

# Final Report

**Title of Project:** Infrared Avionics Signal Distribution Using WDM

**PI** Prof. Mohammed Atiquzzaman  
School of Computer Science  
University of Oklahoma, Norman, OK 73019  
Tel:(405) 325 8077, Fax: (405) 325 4044  
Email: [atig@ou.edu](mailto:atig@ou.edu), [atig@ieee.org](mailto:atig@ieee.org)

**Co-PI:** Prof. James J. Sluss, Jr.  
School of Electrical & Computer Engineering  
University of Oklahoma, Tulsa, OK 74135  
Tel: (918) 660 3254, Fax: (918) 660 3238  
Email: [sluss@ou.edu](mailto:sluss@ou.edu)

**Graduate Assistant:** Hakki H. Refai

**Organization:** University of Oklahoma

**Date of Submission:** September 12, 2004

**Submitted to:** NASA Glenn Research Center,  
Attn: Dr. Duc H. Ngo  
21000 Brookpark Road-Room 34/Bldg.54  
Cleveland, OH 44135

**Program of Funding:** Cooperative Research Agreement

**Grant Number:** NCC3-1069

## ABSTRACT

Supporting analog RF signal transmission over optical fibers, this project demonstrates a successful application of wavelength division multiplexing (WDM) to the avionics environment. We characterize the simultaneous transmission of four RF signals (channels) over a single optical fiber. At different points along a fiber optic backbone, these four analog channels are sequentially multiplexed and demultiplexed to more closely emulate the conditions in existing onboard aircraft. We present data from measurements of optical power, transmission response (loss and gain), reflection response, group delay that defines phase distortion, signal-to-noise ratio (SNR), and dynamic range that defines nonlinear distortion. The data indicate that WDM is very suitable for avionics applications.

## 1. INTRODUCTION

Optical fiber provides many advantages over coaxial cable for the transmission of RF signals onboard aircraft. Optical fiber exhibits considerably less loss, can support signals that need much higher bandwidth, is immune to electromagnetic interference (EMI), and requires significantly smaller size and weight when compared to coaxial cable. Recently, the existence of the Internet in commercial aircraft adds increased goals to ambitions of delivering new information services during flight [1]. Implementing Voice-over-IP (VoIP), high-definition television (HDTV), and radio frequency (RF) signals for transport of cellular signals, onboard commercial aircraft, as shown in Figure 1, ignite the force behind investigations into the use of fiber optic WDM technology to provide the high bandwidth communications backbone needed onboard. WDM is a technique that supports the combination and transmission of multiple signals with different modulation formats and bandwidths over a single optical fiber. Traditionally, WDM has been utilized by the telecommunications industry to increase the capacity of the optical fibers carrying digital information. In this project, a WDM network supporting four analog RF channels multiplexed and demultiplexed at different points of a single fiber has been demonstrated as a successful application that fulfills the requirements of the avionics environment.

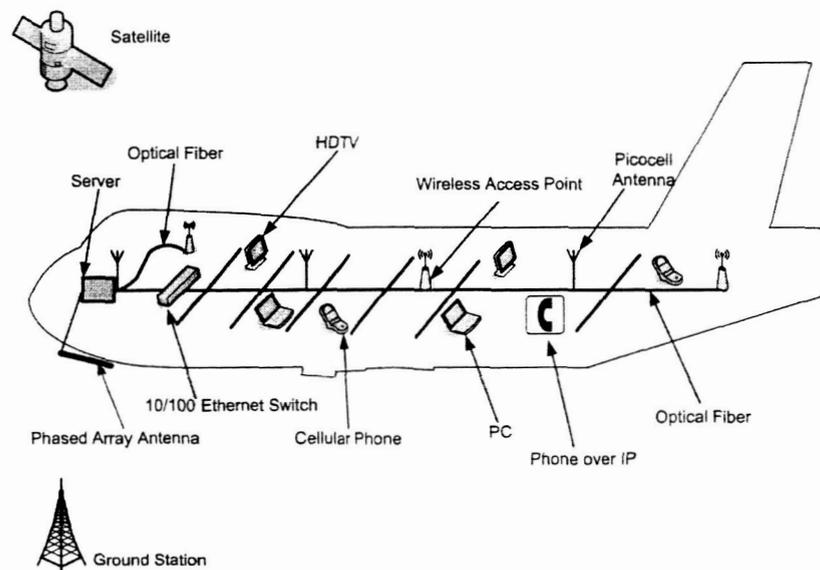


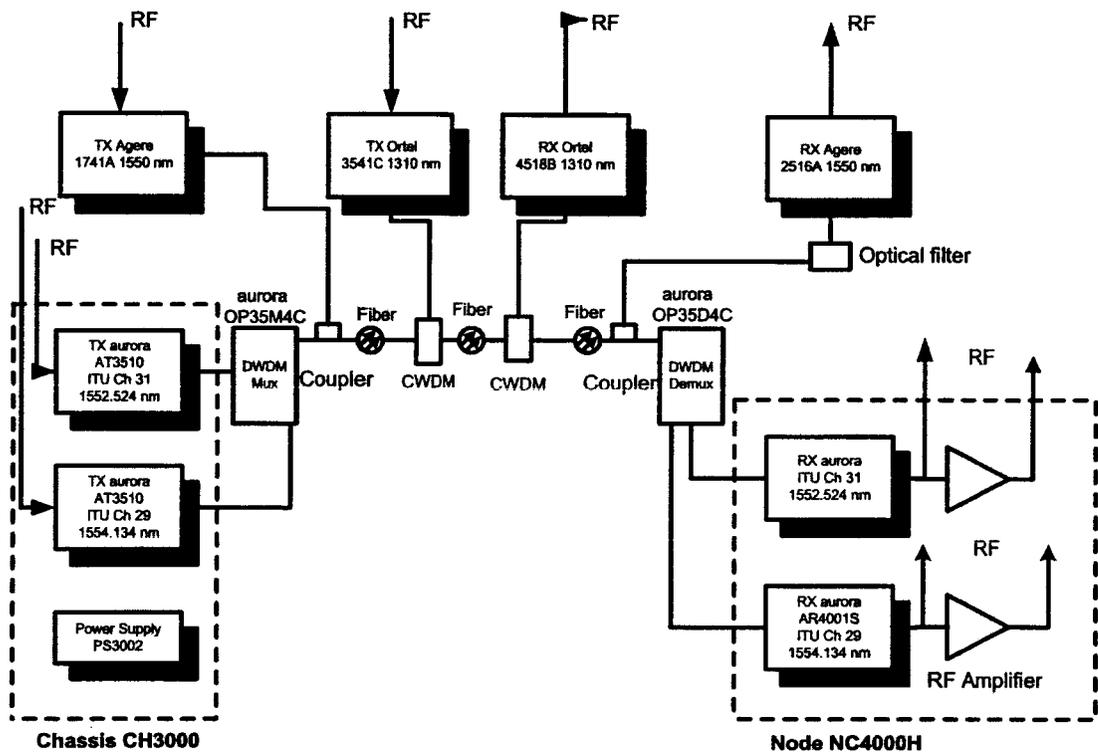
Figure 1. Prospective services onboard of a commercial aircraft in the near future.

The objective of this project is to experimentally characterize four end-to-end communication channels established using modulated analog RF signals transmitted over single fiber using a WDM network.

The rest of this report is organized as follows. Section 3 describes our experimental setup to transmit four channels of RF modulated signals over a WDM network. We report the experimental results from our experiment in the Section 4, which includes measurements of optical power, transmission response, reflection response, group delay, signal-to-noise ratio (SNR), and dynamic range for the transmission of four channels with different wavelengths over the WDM network. Concluding remarks are given in Section 5.

## 2. EXPERIMENTAL SETUP

Figure 2 illustrates the experimental setup for all experiments and measurements that are explained in Section 4. Four wavelengths were used to demonstrate this avionics application: 1552.524 nm, 1554.134 nm, 1550 nm, and 1310 nm, named Ch31, Ch29, Ch1550, and Ch1310, respectively.



**Figure 2. WDM network provides four analog communication channels**

To investigate the characteristics of Ch29, an Aurora AT3510 analog laser transmitter, with an ITU grid compliant output wavelength of 1552.524 nm, was connected using optical fiber to an Aurora OP35M4C multiplexer which was connected to an Aurora OP31M2D optical combiner that multiplexes 1310 nm and 1550 nm wavelengths.

The multiplexer and combiner were connected by 20 m of optical fiber. The combiner and the Aurora OP31D2D optical splitter were connected by 3 m of optical fiber. The 1310/1550 splitter and the OP35D4C demultiplexer were connected by 20 m of optical fiber.

Finally, an Aurora AR4001S receiver converted the received optical signal into an RF signal that traveled through an Aurora OA4444T-42 RF amplifier linked to the receiver output to provide RF signal gain. The RF frequency range of operation of the Aurora transmitter and receiver is 46 MHz to 870 MHz. Similarly, as shown in Figure 1, the signal of Ch31 passes the same path as that of Ch29.

Ch1310 was coupled using an Aurora combiner to several meters of optical fiber and exited the network through an Aurora splitter. Ch1510 was coupled using a 50/50 coupler to tens of meters and left the main backbone via another 50/50 coupler and tunable bandpass fiber optic filter.

The total length of fiber traversed by the four channels, Ch29, Ch31, Ch1310, and Ch1550, were 47 m, 47 m, 9 m, and 41 m, respectively. These communication channel distances were chosen as they represented typical backbone lengths that would be expected onboard aircraft.

### 3. EXPERIMENTAL RESULTS

In this section, we report results obtained from our experimental setup described in the previous section. The results include optical power measurements, transmission response measurements, reflection response measurements, group delay measurements, signal-to-noise ratio (SNR) measurements, and dynamic range measurements. These measurements completely characterize the transmission of four communication channels using four different wavelengths over a single optical fiber.

Two ITU Optical transmitters and two wideband Optical transmitters are used to transmit the RF channels, as shown in Figure 3.

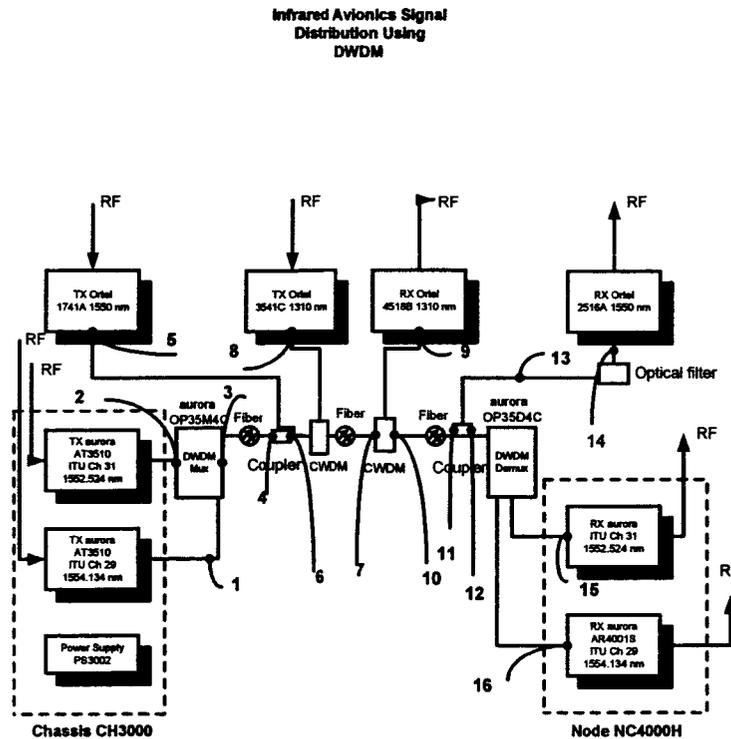


Figure 3 - The configuration for distributing four RF channels over fiber optic cables in an experimental WDM system. An Optical Spectrum Analyzer was connected at major test points (numbered from 1-16) to measure the optical channel location and power.

## A. Optical Power Measurements and Analysis

The outputs from the optical spectrum analyzer at the test points shown in Figure 3 are presented in Figures 4 - 19. Each output has a plot and a table: The value shown on the horizontal axis of the plot is the wavelength (or frequency) for the optical signal, and the value in the vertical axis is the power (dBm) of the wavelength component.

### A.1. ITU Ch 29 Transmitter (Test point 1)

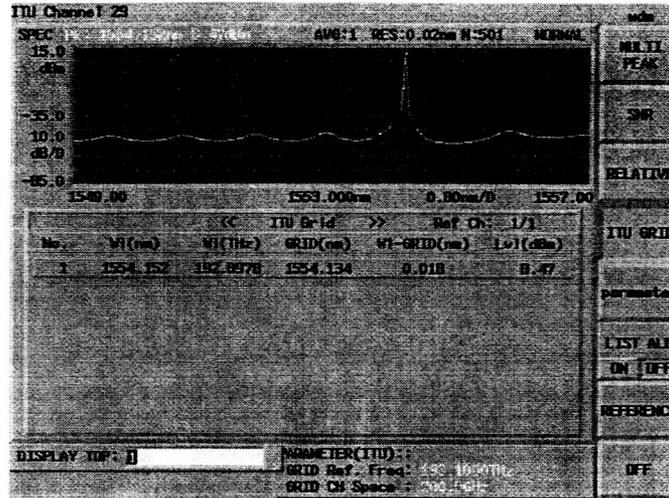


Figure 4 Test point 1

The optical output of ITU Ch 29 Transmitter is shown in Figure 4. The wavelength, peak power value, and frequency were measured and found to be 1554.152 nm, 8.47 dBm, and 192.8978 THz, respectively. These values are shown in the table of Figure 4. The measurements are to demonstrate the validation of the optical channel, i.e., we can see that the optical power budget (difference between the transmitter output power and receiver sensitivity) is not over-subscribed.

### A.2. ITU Ch31 Transmitter (Test point 2)

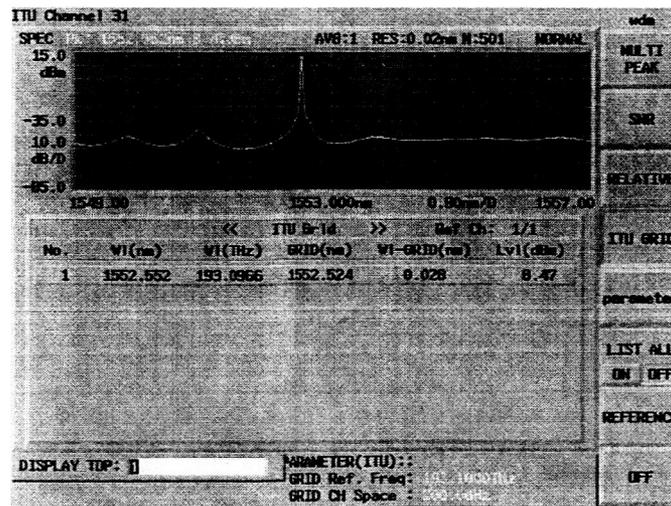


Figure 5 Test point 2

The optical output of ITU Ch 29 Transmitter is shown in Figure 5. The wavelength, peak power value, and frequency were measured and found to be 1552.552 nm, 8.47 dBm, and 193.0966 THz, respectively. The frequencies of Ch29 and Ch31 are separated from each other by 200 GHz, as shown in the tables in Figures 4-5. This spacing is defined by the standard ITU grid for DWDM channel separation.

### A.3 ITU Ch29 & Ch31 Multiplexed (Test Point 3)

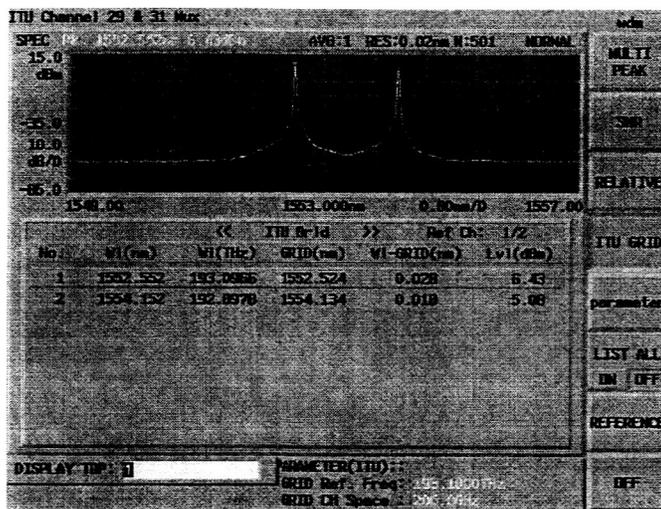


Figure 6 Test point 3

ITU Channels 29 & 31 were multiplexed together via WDM, as shown in Figure 3. The optical spectrum of the multiplexed signal (as measured by the optical spectrum analyzer) is shown in Figure 6. Some loss in the power level for each channel has occurred during the multiplexing process, as shown in the table of Figure 6. Such loss is typical for WDM systems, as the insertion loss of individual components is generally high (1-3 dB).

### A.4 ITU Ch29 & Ch31 passed through a spool of fiber (Test point 4)

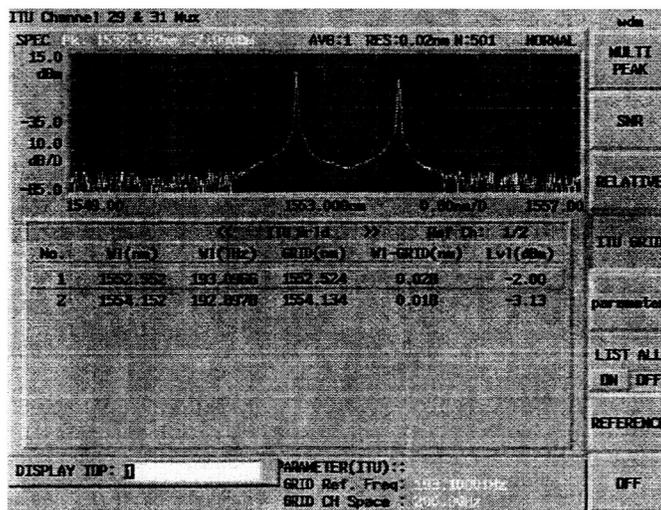


Figure 7 Test point 4

The WDM signal was passed through a spool of fiber, and the resulting optical signal is shown in Figure 7. Notice that the signal has been attenuated due to the long length of fiber, as shown in the table of Figure 7. The power levels of the optical signals have been reduced due to transmission through the spool of fiber.

*A.5 1550 nm Ortel Transmitter (Test Point 5)*

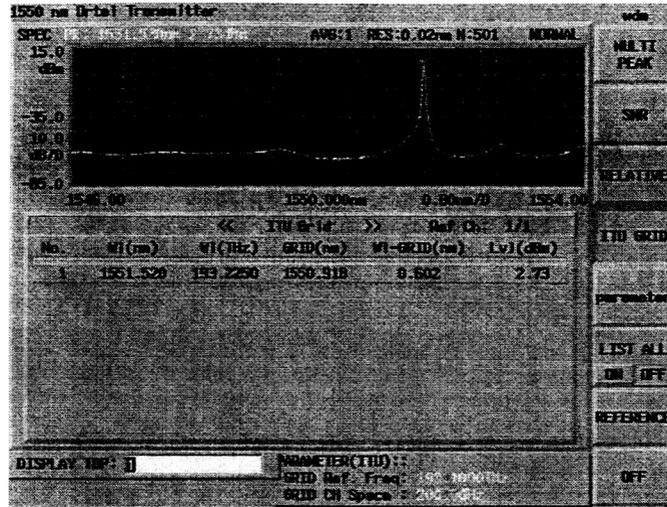


Figure 8 Test point 5

The optical output of the 1550 nm Ortel transmitter is shown in Figure 8. The wavelength, peak power value, and frequency were measured and found to be 1551.520 nm, 2.73 dBm, and 193.2250 THz, respectively. Unfortunately, the output wavelength of this transmitter is not stable over time. The wavelength stability is dependent upon the stability of the supply voltage and the operating temperature. In the future, a voltage regulator should be used to stabilize the supply voltage. However, stabilization of the temperature is not straightforward as there is no integral thermoelectric cooling system in the transmitter.

*A.6 1550 nm, Ch29, & Ch31 Multiplexed by a 50/50 Coupler at (Test Point 6)*

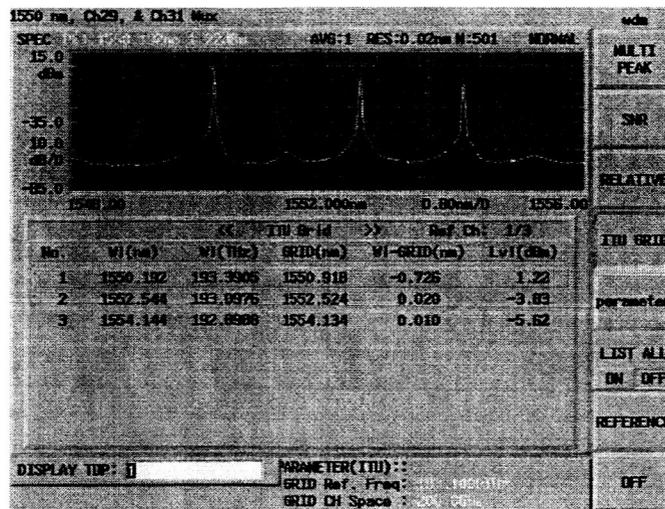


Figure 9 Test point 6

The wideband 1550 nm Ortel Transmitter was added to the WDM signal using a coupler. The resulting multiplexed signal is shown in Figure 9. Notice that the three wavelengths multiplexed by the coupler have been attenuated at the output of the coupler.

A.7 1310 nm, 1550 nm, Ch29, & Ch31 Multiplexed (Test point 7)

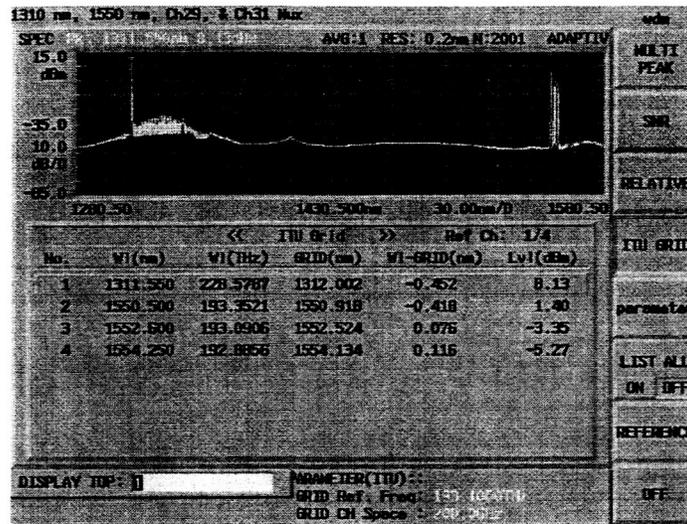


Figure 10 Test point 7

Finally, another signal at 1310 nm was multiplexed into the composite optical signal using WDM. The resulting signal, consisting of all four wavelengths, is shown in Figure 10. Note that the three channels around 1550 nm are very closely spaced, and thus are not easily resolvable at this level of magnification.

A.8 1310 nm Transmitted (Test Point 8)

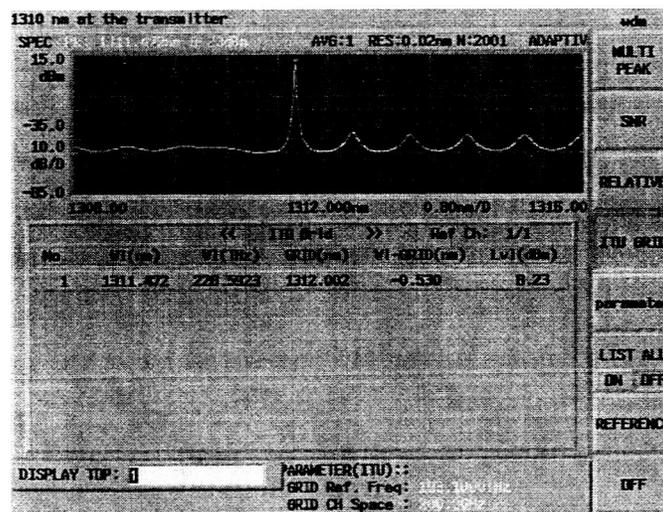


Figure 11 Test point 8

The optical output of the 1310 nm Transmitter is shown in Figure 11. The wavelength, peak power value, and frequency were measured and found to be 1311.472 nm, 8.23 dBm, and 228.5923 THz, respectively.

A.9 1310 nm received (Test Point 9)

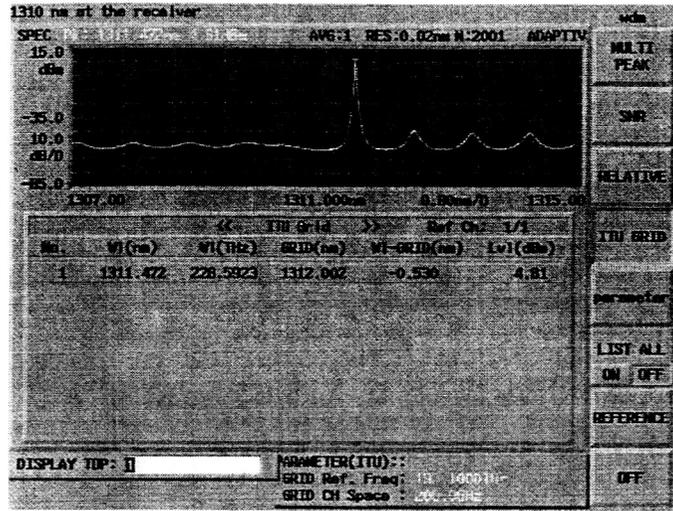


Figure 12 Test point 9

The 1310 nm channel is demultiplexed after passing through several meters of fiber. The 1310 nm channel at the input of the receiver is shown in Figure 12. Notice that the received power of 4.81 dBm is high enough to achieve error free data transmission from this channel, because the sensitivity of this receiver is approximately 0 dBm.

A.10 1550nm, Ch29, & Ch31 after the 1310/1550 Demultiplexer (Test Point 10)

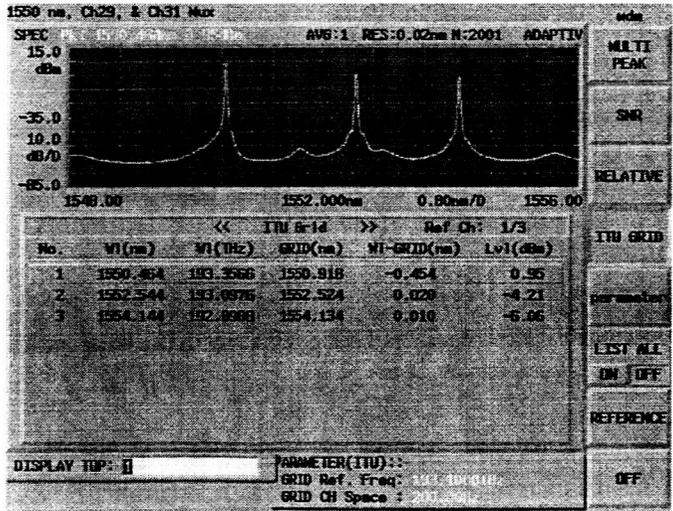
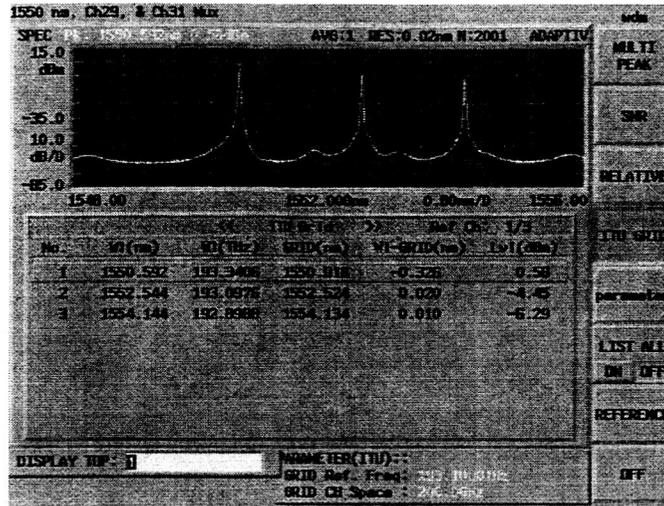


Figure 13 Test point 10

The 1310 nm channel is demultiplexed after passing through several meters of fiber. The remaining channels in the WDM link are 1550nm, Ch29, and Ch31, as shown in Figure 13. The peak power of

these channels have faced more attenuation; however, it is still appropriate compared with the sensitivities of the receiving diodes at the receivers.

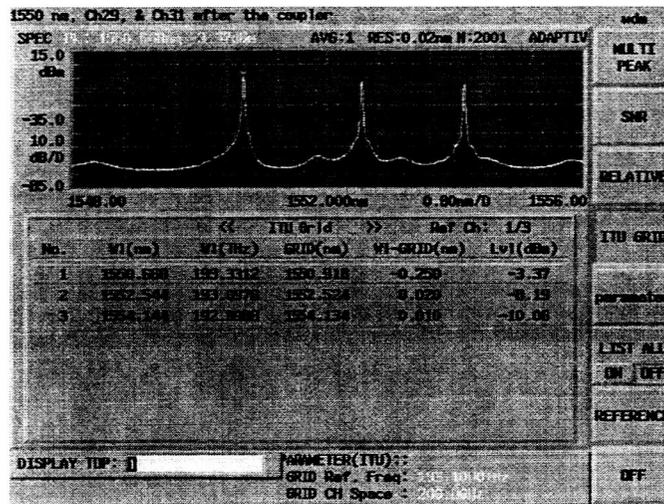
*A.11 1550nm, Ch29, & Ch31 after passing a spool of fiber at (Test Point 11)*



**Figure 14 Test point 11**

The optical signal passes through another spool of fiber, reducing the signal strength further, as shown in Figure 14. Noting the amount of attenuation that the channels have suffered through the transmission in the optical fiber compared with that through the multiplexing and demultiplexing steps shows that combining and splitting the signals have more responsibility of causing the attenuation throughout the link.

*A.12 1550 nm, Ch29, & Ch31 after the Coupler at (Test Point 12)*



**Figure 15 Test point 12**

The second output coupler distributes the optical signal 50/50 between two paths. One goes to the optical filter and the other goes to the WDM demultiplexer to demultiplex both Channels 29 & 31, as shown in Figure 15.

Notice that the coupler has significantly attenuated the WDM signal at its output.

*A.13 1550 nm, Ch29, & Ch31 after the Coupler to the 1550 nm Receiver at ( Test Point 13)*

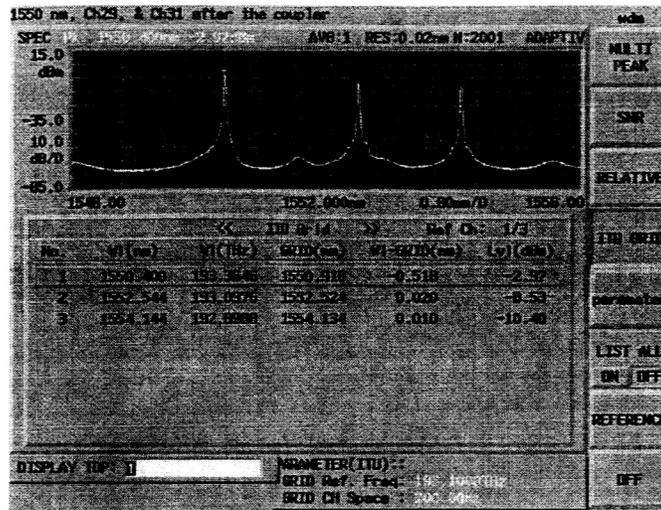


Figure 16 Test point 13

The second output coupler distributes the optical signal 50/50 between two paths. One goes to the optical filter as shown in Figure 16, and the other goes to the WDM demultiplexer to demultiplex both Channels 29 & 31, as shown in Figure 15.

*A.14 1550 nm after the Optical Filter at (Test Point 14)*

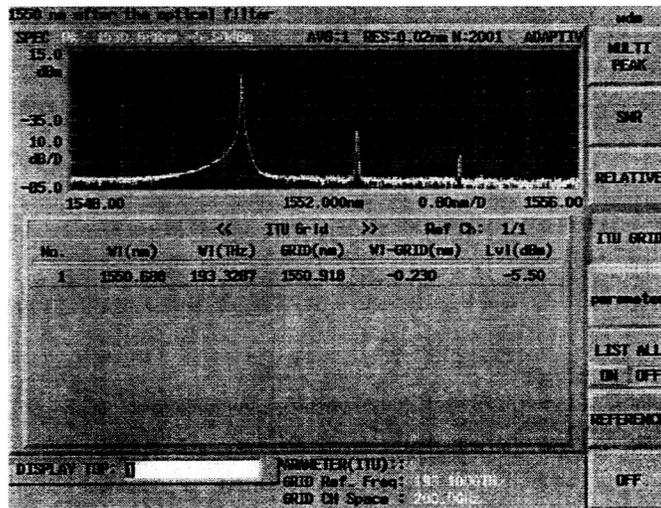


Figure 17 Test point 14

The optical filter attenuates the ITU channels and passes the 1550 nm wideband channel, as shown in Figure 17. However, the remaining peak power of channel 1550 nm at the output of the optical filter is still sufficient to allow the receiving diode to detect the optical signal and convert it to a RF signal.

### A.15 Ch31 at the receiver side (Test Point 15)

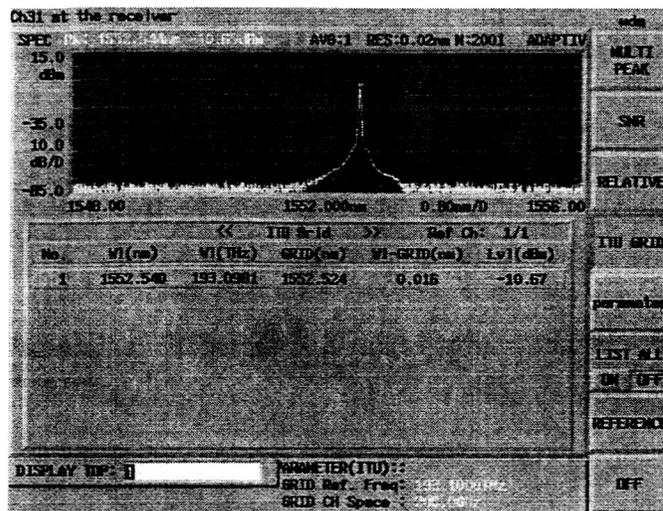


Figure 18 Test point 15

Note that the optical power level of -10.67 dBm is sufficient to allow error free data transmission in this channel as the sensitivity of this particular receiver is lower (better) as compared to the former.

### A.16 Ch29 at the receiver side (Test Point 16)

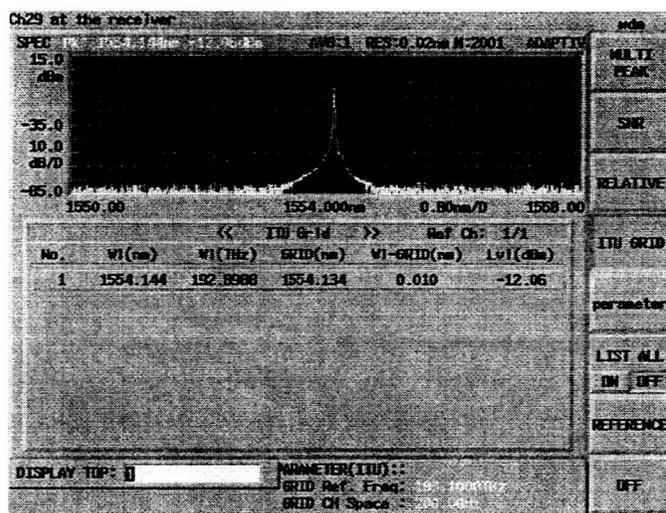


Figure 19 Test point 16

Note that the optical power level of -12.06 dBm is sufficient to allow error free data transmission in this channel.

## B. Transmission Response Measurements

RF transmission response measurements provide the relative loss, or gain, in a communications link. Any signal distortion due to the communication link will manifest itself in the transmission response measurement. The vector network analyzer computes the output measurement trace using

$$Transmission(dB) = 10 \log \left( \frac{P_{trans}}{P_{inc}} \right)$$

where  $P_{trans}$  is the RF power measured at the output of the receiver, and  $P_{inc}$  is the RF power measured at the input to the laser transmitter.

### B.1 Transmission response for channel 29

Figure 20 shows the results of the transmission response measurements for channel 29, with and without the RF amplifier included.

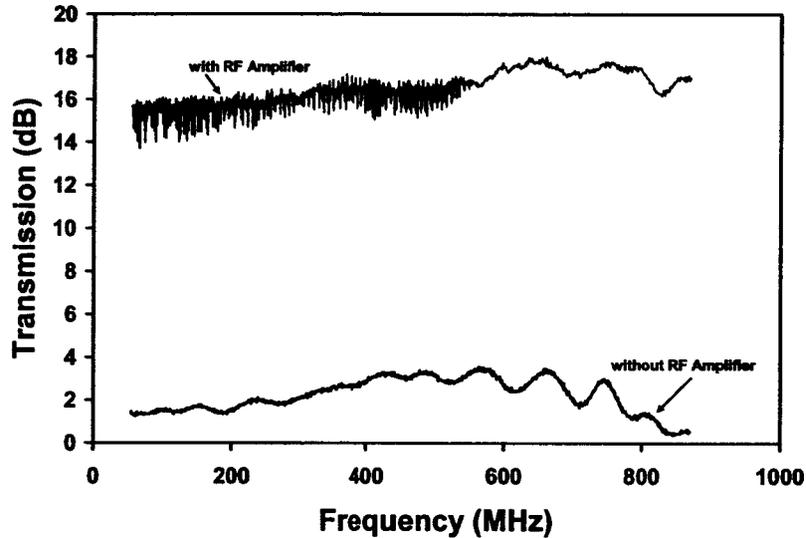


Figure 20 Results of transmission response measurements for channel 29.

Without the RF amplifier, the transmission response (loss) varied around 2 dB over the frequency range of 55-900 MHz. With the RF amplifier, the transmission response (gain) varied around 16 dB over the same frequency range. Inclusion of the RF amplifier produced sufficient gain to overcome link losses, thus allowing the optical signal to travel further distances.

### B.2 Transmission response for channel 31

Results of the transmission response measurements, with and without the RF amplifier included, for channel 31 are shown in Figure 21. Channel 29 and channel 31 are ITU channels that use different wavelengths near 1550 nm, and their corresponding wavelengths are 1554.134 nm and 1552.524 nm, respectively.

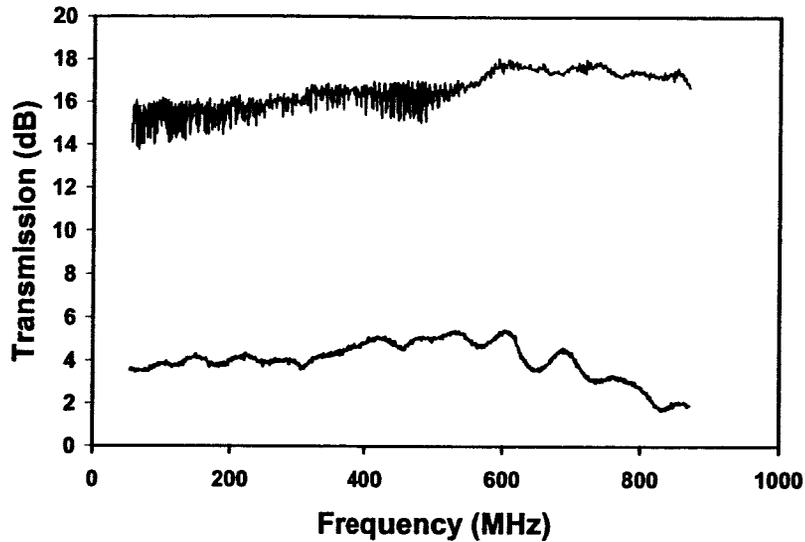


Figure 21 Results of transmission response measurement for channel 31.

Without the RF amplifier, the transmission response (loss) varied around 4 dB over the frequency range of 55-900 MHz. With the RF amplifier, the transmission response (gain) varied around 16 dB over the same frequency range. We can conclude that ITU channels 29 and 31 have approximately the same results over the frequency range 55-900 MHz. That leads to the ability of using up to 20 ITU channels if needed.

### B.3 Transmission response for 1310nm channel

The 1310 nm channel is a wide channel that has higher attenuation and more dispersion when compared with 1550 nm channels. Results of a transmission response measurement for the 1310 nm channel are shown in Figure 22. The figure depicts a flat response (no signal distortion) over the measured frequency range. The transmission response is approximately -35 dB over the frequency range 0-1300MHz.

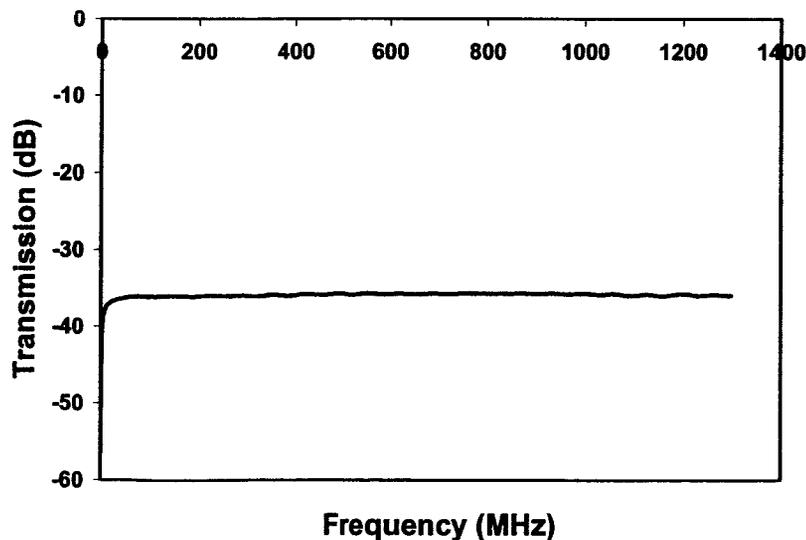


Figure 22 Result of transmission response measurement for channel 1310 nm.

#### B.4 Transmission response for 1550nm channel

The 1550 nm channel is a wide band channel that has lower optical output power and lower built-in optical amplification when compared with the ITU channels 29 and 31. Results of the transmission response measurement for the 1550 nm channel are shown in Figure 23. The transmission response is approximately - 80 dB over the frequency range 0-1300 MHz.

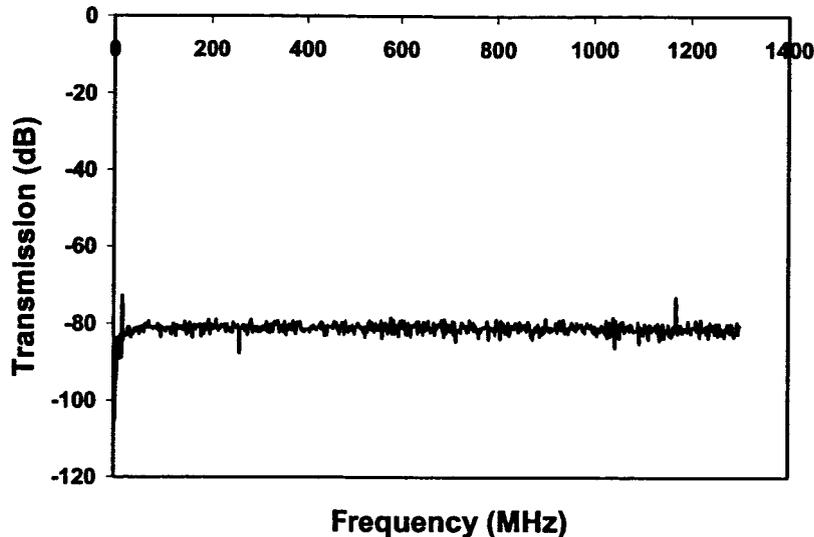


Figure 23 Result of transmission response measurement for channel 1550 nm.

#### C. Reflection Response Measurements

Reflection response provides a measure of how much power is reflected relative to the incident power at the point of insertion into the transmitter. This reflected power can be due to the impedance mismatch between the RF input cable and the transmitter, as well as reflections within the transmitter laser modulation circuitry. In determining the RF reflection response, the network analyzer computes the output measurement trace using

$$Reflection(dB) = 10 \log \left( \frac{P_{refl}}{P_{inc}} \right)$$

where  $P_{inc}$  is the RF power measured at the input to the laser transmitter and  $P_{refl}$  is the reflected RF power measured at the same point.

##### C.1 Reflection response for channel 29

Results of reflection response measurements over the frequency range 55-900 MHz for channel 29 are shown in Figure 24.

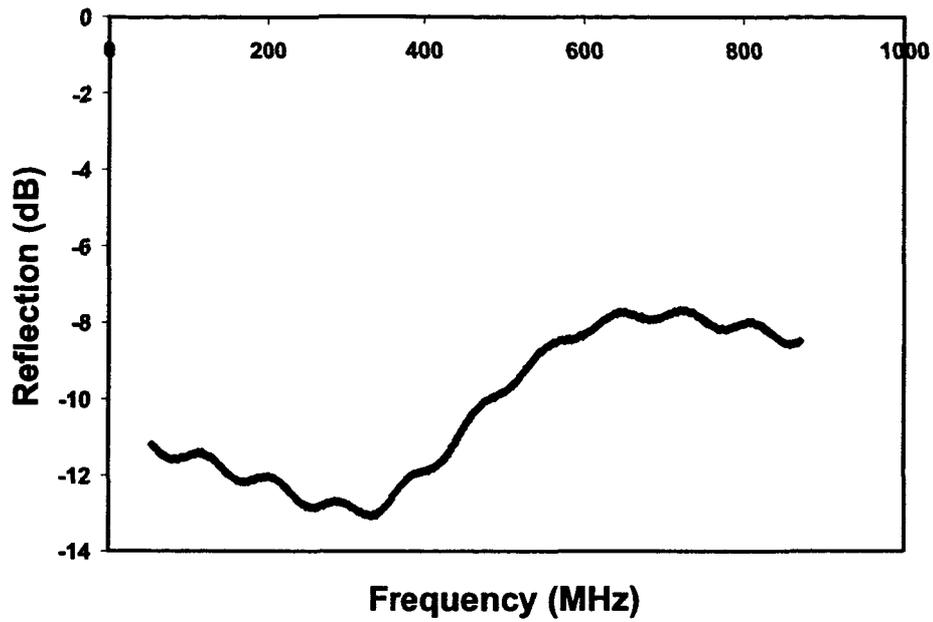


Figure 24 Results of reflection response measurement for channel 29.

*C.2 Transmission response for channel 31*

Results of reflection response measurements over the frequency range 55-900 MHz for channel 31 are shown in Figure 25.

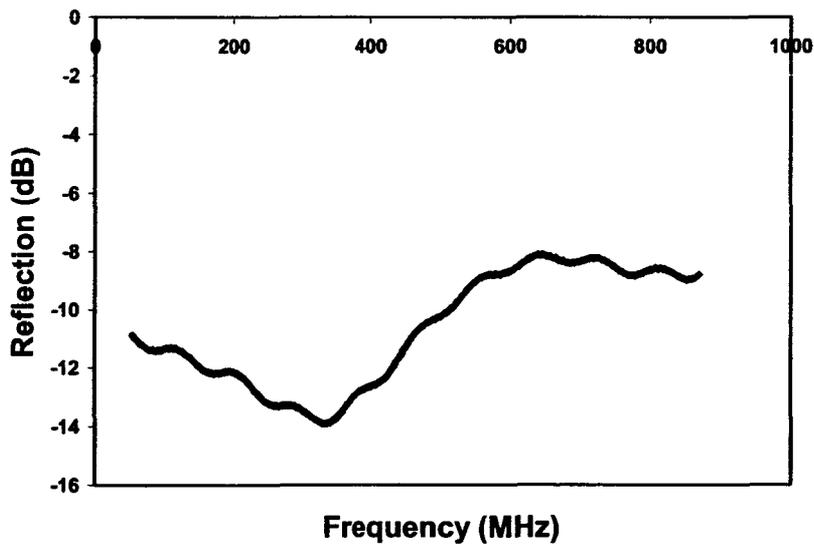


Figure 25 Results of reflection response measurement for channel 31.

*C.3 Transmission response for 1310nm channel*

Results of reflection response measurements over the frequency range 33-1300 MHz for channel 1310 nm are shown in Figure 26.

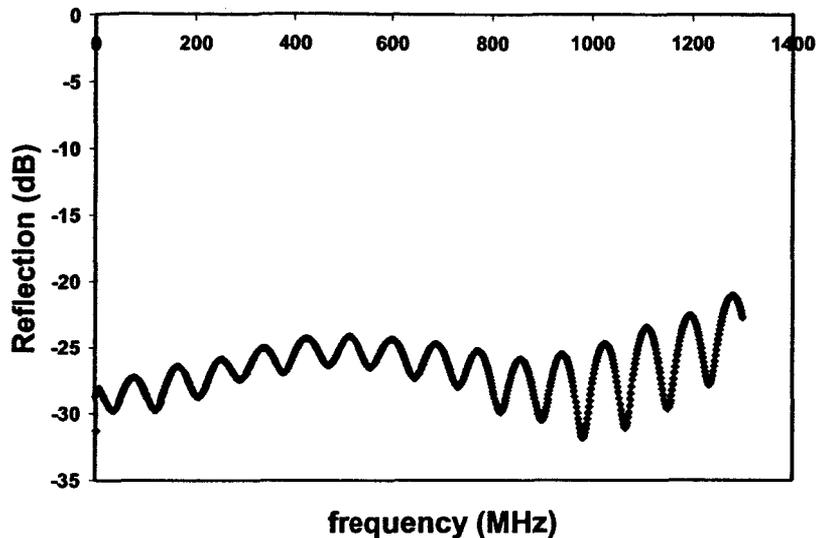


Figure 26 Results of reflection response measurement for channel 1310 nm.

These measurements compare favorably with the -20 to -50 dB loss reported for a single analog fiber optic communication link [2], except for Ch1550 which needs an amplification stage. The RF amplifier provides sufficient gain to overcome the losses resulting from the coupling and splitting of the WDM equipment over the communication link, thus allowing the optical signal to travel farther distances.

#### D. Group Delay Measurements

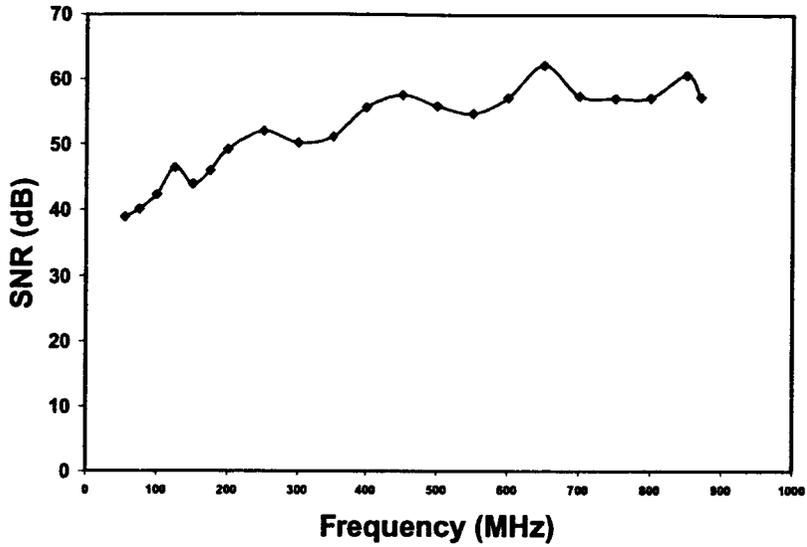
The group delay is a measure of the total delay a signal experiences when traversing a communications link, which thus gives rise to a phase shift in the signal. To ensure that a communications link does not introduce phase distortion, it is important to verify that the group delay does not vary appreciably with frequency. The group delay measurements for all channels are illustrated in Table 1. Note that the group delay has an approximately constant value for all channels.

Table 1 Group delays results for all channels

	Ch29	Ch31	1310 nm	1550 nm
GD (ns)	310	310	100	220

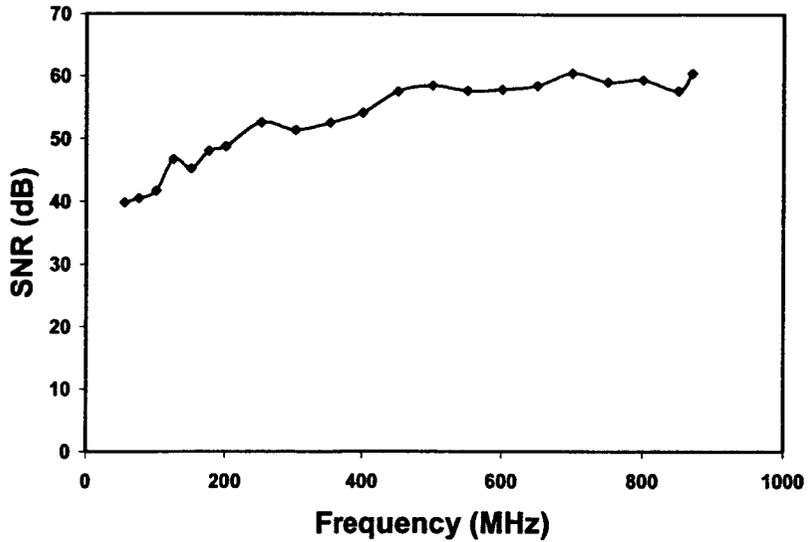
#### E. SNR Measurements

SNR is a widely cited performance measure for communications links. Major sources of noise in optical communications links include relative intensity noise (RIN) generated by the laser transmitter, shot noise generated by the photodiode in the receiver, and thermal noise generated by resistors. Results of SNR measurements over the frequency range 55-900 MHz for channel 29 are shown in Figure 27.



**Figure 27 Results of SNR measurement for channel 29.**

Results of SNR measurements over the frequency range 55-900 MHz for channel 31 are shown in Figure 28.



**Figure 28 Results of SNR measurement for channel 31.**

Results of SNR measurements over the frequency range 55-900 MHz for channel 1310 nm are shown in Figure 29.

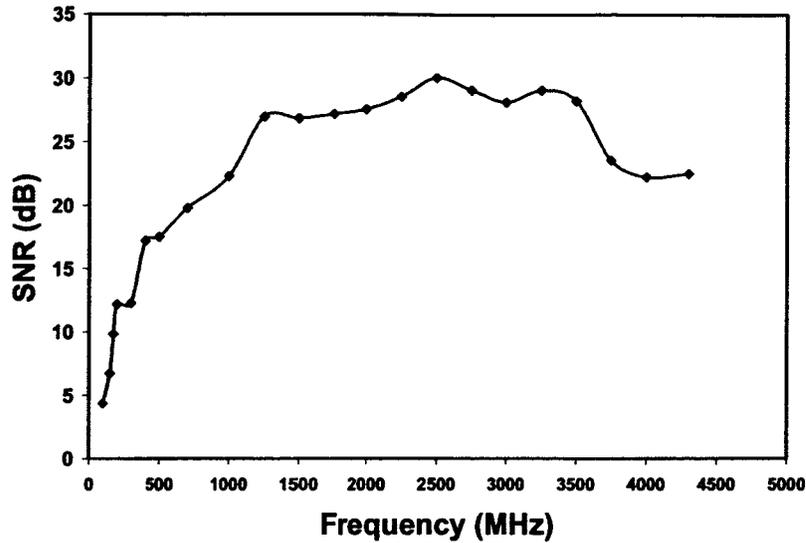


Figure 29 Results of SNR measurement for channel 1310 nm.

We are investigating more tests to improve the SNR measurements for channel 1550 nm, because of the high degradation it faced compared with the other channels.

Compared with results of other measurements conducted on analog fiber optic links reported in [3, 4], Channels 29 and 31 have better SNR. Channels 1310 and 1550, while lower, have acceptable SNR.

#### ***F. Dynamic range measurements***

Major causes of distortion in an optical communication link are due to the nonlinear devices incorporated in the analog transmitter and receiver, particularly the analog modulators [5]. Dynamic range measurements provide the range of the RF input power over which no distortion occurs due to harmonics.

Two principle methods to measure the dynamic range are [5,6] :

1. Supply a single RF sinusoid signal  $f$  through the optical communication link, and measure the resulting second- and third-order harmonic distortions at  $2f$  and  $3f$ , respectively.
2. Supply two equal amplitude sinusoidal RF signals that are close in frequency spacing through the optical communication link and measure the second-order intermodulation distortion at  $f_2 + f_1$  or  $f_2 - f_1$  and the 3<sup>rd</sup> order intermodulation distortion at  $2f_1 - f_2$ ,  $2f_2 - f_1$ ,  $2f_1 + f_2$ , or  $2f_2 + f_1$ . Narrowband communication links allow the following frequencies  $2f_1 - f_2$  and  $2f_2 - f_1$  third-order intermodulation (3IM) distortion to pass and eliminate the rest.

The second method, the more practical way, was used to measure the dynamic range for Channels 29 and 31, as shown in Figure 30.

Two equal power sinusoidal RF signals at closely spaced frequencies  $f_1 = 499 \text{ MHz}$ ,  $f_2 = 501 \text{ MHz}$  were multiplexed using a RF multiplexer. Injecting the composite RF signal into Ch29 and Ch31, the 3IM signal power was measured at frequencies  $2f_1 - f_2 = 497 \text{ MHz}$ , and  $2f_2 - f_1 = 503 \text{ MHz}$ .

Repeating the same measurements while increasing the input power for both sinusoidal signals will allow the 3IM trend to be plotted. Measuring the output power of the fundamental frequency ( $f = 500 \text{ MHz}$ ) while increasing the input power over the same range of power leads to the fundamental output trend to be plotted, thus the plotted line intersects the 3IM line. The third-order intermodulation free dynamic range for Ch29 is 39 dB, as shown in Figure 30.

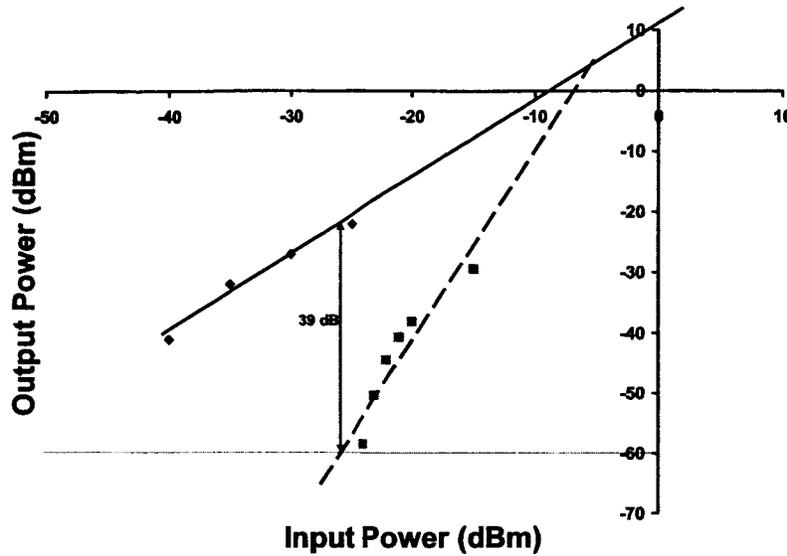


Figure 30. Dynamic range for Channel 29

Also, the third-order intermodulation free dynamic range for Ch31 is 38 dB, as shown in Figure 31. Compared with previously reported results for single optical fiber links[4,7], the third-order intermodulation free dynamic ranges measured over the WDM link are acceptable. Dynamic range has been measured just for Channels 29 and 31.

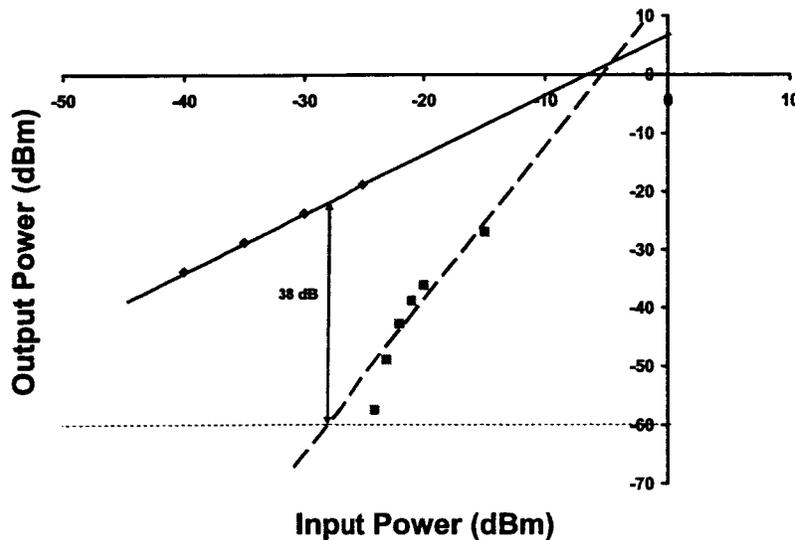


Figure 31. Dynamic Range for Channel 31

## 4. CONCLUSION

This project reported the results of an investigation into the use of wavelength division multiplexing (WDM) technology to simultaneously transport four different channels of analog RF signal transmissions over an optical fiber backbone. The overall system analyses of transmission response, reflection response, group delay, signal-to-noise ratio (SNR), and dynamic range that were carried out during the investigation were promising and indicated the WDM suitability for avionics applications. With the recent publicity of Internet availability during commercial air flights, WDM technology can be used to simultaneously transmit Voice-over-IP, IP-Television, and RF signals on a single fiber.

## References

- [1] Dipert, B., December, 2003, Fly with the Internet at your seat, EDN Magazine, pp.41-47.
- [2] Cox III, Charles H., Gary E. Betts, Leonard M. Johnson, "An Analytic and Experimental Comparison of Direct and External Modulation in Analog Fiber-Optic Links", IEEE Transactions on Microwave Theory and Techniques, Vol. 38, No. 5, May 1990, pp.501-509.
- [3] Slaveski, F., Sluss, J., Jr., Atiquzzaman, M., Nguyen, H., and Ngo, D., (2003), "Optical Fiber Wavelength Division Multiplexing", IEEE Aerospace and Electronic Systems Magazine, Vol. 18, No. 8, Aug 2003, pp. 3-8.
- [4] Stephens, William E., and Thomas R. Joseph, "System Characteristics of Direct Modulated and Externally Modulated RF Fiber-Optic Link", IEEE Journal of Lightwave Technology, Vol. LT-5, No. 3, March 1987, pp. 380-387.
- [5] Cox, III, Charles H., 2004, Analog Optical Links Theory Practice, Cambridge, Chapter 6,
- [6] Chang, William S. C., 2002, RF photonic technology in optical fiber links, Cambridge, Chap. 1.
- [7] Cox, C., III., Ackerman, E., Helkey, R., and Betts, G.E., "Direct-Detection Analog Optical Links", IEEE Transactions on Microwave Theory and Techniques, Vol. 45, No. 8, August 1997.

**Appendix A**

**Paper accepted at**

**23<sup>rd</sup> DASC Digital Avionics Systems Conference  
Hilton Salt Lake City Center, October 24-28, 2004**

# The Application of Fiber Optic Wavelength Division Multiplexing in RF Avionics

*Hakki H. Refai<sup>1</sup>, James J. Sluss, Jr.<sup>1</sup>, and Mohammed Atiquzzaman<sup>2</sup>*

*<sup>1</sup>School of Electrical & Computer Engineering, The University of Oklahoma, Tulsa, Oklahoma USA*

*<sup>2</sup>School of Computer Science, The University of Oklahoma, Norman, Oklahoma USA*

*Hung Nguyen and Duc Ngo, NASA Glenn Research Center, Cleveland, Ohio USA*

## Abstract

This paper demonstrates a successful application of wavelength division multiplexing (WDM) to the avionics environment to support analog RF signal transmission. We investigate the simultaneous transmission of four RF signals (channels) over a single optical fiber. These four analog channels are sequentially multiplexed and demultiplexed at different points along a fiber optic backbone to more closely emulate the conditions found onboard aircraft. We present data from measurements of signal-to-noise ratio (SNR), transmission response (loss and gain), group delay that defines phase distortion, and dynamic range that defines nonlinear distortion. The data indicate that WDM is well-suited for avionics applications.

## Introduction

Optical fiber offers many advantages over coaxial cable for the transmission of RF signals in avionics applications. Optical fiber exhibits considerably less loss, can support signals requiring much higher bandwidth, is immune to electromagnetic interference (EMI), and offers significant size and weight savings when compared to coaxial cable. Recently, the availability of the Internet onboard commercial aircraft adds increased credence to ambitions of delivering new information services during flight [1]. The onboard implementation of Voice-over-IP (VoIP), high-definition television (HDTV), and radio frequency (RF) signals used to transport cellular signals, as shown in Figure 1, is a driving force behind investigations into the use of fiber optic wavelength division multiplexing (WDM) technology to support high bandwidth communications backbone

requirements. WDM is a technique that allows multiple signals with different modulation formats and bandwidths to be combined and transmitted over a single optical fiber. Traditionally, WDM has been used by the telecommunications industry to increase the digital information carrying capacity of optical fibers. In this paper, a WDM network supporting four analog RF channels has been demonstrated as a successful application that meets the demands of the avionics environment.

The objective of this paper is to characterize four end-to-end communication channels established when modulated analog RF signals are transmitted over single fiber using a WDM network. We expect that the promising and novel results presented in this paper will stimulate further research in this emerging area.

The rest of this paper is organized as follows. Next section describes our experimental setup to transmit four channels of RF modulated signals over a WDM network. We report the experimental results from our experiment in the third section, which includes measurements of signal-to-noise ratio (SNR), transmission response, group delay, and dynamic range for the transmission of four channels with different wavelengths over the WDM network. Concluding remarks are given in the last section.

## Experimental Setup

Figure 2 illustrates the experimental setup for all measurements that are explained in the following section. Four wavelengths were used to demonstrate this avionics application 1552.524 nm, 1554.134 nm, 1550 nm, and 1310 nm, named Ch31, Ch29, Ch1550, and Ch1310, respectively.

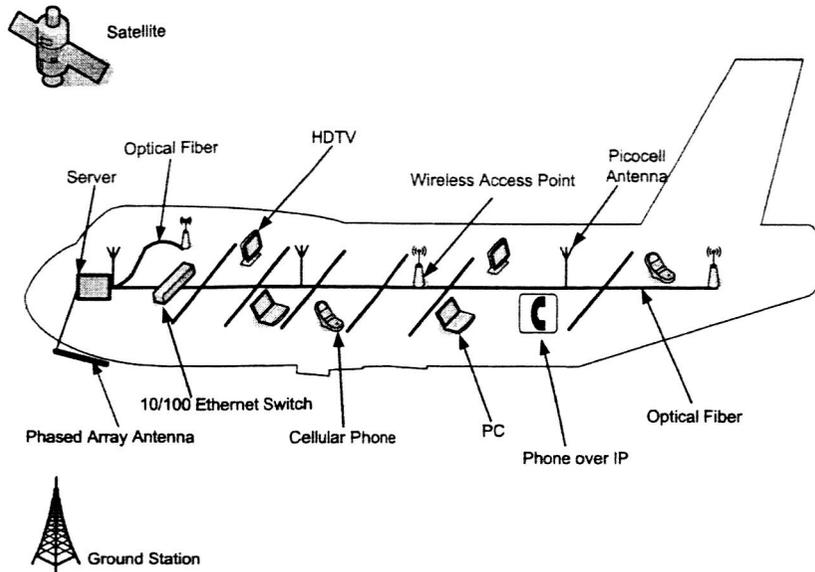


Figure 1. Prospective services onboard of a commercial aircraft in the near future

Examining the communication link of Ch29, an Aurora AT3510 analog laser transmitter, with an ITU grid compliant output wavelength of 1552.524 nm, was fiber-coupled to an Aurora OP35M4C multiplexer connected to an Aurora OP31M2D optical combiner that multiplexes 1310 nm with 1550 nm wavelengths.

A coil of optical fiber, 20 m in length, delivers the optical signal between the multiplexer and the combiner. Passing 3 m of optical fiber after the combiner, an Aurora OP31D2D optical splitter is connected. Another coil of optical fiber, 20 m in length, connects the 1310/1550 splitter with the OP35D4C demultiplexer.

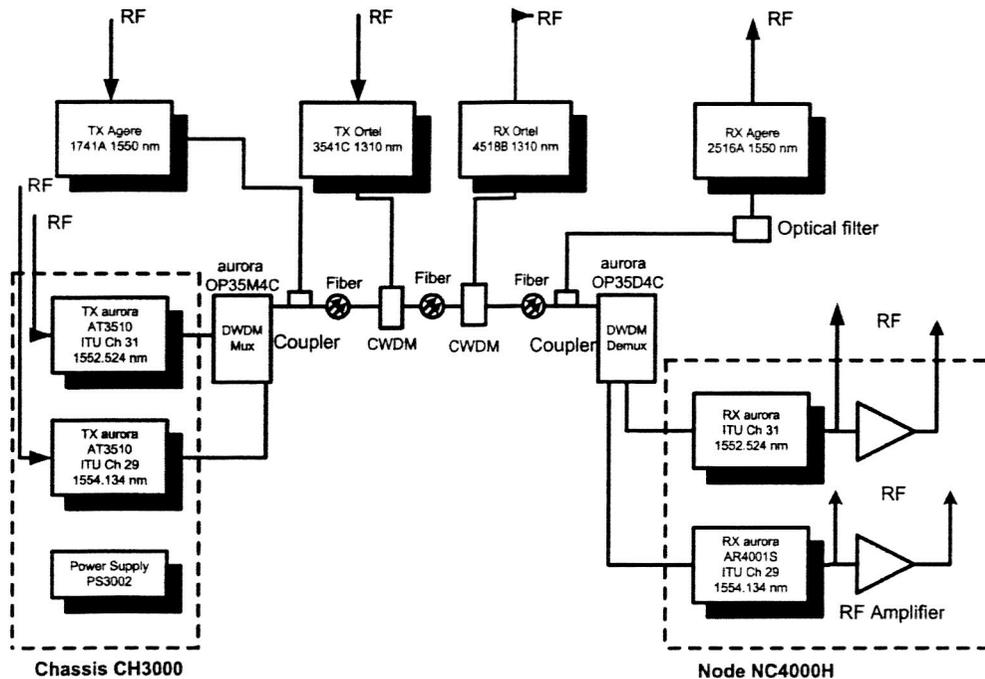


Figure 2. WDM network provides four analog communication channels

Finally, an Aurora AR4001S receiver translates the received optical signal into a RF signal that passes through an Aurora OA4444T-42 RF amplifier linked to the receiver output to provide RF signal gain. The RF frequency range of operation for the Aurora transmitter and receiver is from 46 MHz to 870 MHz. Similarly, the signal of Ch31 travels the same path as shown in the layout.

Ch1310 is coupled via an Aurora combiner to several meters of optical fiber and leaves the network through an Aurora splitter. Ch1510 was coupled via a 50/50 coupler to tens of meters and splits out of the main backbone using another 50/50 coupler and tunable bandpass fiber optic filter.

The extended distances for each link of the four channels, Ch29, Ch31, Ch1310, and Ch1550, are 47 m, 47 m, 9 m, and 41 m, respectively.

## Experimental Results

In this section, we report results obtained from our experimental setup described in the previous section. The results include signal-to-noise ratio (SNR) measurements, transmission response measurements, group delay measurements, and dynamic range measurements. These measurements completely characterize the performance of four communication channels using four different wavelengths over a single optical fiber.

### SNR Measurements

Figure 3 shows the experimental setup for SNR measurements for all channels.

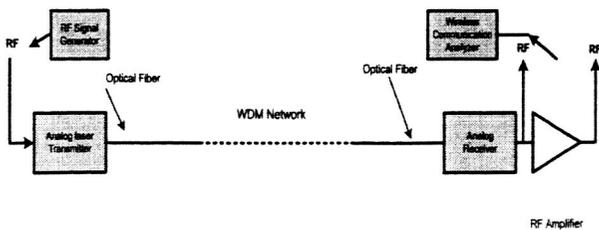


Figure 3. The Experimental Setup for Measuring Signal-to-Noise Ratio (SNR)

SNR provides a well-known measure of the transmission performance for each of the four communication channels in the WDM network. The major sources of noise in an optical communication link are relatively intensity noise (RIN) generated by the analog laser transmitter, shot noise generated by the photodiode in the analog receiver, and thermal noise generated by the circuitry. SNR measurements for the four channels of the WDM communication link are shown in Figures 4 through 7 from which we can list the following observations

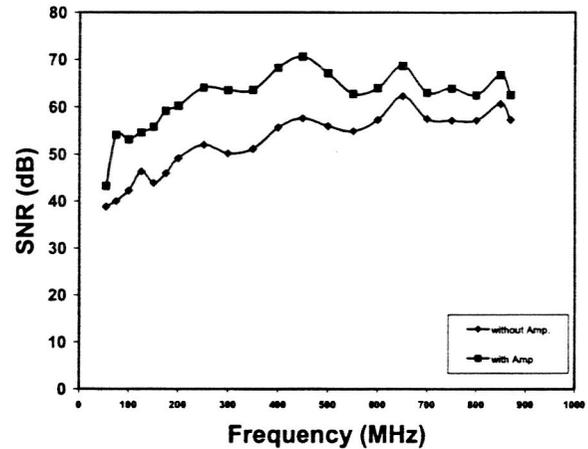


Figure 4. Results of SNR Measurements for Ch29

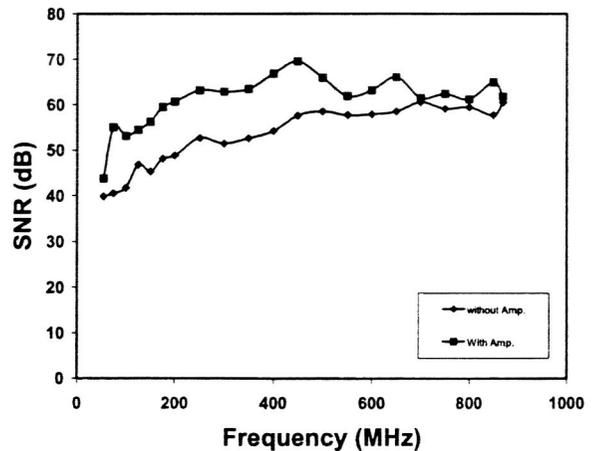


Figure 5. Results of SNR Measurements for Ch31

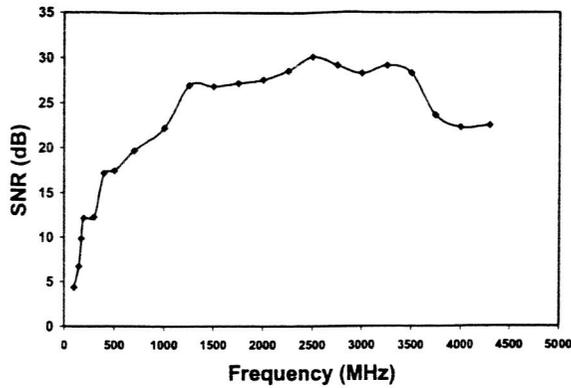


Figure 6. Results of SNR Measurements for Ch1310

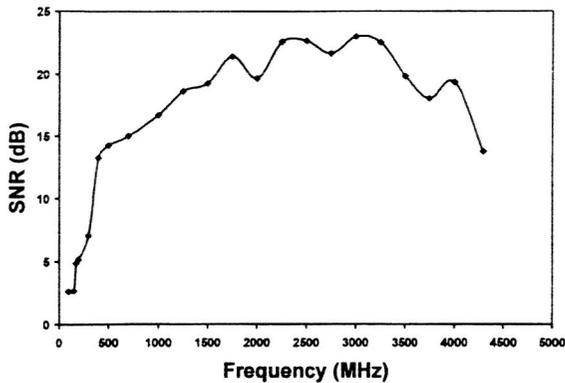


Figure 7. Results of SNR Measurements for Ch1550

- Figure 4 shows that SNR for Ch29 without the RF amplifier varied between 38.77 dB and 60.69 dB over the frequency range 55-900 MHz while SNR with the RF amplifier varied between 43 dB and 68.69 dB over the same frequency range.
- Figure 5 shows that SNR for Ch31 without the RF amplifier varied between 39.81 dB and 60.53 dB over the frequency range 55-900 MHz while SNR with the RF amplifier varied between 43.71 dB and 69.51 dB over the same frequency range.
- Figure 6 shows that SNR for Ch1310 varied between 4.36 dB and 30.08 dB over the frequency range 100-4300 MHz.
- Figure 7 shows that SNR for Ch1510 varied between 2.62 dB and 22.98 dB over the frequency range 100-4300 MHz. Ch1550 uses bare analog transmitter and receiver, which they missed the peripheral circuitry that provide the stability and cooling.

Compared with results of other measurements conducted on analog fiber optic links reported in [2, 3], Ch29 & Ch31 have better SNR and Ch1310 & Ch1550 have acceptable SNR.

### Transmission Response Measurements

RF transmission response measurements provide the relative gain, or loss, in a communication link. Any signal attenuation or amplification in the communication link will manifest itself in the transmission response measurements. The vector network analyzer plots the result measurement trace using

$$Transmission(dB) = 10 \log \left( \frac{P_{trans}}{P_{inc}} \right)$$

where  $P_{trans}$  is the RF power measured at the output of the analog receiver and  $P_{inc}$  is the RF power measured at the input to the analog laser transmitter, as shown in Figure 8.

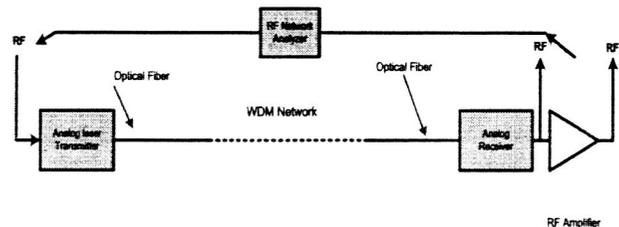


Figure 8. The Experimental Setup for Measuring Transmission Response

Results of the transmission response for Channels 29 & 31, with and without the RF amplifier connected, are shown in Figures 9 & 10. We observe that:

- Transmission response (gain) for Ch29 without the RF amplifier varied around 2 dB and with the RF amplifier varied around 16 dB over the frequency range of 55-900 MHz.
- Transmission response (gain) for Ch31 without the RF amplifier is approximately 4 dB and with the RF amplifier is approximately 16 dB over the frequency range 55-900 MHz.

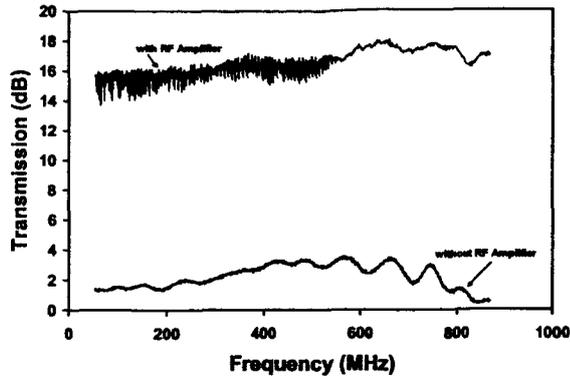


Figure 9. Results of Transmission Response Measurements for Ch29

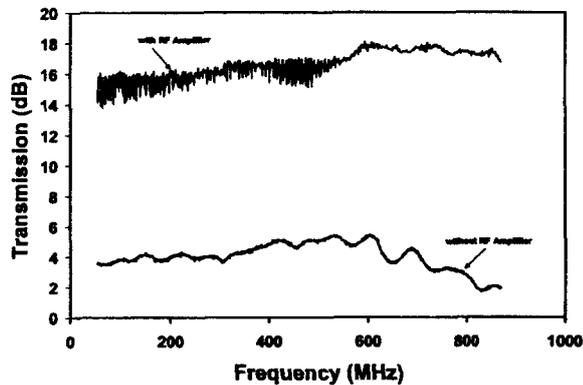


Figure 10. Results of Transmission Response Measurements for Ch31

Results of the transmission response for channels 1310 & 1550 are shown in Figures 11 & 12. It can be seen that:

- The transmission response (loss) for channel 1310 is approximately -35 dB over the frequency range 0-1300 MHz.
- The transmission response (loss) for channel 1550 is approximately -60 dB over the frequency range 0-1300 MHz.

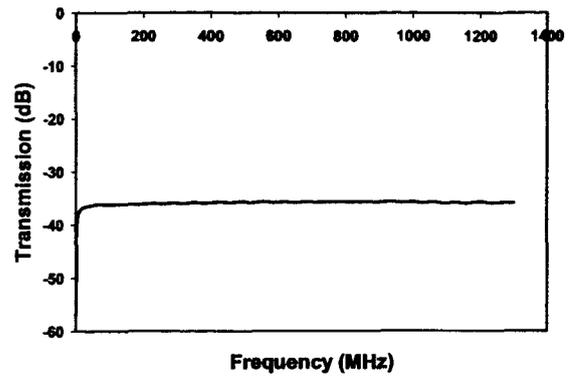


Figure 11. Results of Transmission Response Measurements for Ch1310

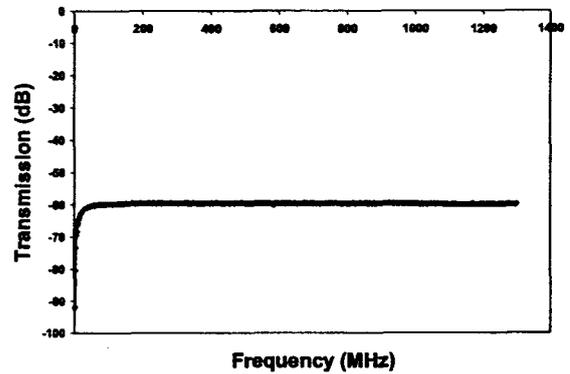


Figure 12. Results of Transmission Response Measurements for Ch1550

These measurements compare favorably with the -20 to -50 dB loss reported for a single analog fiber optic communication link [4], except for Ch1550 which needs an amplification stage. The RF amplifier provides sufficient gain to overcome the losses resulting from the coupling and splitting of the WDM equipment over the communication link, thus allowing the optical signal to travel farther distances.

### *Group Delay Measurements*

Group delay is measure of the propagating delay that the signal experiences when traveling throughout a communication link. Variable group delay over the operating frequency range can

produce a phase shift in the signal. To ensure that a communication link does not introduce a phase shift to the propagating signal, it is important to verify that the group delay is stable over the operating frequency range. The experimental setup used to measure the group delay is shown in Figure 8.

Results of group delay measurements for all channels are:

- Group delays for Ch29, without and with RF amplifier, are approximately 304 ns and 313 ns, respectively. These measured group delays were approximately constant over the frequency range 55-870 MHz, which indicates that the communication link is free of phase distortion..
- Group delays for Ch31, without and with RF amplifier, are approximately 300 ns and 315 ns, respectively. These values for group delay were constant over the operating frequency range 55-870 MHz, which again indicates that the communication link is free of phase distortion..
- Group delay for Ch1310 is approximately 101 ns and constant over the frequency range 50-1300 MHz.
- Group delay for Ch1550 is approximately 218.5 ns and constant over the frequency range 50-1300 MHz, except over specified frequencies 590 MHz and 780 MHz, which leads to a small phase distortion over at some frequencies.

### Dynamic range measurements

Major causes of distortion in an optical communication link are due to the nonlinear devices incorporated into the analog transmitter and receiver, particularly the analog modulators [5]. Dynamic range measurements provide the range of the RF input power over which no distortion occurs due to harmonics.

Two principle methods to measure the dynamic range are [5, 6]:

3. Supply a single RF sinusoid signal  $f$  through the optical communication link and measure the resulting second- and third-order harmonic distortions at  $2f$  and  $3f$ , respectively.
4. Supply two equal amplitude sinusoidal RF signals that are close in frequency spacing through the optical communication link and measure the second-order intermodulation distortion at  $f_2 + f_1$  or  $f_2 - f_1$  and the 3<sup>rd</sup> order intermodulation distortion at  $2f_1 - f_2$ ,  $2f_2 - f_1$ ,  $2f_1 + f_2$ , or  $2f_2 + f_1$ . Narrowband communication links allow the following frequencies  $2f_1 - f_2$  and  $2f_2 - f_1$  third-order intermodulation (3IM) distortion to pass and eliminate the rest.

The second method, the more practical way, was used to measure the dynamic range for Ch29 and Ch31, as shown in Figure 13.

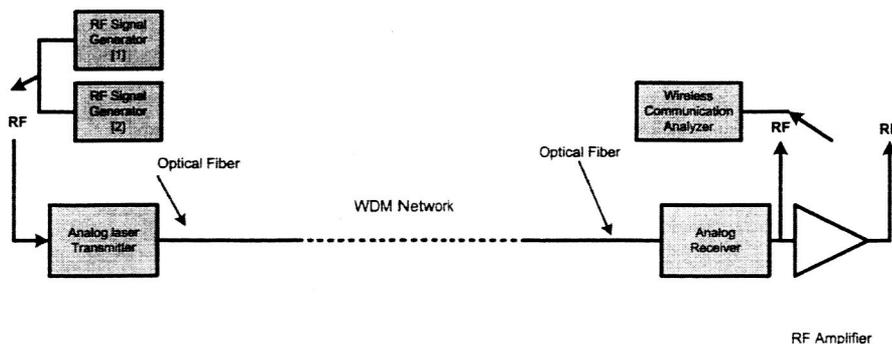


Figure 13. The Experimental Setup for Measuring the Dynamic Range

Two equal power sinusoidal RF signals at closely spaced frequencies  $f_1 = 499 \text{ MHz}$ ,  $f_2 = 501 \text{ MHz}$  were multiplexed using a RF multiplexer. Injecting the composite RF signal into Ch29 and Ch31, the 3IM signal power was measured at frequencies  $2f_1 - f_2 = 497 \text{ MHz}$ , and  $2f_2 - f_1 = 503 \text{ MHz}$ . Repeating the same measurements while increasing the input power for both sinusoidal signals will allow the 3IM trend to be plotted. Measuring the output power of the fundamental frequency  $f = 500 \text{ MHz}$  while increasing the input power over the same range of power leads the fundamental output trend to be plotted, thus the plotted line intersects the 3IM line.

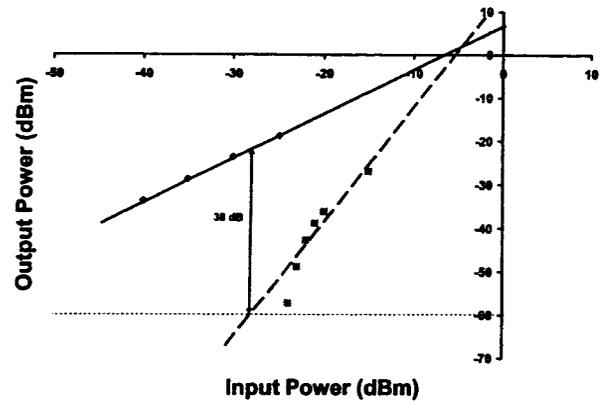


Figure 15. Dynamic Range for Ch31

The third-order intermodulation free dynamic range for Ch29 is 39 dB, as shown in Figure 14.

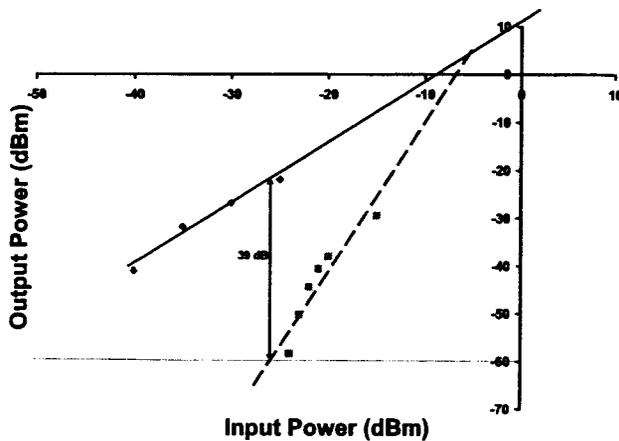


Figure 14. Dynamic range for Ch29

Also, the third-order intermodulation free dynamic range for Ch31 is 38 dB, as shown in Figure 15. Compared with previously reported results for single optical fiber links [3, 7], the third-order intermodulation free dynamic ranges measured over the WDM link are acceptable. Dynamic range has been measured just for Ch29 and Ch31.

## Conclusion

This paper reported and depicted the results of an investigation into the use of wavelength division multiplexing (WDM) technology to simultaneously transport four different channels of analog RF signal transmissions onboard an aircraft. The overall system analyses of signal-to-noise ratio (SNR), transmission response, group delay, and dynamic range that were carried out during the investigation were promising and indicated that the WDM suitability for avionics applications. With the recent publicity of Internet availability during commercial air flights, WDM technology can be used to simultaneously transmit Voice-over-IP, IP-Television, and RF signals on a single fiber.

## Acknowledgements

The project was funded by NASA grant no. NCC3-1069. The authors acknowledge and greatly appreciate the support of NASA Glenn Research Center for funding this project.

## References

- [1] Dipert, B., December, 2003, Fly with the Internet at your seat, EDN Magazine, pp.41-47.
- [2] Slaveski, F., Sluss, J., Jr., Atiquzzaman, M., Nguyen, H., and Ngo, D., (2003), Optical Fiber Wavelength Division Multiplexing, IEEE Aerospace and Electronic Systems Magazine.
- [3] Stephens, William E., and Thomas R. Joseph, March 1987, System Characteristics of Direct Modulated and Externally Modulated RF Fiber-Optic Link, IEEE Journal of Lightwave Technology, Vol. LT-5, No. 3, pp. 380-387.
- 4] Cox III, Charles H., Gary E. Betts, Leonard M. Johnson, May 1990, An Analytic and Experimental Comparison of Direct and External Modulation in Analog Fiber-Optic Links, IEEE Transactions on Microwave Theory and Techniques, Vol. 38, No. 5, pp.501-509.
- [5] Cox, III, Charles H., 2004, Analog Optical Links Theory Practice, Cambridge, Chapter 6,
- [6] Chang, William S. C., 2002, RF photonic technology in optical fiber links, Cambridge, Chap. 1.
- [7] Cox, C., III., Ackerman, E., Helkey, R., and Betts, G.E., August 1997, Direct-Detection Analog Optical Links, IEEE Transactions on Microwave Theory and Techniques, Vol. 45, No. 8.

**Appendix B**

**EQUIPMENT USED IN THE TESTBED**

The following equipment received from NASA were used in the testbed.

1.	CH3000N	Chassis	1
2.	PS3002D	Power Supply	1
3.	AT3510-29-1-AS	QAM Transmitter Ch29	1
4.	AT3510-31-1-AS	QAM Transmitter Ch31	1
5.	BP-A4	Back Plates	2
6.	OP35M4C-0-00-AS	Multiplexer for four ITU Channels	1
7.	OP35D4C-0-00-AS	Demultiplexer for four ITU channels	1
8.	OP31M2D-0-00-AS	1310/1550 nm Multiplexer	1
9.	OP31D2D-0-00-AS	1310/1550 nm Demultiplexer	1
10.	NC4322T51-00000000	Optical node with two analog receivers	1
11.	FLTR-OPT-75-15-75	Tunable Optical Filter	1
12.	F-CPL-1x2-opt-75-16-75	Y Coupler SW	2
13.	1741A-020	Tx Agere 1550 nm	1
14.	2516A-32	Rx Agere 1550 nm	1
15.	3541C	Tx Ortel 1310 nm	1
16.	4518B	Rx Ortel 1310 nm	1
17.	WD202B-FC	1310/1550 Couplers	4
18.	PI-SMF-28-FC-10	Fiber Cable	2
19.	ADA FC2	FC-FC Adaptor	3

The following equipment and accessories were also used to build the prototype. These will be required if a similar testbed is to built at NASA GRC to repeat the experiments or obtain more results.

1.	Cable SM Simplex SC/APC-SC/APC, 1 Meters (3 feet)	5
2.	Cable SM Simplex SC/APC-SC/APC, 3 Meters (10 feet)	2
3.	Cable SM Simplex FC/APC-FC/PC, 3 Meters (10 feet)	2
4.	Cable SM Simplex SC/APC-FC/PC, 3Meters (10 feet)	4
5.	Variable Auto Transformer	1
6.	Power Supply 5v	1
7.	Power Supply 15v	2

Connections between these items are shown in Figure 3.