Er-Doped Fiber Amplification

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Using a length of optical fiber doped with the element Erbium, an optical fiber amplifier for light between an ultraviolet 1525 nm and 1600 nm source laser was created, pumped by a fixed frequency 980 nm laser. Utilizing an optical spectrum analyzer (OSA), the amplified spontaneous emission characteristics of the Erbium fiber. Next, each component of the amplifier system is characterized by passing white light through the component directly into the OSA. Next, after calibrating the current required to produce a given power in the tunable source laser for a number of frequencies, the gain of the amplifier was measured for two different pump powers. Finally, the threshold pump power, the pump power that produces zero gain, is measured and determined to be independent of input power.

I. INTRODUCTION

As no optical fiber is perfectly transparent, optical signals sent through fiber will be attenuated. The use of Erbium doped fiber amplification can combat this attenuation without having to convert the initially optical system to an electrical signal, and then back, as would be necessary in a standard amplification scheme. The Er-doped fiber amplifier was constructed in the following way. A tunable laser (outputting between 1500 nm and 1620 nm) was used as the signal laser, and a fixed frequency 980 nm laser was used as a pump. The pump and source beam are combined using a wavelength division multiplexer (WDM), the output of which is sent through a length of optical fiber doped with Er^{3+}. Inside the doped fiber, the pump laser excites the Erbium ion into one of its excited states that has a comparatively long lifetime. Via stimulated emission, the source light causes the excited ion to radiate a photon of the same wavelength and direction as the source photon, which is the actual mechanism of amplification. However, the excited ion can also radiate spontaneously, which in essence would produce a ”noise” photon, which is a limitation of the EDFA system. The amplified light and the pump light are then passed through a fiber optical isolator, which helps to reduce back reflection, filters out the 980 nm pump light, leaving only the amplified signal light as the isolator’s output.

The analysis of the EDFA system will begin with observing the amplified spontaneous emission (ASE) of the erbium doped fiber, in which only the 980 nm light is passed though the WDM and subsequently the Er-doped fiber. Analysis of the resulting signal on the OSA will be the amplification of the noise (as described above), and as this noise can be considered ”white”, peaks in the resulting spectrum analysis correspond to frequencies preferentially amplified by the EDFA system. Preferential frequency amplification, for such applications as communications, is a undesirable characteristic; the more flat the ASE curve, the more equally different frequencies of an input signal will be amplified.

The absorption properties of each of the components of the EDFA system, the connecting fiber, the WDM, the Er-doped fiber, and the optical isolator, will be measured by passing white light directly through each component, then directly into the OSA, not only to characterize them, but to determine that component’s viability and purpose in an optical fiber amplifier. After this, the gain characteristics for different pump powers will be analyzed and plotted.

II. PROCEDURE

A. Measuring the ASE of the Er-doped Fiber

To determine the ASE of the Er-doped fiber, first connect the output of the 980nm laser to the input of the WDM marked 980. Place a cap over the end of the 1530 input. As this input will not be used, using a cap is good practice as the laser power levels used in this experiment are not eye-safe. Next, connect the output of the WDM to the Er-doped fiber. Finally, connect the loose end of the Er-doped fiber to the input of the OSA. Turn on the OSA and the temperature controller for the 980 nm laser, and make sure the temperature of the 980 laser system stays between 21.9 and 22.1 degrees C. During this entire experiment, the temperature should never stray from this range. On the OSA, set the wavelength span to scan between 1500nm-1620nm, with a resolution of 0.5nm, an averaging of 3, and the sweep set to repeat. Next, with all connections secure, turn on the power to the 908nm laser, and increase the 980 current up to 30.0mA. After waiting a few seconds for the OSA output to settle, save this result to floppy disk. Then, repeat this procedure for 980 currents of 40mA, 50mA, 100mA, 200mA, saving each OSA output to the floppy disk. This will demonstrate how quickly the amplifier becomes saturated.

To detect the green emission of the Er-doped fiber, first set the OSA to scan between 500nm and 650nm, and then turn the 980 nm current up to 200mA, and attempt to observe a peak in that region that does not dip down below -60dBm. This is the green emission that is most robbed of energy by the emission at 1530nm. Save this data to disk as well.

B. Characterizing the Components of the EDFA System

In this section, the absorption properties of each of the components of the EDFA system in use will be characterized. Specifically, the components analyzed will be each piece of connecting wire, the optical isolator, and the Er-doped fiber itself. Connect each one of these components directly to the output of a white light source, and also directly to the input of the OSA. Set the settings of the OSA to scan between 500nm to 1750nm, and the resolution to 10nm, the lowest allowed by this wavelength range. After once again letting the OSA output settle to constancy, save this OSA output to disk. Repeat for each other component in the EDFA system.

C. Determining the Gain Characteristics of the EDFA

1. Measuring the Operating Parameters of the Tunable Laser

To measure the gain of the EDFA system, we must first determine what currents of the tunable laser correspond to what power at a given wavelength. Do do this, connect the tunable laser output directly to the input of the OSA. Next, set the OSA to scan between 1550nm and 1570nm. This time, set the averaging to one sweep, so that the OSA might be quickly responsive to a change in signal, and then set the resolution to 0.2 nm. With the connections secure, turn on the tunable laser and cooling. Tune the frequency of the tunable laser such that the center of the laser spectrum peak on the OSA is 1560nm (or as close as possible), and then record this value of wavelength. Next change the current of the tunable laser such that the peak of the laser spectrum is -10.0dBm±0.5dBm, and record this value. For 1560mn again, then find the current that produces 0.0dBm±0.5dBm. These will be used as reference values further on in the experiment. Repeat this entire procedure for 1550nm, 1540nm, 1530nm, and 1550nm tunable laser light.

2. Measuring the Gain of the EDFA

Now the EDFA will be fully assembled, and it's gain characteristics measured for different wavelength and pump powers. To do this, make the following connections. First, connect the 980nm laser output to the 980 input on the WDM. Next, connect the tunable laser output to the input of the WDM marked 1530. Connect the output of the WDM to one end of the Er-doped fiber. Connect the loose end of the Er-doped fiber to the input of the optical isolator, and finally connect the output of the optical isolator the input of the OSA. Starting with a wavelength of 1560 nm, set the OSA to scan a range 20nm wide centered on this value. On the OSA, make sure the tunable laser is outputting at a wavelength that is as close to the value used above for 1560 nm as possible. For pump (980nm) laser currents of 0mA, 100mA and 200mA, set the current of the tunable laser such that it will output -10dBm of power (recorded in the previous section), and using the "peak search" function of the OSA, record the power at the peak of the EDFA output spectrum. Repeat this procedure for the tunable laser current set such that it will be outputting 0dBm of power. Then repeat this entire procedure for wavelengths of 1550nm, 1540nm, 1530nm, and 1550nm tunable laser light. From the values of the EDFA output power with zero pump power, a measure of the losses inherent to the system can be made. From all these data, calculate a value of the gain without including losses, and a value of the true gain (including losses), and plot them as a function of wavelength for the two different signal powers.

D. Measuring the Threshold Pump Power

The threshold pump power can be defined as the pump power that produces zero true gain, and ideally should be independent of input power. To measure this, maintain the setup as when measuring gain, and select three input

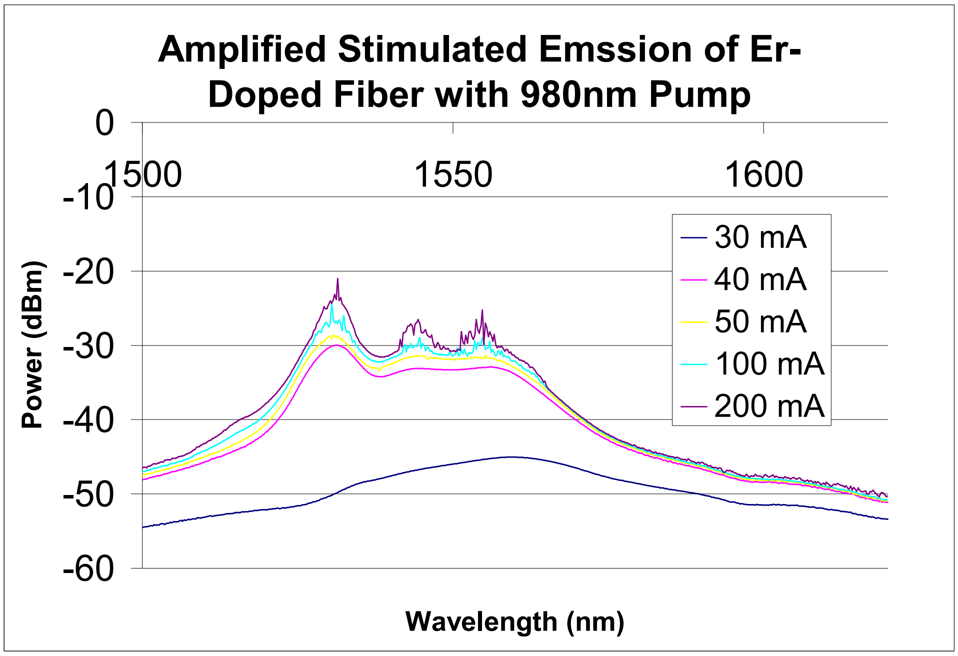

FIG. 1

currents (which correspond to powers), over which to measure Gain vs. pump power. For each of these three currents at a given wavelength, determine as before the power output of the tunable laser by connecting it directly to the OSA, and record these three values, which will be necessary to calculate gain. Next, with the amplifier fully constructed as before, increase the pump current in given intervals between 15mA and 60mA, at each interval recording the value of the EDFA power output. Repeat this process for the other two input powers. Next, for every value of the pump current at which data was taken, determine the power output by disconnecting the pump laser with power off, placing the tip of the fiber very close the surface of the power meter, and shielding it with the iris of the meter, record the power output for each current. Plot the three gain curves, one for each input power, as a function of the pump power. The intersection of the three curves with zero gain (and their common intersection) is then the threshold pump power.

III. EXPERIMENTAL RESULTS

A. Measuring the ASE of the Er-doped Fiber

The amplified stimulated emission of the Er-doped fiber was gathered and is plotted in FIG.1 for various 980nm pump laser currents. From the closeness of the 100mA curve to the 200mA curve, it may be inferred that the system is close to reaching full saturation at 200mA. Especially from the 200mW curve, we may also locate wavelengths that will be preferentially amplified, which correspond to the peaks of the ASE curves. Furthermore, the shape of the ASE should also be roughly similar to that of the gain curve (without losses), as once again this curve is an indication of the wavelengths of signal light that will be preferentially amplified.

With the current of the pump laser set to 200mA, the ASE in the green wavelength range was gathered, and is plotted in FIG.2. Though this ”peak” is of a much lower magnitude than those of FIG.1 (the 1530nm emission robs it of energy), the smooth curve above -60dB is a definite indication of green light emission. Furthermore, for high pump powers, when the cover of the Er-doped fiber container was removed, this green emission was visible to the naked eye.

B. Characterizing the Components of the EDFA System

All white light absorption spectra were analyzed between 500nm and 1750nm. The white light absorption of the three pieces of connecting fiber used throughout the remainder of the experiment was gathered and is plotted in

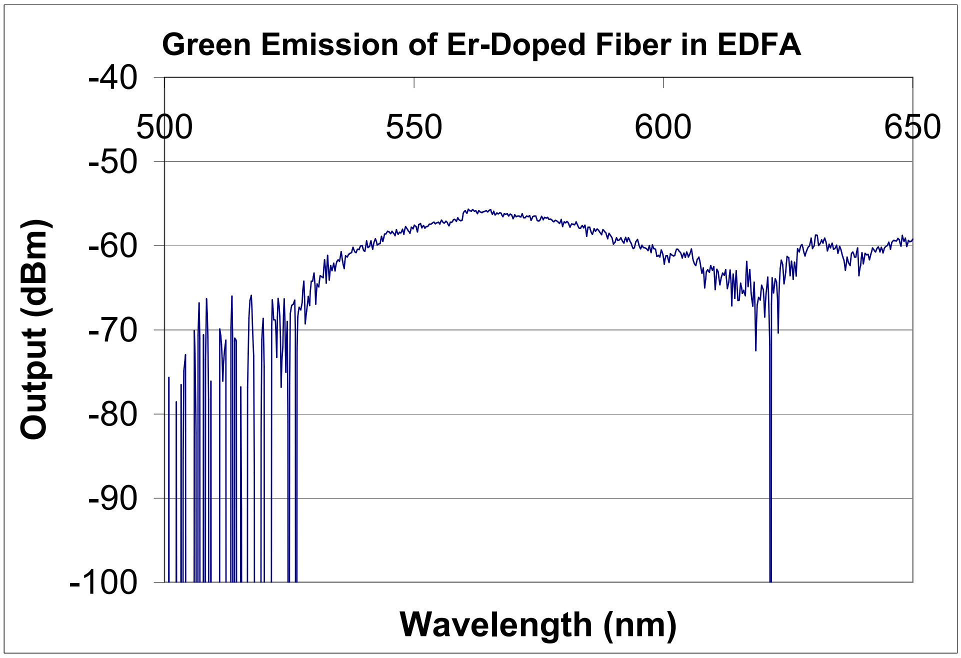

FIG. 2

FIG.3. From this figure, the relatively flat-band behavior of the connecting fiber is demonstrated. This is precisely the desired behavior for the connecting wire, as for any application the transmission line should enact no appreciable change on the signal. Thus, from these curves, the three connecting fibers were determined to be in good working order.

The next component to be analyzed was the absorption of the erbium fiber itself. This absorption was gathered and is plotted in FIG.4. From this plot, the many energy energy levels (which correspond to the dips in the plot) are readily visible. In particular, this figure includes emission from the three energy levels that are used in EDFA systems, namely $E_2 - E_1 \rightarrow$1530nm emission, as well as $E_3 - E_1 \rightarrow$980nm emission.

Next, the white light absorption of the two optical isolators available in the lab were gathered and are plotted in FIG.5. We expect that the optical isolator should not pass light around the region of 980nm (as this is one of its functions in the EDFA system), and should pass light in the 1500nm-1550nm range. This is indeed what was found for isolator 1: all light with wavelength less than approximately 1100nm (and within the plot range) is shown to be absorbed, and all light above 1100nm (up to at least 1750nm) is passed in a relatively flat-band fashion. Isolator 2 did show similar absorption of all light below 1100nm, however, a second region of absorption was observed for light of wavelength greater than 1400nm (at least up to 1750nm), which is squarely in the region of the signal wavelength, which deems isolator as wholly unacceptable for use in the EDFA system. Thus, for the remainder of the experiment, only isolator 1 was used.

C. Determining the Gain Characteristics of the EDFA

As the all powers associated with the output of the EDFA have been measured in dBm thus far, the gain of the system without including losses is then defined as difference between the power output of the system with zero pump power and the pumped output. Similarly the true gain (which includes losses) is defined as the difference between the input power and the output power. Gain was measured for four system configurations: input powers of both 0dBm and -10dBm, as well as pump laser currents of 100mA and 200mA. The gain without including losses is plotted in FIG.6, and the true gain of the system is plotted in FIG.7. The prediction that the shape ASE of the should resemble that of the gain without losses is qualitatively apparent, however, the number of data points is too low to be conclusive on this matter. Unsurprisingly for both gain definitions gain increases as the pump current is increased from 100mA to 200mA. It is also apparent from these figures that the system produces more gain for the an input power of -10dBm, for any wavelength. A rough error estimate may be inferred from the fluctuations of the OSA (set to one sweep averaging) during measurement. We found for a typical measurement of power, the value would fluctuate around ±0.5dBm. Thus, as the gain is the difference of two power measurements, any gain measurement has therefore an error of ±1.0dB. This is a vast simplification of the system, however, as the error was much greater for some measurement and smaller for other. For instance, measurements near the strong 1530nm emission were quite uncertain; the power output varied by up to a few dBm. However, this was uncharacteristic of the entire span of measurements, and thus the above error estimate suffices for error analysis.

D. Measuring the Threshold Pump Power

The measurement of true gain (including losses) as a function of pump power was taken three times: for a input powers of -18.4dBm, -5.6dBm and -2.0dBm, the data from which is plotted in FIG.8. Theoretically the threshold pump power should be independent of the input power, and though the ”curves” in FIG.8 do have a common intersection at 4mW, this does not correspond to zero gain. The curves would intersect the the zero gain line in relatively different places; I asses the range through which these curves may intersect the zero gain line to be between pump powers of 5mW and 11mW, which is also an estimate of the error of this measurement.

E. Conversion Efficiency

The conversion efficiency of the EDFA amplifier is defined as the ratio of the input power to the output power, both of which are expressed in mW. It’s theoretical maximum is the ratio of the pump wavelength to the signal wavelength. The conversion efficiency was calculated for the gain measurement in which the input power was -10dBm, and the pump current was set to 100mA, and both this and the value of the theoretical maximum is plotted in FIG9 as a function of wavelength. From this we see that thought the EDFA is a useful amplification tool, this system was operating well below it’s theoretical maximum efficiency.

IV. CONCLUSIONS

In this lab, the ASE of a length of erbium doped was measured various pump powers, and the white light absorption of each of the components of the EDFA system were gathered and plotted, allowing an analysis of the functionality of each system component. This analysis enabled the removal of a faulty isolator from the potential EDFA system. Then the EDFA system was constructed, and measurements of the gain without loss and the true gain of the EDFA were measured for different configurations of pump and signal power, and the ASE was found to be qualitatively similar to the gain without loss curve. A experimental range of threshold powers was determined, though the independence of the threshold intensity on input power was not demonstrated precisely. Finally, the conversion efficiency of one configuration of input power and pump power was calculated as an example of how far the EDFA in use falls short of the theoretical maximum conversion efficiency.

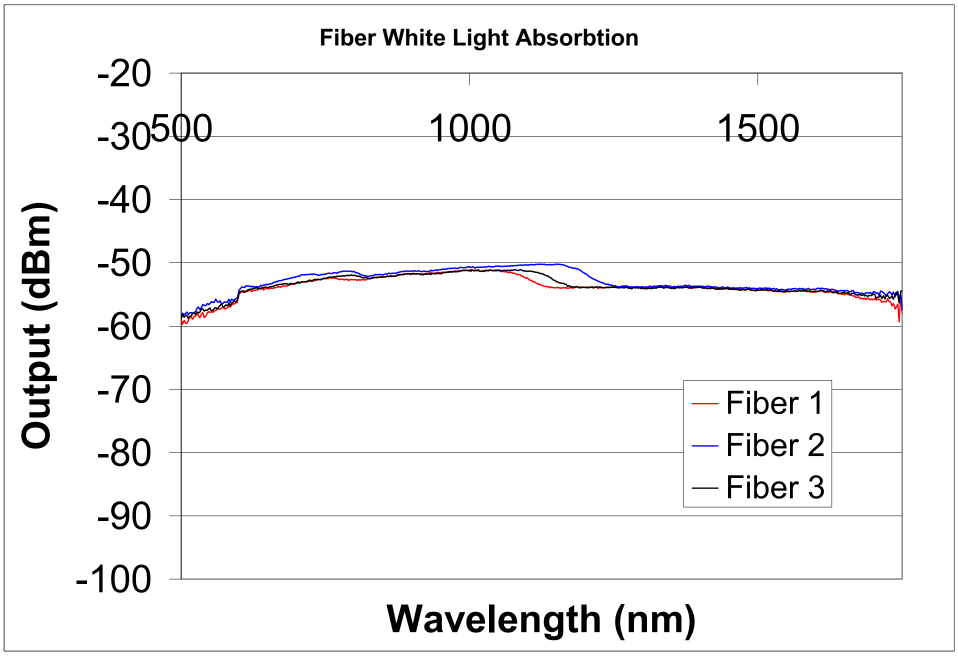
Fiber White Light Absorbtion
-20
-30
-40
-50
-60
-70
-80
-90
-100
500
1000
1500
Output (dBm)
Wavelength (nm)
Fiber 1
Fiber 2
Fiber 3

FIG. 3

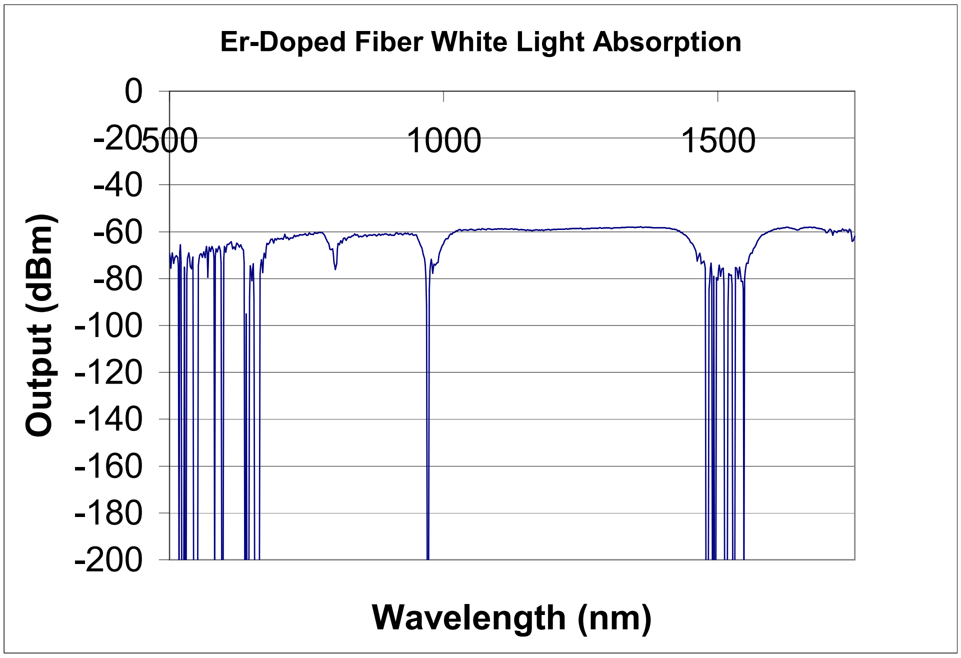
Er-Doped Fiber White Light Absorption
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
500
1000
1500
Output (dBm)
Wavelength (nm)

FIG. 4

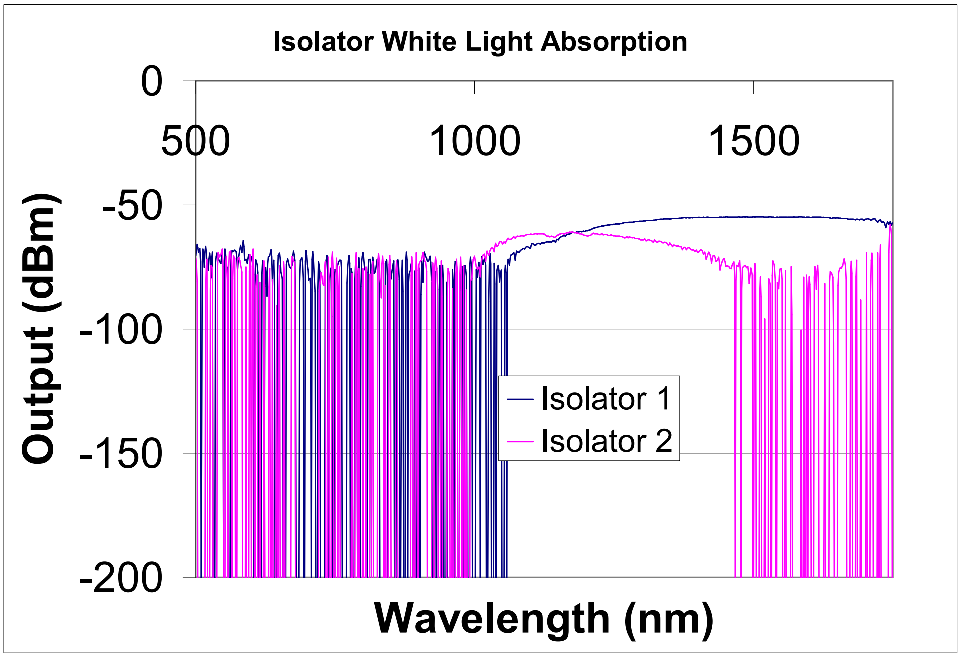
Isolator White Light Absorption
0
500
1000
1500
-50
-100
-150
-200
Output (dBm)
Wavelength (nm)
Isolator 1
Isolator 2

FIG. 5

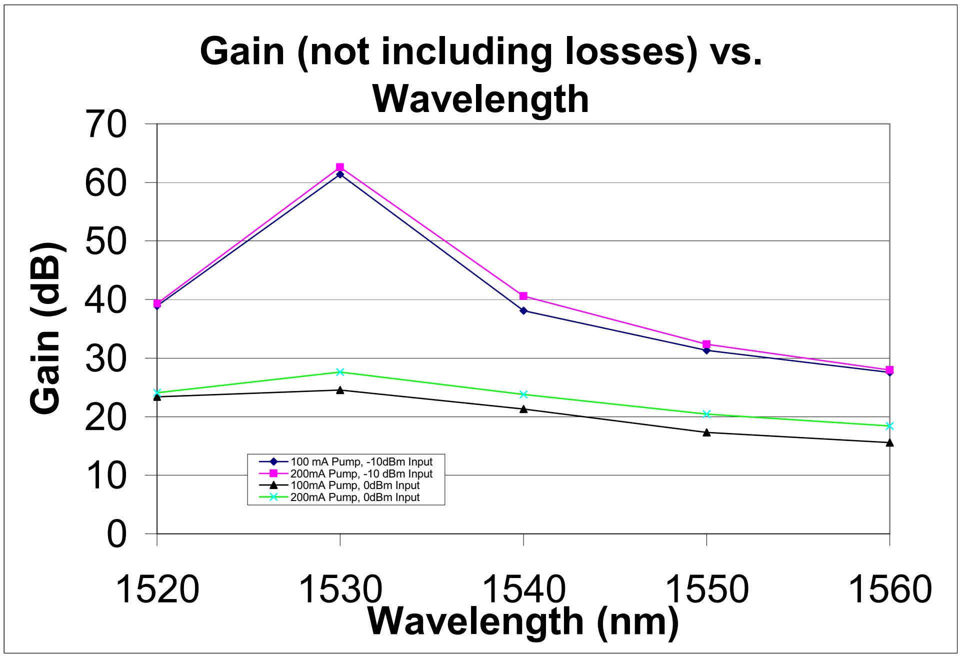
Gain (not including losses) vs. Wavelength
70
60
50
40
30
20
10
0
Gain (dB)
100 mA Pump, -10dBm Input
200mA Pump, -10 dBm Input
100mA Pump, 0dBm Input
200mA Pump, 0dBm Input
1520
1530
1540
1550
1560
Wavelength (nm)

FIG. 6

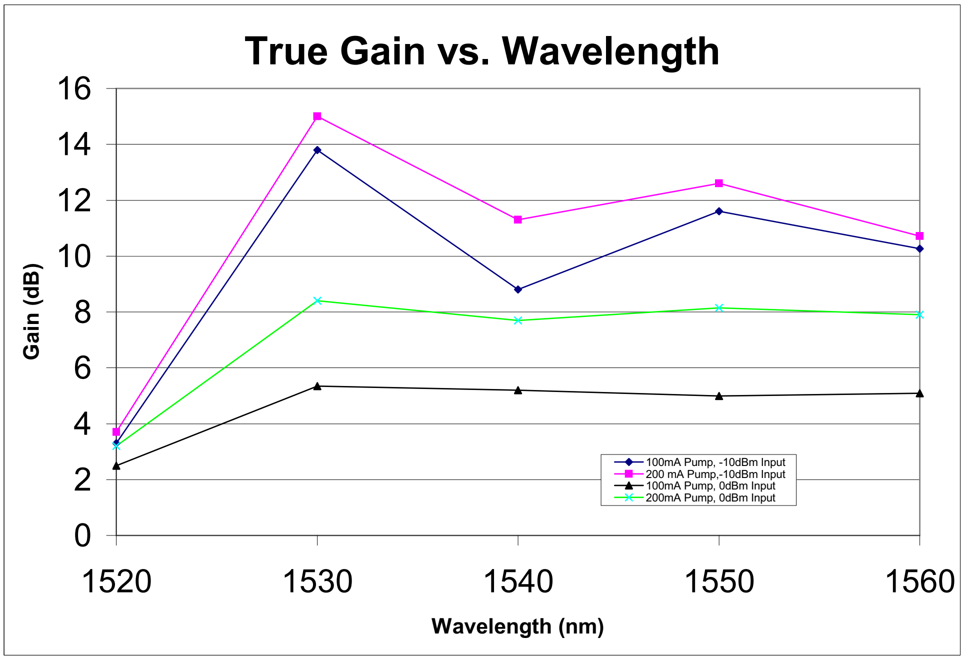
True Gain vs. Wavelength
Gain (dB)
16
14
12
10
8
6
4
2
0
1520
1530
1540
1550
1560
Wavelength (nm)
100mA Pump, -10dBm Input
200 mA Pump,-10dBm Input
100mA Pump, 0dBm Input
200mA Pump, 0dBm Input

FIG. 7

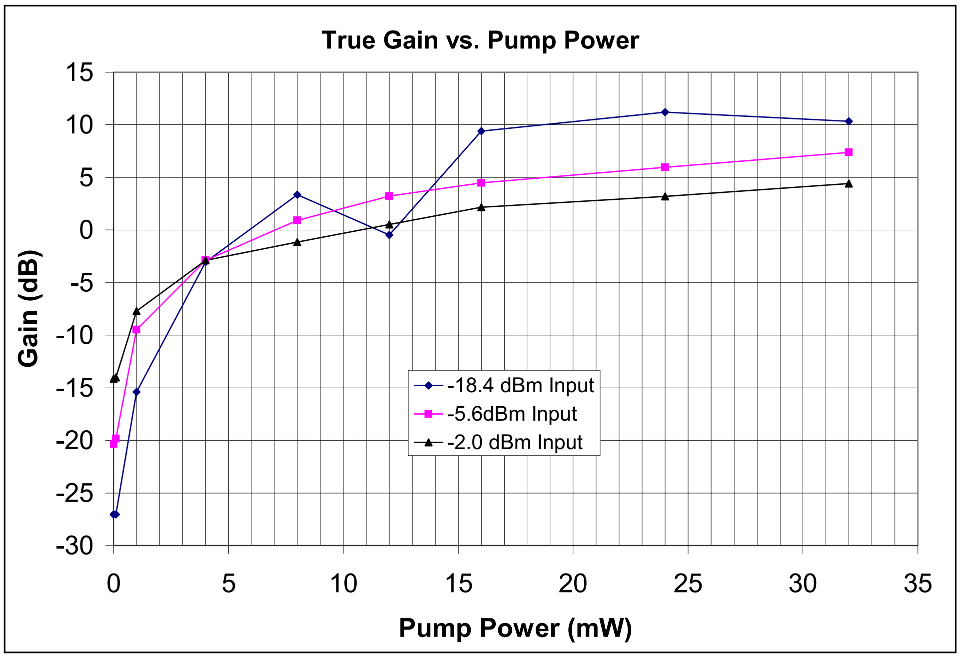
True Gain vs. Pump Power
Gain (dB)
15
10
5
0
-5
-10
-15
-20
-25
-30
0
5
10
15
20
25
30
35
Pump Power (mW)
-18.4 dBm Input
-5.6dBm Input
-2.0 dBm Input

FIG. 8

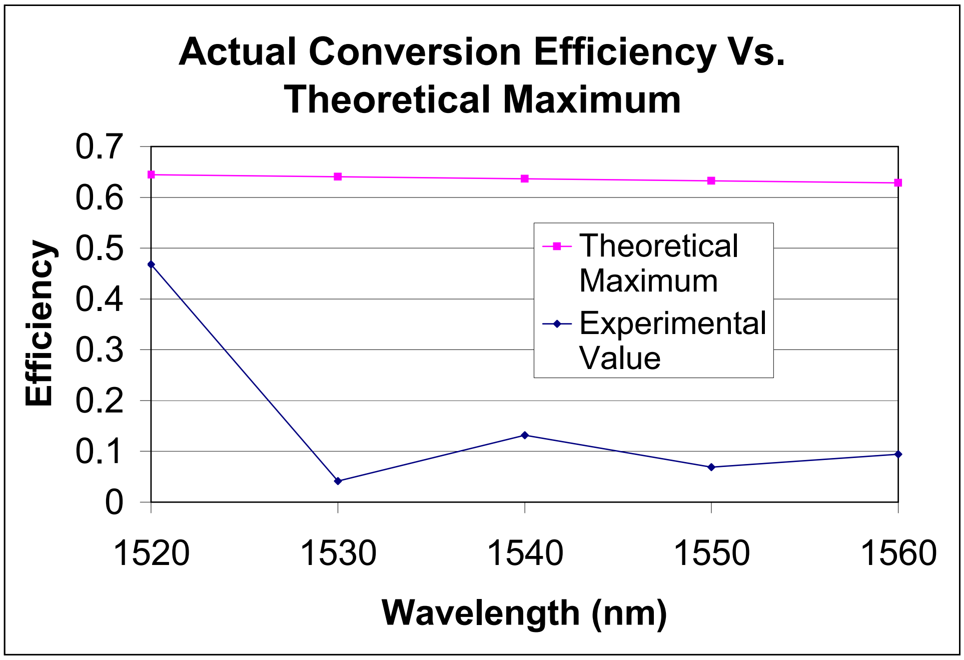
Actual Conversion Efficiency Vs. Theoretical Maximum
Efficiency
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1520
1530
1540
1550
1560
Wavelength (nm)
Theoretical Maximum
Experimental Value

FIG. 9