

Optical Fiber Amplifiers

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Abstract

The primary goal of this experiment was to gain an understanding of the basic components of an Erbium doped fiber amplifier (EDFA) system. The first step in this undertaking was to characterize the amplifier system, and check the capabilities and limitations of each component. Most of this was performed by connecting the individual pieces of the systems between a white light source and an Optical Spectrum Analyzer (OSA). After the completion of the characterization, data was taken and plotted to determine the relationship between gain characteristics of the EDFA and the wavelength sent into the system. Also, the threshold pump power was calculated and shown to be independent of the input power. A value for this was calculated as $P_p^{th} \approx 4 \text{ mW}$. The conversion efficiency, η , was also calculated for the many different setups for the system, showing that they were far from ideal, but became closer to the theoretical maximum with higher pumping power. This theoretical maximum was calculated to be $\eta_{max} = 0.63$ at 1550 nm.

Introduction

The simplest, yet one of the most important things about an Erbium-doped fiber amplifier (EDFA) is that it uses a short length of optical fiber that was treated, “doped”, with a trace amount of the rare-earth metal Erbium. The Erbium ion used in the EDFA, like the other rare earth ions, is characterized by an unfilled 4f-shell. The valence electrons in this shell are well protected from their environment by the much larger 5s and 5p shells. In addition to this, the 4f energy levels are split due to electron-electron, spin-orbit interactions. The individual levels of the shell are denoted by the LS-coupling scheme, since the angular momenta and spins of the electrons are added up first, giving the quantum numbers L and S. Despite the effectiveness of using this scheme, it is important to note that it does not hold perfectly well. These quantum numbers are added as vectors to obtain a total momentum, J. Figure 1, below, shows these labels applied to the energy levels of the Erbium ion in the form of: $^{2S+1}L_J$, where L is denoted with a letter (S,P,D,F,G,... for L = 0,1,2,3,4...).

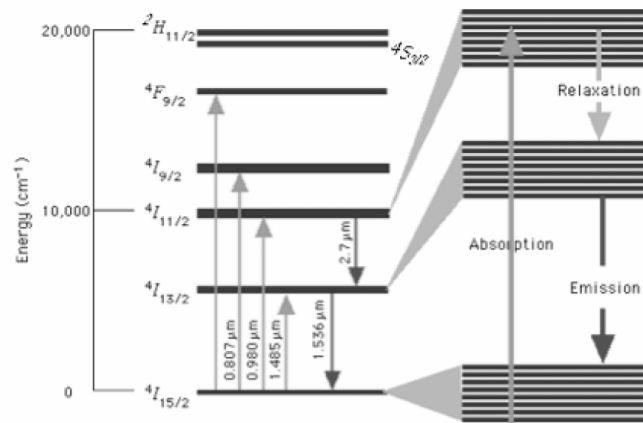


Figure 1 – Detailed energy level scheme.

In an EDFA, an optical laser beam is amplified directly, without the need for opto-electronic and electro-optical (O/E and E/O) conversion. When the laser carrying a signal passes through the Erbium-doped fiber, extra energy is added to the system to amplify the level of this signal. Amplification in a fiber optic system is a necessity because no system is perfectly transparent, and therefore losses in the signal occur along the length of the optic fibers. Because of these losses, repeaters are used in spans of optical fiber that run for lengths greater than ~100km.

Standard EDFAs operate over a wavelength range that covers the “C band” (1530-1560nm) which allows for the amplification of numerous wavelength channels that are used in wavelength division multiplexing (WDM) applications. This is much better than having to convert an optical signal to an electrical for amplification. Under this type of situation, in O/E-E/O regenerators, each WDM channel at each regenerator site must undergo demultiplexing and multiplexing, with a separate O/E-E/O pair for each of these channels.

The operation of the EDFA functions primarily by the principle of stimulated emission. Taking advantage of just one of the many energy levels of the Erbium ion, a 980nm pump laser is used to excite the ion into an excited state with a reasonably long lifetime. This leads to energy storage within the amplifier fiber which the signal can later use. When the signal encounters this

stored energy, stimulated emission occurs, creating a photon with the same wavelength and direction as the incident signal photon, leading to an amplification of the original signal. Without such a signal, the stored energy of the Erbium fiber is slowly released, resulting in spontaneous emission in all directions, leading to noise, which actually limits the performance of the fiber.

While this describes a very simplified version of an Erbium fiber, a more detailed analysis of the energy levels is shown in Figure 1, above. When the fiber is pumped with the 980nm laser, the fiber gives off a very noticeable green color due to emission. The interaction of with the host ions is small and only leads to a splitting of the $(2J+1)$ degenerate levels, which is shown for three levels in Fig. 1. While this splitting is small, it allows for amplification and lasing between these two lowest states of the Erbium ion. The populations of the sublevels within each of these levels are governed by the Boltzmann distribution, and for that reason, the absorption and emission spectra are not identical. This can be seen in Figure 2. Because of this relationship, gain can be achieved on the low energy (long wavelength) side by pumping the high energy (short wavelength) side of the absorption, essentially resulting in a four level system.

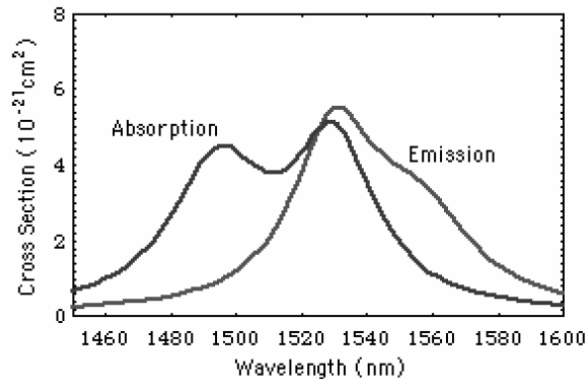


Figure 2 – Emission and Absorption Spectra

The principle set up of the EDFA is shown below in Figure 3. The 980nm pump laser and the signal laser are combined using a WDM, and then co-propagate through the Erbium-doped fiber. The pump laser is then separated at the end by using a 1550nm wavelength isolator. A second WDM can be used to separate the pumping laser from the signal, but an isolator reduces back-reflection while doing the same job of filtering the 980nm light.

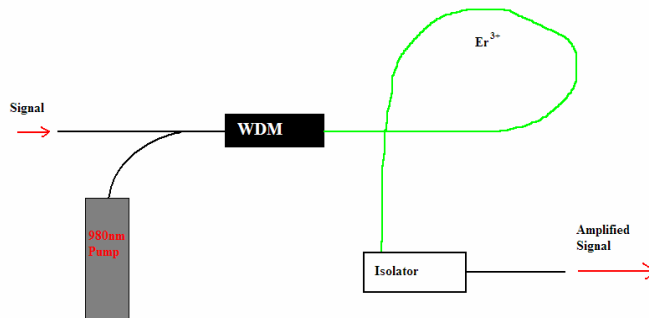


Figure 3 – Basic Set-up of EDFA

Apparatus

The primary equipment used in this experiment is listed below:

- 1525 to 1600nm tunable laser source
- 980nm laser source
- 980/1550nm WDM
- 1550nm isolator
- Erbium doped fiber
- Optical Spectrum Analyzer (OSA)
- Standard optical fiber and connectors
- White light source

I. Measurement of the Amplified Spontaneous Emission and Characterization of EDFA Components

Method

Quite a lot can be learned about the EDFAs amplification capabilities by amplifying nothing but the noise it produces. Since amplified spontaneous emission (ASE) amplifies everything, it is possible to observe the amplification of just the noise to determine which wavelengths are preferentially amplified by the EDFA.

First, the 980nm pump laser is attached to the WDM, with the output end of the WDM attached to the Er-doped fiber, and with the 1530nm input covered. The Er-doped fiber is then connected to the OSA. The amplification levels were recorded for pumping powers of 30, 40, 50, 100, and 200 mA, while observing a wavelength range of 1500-1620nm, which is the range of the tunable laser system to be used later. The amplification was also observed over a range of 500-650nm in effort to observe the energy level of Erbium that corresponds to green light at a wavelength of about 550nm.

For characterization of the singular components of the EDFA, each piece was connected between the white light source and the OSA. All three of the connecting fibers were tested, as were both isolators, the Erbium-doped fiber and the WDM. The wavelength range for these tests was from 500-1750nm.

Results

The plot of the data for all powers of the ASE is shown below in Chart 1. The mean peak wavelengths for pumping powers greater than 40 mA are: 1531nm, 1544.5nm, and 1554.7nm. All pumping powers show strong amplification over the range 1520-1570nm.

Green emission was certainly observed when pumping with the 980nm laser at 200 mA. The peak of this green emission is at approximately 560nm. The plot of the data taken for this is shown below in Chart 2. Values below -65 dB essentially show no emission.

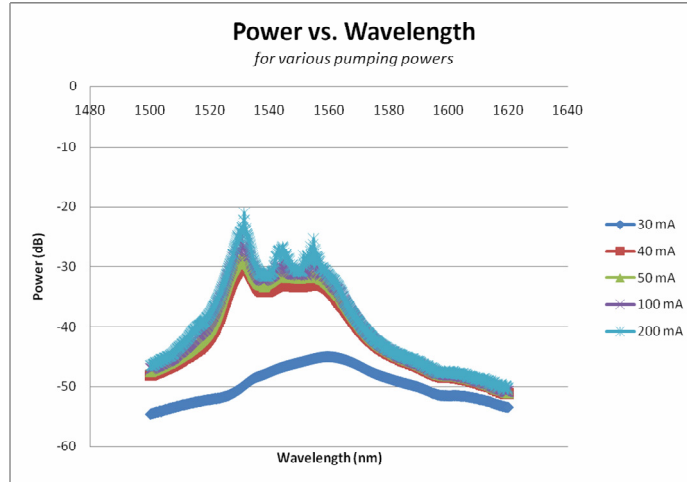


Chart 1 – Plot of output power readings for various pumping powers from the 980nm pump laser over a range of 1500-1620nm.

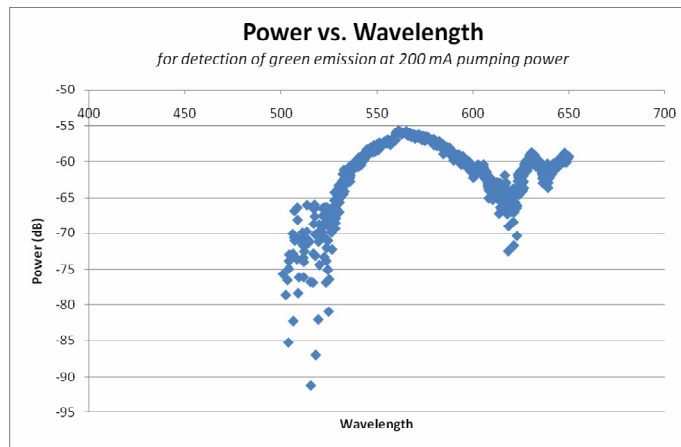


Chart 2 – Plot of output power readings for 200 mA pumping power from the 980nm over a range of 500-650nm.

After testing the three connecting fibers, all showed nearly the same attenuation across wavelengths, proving the functionality of the fibers. The plot of the fibers is shown below in Chart 3.

Checks for both isolators were performed. Since the isolators are meant for use around 1550nm, they should only permit light waves within a relatively narrow range of this wavelength. As can be seen in Chart 4, the isolator N1 did not permit wavelengths over the proper range and was therefore not used throughout the rest of the experiment. Fortunately, the setup only required the use of one isolator.

The check of the Erbium-doped fiber was the last component to be functionally checked. The dips seen in the plot of Chart 5 shows but a few of the many energy levels associated with the element, Erbium.

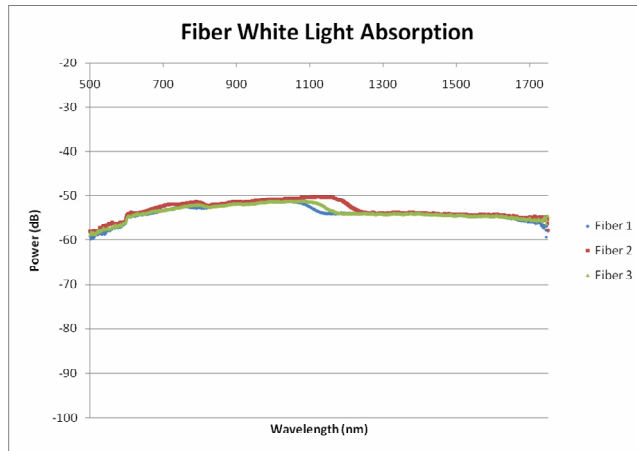


Chart 3 – Absorption patterns of the three connecting fibers. All are approximately equal, and functioning according to standards for this experiment.

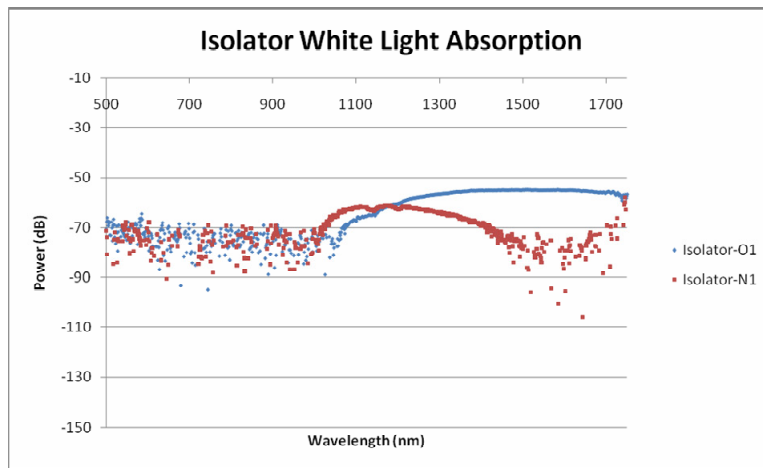


Chart 4 – Absorption pattern for the two 1550nm isolators. The N1 isolator was malfunctioning, and did not permit light to pass at the 1550nm wavelength, therefore rendering it useless for the needs of this experiment.

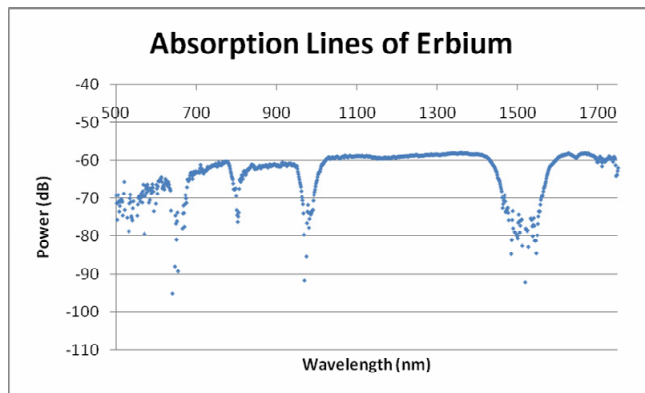


Chart 5 – Absorption patterns for the energy levels of Erbium

II. Measurement of Gain Characteristics for the EDFA

Method

The first step in measuring the gain characteristics of the EDFA is to determine the operating parameters of the tunable laser source. It is necessary to do this the output power vs. current decreases dramatically toward the lasers' limits. To do this for the tunable laser, it is connected directly to the OSA. The current is set at a value greater than 85 mA, and five individual wavelengths are tested to determine the output power vs. current relationship for each. For each wavelength, the laser current is adjusted until the output power reaches a value of 0 dB, and adjusted again to achieve an output power of -10 dB.

Once these standards are determined, the tunable laser is connected to the '1530' input of the WDM. The 980nm pumping laser is connected to its associated input on the WDM as well. Next, the output of the WDM is attached to the Erbium-doped fiber, which is then connected to the 1550nm isolator, which in turn is connected into the OSA. Using the currents for each laser wavelength that are associated with the 0 dB and -10 dB, the pumping laser is set at 0, 100, and 200 mA, and the output current is measured. Upon completion of gathering this data, it can be used to calculate the gain of the system.

Further data is collected in effort to determine the independence of the threshold pump power from the input power. To do this, three powers of signal input are chosen, and for each of these, the power of the pump laser is increased and the gain recorded. The resulting plot of this data leads to the determination of the threshold pump power

The conversion efficiency was also to be calculated for the system. This was done at a steady wavelength of 1560nm.

Results

The resulting table of data for measuring the output power vs. current for the tunable laser is shown below.

Wavelength	1519.84	1529.76	1539.8	1549.92	1560.24
Current for -10 dBm (mA)	70.2	56.6	52.8	49.6	44.1
Current for 0 dBm (mA)	116.1	128.5	100.1	107.1	94.2

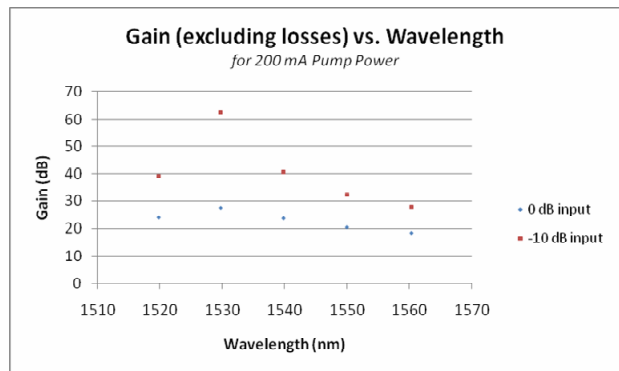
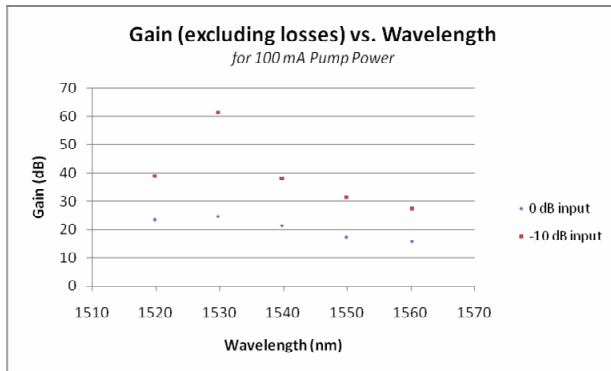
Table 1 – Data showing the current vs. output power relationship for the tunable laser source

The table showing the data collected is shown below for the tunable laser running through the EDFA and being pumped by the 980nm laser at multiple powers.

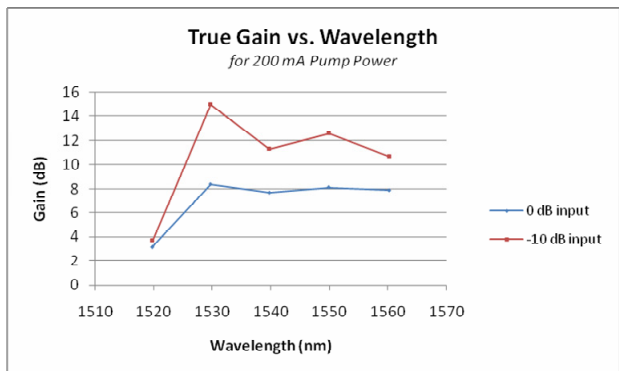
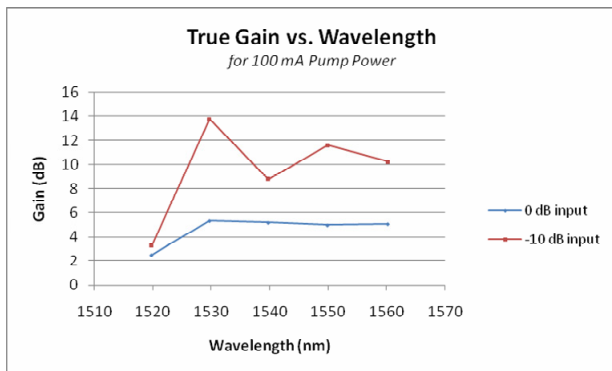
	Wavelength	1519.84	1529.76	1539.8	1549.92	1560.24
Input Power (dBm)	Pumping Power (mA)	Output Power (dBm)				
-10	0	-45.6	-57.6	-39.3	-29.75	-27.27
-10	100	-6.7	3.8	-1.2	1.6	0.27
-10	200	-6.3	5	1.3	2.6	0.72
0	0	-20.9	-19.2	-16.12	-12.3	-10.5
0	100	2.5	5.35	5.2	4.99	5.09
0	200	3.2	8.4	7.7	8.15	7.9

Table 2 – Data showing the input power vs. output power for multiple pumping powers of the 980nm laser over a range of signal laser wavelengths.

The charts relating these relationships to the gain of the lasers are shown below.



Charts 6 & 7 – Graphs of the gain vs. wavelength for the tunable laser, neglecting losses, at 100 mA and 200 mA, respectively.



Charts 8 & 9 – Graphs for the gain vs. wavelength for the tunable laser, taking losses into account, at 100 mA (and 200 mA, respectively).

The values obtained for determining the threshold pump power are listed in the table below.

Pump Current (mA)	Pump Power (mW)	-2 dB Signal	-5.6 dB Signal	-18.4 Signal
10	0.1	-16.13	-25.96	-45.45
15	0.25	-16.01	-25.34	-45.05
20	1	-9.71	-15.08	-35.8
25	4	-4.87	-8.49	-21.43
30	8	-3.14	-4.69	-15.03
35	12	-1.47	-2.38	-10.88
40	16	-0.18	-1.12	-9.01
50	24	1.2	0.35	-7.19
60	32	2.41	1.77	-8.07

Table 3 – Data showing the input power vs. output power for multiple pumping powers and multiple signal laser powers at a single wavelength. This was used for determining the threshold pump power.

With the values above plotted in terms of true gain, the threshold pump power becomes apparent. Based from this plot, the threshold pump power is: $P_P^{th} \approx 4 \text{ mW}$.

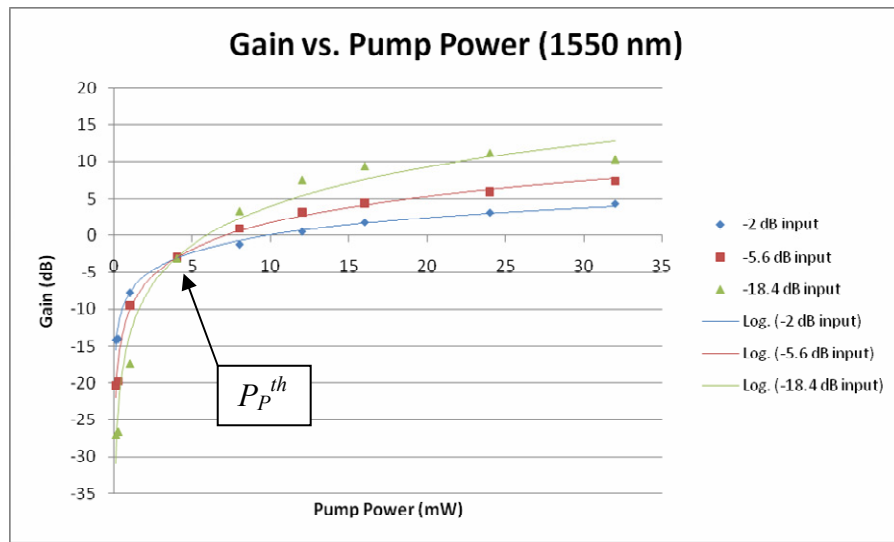


Chart 10 – Logarithmic plot of Gain vs. Pump Power. The point at which the trendline of the three input powers converge is the threshold pump power.

The following table shows the results of calculations for conversion efficiency, η . The theoretical maximum for this value at 1550 nm is calculated to be

$$\eta_{max} = \lambda_{pump} / \lambda_{signal} = 980 \text{ nm} / 1550 \text{ nm} = 0.63$$

The values in the table appear to approach this value with greater pump power, and even more so with lower signal power.

Pump Current (mA)	Pump Power (mW)	Conversion Efficiency		
		70.2 mW Signal	50.6 mW Signal	39.1 mW Signal
20	1	70.20	50.60	39.10
25	4	17.55	12.65	9.78
30	8	8.78	6.33	4.89
35	12	5.85	4.22	3.26
40	16	4.39	3.16	2.44
50	24	2.93	2.11	1.63
60	32	2.19	1.58	1.22

Table 4 – Data and showing the pumping power and calculated values for conversion efficiency using the data taken for calculating the threshold pump power.

Error Analysis

The biggest source of error in this experiment is undoubtedly the relative unreliability of the measurement of the output power on the OSA. For some of these measurements, especially the values with lower power, the plot would jump back and forth over a range of nearly 5 dB. The data was taken at the most reliable of these points, the values at which the signal was recorded the majority of the time. While this error analysis is certainly limited on the quantitative side, it is safe to say that all of the measurements of power are accurate to within ± 3 dB. Since the largest variation that were seen were of magnitude 5 dB, and the average reading for all was in the middle of these ranges, the error is limited to half of this range.

The gain calculations were also affected by this measurement error. For the gains not taking loss into account, the errors were ± 6 dB. However, in calculating the true gain, the error was closer to ± 3.5 dB, since the measurements for setting the power output to 0 dB and -10 dB had an error of under ± 0.5 dB.

Conclusion

Overall, this experiment was very interesting. Fiber optics are becoming more and more a part of daily life, from lighting up Christmas trees, to carrying our bandwidth for the internet. It was very good to see what methods go into making communication work over such systems.

Nearly all of the data collected match very well with expectations. The only discrepancies that appeared came in the measurements for true gain when pumping the signal laser with the 980 nm laser. The 1540 nm wavelengths had lower gain than was expected, but this falls within the range of error allowed. Also, the small number of data points very likely played a role in this observation.