

# TRANSMISSION OF RF SIGNALS OVER OPTICAL FIBER FOR AVIONICS APPLICATIONS<sup>1</sup>

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## Abstract

During flight, aircraft avionics transmit and receive RF signals to/from antennas over coaxial cables. As the density and complexity of onboard avionics increases, the electromagnetic interference (EMI) environment degrades proportionately, leading to decreasing signal-to-noise ratios (SNRs) and potential safety concerns. The coaxial cables are inherently lossy, limiting the RF signal bandwidth while adding considerable weight. To overcome these limitations, we have investigated a fiber optic communications link for aircraft that utilizes wavelength division multiplexing (WDM) to support the simultaneous transmission of multiple signals (including RF) over a single optical fiber.

Optical fiber has many advantages over coaxial cable, particularly lower loss, greater bandwidth, and immunity to EMI. In this paper, we demonstrate that WDM can be successfully used to transmit multiple RF signals over a single optical fiber with no appreciable signal degradation. We investigate the transmission of FM and AM analog modulated signals, as well as FSK digital modulated signals, over a fiber optic link (FOL) employing WDM. We present measurements of power loss, delay, SNR, carrier-to-noise ratio (CNR), total harmonic distortion (THD), and bit error rate (BER). Our experimental results indicate that WDM is a fiber optic technology suitable for avionics applications.

## Introduction

Coaxial cable has long been used to transport analog radio frequency (RF) signals between antennas and avionics equipment onboard aircraft. However, coaxial cable is lossy, limits the signal bandwidth, and adds considerable weight. As a transmission medium, optical fiber has many advantages over coaxial cable, most notably lower loss, larger bandwidth, and immunity to electromagnetic interference (EMI). In addition, the relative small size and low weight of optical fiber as compared to coaxial cable makes it well-suited for avionics applications where space and weight savings are a sought after premium.

Previous studies of RF transmission over fiber optic links (FOLs) have reported measurements of power losses, signal-to-noise ratio (SNR), etc. [1-2], validating the suitability FOLs for avionics applications. We propose to enhance the applicability of these FOLs by including the use of wavelength division multiplexing (WDM) techniques. WDM enables multiple optical signals to be transmitted at different wavelengths over a single optical fiber [3].

In this paper, we demonstrate that WDM can be used to transmit multiple RF signals on a single optical fiber with no appreciable signal degradation. We investigate the transmission of FM and AM analog modulated signals, as well as FSK digital modulated signals, over a FOL employing WDM. We present measurements of power loss, delay, SNR, carrier-to-noise ratio

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(CNR), total harmonic distortion (THD), and bit error rate (BER). Our experimental results validate the suitability of WDM in FOLs for avionics applications.

## Background

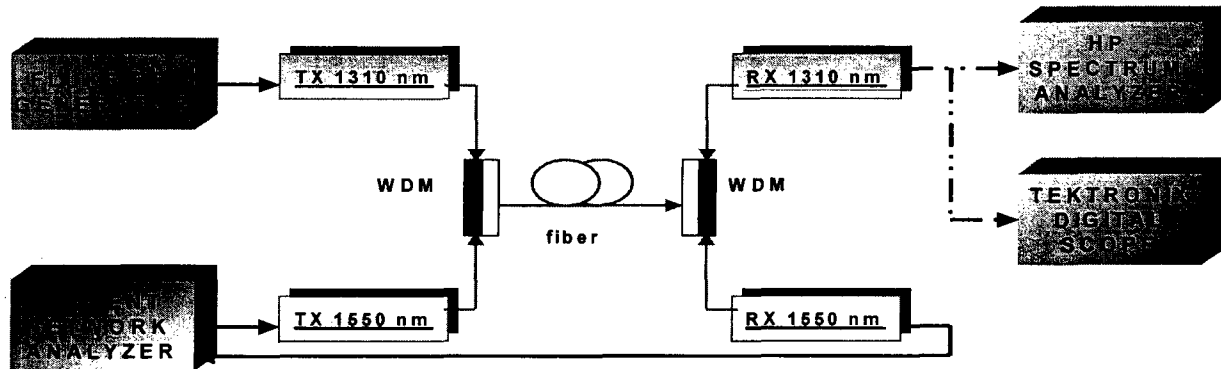
A FOL consists of a transmitter containing an optical source (e.g., a semiconductor laser diode or light emitting diode) that can be internally or externally modulated, an optical fiber as the transmission medium, and a receiver containing a photodiode. Previous research into the transmission of RF signals over FOLs has been conducted for operating wavelengths of 850 nm and 1310 nm [1-2,4-5]. Critical performance characteristics of these FOLs have been reported in the literature and a review of several key results follows.

Losses due to electrical-to-optical conversion in the transmitter and optical-to-electrical conversion in the receiver can amount to 20 to 50 dB loss [6]. The total insertion loss, combined with the loss due to the electrical-to-optical conversion and the loss due to attenuation in the fiber medium, was measured to be  $-40$  dB for an 850 nm FOL and  $-50$  dB for a 1310 nm FOL [2]. Insertion loss can be as high as  $-67$  dB for FOLs that employ wide-bandwidth, externally modulated sources [1]. These results apply for both AM and FM modulated RF signals. Results show that CNR and SNR range between 50 and 60 dB for RF inputs to internally and externally modulated FOLs [1,4-5]. The noise in these measurements is due to the shot and thermal noise in the receiver, and relative intensity

noise in the transmitter. The main difference between our study and the ones cited above is the introduction of a simple WDM architecture into the FOL. All of our measurements were performed in an experimental setup that contained this WDM architecture, which is illustrated in the next section.

## Experimental Setup

Figure 1 illustrates the first of two basic configurations for our experimental setup. The basic WDM architecture supports two optical channels operating at wavelengths of 1310 and 1550 nm. The 1310 nm channel has Ortel 3541C transmitter and Ortel 4518A receiver. The frequency range of operation for these fiber optic devices is between 10 MHz and 10 GHz. Likewise, the 1550 nm channel has Ortel 1741A transmitter and Ortel 2516A receiver, which again operate between 10 MHz and 10 GHz. Next, RF signals were produced using the Fluke 6060B RF generator, which operates between 10 KHz and 1050 MHz, and the Agilent 8712 ET network analyzer, which operates between 10 and 1300 MHz. Thus, the highest frequency for which we have obtained measurements is 1300 MHz, which is in the UHF frequency range. The RF generator provided the capability of internal and external FM and AM modulation. It should be noted that optical signals at both 1310 and 1550 nm were continuously present throughout the following experiments to verify that there is no crosstalk between the signals in the WDM FOL.



**Figure 1. WDM FOL Experimental Setup**

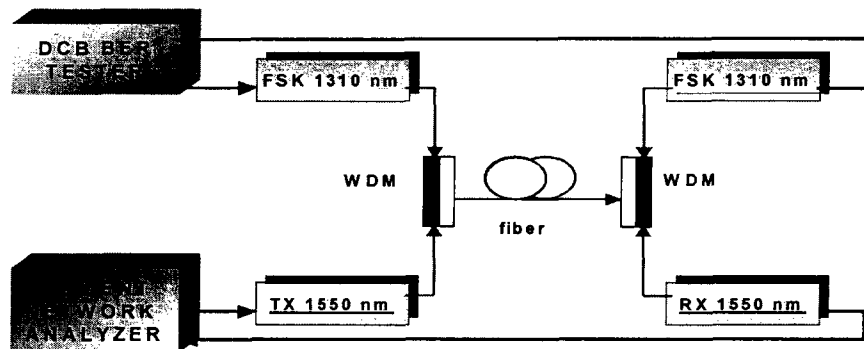
With the experimental setup depicted in Figure 1, we measured transmitted and reflected power losses, delay, CNR, SNR, THD, and signal quality for FM and AM modulation schemes at both 1310 and 1550 nm. The transmitted and reflected power loss, as well as the delay, was measured using the Agilent 8712 ET network analyzer. The network analyzer gave the power measurements in terms of ratios since it supplies the input and reads the output from the circuit at the same time. Also, the network analyzer was able to display measurements in linear and log scale, amplitude and phase format, and store the measurements in ASCII format on a local or floppy disc.

The HP 8554B spectrum analyzer was used to measure the CNR, SNR and THD for both AM and FM modulation. The HP 8554B had a frequency span of 1200 MHz, scan width up to 100 MHz, and 80 dB dynamic range. The THD was calculated upon measurement of the fundamental and the first three positive harmonics of the signal. The equation used for calculating THD was [7]:

$$THD \text{ (\%)} = \frac{\sqrt{a_1^2 + a_2^2 + a_3^2}}{a_0} * 100 \%$$

where  $a_0$  is the fundamental frequency and  $a_1$ ,  $a_2$  and  $a_3$  are the harmonics.

While the THD gives a quantitative measure of signal quality, we also qualitatively examined the AM and FM modulated signals by capturing their respective waveforms using a Tektronix TDS 784C digital oscilloscope (DSO). The DSO was able to measure waveforms up to 1000 MHz and its scan speed reached four Giga-samples per second. Input and output waveforms of FM and AM modulated signals were compared accordingly. The AM and FM signals were produced with the RF generator, where an external modulator at 200 KHz was used to modulate the carrier. The AM signal was at 30 % modulation and the FM signal had a 20 KHz frequency deviation.



**Figure 2. BER Test Setup in the WDM FOL**

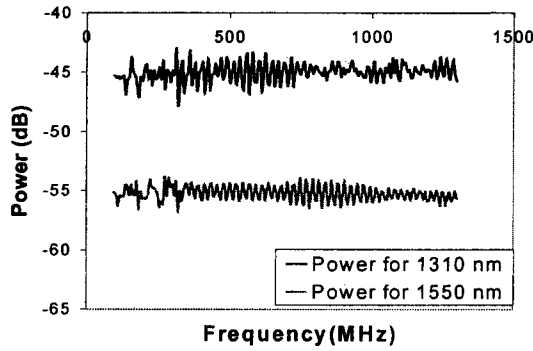
Figure 2 illustrates the second experimental setup in which BER was measured for an FSK modulated signal. An analog signal was also present in the fiber to further verify that there is no crosstalk between the optical signals in the WDM FOL. The BER tester supplies a pseudo random sequence to the transmitter via an EIA-232 port. At the transmitter, the sequence is FSK modulated and put onto the fiber at 1310 nm. The FSK signal is then multiplexed with the 1550 nm analog signal and coupled into the fiber. After demultiplexing at the other end, the receiver converts the FSK signal back into a digital stream and feeds it to the BER tester. The BER tester then compares the input and output streams and displays the bits in error for a given time. Besides the pseudo random sequence, the BER tester supplies different digital messages at different data rates up to 38,400 bits per second.

## Experimental Results

### *Power and Delay Measurements*

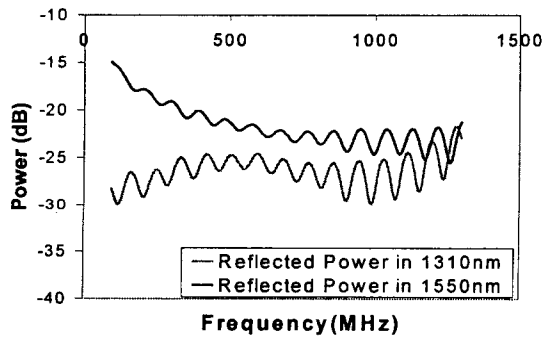
Transmitted and reflected power was measured and the results are depicted in Figures 3 and 4.

From Figure 3, the power transmitted in the 1310 nm channel is approximately - 45 dB and the power transmitted in the 1550 nm channel is approximately - 55 dB for the frequency range between 100 and 1300 MHz. Transmitted power is power that is left in the signal after all the insertion losses are incurred due to the electrical-to-optical conversion and coupling into the fiber and WDM. It is obvious that the power is lower in the 1550 nm channel as compared to 1310 nm and we attribute this difference to greater WDM insertion loss at 1550 nm. This was verified by removing WDM components from the setup testing the 1310 and 1550 nm FOLs separately. In this configuration, the 1550 nm had slightly lower power loss due to the fact that there is less material absorption in the fiber at this wavelength [3]. Compared with other reported results, our measurements for 1310 nm are slightly better than the previously documented - 50 dB [2]. Upon a thorough review of the relevant literature, no similar measurements have been reported for 1550 nm.



**Figure 3. Transmitted Power in the WDM FOL**

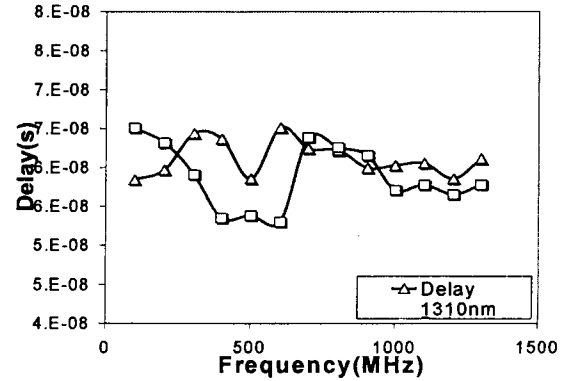
Next, from Figure 4 we can see that the reflected power is approximately  $-25$  dB for the 1310 nm channel and  $-30$  dB for the 1550 nm channel. The rippling effect in the plotted data can be attributed to the harmonics produced when the input signal is swept through the frequency range. The reflected power is the measure of how much power is rejected from system at the point of insertion. This rejected power is due to the electrical-to-optical conversion, which typically accounts for  $-20$  to  $-50$  dB of loss [6]. Comparing our results with those in [6], they are within the reported bounds.



**Figure 4. Reflected Power in the WDM FOL**

The measured delay illustrated in Figure 5 is approximately 60 ns for both 1310 and 1550 nm channels. The delay is due to the propagation delay of the signal in the optical fiber and the transmission delay through the electronic/optoelectronic devices comprising the transmitter and receiver. Given the overall length of our FOL, we estimated the propagation delay in the fiber to be approximately 50 ns. That leaves us

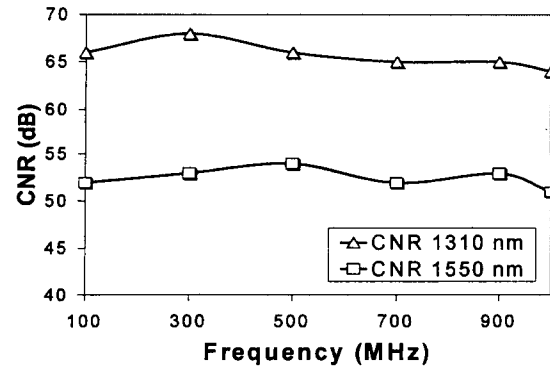
with 10 ns delay attributable to the electrical circuit, which should not lead to any appreciable phase distortion. Also, the phase of the signals for both channels was linear over the whole frequency range, which also ensures no phase distortion [8].



**Figure 5. Delay in the WDM FOL**

### **CNR and SNR**

The results from CNR and SNR measurements are given in Figures 5 and 6, respectively. From Figure 5, the CNR for the 1310 nm channel is approximately 65 dB, while for the 1550 nm we note a decrease to approximately 52 dB for the frequency range between 100 and 1000 MHz. Our results compare reasonably with the CNR of 57 dB reported in [1].



**Figure 6. CNR in the WDM FOL**

From Figure 6 we can see that the SNR for AM and FM at 1310 nm is approximately 55 dB and at 1550 nm, is approximately 40 dB. These measurements suggest good analog signal transmission over WDM FOLs since they exceed

the 30 dB standard for good AM radio reception [9].

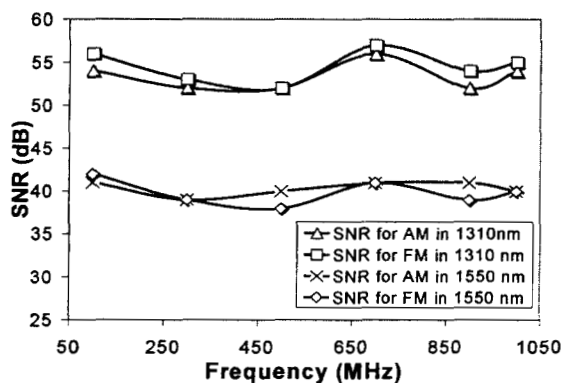


Figure 7. SNR in the WDM FOL

It should be noted that both the CNR and SNR measurements are slightly better at 1310 nm than at 1550 nm. Again, this can be attributed to higher insertion loss for the WDM components at 1550 nm.

### Signal Quality

Figure 7 shows the AM modulated signal input to the WDM FOL. Figure 8 shows the corresponding output. From these figures, we can see qualitatively that the output exhibits almost no distortion when compared to the input. This statement will be supported with subsequent determination of the THD to provide a quantitative measure of signal quality. In comparing Figures 7 and 8, we note that the modulation index seems to be higher for the output signal. Since the modulation index is the ratio of signal power to carrier power, this difference can be attributed to the carrier experiencing more attenuation than the modulating signal, the cause of which is unclear at this time.

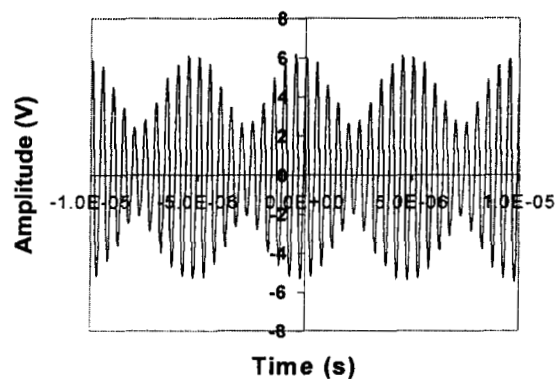


Figure 8. AM input to the WDM FOL

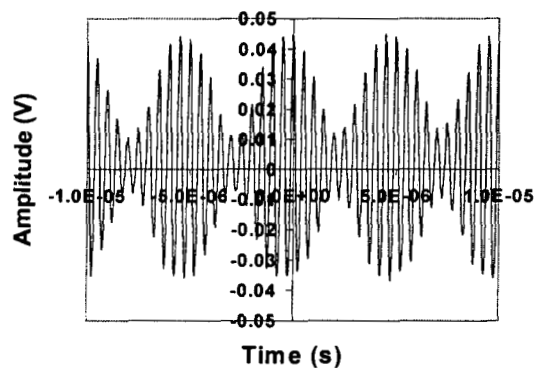


Figure 9. AM output from the WDM FOL

Likewise, the input/output waveforms for the FM modulated signal are shown in Figures 9 and 10, respectively.

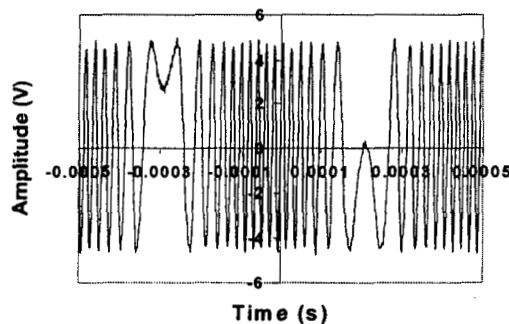
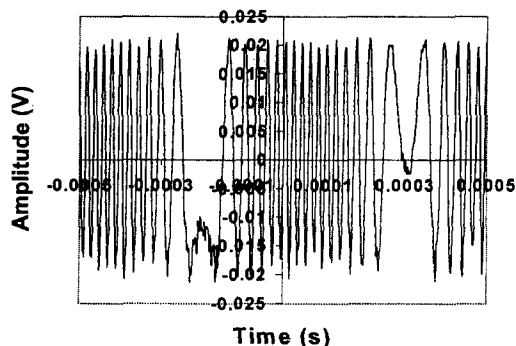
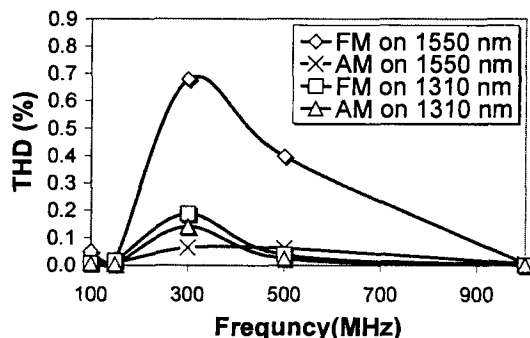


Figure 10. FM input to the WDM FOL



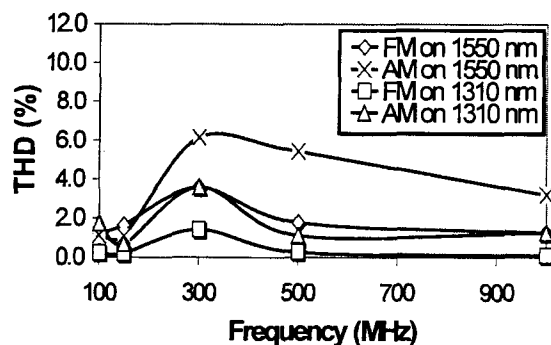
**Figure 11. FM output inform the WDM FOL**

THD is a quantitative measure of analog signal quality. The method for determining THD was described in an earlier section. Figure 11 shows the THD for the carrier, while Figure 12 shows THD for the modulating signal.



**Figure 12. Carrier Distortion in the WDM FOL**

From Figure 11, we note that the output carrier distortion ranges from 0 to 0.8% for all the different configurations.



**Figure 13. Signal Distortion in WDM FOL**

From Figure 12, we note that the output distortion levels for the modulating signal range from 0 to 7%. The reason for higher values in the modulating signal is that the modulating signal externally modulates the carrier of the RF generator and incurs distortion when it is inserted in the RF generator.

### BER Test

Various digitally encoded messages were transmitted at different data rates up to 38,400 bits per second. *No bit errors* were observed for the testing period of 30 minutes in all the different tests. Therefore, the BER was measured to be better than  $1.85E-07$  for the highest data rate (e.g., 38,400 bps). This result indicates that there was no interference between the optical channels in the WDM FOL that led to a degradation of the BER.

### Summary/Conclusion

In conclusion, the simple WDM FOL in the experimental analysis showed very good results. We have obtained an overall insertion loss less than -55 dB, CNR and SNR ratios greater than 40 dB, THD less than 7%, and BER greater than  $1.85E-07$ . Similar to the coaxial cables, with these results the optical fiber ensures a good transmission of the RF signals between the antennas and the cockpit of the aircraft. On top of the above consideration, optical fibers save great amount of space and weigh much less than the coaxial cables. Furthermore, unlike the coaxial cables, a single optical fiber can manage a great number of RF signals in WDM setup. With all these advantages over the coaxial cables, the WDM setup should definitely become an integral part of the aircraft to carry RF communication between the antennas and the cockpit.

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