## Revision History

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1. Introduction to Erbium-Doped Fiber Amplifiers

Similar to electrical signaling over a wire, optical signals attenuate as they travel through an optical fiber. To compensate for this attenuation, erbium-doped fiber amplifiers (EDFAs) are commonly used to amplify the optical signal in the 1550 nm range. Inside an EDFA is a length of optical fiber with erbium ions (Er\(^{3+}\)) inserted within its core during fabrication. This type of fiber is called erbium-doped fiber, and is the key component in amplifying an optical signal in an EDFA.

How erbium-doped fibers amplify optical signals is related to the energy bands of Er\(^{3+}\) in the silica glass of optical fibers. The amorphous nature of the silica broadens the energy levels of Er\(^{3+}\) into bands of levels that correspond to different wavelengths, as shown in the inset of Figure 1. The upward arrows in Figure 1 show a number of different photon wavelengths that can pump the Er\(^{3+}\) from the ground energy band up to a higher energy band.

![Energy Diagram](image)

**Figure 1.** Energy level diagram of the erbium ion (Er\(^{3+}\)). Inset shows that the energy levels are bands of smaller energy levels.

**Optical Pumping**

Commonly, 980 nm or 1480 nm lasers are used to optically pump Er\(^{3+}\) to higher energy bands. The purpose of optical pumping is to achieve a population inversion, where there are more ions in a higher energy band than there are in the ground energy band. It is necessary for optical gain, otherwise the rate of optical signal photons absorbed by the erbium-doped fiber will be greater than the rate
generated by stimulated emission. A metastable energy level at $^4I_{13/2}$, with a long decay time (~10 ms), is essential for collecting ions for a population inversion. Increasing the pump power will also increase the rate of ions excited to higher energy bands for population inversion.

The 980 nm pump wavelength is considered a three-level system where a 980 nm photon excites an erbium ion with enough energy to jump from the ground energy band $^4I_{15/2}$ to the $^4I_{11/2}$ energy band. Once there, the ion quickly decays (~2 µs) to the $^4I_{13/2}$ metastable energy level by emitting heat, and then awaits stimulated or spontaneous emission to take the ion back down to the ground energy band. This pump wavelength gives the best EDFA noise performance but requires a higher degree of wavelength accuracy because of its narrow absorption band.

The 1480 nm pump wavelength is considered a two-level system where a 1480 nm photon excites an erbium ion in the ground energy band $^4I_{15/2}$ to the metastable energy level $^4I_{13/2}$. Once there, the ion awaits stimulated or spontaneous emission to take the ion back down to the ground energy band. This pump wavelength has the advantages of having high pump power laser diodes available, good power efficiency due to the small energy difference between 1480 nm and 1550 nm, a broad absorption spectrum that is less demanding on the wavelength accuracy of the pump laser, and lower attenuation in optical fibers for the remote pumping of EDFAs.

**Optical Gain and Spontaneous Emission**

Once population inversion is achieved, optical gain or amplification is possible. The rate of photons emitted by stimulated emission will now be greater than the rate of those absorbed. Amplification occurs when an optical signal photon arrives at an excited erbium ion along the optical fiber and stimulates its decay from the metastable level $^4I_{13/2}$ to the ground energy band $^4I_{15/2}$. As shown in Figure 2(a), an additional photon with the same optical phase and direction of the original photon is emitted in the decay. The photons can then continue down the fiber to stimulate the emission of more photons with the same optical phase and direction. Therefore the optical signal will be amplified many times larger. A metric of the amplification is the optical gain, which is the ratio of output signal power to input signal power.

![Figure 2. Photons emitted by excited erbium ions through (a) stimulated emission by another photon, and (b) spontaneous decay.](image-url)
Excited erbium ions that don’t interact with incoming photons can decay to the ground energy band spontaneously after 10 ms, and will emit photons random in phase and direction, such as the photon in Figure 2(b). These random photons become a source of optical noise and are amplified to become amplified spontaneous emission (ASE). This ASE degrades the signal-to-noise ratio (SNR) of the optical signal passing through the EDFA.

It should be noted that the decay of the Er$^{3+}$ from the metastable level to the ground energy band emits photons over a span of 1530 to 1565 nm, not only at 1550 nm. This means that any optical signal in this spectrum will be amplified by the erbium-doped fiber. In addition, the ASE noise will also be distributed over this spectrum.

Once the erbium ions reach the ground energy band they are ready to absorb another pump photon to repeat the process again.

2. Assembling the EDFA

2.1 User Safety

Please read the following warnings before proceeding to handle or operate the components.

1. High intensity and invisible light is emitted from the optical output receptacle of the 980 nm Pump Laser and DFB Laser units. Direct irradiation to skin and eyes should be avoided.

2. The equipment cases are fully certified for EMS protection and the user should never attempt to open it, which may result in electric shock and/or EMS attack to vicinity equipments. Note that equipment warranty is valid only with equipment case intact.

3. The user should avoid using any solvent or vaporizing chemicals to clean the equipment panel and case as it may damage the surface and possibly internal circuitries.
2.2 Components

2.2.1 The 980 nm Pump Laser

The 980 nm pump laser serves to optically pump the erbium-doped fiber. By controlling the power to the pump laser, the rate of 980 nm photons supplied to the erbium-doped fiber can be tuned.

![Image of the front panel of the 980 nm Pump Laser Source.](image)

**Figure 3. The front panel of the 980 nm Pump Laser Source.**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>📈 Laser Current Display</td>
<td>The LED display shows the pump laser power in mW.</td>
</tr>
<tr>
<td>🍃 Main Switch</td>
<td>The key switch is the master AC power switch for the unit including the optical output. Before turning it on, make sure the optical power control knob is in full counter-clockwise position.</td>
</tr>
<tr>
<td>🌿 Optical Output Enable Button</td>
<td>This push button toggles the optical output on and off. When the optical output is enabled the button indicator will light up.</td>
</tr>
<tr>
<td>🌡 Over-Temperature Indicator</td>
<td>This indicator lights up when the pump laser module overheats. If this should occur, switch the Main Switch to the Off position and restart.</td>
</tr>
<tr>
<td>🛍️ Optical Power Adjust Knob</td>
<td>The multi-turn knob controls the output optical power. Turning the knob clockwise will increase the output optical power.</td>
</tr>
<tr>
<td>🌐 FC/APC Optical Output Receptacle</td>
<td>This receptacle accepts the FC/APC fiber-optic connector for optical output.</td>
</tr>
</tbody>
</table>
2.2.2 The 980/1550 nm Wavelength-Division Multiplexer (WDM)

The 980/1550 nm WDM combines the input signal light and pump light into the erbium-doped fiber. It has three ports, Port 1 for 980 nm, Port 2 for 1550 nm, and a Port 3 that can carry light at both 980 and 1550 nm. Inversely, if 980 and 1550 nm light enters Port 3, they will be separated to exit at their respective ports.

![Figure 4. The 980/1550 nm Wavelength-Division Multiplexer.](image)

2.2.3 The Erbium-Doped Fiber

Erbium-doped fiber looks very much like any ordinary optical fiber. The important difference is that the core of the fiber is implanted with erbium ions. These erbium ions get excited to a higher energy level by the 980 nm photons from the pump laser, then release their energy when 1550 nm input signal photons bump into them, emitting more 1550 nm signal photons. The erbium-doped fiber module has two ports that are direction independent, either port can be used to input light and the other will act as the output port.

![Figure 5. The Erbium-Doped Fiber module.](image)
2.2.4 The Isolator

The isolator allows light to pass in the forward direction and attenuates light traveling in the backward direction. Since it is a directional component there is an Input Port and an Output Port. The isolator is used to prevent reflected light from reaching the DFB laser and the erbium-doped fiber, reducing undesirable noise.

![Isolator Module](image)

Figure 6. The Isolator module.

2.2.5 The Optical Filter

The optical filter allows light to pass at a specified wavelength in either direction. The optical filter is used to filter the background ASE source, reducing undesirable noise.

![Optical Filter Module](image)

Figure 7. The Optical Filter module.
2.2.6 The FC/APC Adapter

The FC/APC Adapter is used to connect together fibers terminated with FC/APC connectors. Using this type of adapter to connect other connectors will result in higher optical losses. All components in this education kit use FC/APC connectors.

![Figure 8. FC/APC Adapters.](image)

2.2.7 The DFB Laser and Photo-detector

The DFB laser and photo-detector are combined in one case. Both are not normally considered part of the EDFA.

The DFB laser is used as an input signal source for the experiments. Its 1550 nm wavelength is within the amplification bandwidth of the EDFA. Increasing the power to the DFB laser will raise the rate of 1550 nm input signal photons entering the erbium-doped fiber.

The photo-detector is used to detect the amount of optical power in various parts of the experiments.

![Figure 9. The front panel of the 1550 nm DFB Laser and Photo-detector unit.](image)
<table>
<thead>
<tr>
<th>Feature</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>① DFB Laser Power Display</td>
<td>The LED display shows the DFB laser power in dBm.</td>
</tr>
<tr>
<td>② Photo-detector Power Display</td>
<td>The LED display shows the power received by the photo-detector in dBm.</td>
</tr>
<tr>
<td>③ Main Switch</td>
<td>The key switch is the master AC power switch for the unit including the optical output. Before turning it on, make sure the optical power control knob is in full counter-clockwise position.</td>
</tr>
<tr>
<td>④ Optical Output Enable Button</td>
<td>This push button toggles the optical output on and off. When the optical output is enabled the button indicator will light up.</td>
</tr>
<tr>
<td>⑤ DFB Temperature Adjust</td>
<td>The multi-turn screw controls the DFB temperature. Turning the knob counter-clockwise will increase the DFB temperature, thereby increasing the DFB wavelength.</td>
</tr>
<tr>
<td>⑥ Optical Power Adjust</td>
<td>The multi-turn screw controls the output optical power. Turning the knob counter-clockwise will increase the output optical power.</td>
</tr>
<tr>
<td>⑦ FC/APC Optical Output Receptacle</td>
<td>This receptacle accepts the FC/APC fiber-optic connector for the optical output of the DFB laser.</td>
</tr>
<tr>
<td>⑧ FC/APC Optical Input Receptacle</td>
<td>This receptacle accepts the FC/APC fiber-optic connector for the optical input of the photo-detector.</td>
</tr>
</tbody>
</table>
### Feature | Function
---|---
1. **AC Power Socket** | The AC power socket is the input for the AC power source. A three-pin standard power cord should be used to connect this equipment to the main supply. The fuse socket accepts a 5 x 20mm mini fuse. A Quick-acting fuse should be used for maximum protection.
2. **Ventilation Fan** | The ventilation fan ensures good ventilation inside the unit. The back panel of this equipment should be placed at least 3 inches from the wall to dissipate heat effectively.
3. **Nameplate** | The nameplate records the equipment’s serial number and power supply information.
4. **Mode Selection Button** | This button selects the operation mode of the DFB: Either in CW or external analog modulation.
5. **Analog Modulation Input** | This BNC connector is used for external analog modulation operation. A 0 to 2.5V analog signal up to 2kHz can be used.
6. **Photo Detector Output** | This BNC connector is used for measuring the signal received by the photo detector.

Figure 10. The back panel of the 1550 nm DFB Laser and Photo-detector unit.
2.3 Assembly

The block diagram in Figure 11 shows how the components are assembled to build a simple one stage EDFA. On the left is the IN port of the EDFA where the signal light enters. And on the right is the OUT port where the signal light exits the EDFA after amplification.

![Block diagram of a one stage EDFA.](image)

**Figure 11. Block diagram of a one stage EDFA.**

1. Connect Output Port of pump laser to Port 1 of the WDM.
2. Connect Output Port of one of the isolators to Port 2 of the WDM. Use a FC/APC adapter to connect the two fiber pigtails.
3. Connect Port 3 of the WDM to Port 1 of the erbium-doped fiber. Use a FC/APC adapter to connect the two fiber pigtails.
4. Connect Port 2 of the erbium-doped fiber to Input Port of the second isolator. Use a FC/APC adapter to connect the two fiber pigtails.
5. Connect Output Port of the second isolator to Port 1 of optical filter.
6. Connect Port 2 of the optical filter to Input Port of Photo-detector
7. Turn on power to the pump laser. Turn Main key clockwise to the On position and press the Enable button. Turn knob clockwise to increase the pump power to the maximum value, the display should read 145 mW.
8. Measure the maximum optical power using the Photo-detector by adjusting the DFB temperature. The Photo-detector display should read about 8.0 dBm.

Congratulations, the EDFA is now assembled, and should look something like Figure 12. The Input Port of the first isolator is the input to the EDFA. The output of the optical filter is the output of the EDFA.
3. EDFA Parameters

Common parameters used in the characterization of EDFAs include gain, gain saturation, saturation output power, pump saturation and noise figure. This section introduces each of these parameters briefly and demonstrates how they can be measured in experiments.

3.1 Small-Signal Gain

The gain of an amplifier is defined as the ratio of output signal power to input signal power, with the output signal power corrected for the ASE noise of the EDFA.

\[ G = \frac{P_{\text{out}} - P_{\text{ASE}}}{P_{\text{in}}} \]

where \( P_{\text{in}} \) and \( P_{\text{out}} \) are the respective input and output signal powers in Watts, and \( P_{\text{ASE}} \) is the ASE noise power in Watts at the signal wavelength. However, in most cases where the input signal power is sufficiently large, the ASE noise adjustment is negligible and can be set to zero. The gain is also commonly expressed in the decibel form, dB, while the signal and ASE noise powers can be expressed in decibels with respect to 1 mW, the unit is dBm.

\[ G(dB) = 10 \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \]

or

\[ G(dB) = 10 \log \left[ \frac{P_{\text{out}}}{1 \text{mW}} \right] - 10 \log \left[ \frac{P_{\text{in}}}{1 \text{mW}} \right] = P_{\text{out}} (\text{dBm}) - P_{\text{in}} (\text{dBm}) \]  \textbf{Equation 1}

The small-signal gain region is considered the range of input signal powers where the signal amplification does not significantly reduce the gain of the amplifier. In this
situation, it is assumed that the rate of erbium ions excited into the metastable
energy level is greater than the rate of stimulated emission. Therefore the gain will
remain constant as the input signal power is increased.

3.1.1 Measuring Small-Signal Gain with the Photo-detector

1. Turn on power to the pump laser. Turn Main key to the On position and press
the Enable button. Turn knob clockwise to increase the pump power to the
maximum value, the display should read 145 mW.

2. Turn on power to DFB laser source. Turn Main key to the On position and press
the Enable button.

3. Adjust screw so that the display reads -40 dBm. Turn clockwise to decrease or
counter-clockwise to increase the input signal power. This is the EDFA input
signal power, $P_{in}$.

4. Connect the DFB laser output port to input port of the first isolator, which is also
the input signal port for the EDFA.

5. Connect port 2 of the optical filter, which is also the output signal port of the
EDFA to the Photo-detector input port.

6. The Photo-detector will display the optical power in dBm. Obtain the maximum
Photo-detector power by adjusting the DFB temperature to shift the signal
wavelength within the filter range. This is the EDFA output signal power, $P_{out}$.

7. The gain will be the EDFA output signal power, $P_{out}$, minus the input signal
power, $P_{in}$. $G = P_{out} - P_{in}$. The units will be in dB.

8. Repeat steps 1 to 7 for input signal powers from -35 dBm to -10 dBm, in 5 dBm
steps.

9. Plot gain in dB versus input signal power in dBm.

The plot should show that the gain is relatively flat until the input signal power is
increased to a certain level. This flat region from -40 dBm to -20 dBm is the small-
signal gain region.
3.2 Gain Saturation

Gain saturation is experienced when the metastable energy level population is severely depleted by a high rate of stimulated emission, as when the input signal power is sufficiently high. For a fixed pump power, the rate of erbium ions excited for population inversion will be constant. As the input signal power is increased past the small-signal region, the more photons will enter the erbium-doped fiber stimulating emission of photons and depleting the metastable energy level faster than it can be filled. Therefore, the amplification will reach a limit and the gain will decrease with increasing input signal power.

3.2.1 Measuring Gain Saturation with the Photo-detector

1. Turn on power to the pump laser. Turn Main key to the On position and press the Enable button. Turn knob clockwise to increase the pump power to the maximum value, the display should read 145 mW.

2. Turn on power to DFB laser source. Turn Main key to the On position and press the Enable button.

3. Adjust screw so that the display reads -40 dBm. Turn clockwise to decrease or counter-clockwise to increase the input signal power. This is the EDFA input signal power, \( P_{\text{in}} \).

4. Connect the DFB laser output port to input port of the first isolator, which is also the input signal port for the EDFA.

5. Connect port 2 of the optical filter, which is also the output signal port of the EDFA to the Photo-detector input port.

6. The Photo-detector will display the optical power in dBm. Obtain the maximum Photo-detector power by adjusting the DFB temperature to shift the signal wavelength within the filter range. This is the EDFA output signal power, \( P_{\text{out}} \).
7. The gain will be the EDFA output signal power, \( P_{\text{out}} \), minus the input signal power, \( P_{\text{in}} \). The units will be in dB.

\[ G = P_{\text{out}} - P_{\text{in}} \]

8. Repeat steps 1 to 7 for input signal powers from -35 dBm to 0 dBm, in 5 dBm steps.

9. Plot gain in dB versus input signal power in dBm.

The plot should show that as the input signal power is increased beyond -20 dBm the gain would begin to decrease. This gain decrease is the effect of gain saturation.

![Gain Saturation Graph](image)

**Figure 14.** Gain saturation of the EDFA with pump power at 145 mW.

### 3.3 Saturation Output Power

The saturation output power is the output signal power at which the gain has been reduced by 3 dB of its small-signal gain. This parameter shows the maximum output power capabilities of the EDFA for a fixed pump power, and is an outcome of gain saturation. So as the input signal power is increased past the small-signal region the gain will decrease even as the output signal power increases.

#### 3.3.1 Measuring Saturation Output Power with the Photo-detector

1. Turn on power to the pump laser. Turn Main key to the On position and press the Enable button. Turn knob clockwise to increase the pump power to the maximum value, the display should read 145 mW.

2. Turn on power to DFB laser source. Turn Main key to the On position and press the Enable button.

3. Adjust screw so that the display reads -40 dBm. Turn clockwise to decrease or counter-clockwise to increase the input signal power. This is the EDFA input signal power, \( P_{\text{in}} \).

4. Connect the DFB laser output port to input port of the first isolator, which is also the input signal port for the EDFA.
5. Connect port 2 of the optical filter, which is also the output signal port of the EDFA to the Photo-detector input port.

6. The Photo-detector will display the optical power in dBm. Obtain the maximum Photo-detector power by adjusting the DFB temperature to shift the signal wavelength within the filter range. This is the EDFA output signal power, $P_{out}$.

7. The gain will be the EDFA output signal power, $P_{out}$, minus the input signal power, $P_{in}$. $G = P_{out} - P_{in}$. The units will be in dB.

8. Repeat steps 1 to 7 for input signal powers from -35 dBm to 0 dBm, in 5 dBm steps.

9. Plot gain in dB versus output signal power in dBm.

The plot should show that as the input signal power is increased beyond a certain level the gain would begin to decrease. At the point where the gain has decreased 3 dB, the corresponding output signal power is the saturation output power. In the case of Figure 15, the saturation output power is about 9 dBm.

![Figure 15. Saturation output power of the EDFA with pump power at 145 mW. The 3 dB drop in gain occurs at about 9 dBm.](image)

3.4 Pump Saturation

Pump saturation occurs when the pump power is large enough to significantly deplete the ground energy band, which reduces the pumping rate of the erbium ions. Gain will increase with pump power, but will flatten out as pump saturation takes over.

3.4.1 Measuring Pump Saturation with the Photo-detector

1. Turn on power to the pump laser. Turn Main key to the On position and press the Enable button. Turn knob clockwise to increase the pump power current to the maximum value, the display should read 145 mW.
2. Turn on power to DFB laser source. Turn Main key to the On position and press the Enable button.

3. Adjust screw so that the display reads -20 dBm. Turn clockwise to decrease or counter-clockwise to increase the input signal power. This is the EDFA input signal power, $P_{in}$.

4. Connect the DFB laser output port to input port of the first isolator, which is also the input signal port for the EDFA.

5. Connect port 2 of the optical filter, which is also the output signal port of the EDFA to the Photo-detector input port.

6. The Photo-detector will display the optical power in dBm. Obtain the maximum Photo-detector power by adjusting the DFB temperature to shift the signal wavelength within the filter range. This is the EDFA output signal power, $P_{out}$.

7. The gain will be the EDFA output signal power, $P_{out}$, minus the input signal power, $P_{in}$. $G = P_{out} - P_{in}$. The units will be in dB.

8. Repeat steps 1 to 7 for pump powers 10, 15, 20, 40, 60, 80, 100, 120, 140 and 145 mW.

9. Plot gain in dB versus pump power in mW.

   The plot should show at low pump powers below 20 mW the gain increases linearly. But as the pump power is increased even more, the gain slope begins to get smaller and level out. This decrease in the gain slope is the effect of pump saturation.

![Pump Saturation](image)

Figure 16. Pump saturation of the EDFA for -20 dBm input signal power.
3.5 Noise Figure (NF)

The EDFA noise figure (NF) quantifies the signal-to-noise ratio (SNR) degradation experienced by an optical signal passing through the amplifier. The NF will always be greater than one since the EDFA adds noise during the amplification process in the form of ASE. So the output SNR is always less than the input SNR. In theory the best NF achievable by an EDFA is 3 dB.

\[
NF = \frac{SNR_{\text{in}}}{SNR_{\text{out}}}
\]

\[
NF(dB) = 10 \log \left( \frac{SNR_{\text{in}}}{SNR_{\text{out}}} \right)
\]

where \(SNR_{\text{in}}\) is the signal-to-noise ratio for the EDFA input signal, and \(SNR_{\text{out}}\) is the signal-to-noise ratio for the EDFA output signal.

3.5.1 Measuring Noise Figure with an Optical Spectrum Analyzer – Source Subtraction Method

A problem encountered when measuring the noise figure of EDFAs is laser noise. Just as EDFAs generate ASE, laser sources generate noise, referred to as source spontaneous emission (SSE). So when the laser source is connected to the EDFA, the SSE is amplified and contributes to the ASE noise of the EDFA, causing an error in the noise figure measurement. In the source subtraction approach the SSE is estimated by interpolation and subtracted from the total noise emitted by the EDFA to obtain the true ASE.

\[
NF(dB) = 10 \log \left( \frac{P_{\text{ASE}}}{GhB_0} + \frac{1}{G} \left( \frac{P_{\text{SSE}}}{hB_0} \right) \right) \quad \text{Equation 2}
\]

where:
- \(P_{\text{ASE}}\) is the total noise spectral density, including SSE, at the signal wavelength.
- \(P_{\text{SSE}}\) is the SSE spectral density at the signal wavelength.
- \(B_0\) is the effective noise bandwidth of the OSA.
- \(G\) is the optical gain.
- \(\nu\) is the optical frequency.
- \(h\) is Planck’s constant, \(6.63 \times 10^{-34}\) J·s.

While some Optical Spectrum Analyzers (OSAs) have functions that can measure and calculate the gain and noise figure of an optical amplifier, most do not apply the SSE correction.

1. Set OSA resolution to 0.1 nm, and wavelength span to 10 nm.
2. Turn on power to the pump laser. Turn Main key to the On position and press the Enable button. Turn knob clockwise to increase the pump power current to the maximum value, the display should read 145 mW.

3. Turn on power to DFB laser source. Turn Main key to the On position and press the Enable button.

4. Adjust screw so that the display reads -40 dBm. Turn clockwise to decrease or counter-clockwise to increase the input signal power.

5. Connect the DFB laser output port to the OSA using a patchcord.

6. On the OSA, measure the optical power on the OSA at the signal wavelength in dBm. This is the EDFA input signal power, $P_{in}$.

![Figure 17. Measure input signal power at signal wavelength.](image)

7. Measure the optical powers on the OSA at 1 nm on both sides of the signal wavelength in dB/(resolution). Use these powers to interpolate a value at the signal wavelength. This is the SSE spectral density, $P_{SSE}$. 
Figure 18. Measure SSE power levels 1 nm on both sides of signal wavelength.

8. Disconnect the DFB laser from the OSA.

9. Connect the DFB laser output port to the input port of the first isolator, which is the input signal port for the EDFA.

10. Connect the output port of the second isolator, which is also the output signal port of the EDFA to the OSA.

11. On the OSA, measure the optical powers at 1 nm on both sides of the signal wavelength in dB/(resolution). Use these powers to interpolate a value at the signal wavelength. This is the ASE spectral density, $P_{ASE}$.

Figure 19. Measure ASE power levels 1 nm on both sides of the signal wavelength.

12. Measure the optical power on the OSA at the signal wavelength in dBm. This is the EDFA output signal power, $P_{out}$. 
13. The gain will be the EDFA output signal power, $P_{out}$, minus the input signal power, $P_{in}$. $G = P_{out} - P_{in}$. The units will be in dB.

![Diagram of gain calculation]

Figure 20. The gain is the difference between the input signal and output signal powers at the signal wavelength.

14. Calculate the noise figure according to the Equation 2. An example is given in the next section.

15. Repeat steps 2 to 14 for input signal powers from -35 dBm to 0 dBm, in 5 dBm steps.

16. Plot the noise figure in dB versus input signal power in dBm.

![Noise Figure Chart]

Figure 21. Noise Figure for different input signal powers at 1552 nm.

3.5.2 Noise Figure Calculation Example
Values measured for input signal power of -40 dBm for the DFB laser at 1552 nm are:  
\[ G = 30.7 \, \text{dB}, \quad P_{\text{SSE}} = -65.4 \, \text{dBm/(resolution)}, \quad P_{\text{ASE}} = -21.31 \, \text{dBm/(resolution)}. \]  
All these values have to be converted back into their linear form before substituting into the noise figure equation.

\[
Gain, G = 10^{\left(\frac{30.7}{10}\right)} \approx 1174.898
\]

\[
P_{\text{SSE}} = 10^{\left(-\frac{65.4}{10}\right)} \approx 2.884 \times 10^{-10} \, W/(\text{resolution})
\]

\[
P_{\text{ASE}} = 10^{\left(-\frac{21.31}{10}\right)} \approx 7.396 \times 10^{-6} \, W/(\text{resolution})
\]

The effective noise bandwidth, \( B_0 \), is considered to be 0.1 nm for the OSA resolution used.

\[
B_0 = \frac{c \cdot \Delta \lambda}{\lambda^2} = \frac{(3 \times 10^8) \cdot (0.1 \times 10^{-9})}{(1552 \times 10^{-9})} \approx 1.245 \times 10^{10} \, \text{Hz}
\]

The optical frequency is calculated from the signal wavelength 1552 nm using the following equation.

\[
\nu = \frac{c}{\lambda} = \frac{(3 \times 10^8)}{(1552 \times 10^{-9})} \approx 1.933 \times 10^{14} \, \text{Hz}
\]

Substitute all these values into Equation 2 for the noise figure at -40 dBm in Figure 21.

\[
\therefore NF(\text{dB}) = 10\log \left[ \frac{(7.396 \times 10^{-10})}{(1174.898)(6.63 \times 10^{-34})(1.933 \times 10^{14})} + \frac{1}{(1174.898)(6.63 \times 10^{-34})(1.933 \times 10^{14})} \right] \approx 5.78 \, \text{dB}
\]

4. Enhanced DFB Features

4.1 Analog Modulation

Besides CW operation, the DFB can operate under analog modulation mode. An external 0-2.5V analog modulation signal up to 2 kHz can be applied. By connecting the DFB output to the photo detector input, the following signals can be obtained by using a CRO.
Figure 22. Analog modulation signal and the photo detector output without offset voltage. Distortion at the bottom can be observed.

Figure 23. Analog modulation signal and the photo detector output with 0.3V offset voltage. The distortion is eliminated.

Figure 22 and Figure 23 show the analog modulation signal and the photo detector output signal. The upper signal is the modulation signal, and the lower signal show the photo detector output. From Figure 22, a distortion, which is caused by the DFB threshold value, is found. In order to eliminate the effect, an offset voltage about 0.3 V is applied, as the result shown in Figure 23.
4.2 Temperature Adjusting

By adjusting the DFB laser temperature, the output wavelength can be adjusted also. The temperature range can be set from 5 degrees Celsius to 40 degrees Celsius while the DFB wavelength would be varied from around 1559 nm to 1562.5 nm.

Figure 24. Wavelength adjustment measured by adjusting temperature.

5. Measurement Errors

It is most probable the optical power values stated in this manual and those measured will be different. Some of this uncertainty can be attributed to using different equipment and calibration sources. However, there are other sources of uncertainty that will affect the accuracy of your measurements. The optical spectrum analyzer and power meter used in measurements will have an amount of uncertainty that is dependent on the scale used for measurement. The connectors used to connect the fiber pigtails will also introduce an uncertainty of ± 0.25 dB for each connector. Using fusion splices in real EDFAs reduces this connector uncertainty significantly. The polarization dependency of the equipment will also introduce an uncertainty, causing the optical power to fluctuate up and down. Using polarization scramblers and measurement averaging will reduce this kind of uncertainty.
6. References


7. Appendix

7.1 Component Specifications:

7.1.1 The 980 nm Pump Laser

**Mechanical Specifications**

- Weight: ~5 kg
- Dimension: 250 x 230 x 110 mm (WxDxH)
- Case: Aluminum/plastic
- Finish: Bake enamel paint
- Optical Output: FC/APC connector receptacle

**Optical/Electrical Specifications**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Mains Input Voltage</td>
<td>110 or 220</td>
<td>V</td>
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<tr>
<td>Current Consumption</td>
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<tr>
<td>Warm-up Time</td>
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<td>hrs</td>
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<tr>
<td>Optical Output Power</td>
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<tr>
<td>Central Wavelength</td>
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<td>nm</td>
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<td>Storage Temperature (recommend)</td>
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</tr>
<tr>
<td>Operational Temperature</td>
<td>0 to 40</td>
<td>°C</td>
</tr>
<tr>
<td>Power Stability (5 min)</td>
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<td>dB</td>
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<td>Power Stability (2 hr)</td>
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7.1.2 Wavelength Division Multiplexer

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<td>Min. Isolation</td>
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7.1.3 Isolator (Polarization Insensitive)

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<tr>
<td>Max. PMD</td>
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7.1.4 Optical Filter Spectrum

![Figure 25. Optical filter module spectrum measured.](image)

7.1.5 The 1550 nm DFB Laser

**Mechanical Specifications**
- Weight: ~5 kg
- Dimension: 250 x 230 x 110 mm (WxDxH)
- Case: Aluminum/plastic
- Finish: Bake enamel paint
- Optical Output: FC/APC connector receptacle
### Optical/Electrical Specifications

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<th>Unit</th>
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<tr>
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<td>hrs</td>
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<td>Optical Output Power</td>
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<td>Central Wavelength</td>
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<td>Storage Temperature (recommend)</td>
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<tr>
<td>Operational Temperature</td>
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<td>°C</td>
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<td>Fiber Type</td>
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#### 7.2 Maintenance

#### 7.2.1 Care of fiber-optic connectors

More than 70 percent of equipment degradation is due to damage of the fiber-optic connectors. The user should clean the connector by following procedure:

1. Soak the optical tissue with alcohol that is at least 90% pure.
2. Clean the connector with the soaked tissue.
3. Use a clean and dry optical tissue to clean the connector again.

**The reasons:**

1. Any dust on the surface of connector can cause damage to the connector when connections are made. This is because connectors are connected by direct physical contact of optical fibers.

2. The 980 nm Pump Laser and DFB Laser emit high optical powers that could burn the residual alcohol on the surface of the optical fiber and damage the connector. Therefore, the connector should be properly dried after cleaning with alcohol.