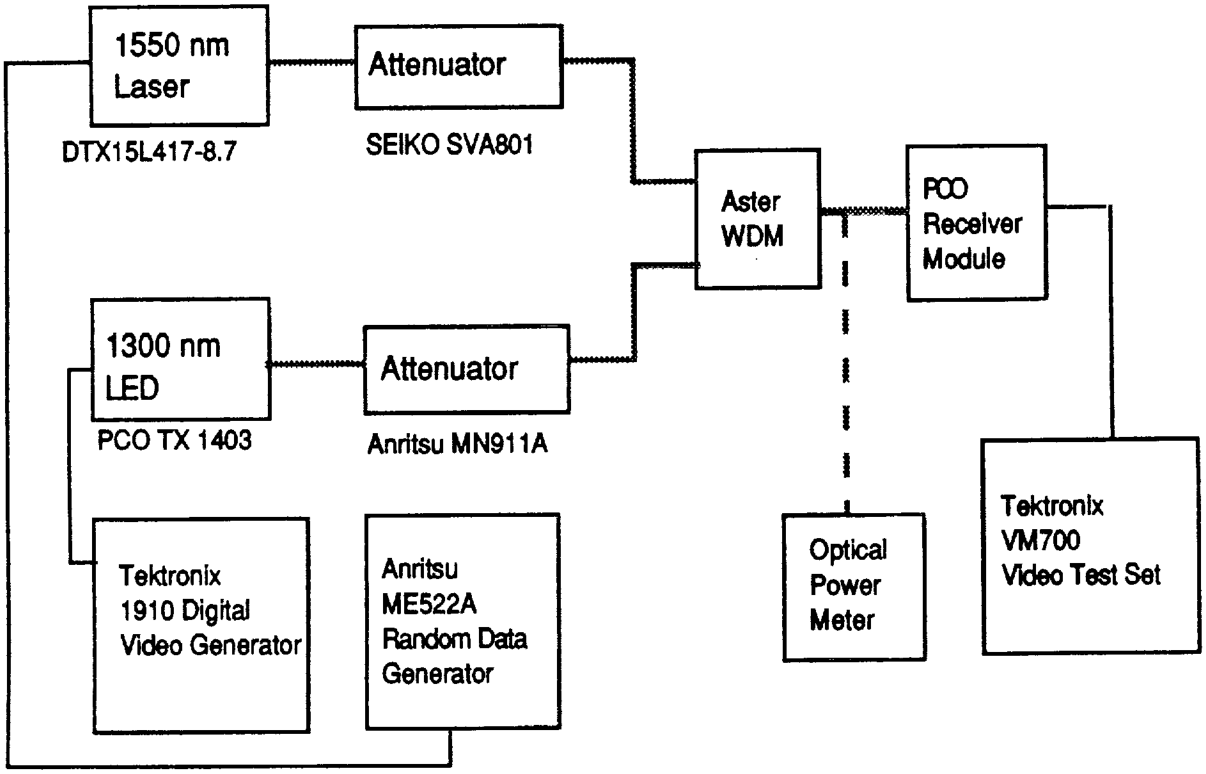

Figure 6-3 Crosstalk Sensitivity Test Setup

The general procedure used in these test was to first calibrate the attenuators. One source at a time was applied to the system. The corresponding attenuator was systematically set to a series of settings and the optical power observed with the power meter. In this way the amount of power at the receiver could be determined by the attenuator setting. Then the interfering source was reduced to negligible level using its attenuator. The video signal was attenuated to the point where it would just meet the RS 250B specifications. The 1550 nm source was then increased in intensity by reducing its attenuator level until the video signal failed the specifications. This combination of attenuator settings was then recorded and the 1300 nm level increased a measured amount until the system passed the test. Again, the interfering light would be increased in intensity until the system failed the attenuator settings would again be recorded...etc. This process was repeated over a wide range of signal levels. The results are shown in the graph below in Figure 6-4. In all cases the observed failure mode was reduction in the periodic signal to noise ratio.

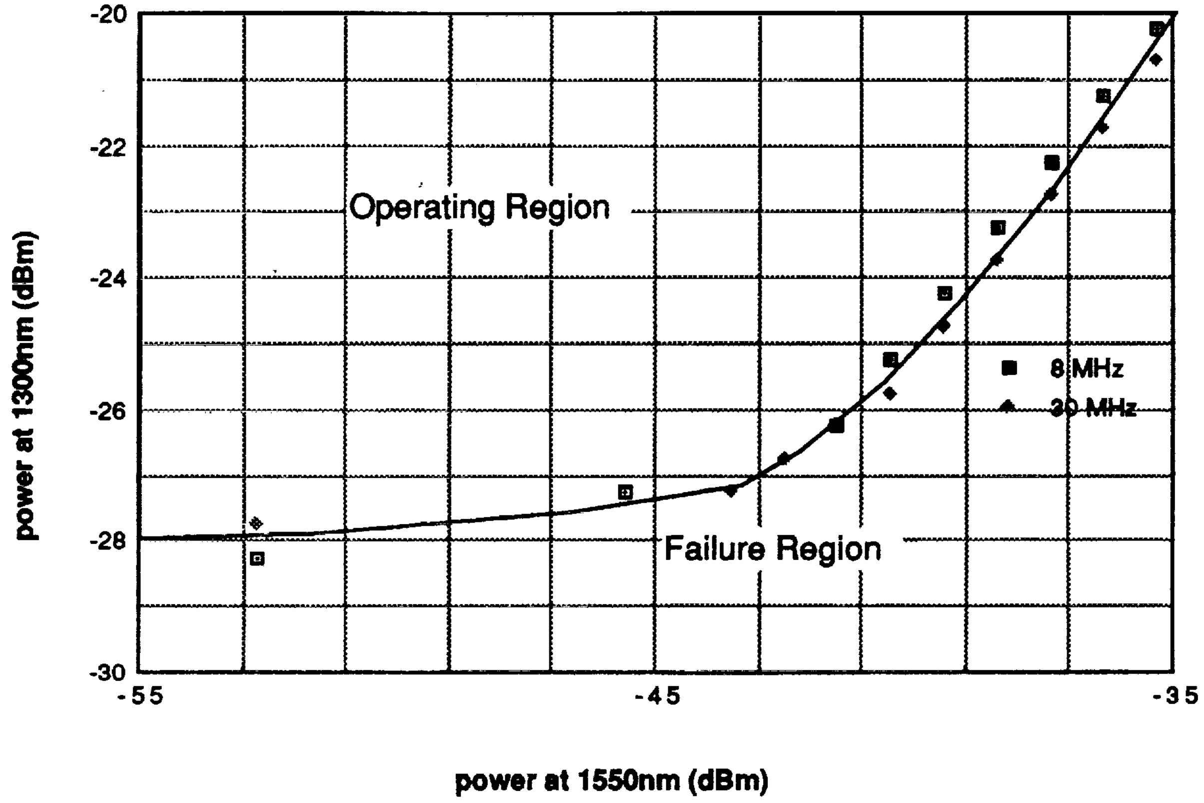

Figure 6-4 WDM Operating Envelope for Video Propagation at 1330 nm

This data will enable the system designer to determine the proper operating parameters or set specifications and safety factors of a 1550 nm/1300 nm WDM system given information about crosstalk, insertion loss, link loss and transmitter spectral power densities.

VII. CONCLUSIONS

The main goals of the research project were met. WDM systems were characterized and a test system constructed using the best WDM devices available to demonstrate the principle. In addition, a considerable amount of data was collected characterizing the spectra of laser and LED transmitter sources, the loss spectra of fiber optic links and crosstalk sensitivity of a typical receiver. This data when taken together can assist the system designer in specifying future systems. By identifying the failure mode for crosstalk in the case of video propagation, this research should also benefit the end user of such systems.

Further work could be done to more completely characterize the nature of the fiber links at KSC and to characterize the transmitters and receivers in the plant. only 10 LED and 10 LID transmitters were measured. In addition the system limits due to fiber nonlinearity could be probed to establish the ultimate transmission distance. The ultimate spectral density of the system using multimode and single mode fiber could be studied as well and a computer system model developed.

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