LEHIGH UNIVERSITY PHYSICS DEPARTMENT

Photonics Laboratory Manual

Fall 2004

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Lab 1

Erbium-doped fiber amplifier (EDFA)

Create and characterize a system capable of coupling power at 980nm or 1480nm into an Er-doped fiber which amplifies an incoming signal at 1525-1600nm

Required equipment:

- 1525 to 1600nm tunable laser source (including power and cooling)
- Either:
    1. 980nm laser source (including power and cooling) and 980/1550nm WDM (wavelength division multiplexer)

  Or:

    2. 1480nm laser source (including power and cooling) and 1480/1550nm WDM
- Two 1550nm isolators
- Er-doped fiber (approx. 18.5m)
- OSA (optical spectrum analyzer)
- Standard fiber and connectors

Objectives

1. Determine the 'gain window' of the Erbium-doped fiber by finding its amplified spontaneous emission (ASE), and determine approximate energy levels by finding absorption by a white light source

2. By tuning the input source, find the gain versus wavelength of the amplifier system for varying pump powers and varying input powers

3. Determine the saturation of the EDFA, and calculate the conversion efficiency

4. Estimate the absorption and reflection loss of each section of the amplifier (fibers, connectors, WDM, isolators)

Part 1 – Understanding the amplifier

You will be able to determine a great deal about the system's amplification abilities without actually amplifying the signal. This section will help you understand some different methods of analysis and how they can be used to understand the results from later sections.

Amplified spontaneous emission (ASE) results from the Er-doped fiber amplifying everything, including noise. Since noise can be considered 'white' (equal for all wavelengths), looking at how much noise is amplified will give us a good idea of which wavelengths are preferentially amplified by our EDFA system.

Note

Fiber connections are very sensitive – always make sure that when connecting fibers, the connectors are aligned and the connections are not over-tightened.

1. Connect the amplification system as follows:
    a. Connect the end of the 980nm laser to the input on the WDM marked '980'
    b. Place a cap on the '1530' input
    c. Connect one end of the Er-doped fiber to the output of the WDM
    d. Connect the other end of the Er-doped fiber to the input of the OSA
2. Turn on the OSA and the temperature controller to the 980nm laser (first push the 'power' button on the left side of the temperature controller and wait until it starts up, then push the 'output' button). The actual temperature should now stay between 21.9 and 22.1°C - if it ever varies from this immediately turn of the current source. If the temperature is set to something other than 22°C, set the temperature by pushing the 'set temp' button and turning the knob to the appropriate value.
3. Set the OSA to the following values:
    a. Span: 1500nm to 1620nm
    b. Setup: Resolution: 0.5nm (the smallest without causing an error)
    c. Setup: Averaging: 3 (will average the last 3 sweeps for display)
    d. Sweep: repeat
4. Ensure the current source is set to 'const I', the limit switch is turned fully CW (otherwise the current supply will not reach 200mA), and the knob above output is turned CCW (so that when output is pressed, the current source will start at 0mA).

Note

Each time before pressing 'output' on the current source, follow the flow of the fibers to make absolutely sure that no connection is left open. Certain parts of these experiments will deal with levels of infrared light that are not eye-safe (are above 10mW), so it is imperative that each fiber ends in a cap or a device.

5. Turn on the current source by pushing the 'power' button, followed by the output button, similarly to how the temperature controller was powered. After the initial value is displayed (should read zero at this point), turn the output knob until 30.0mA is driven through the laser. The OSA should now show a fairly flat range between 1530nm and 1570nm, with two peaks, as shown in Figure 1.

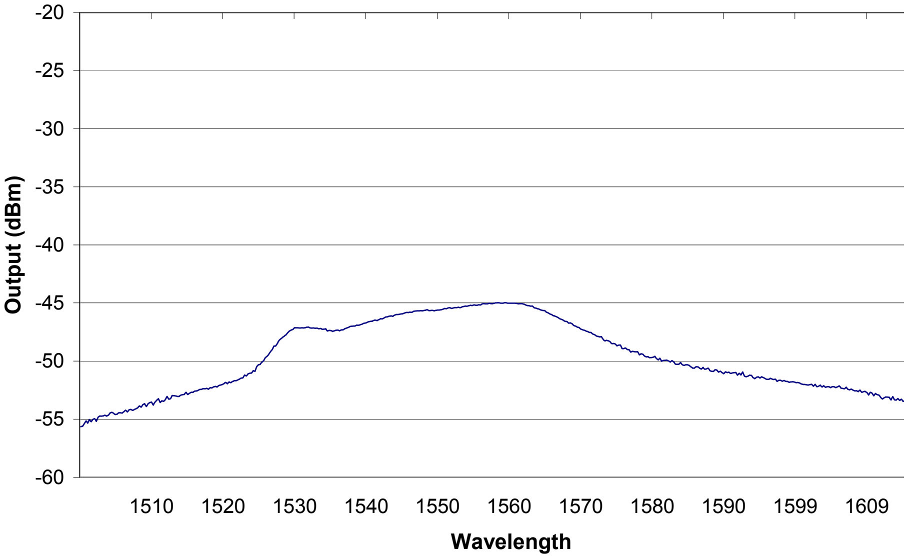
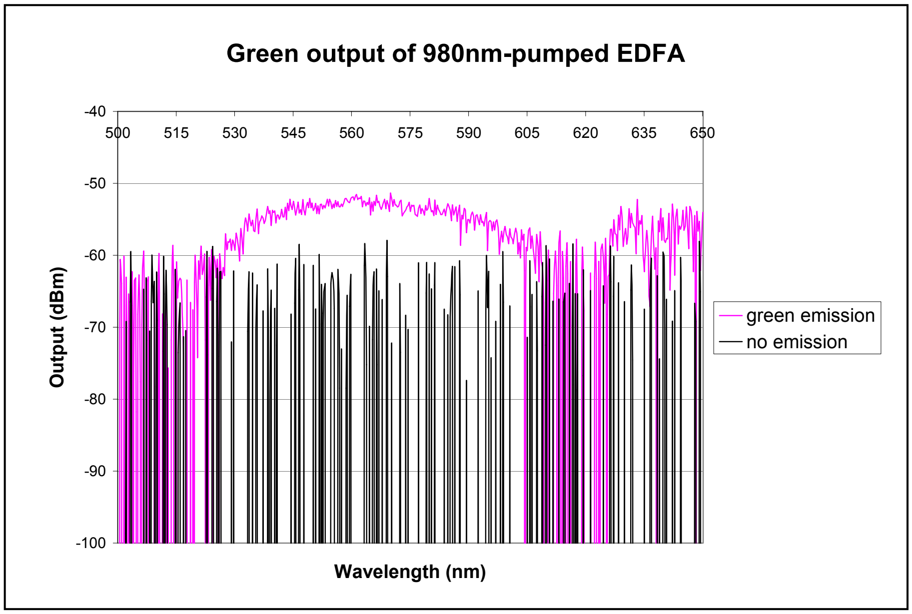


Figure 1. The amplified spontaneous emission of 980-nm pumped Er-doped fiber through a non-isolated WDM at 30.0mA

6. Now save these results to a floppy disk by pressing 'floppy', 'write' (first button from the top next to the display), 'file name' (5th button – use the wheel and enter for letters and the number pad for numbers), done (7th button), execute (7th button), then return (8th button).

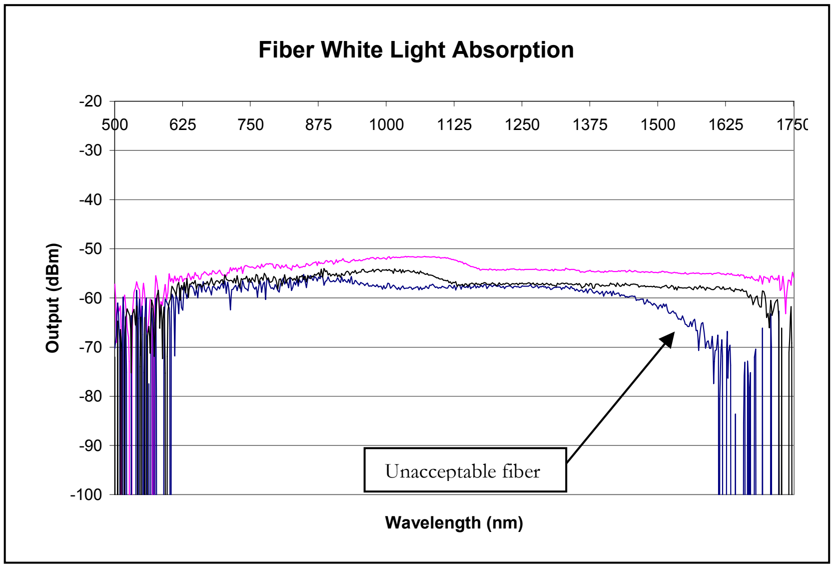
7. Now repeat these results for 40mA, 50mA, 100mA, and 200mA to see how quickly the EDFA system saturates. In your lab report, make sure to note how close the 50mA peak and the 200mA peak are (i.e. 5dB, 10dB, 15dB). This will give you a fairly good idea of which frequencies will be preferentially amplified, and why it is important in communications to create a 'flat-band' amplification system so that some frequencies do not get significantly more amplification than others.

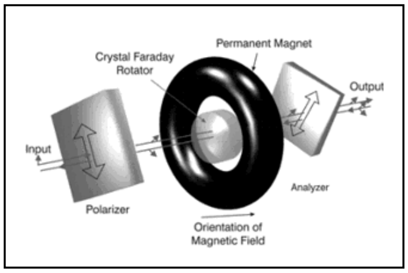
8. One of the energy levels of Erbium happens to be around 550nm (green), but is mostly robbed of energy by the 1530nm emission. With the current source at 200mA, set the span on the OSA from 500nm to 650nm and see if you can detect green emission (look for regions where there are no dips below 60dBm). Turn off the current to the 980nm laser when you are finished.



Now that you have an idea of what the main components of the EDFA system are, it is a good idea to find out exactly how each of the components 'treats' different frequencies of light. To do this, connect each of the following pieces in turn between the white light source and the OSA. Set the span from 500nm to 1750nm, the resolution to the minimum without causing an error (10nm), the average to 3, and remember to save the results of each component to disk.

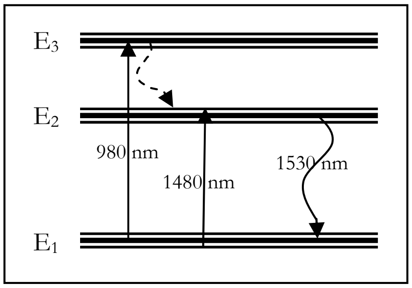
a. Any piece of connecting fiber. In addition to showing how little the fiber affects most wavelengths, this will also show the range of the white light source (becomes irregular below 600nm, and unusable below 500nm). It is a good idea to do this for each piece of fiber you use, to check that the fiber will pass the desired wavelengths without too much attenuation. An example of this is illustrated in the following picture, which shows that one of the fibers absorbs much more of the 1500-1625nm range than the other two fibers (arrow) and should not be used for our experiments.





Behavior of a Faraday rotator optical isolator (www.fiber-optics.info)

b. An optical isolator. If the isolator is aimed at use around 1550nm, it will most likely absorb everything below about 1μm, since it contains magnetically-sensitive materials that do not work for all wavelengths. This is important, since you must remember that these isolators should not be used in between fiber that needs to continue carrying, for example, the 980nm pump laser.



Three energy levels resulting from Er^{3+} doping of silica glass

c. The Er-doped fiber. The 'dips' in this diagram will show the different energy levels. Erbium, like most rare-earth elements, has an immense number of energy levels, three of which are used for EDFA systems ($E_2 – E_1$ = 1530nm, $E_3 – E_1$ = 980nm). Notice that broadening of the energy levels allows pumping at 1480nm (bottom of E_1 to top of E_2) to cause emission at 1530nm (middle of E_2 to middle of E_1).

d. The WDM. It is not necessary to save these results to disk, but notice that sending the white light into the 980 input and measuring at the output results in an almost identical spectrum as sending the white light into the output and measuring at the 980 input. The same is also true for the 1530 input. A WDM can thus be used for combining two frequencies on separate fibers onto one fiber (multiplexing or muxing), as well as taking two frequencies on one fiber and splitting them in two (demultiplexing or demuxing).

Part 2 – Gain characteristics

Now that you understand the limitations of each part of the EDFA, you will investigate the behavior and limitations of the system in amplifying signals. The main task will be to obtain gain vs. wavelength data that will look very similar to the ASE obtained in Part 1 using the 100mA and greater currents.

As you will soon discover, tunable semiconductor lasers can lase at a wide band of frequencies, but the output power vs. current will decrease significantly toward the limits of the lasers. Thus, to be able to obtain data that is consistent over the entire range, you must use the same output power for each wavelength, rather than using the same amount of current.

1. Determine the operating parameters for the tunable laser:

    a. Connect the tunable laser directly to the OSA and turn on the cooling to the laser (in an integrated console, do this simply by turning the key on the console to start the power and the automatic cooling).

    b. Turn on the OSA. Once started, set to the following:

        i. Span: 20nm

        ii. Center: 1560nm

        iii. Setup: Averaging: 1

        iv. Setup: Resolution: 0.2nm

    c. Turn on the laser diode and set the current ≥ 85 mA.

    d. Tune the laser until the output matches the center frequency as closely as possible (make sure there is only one mode – if there are two, tune slightly toward the center frequency until the second mode disappears).

    e. The goal is to find the currents for each frequency that will output both -10 ± 0.5 dBm and 0 ± 0.5 dBm. For 1560 nm, these outputs will occur with input currents between 50-70mA, and 85-105 mA, respectively. Write down these values on the following chart as you acquire them.

	1520	1530	1540	1550	1560
Current for -10 dBm (mA)					
Current for 0 dBm (mA)					

2. Now that you know that the tunable laser is set to 1560nm and what currents are required to output -10dBm and 0dBm to sufficient accuracy, turn off the laser diode and on the OSA, press sweep: stop.

3. Make the following connections:

   a. Connect the tunable laser diode to the input on the WDM marked '1530'.

   b. Connect the 980nm pump laser into the WDM input marked '980' (if not already connected).

   c. Connect the output of the WDM to the Er-doped fiber.

   d. Connect the other end of the Er-doped fiber to the input of the optical isolator, and connect the output of the isolator to the OSA. Once again follow the flow of the fibers to make sure that each fiber is connected at both ends.

4. Turn on the laser diode of the tunable laser and check that the current is still set so that the laser outputs either -10dBm or 0dBm.

5. On the OSA, press 'peak search' to find the level of laser power that is being passed through the system and record this level. Notice that this output power is much less than the amount of energy at the input, which means that the EDFA system must first overcome this 'intrinsic' loss before being able to amplify the system above its original level.

6. Make sure the cooling to the 980nm laser is still set, and pump 100mA of power through the system. Record the output and repeat for 200mA.

7. Repeat these results for the remaining four wavelengths.

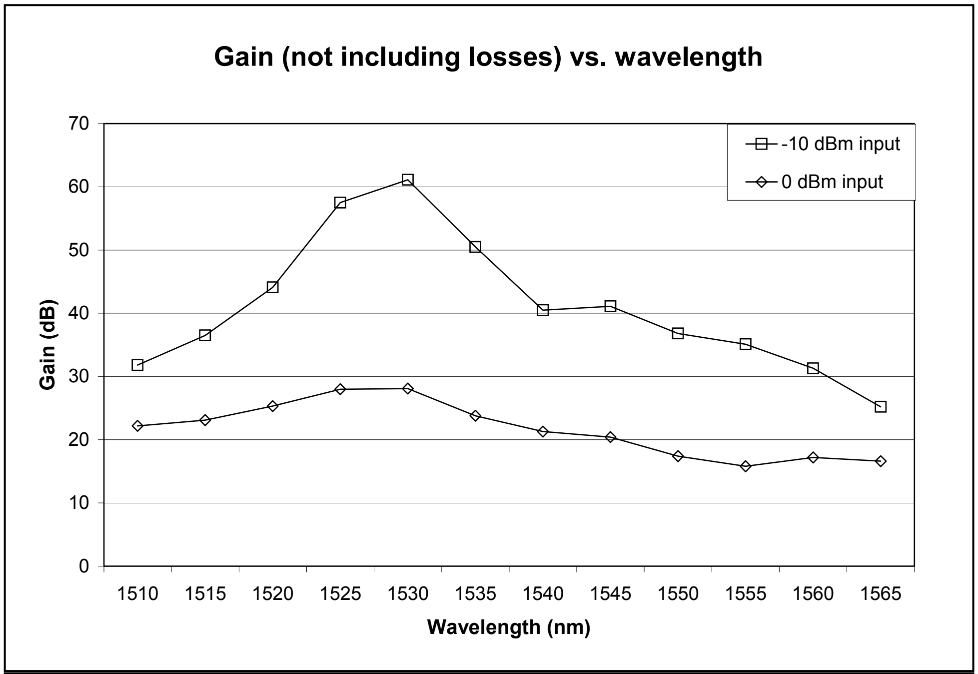
Input power (dBm)	Pump Power	1520	1530	1540	1550	1560
-10	0					
-10	100					
-10	200					
0	0					
0	100					
0	200					

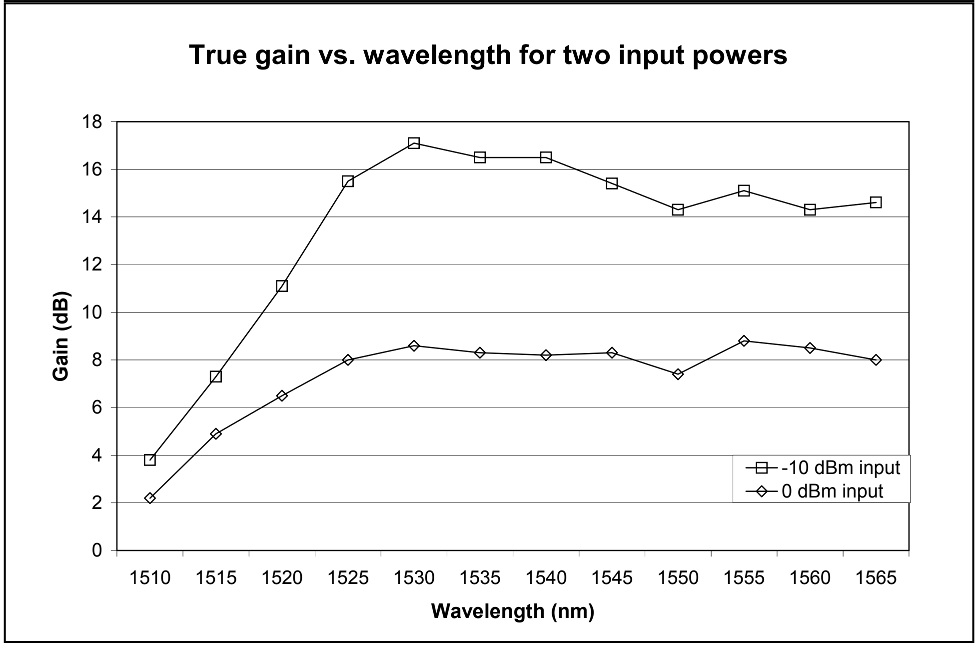
Part 3 – Plots and calculations

With the data you have now collected, you will be able to see how your particular fiber amplifier behaves compared to other fiber amplifiers and amplifiers in general.

Gain vs. Wavelength plot

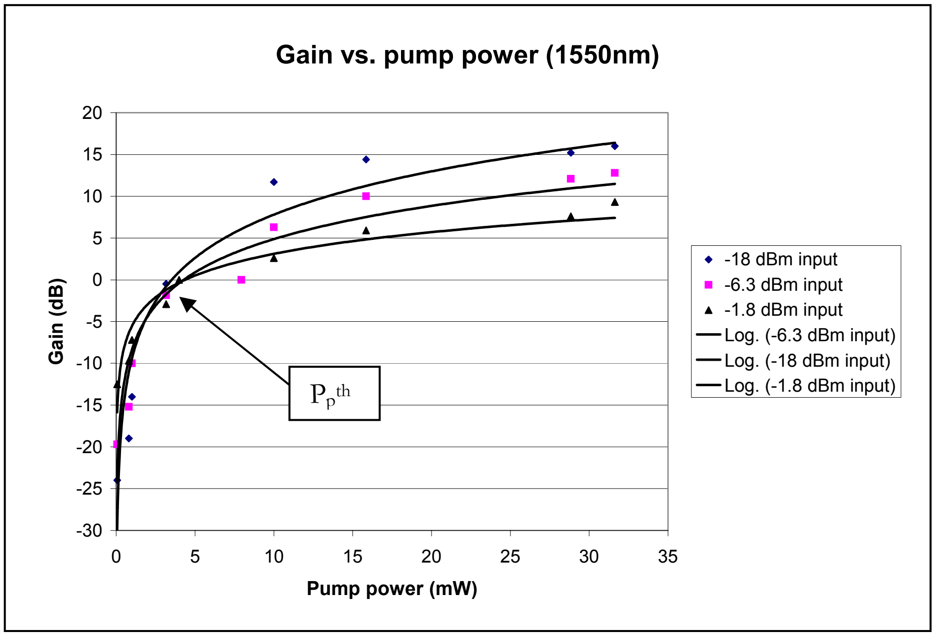
With the data from Part 2, you can now make the following plots. The first should look very similar to the ASE of the 980nm laser, and the second shows the actual gain vs. wavelength after the losses through the system are added.





Threshold Pump Power P_p^{th}

The first calculation is to show that, ideally, the threshold pump power is independent of the input power. The threshold pump power can be defined as the pump power at which the amplifier is transparent (gain is zero). Many factors can affect this value so in your experiments it will not be perfect, but it should be close enough for you to be able to estimate the actual threshold pump power.



Conversion Efficiency η

This calculation will show that although useful, the conversion efficiency of this amplifier configuration is far from approaching the theoretical maximum ($\lambda_{pump}/\lambda_{signal}$). Conversion efficiency can be calculated by dividing the output signal light by the input pump power (both in mW, not dBm).

Stimulated Emission Cross Section σ_s

Knowing this value is very important in designing and evaluating an amplifier system, since many of the gain equations are dependent on the stimulated emission cross section. The following is a simple way to calculate this value, but many of the approximations can be calculated more accurately using better fits.

One of the more difficult steps is to calculate the full-width half-power point of the unfiltered ASE spectrum ($\Delta\lambda$). The other required values (wavelength, refractive index, and spontaneous emission time) are simply constants. To find the FWHP point of the ASE spectrum, you can follow the following steps, or as mentioned above, try more accurate fits.

1. Gather the ASE of the 980nm laser

2. Insert the ASE into a numerical software program, attenuating the main peak to create an amplifier that provides equal gain for the majority of

the spectrum. You are trying to find the FWHP point of the whole spectrum, not just the peak at 1530nm.

3. Find the area under the entire ASE curve, and then, on top of the ASE, plot a Gaussian with the same area. Now adjust the three parameters of the Gaussian (amplitude, mean, and variance) until they best overlap the ASE.

4. Find the FWHP of the Gaussian (the points, in mW, where each side has reduced to half of the maximum). The value should be in the tens of nm.

5. Use this FWHP ($\Delta\lambda$) to compute the stimulated emission cross section as follows:

$$\Delta\nu = c\left(\frac{1}{\lambda-\Delta\lambda}-\frac{1}{\lambda+\Delta\lambda}\right)*10^{6}\ \text{(Hz)}$$

$$g_t(\nu) \sim \frac{1}{\Delta\nu}\ (\text{Hz}^{-1})$$

$$\sigma_s = \frac{1}{8}\frac{\lambda^2 g_t(\nu)}{\pi n_1^{\,2}}*10^{-2}\ (\text{m}^2)$$

Using typical values, the value of σ_s should be in the order of 10^{-25} m^2 (10^{-21} cm^2).

Lab

2

Fiber Laser

Create a fiber laser using a similar setup to Lab 1 with the addition of a fiber grating

Required equipment:

- Fiber gratings at desired lasing wavelength
- Either:
    1. 980nm laser source (including power and cooling) and 980/1550nm WDM (wavelength division multiplexer)

  Or:

    2. 1480nm laser source (including power and cooling) and 1480/1550nm WDM
- One 1550nm isolator
- Er-doped fiber (approx. 18.5m)
- Optical Wavelength Meter (Wavemeter)
- Standard fiber and connectors

Objectives

1. Gain an understanding of laser operation, including the roles of amplifier, filter (grating), and isolator

2. Measure the threshold for lasing using different gratings

Part 1 – Understanding the fiber laser

For lasers with low gain, the reflection of the ends of the laser cavity must be very high, so that the energy has time to build before escaping. The system you will be building, however, has large gain, so the purpose of the reflecting surfaces at each end is more for frequency (mode) control rather than creating a cavity to build up the intensity. This is why only one grating is required at the end of the fiber, instead of a grating on each side of the Er-doped fiber. The other end of the cavity turns out to be whatever the next reflecting surface is after the Er-doped fiber – if the Er-doped fiber is spliced to the WDM (low reflection) then the next surface will be the output of the WDM; if not, the output surface will be the connection between the Er-doped fiber and the WDM.

With the addition of a grating to the EDFA system, specific modes in the emission will overpower the modes at other frequencies and will become dominant. The modes that most closely match the half-lambda spacing of the grating will be those that resonate, since the grating acts as a reflective filter by only reflecting the desired wavelength back into the EDFA and eliminating the rest of the wavelengths. In general, adding a grating to the end of an amplifying system can create a laser at any wavelength in the range of amplification (the EDFA system can amplify signals between 1528 and 1610nm, so the lasing wavelengths are limited to the same range).

If you have not characterized all of the parts of the fiber laser system (laser, grating, fibers, WDM, isolator) using the white light source, do so before continuing. The OSA (Optical Spectrum Analyzer) is more useful for this analysis because it has a greater wavelength range, so it should be used instead of the wavemeter. After all of the components have been characterized, continue as follows using the wavemeter.

Part 2 – Constructing the fiber laser

Question for understanding

Why do you think an isolator cannot be placed between the WDM and the Er-doped fiber? Hint: check your white-light source analysis if you are unsure.

1. Connect the laser system as follows:
    a. Connect the end of the 1480nm laser to the input on the WDM marked '1480'
    b. Connect one end of the Er-doped fiber to the output of the WDM, and connect the other end of the Er-doped fiber to one of the fiber gratings
    c. Connect the 'input' end of an isolator to the input of the WDM marked '1530' so that the isolator points away from the WDM, and connect the Optical Wavemeter to the 'output' end of the isolator
2. Turn on the wavemeter and the temperature controller to the 1480nm laser (first push the 'power' button on the left side of the temperature controller and wait until it starts up, then push the 'output' button). The actual temperature should now stay between 21.9 and 22.1°C - if it ever varies from this immediately turn of the current source. If the temperature is set to something other than 22°C, set the temperature by

pushing the 'set temp' button and turning the knob to the appropriate value.

3. On the wavemeter, set averaging to 6 and make sure that averaging is turned on, and start with a wavelength range of 1520 to 1627nm. Now, using the horizontal position and horizontal scale functions, set the scale to roughly 1520 to 1550nm (assuming the gratings are 1530nm and 1545nm – if not, make sure the scale will show the wavelengths of all of the gratings).

4. Turn on the current source, and try to find the minimum current that causes the output to peak at the grating's wavelength. Record this output to disk (use the 'save data' function – 'save display' will just save a picture of the current display). The wavemeter does not seem to have a way to set filenames, so it may be worthwhile to take the disk to a computer after each save to change the filename.

5. Record the output for pump current values of 100mA and 200mA.

6. Remove the isolator from the system and repeat the measurements for the threshold current value, 100mA, and 200mA. Based on what you know about modes in a laser, what do you think this will do to the output linewidth (narrower or broader)? Plot the data from your two experiments, and for each pump current value, see if your prediction was true.

7. To obtain the threshold pump power for your laser, connect the pump laser directly to the wavemeter and set the current to your threshold obtained in steps 4 and 6 (to obtain the values with and without the isolator, respectively). This will give you the threshold pump power in dBm and mW.