GAIN AND NOISE CHARACTERISTICS OF ERBIUM DOPED FIBRE AMPLIFIERS

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Abstract

The gain and noise characteristics of an erbium doped fibre amplifier were demonstrated using a pump laser, signal laser and photoreceiver kit along with patchcords, a fixed attenuator and an oscilloscope. The experiments demonstrated the effects of stimulated emission and gain saturation. The saturation input power was found to be (-25±5) dBm. The point of transparency was found to be (7.3±0.6) mW. The gain gradient was found to be (7.4±1.9) dBmW^{-1} and the gain efficiency was found to be (1.47±0.10) dB mW^{-1}

The investigation of EDFA noise demonstrated various forms of noise - thermal noise and amplified spontaneous emission (ASE) noise. At a signal power when signal-ASE noise is dominant, the signal-to-noise ratio and noise figure (NF) were estimated from experimental readings and compared with theoretical results. The experimentally observed NF was found to be (3.1 ± 0.9) and the theoretical NF was calculated to be (3.79 ± 0.16). These values agree with each other to within the stated uncertainties.

The investigation of the EDFA as a laser gain medium demonstrated the operation of a ring laser. The variation of the laser output with pump power at various output coupling ratios and excess intra-cavity losses agreed with theory. From these plots the small signal gain at threshold was calculated and was found to increase with the excess intra-cavity loss as expected. The threshold and slope efficiency were found to increase with output coupling ratio as expected.

Overall the experiment provided a clear demonstration of the characteristics of the EDFA, which has applications in laser systems and optical communications.

1. Introduction

In long distance optical fibre communication systems the optical signal suffers attenuation as it passes along the fibre. Therefore it becomes necessary to regenerate the light signal at certain intervals throughout the system.

This can be achieved by using electronic regenerators which convert the optical signal to an electrical signal, amplify the electrical signal and convert back from electrical to optical. However, an alternative is to use an optical amplifier. These amplifiers amplify the optical signal directly. Optical amplifiers consist of a section of optical fibre doped with a rare-earth element such as erbium or praseodymium.

An erbium doped fibre amplifier (EDFA) consists of erbium ions doped in a silica matrix. This forms a 3 level gain medium. The ions can be pumped to a higher energy level by a laser.

A schematic diagram of an erbium doped fibre amplifier is shown:

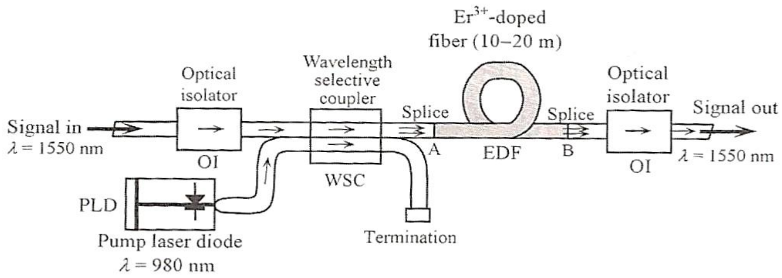


Fig.1- A schematic diagram of an EDFA

The purpose of this investigation is to develop a practical appreciation and understanding of the principles and characteristics of the erbium doped fibre amplifier and by extension optical amplifiers in general.

A. Stimulated Emission

Optical amplification in an EDFA is based on the process of stimulated emission. [3]
Under thermal equilibrium, most ions are in the ground level. A pump laser at 980nm excites the erbium ions from the ground level to the level E_3. This is a short-lived level and the ions fall to E_2 after less than 1μs. The ions remain in E_2 for a longer time, around 12ms. So by pumping with enough power, the population of E_2 can be made greater than E_1. This is known as population inversion.

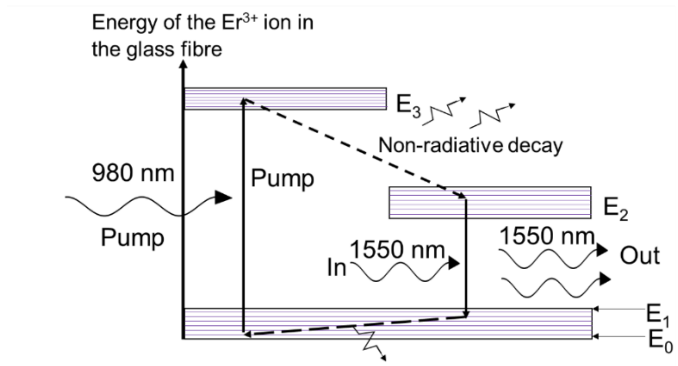


Fig.2- A schematic diagram showing stimulated emission [3]

A light signal with a frequency that corresponds to the energy difference between the levels is pumped through the core and interacts with the excited ions in E_2. If the majority of ions are in the ground state the light photons will be mostly absorbed and the signal is attenuated. However if population inversion has been achieved, the signal will be amplified [1].
The erbium ions then give up some of their energy as they fall back to E_1 in the form of photons in phase and exactly the same wavelength as the light signal. The light signal is therefore amplified. For erbium ions, this frequency corresponds to the 1550nm band. So an EDFA amplifies optical signals in this window.
Pumping at 980nm or 1480nm results in a population inversion between an intermediate state and the ground state that provides amplification of signals in an approximate band of 1520nm to 1580nm.

B. Gain

Gain is a measure of the amplification of an optical signal. It is equal to the ratio of the output signal and input signal, and can be expressed in dB if the input and output signal powers are measured in watts or milliwatts. The decibel is a logarithmic unit.

$$Gain\ G\ (dB) = 10\log_{10}\left(\frac{output\ power}{input\ power}\right) \qquad \text{Equation (1)}$$

Output power and input power may also be measured in dBm, which is the decibel referenced to a milliwatt mW. A conversion can be made between the units as follows:

$$Power\ (mW) = 10^{\left(\frac{power(dBm)}{10}\right)} \qquad (2)$$

The detailed theory related to the longitudinal pumping geometry and the transverse distributions of the pump and signal modes are not included in this introduction. However a simpler model of a bulk optical amplifier pumped in transverse and longitudinal directions is sufficient to gain an appreciation of the EDFA characteristics.

The gain equations required for this investigation are shown below [4]:

A small signal which has insignificant intensity to perturb the population of the upper gain state will produce a gain in intensity per unit length at distance z along a uniformly pumped amplifier. Integrating over the length gives the intensity as a function of z:

$$I_v(z) = I_v(0)\exp[\gamma_0(v)z] \qquad (3)$$

Where: $I_v(z)$ is the intensity at z
$I_v(0)$ is the input intensity
$\gamma_0(v)$ is the small signal gain coefficient, given by:

$$\gamma_0(v) = \sigma_{SE}(v)\cdot\left[N_j - \frac{g_2}{g_1}N_i\right] \qquad (4)$$

Where: σ_{SE} is a constant, the emission cross section
The term in the brackets is the population inversion, the difference in the populations of two energy levels.

For a gain medium of length l, equation 4 becomes:

$$I_v(l) = G_0(v)\cdot I_v(0) \qquad (5)$$

Where $G_0(v)$ is the small signal gain of the amplifier length l,

$$G_0(v) = \exp[\gamma_0(v)l] \qquad (6)$$

The gain in dB can also be expressed as:

$$Gain(dB) = 10\log_{10} G_0(v) = 10\log_{10} e^{\gamma l} = 4.34\gamma l \qquad (7)$$

Increasing the pump power causes a linear increase in the population of the upper gain state, the population inversion and the gain coefficient. Equation (7) predicts that gain increases linearly with pump power.

The equations (3)-(7) only apply to weak pumping conditions as they assume that the ground state does not become significantly depleted.

For stronger pumping, the population inversion increases and the ground state becomes depleted. Eventually the amplifier reaches pump saturation where further increases in pump power do not produce any further population inversion and the gain and output power increase minimally.

When weak pumping is not assumed, the gain coefficient becomes:

$$\gamma(v) = \frac{1}{I_v} \cdot \frac{dI_v}{dz} = \frac{(I_p^* - 1)\sigma_{SE} N_t}{1 + 2I_v^* + I_p^*} \qquad (8)$$

Where: N_i is the atomic density of the medium
$I_p^* = \frac{I_p}{I_{ps}}$
$I_v^* = \frac{I_v}{I_s}$
I_{ps} and I_s are constants, the saturation pump intensity and saturation signal intensity respectively

As the signal intensity increases, the term $2I_v^*$ in the denominator increases and the gain falls off at saturation.
For a fixed signal intensity, the gain coefficient (and therefore the gain) initially increases linearly with pump intensity I_p but then flattens out as I_p approaches and exceeds I_{ps} , which causes I_p^* to increase in the denominator.

C. Noise

A disadvantage of using an EDFA is that it introduces noise to the signal. Noise is an unwanted effect as it results in random fluctuations in the signal. Different forms of noise are present within the amplifier due to the nature of the amplifier itself:

Thermal noise in the receiver arises from the thermal fluctuations in the electron density within a conductor. It is present at all non-zero temperatures [8][9].

Shot noise is present in this system this noise consists of random fluctuations of the electric current originating from the fact that current consists of a flow of discrete charges.

Any gain medium in which there is a population inversion is a source of spontaneous emission. Noise resulting from this is amplified spontaneous emission (ASE) noise.
Erbium ions occupying the upper energy level can also make spontaneous transitions to the ground level and emit radiation. Part of this spontaneous emission can be amplified just like the signal as it propagates through the fibre. ASE accompanies the signal as it travels along the fibre to the receiver and there it can beat with itself to produce ASE-ASE beat noise or with the signal to give Signal-ASE beat noise. Noise is an unwanted effect as it limits the maximum gain so the noise level is a measure of the efficiency of the EDFA.
A full mathematical description of EDFA noise is not included. The required noise equations are shown below [4]:

The total ASE power in a frequency interval dv emerging through a linear polariser is given by:

$$P_{ASE} = \mu[G - 1] \cdot hv \cdot dv = \rho_{ASE} dv \qquad (9)$$

Where: $\mu = \frac{N_2}{\left[N_2 - \left(\frac{g_2}{g_1}\right)N_1\right]}$, the population inversion factor

G is the gain

h is Planck's constant

v is the light frequency

ρ_{ASE} is the ASE spectral density measured through a linear polariser

In these experiments the ASE power is only considered in a linear polarisation state because the main noise terms arise from beating between the ASE with itself and with a linearly polarised signal.

The noise terms at the receiver output for Signal-ASE and ASE-ASE beat noise are:

$$\sigma_{S-ASE} = 4R^2 G P_0 \rho_{ASE} B_e = 4R^2 G P_0 P_{ASE}^{B_e} \qquad (10)$$

$$\sigma_{ASE-ASE} = 2R\rho_{ASE}^2 B_0 B_e = 2R^2 P_{ASE}^{B_0} P_{ASE}^{B_e} \qquad (11)$$

Where: R is the photodiode responsivity $R = \frac{\eta q}{hv}$, η is the quantum efficiency

B_e is the receiver bandwidth

P_0 is the signal input power

$P_{ASE}^{B_0}$ and $P_{ASE}^{B_e}$ are the polarisation selective ASE powers in optical an electrical bandwidths respectively

From equations (10) and (11), the Signal-to-Noise ratio at the receiver is given by:

$$SNR_{out} = \frac{(RGP_0)^2}{4R^2 G P_0 P_{ASE}^{B_e} + 2R^2 P_{ASE}^{B_0} P_{ASE}^{B_e}} \qquad (12)$$

If the Signal-ASE beat noise is dominant, the ASE-ASE beat noise term in the denominator can be ignored, giving:

$$SNR_{out} = \frac{(RGP_0)^2}{4R^2 G P_0 \rho_{ASE} B_e} = \frac{GP_0}{4P_{ASE}^{B_e}} \qquad (13)$$

At the input, the optical noise is signal shot noise, and the Signal-to-Noise ratio is given by:

$$SNR_{in} = \frac{(RP_0)^2}{2eRP_0 B} = \frac{P_0}{2hvB_e} \qquad (14)$$

Assuming η=1 so $R = \frac{e}{hv}$

The noise figure NF of an amplifier is a parameter used to characterise the noise by taking the ratio of the Signal-to-Noise ratio at the amplifier output to that at the input. An assumption made here is that the optical noise is greater than the thermal noise at the input and receiver.

$$NF = \frac{SNR_{in}}{SNR_{out}} = \frac{\left(\frac{P_0}{2hvB_e}\right)}{\left(\frac{GP_0}{4P_{ASE}^{B_e}}\right)} = \frac{2P_{ASE}^{B_e}}{GhvB_e} \qquad (15)$$

If a substitution is made using equation (9) and assuming the gain is significant, $G >> 1$. For an ideal amplifier, the population is completely inverted so $N_i = 0$ and $\mu = 1$, giving:

$$NF = 2\mu \quad (16)$$

This means the minimum possible noise figure for an ideal amplifier is 2. So it is unavoidable that the input SNR will be degraded between the input and the receiver.

This section of the investigation involved observing the various noise terms and how they change depending on variables such as signal and pump power. The experiments allowed a value of NF to be estimated.

D. Use of an EDFA as a Laser Gain Medium

A laser is fundamentally an optical oscillator which in this case is an optical amplifier with positive feedback. In this investigation an EDFA is used as the gain medium. The amplifier ensures that sufficient optical power resides in the system to maintain the stimulated emission process and provide oscillation which is self-sustaining.
A simple way to ensure suitable feedback is to place the optical amplifier between two mirrors so that the light is reflected back and forth, this is known as a Fabry-Perot cavity. One mirror has less than 100% reflectivity and therefore transmits some of the light. This produces a narrow output beam. For self-sustained oscillation, the following condition must be satisfied:

NET ROUND TRIP GAIN=NET ROUND TRIP LOSS

In the cavity, optical power would continue to grow if the gain was greater than loss or decrease to zero if the loss was greater than the gain and this would prevent self-sustaining oscillation.

By increasing the pump power to the fibre, erbium ions begin to be promoted to higher energy states. This means that spontaneous emission begins to occur in all directions (as seen in ASE). As the pump power increases further a population inversion is achieved which means the fibre is now an EDFA. Eventually the gain of the EDFA is greater than the losses in the cavity for a round trip of the cavity. This means the laser has reached its threshold condition for operation, the pump power is sufficient that stimulated emission depletes the population inversion and the oscillation becomes self-sustaining. Above this threshold pump power, stimulated emission is dominant over spontaneous emission, and the increasing pump power causes the output power of the laser to increase linearly with pump power. The gain remains equal to the net round trip loss.

The EDF laser is in principle identical to the ring laser shown in fig.3:

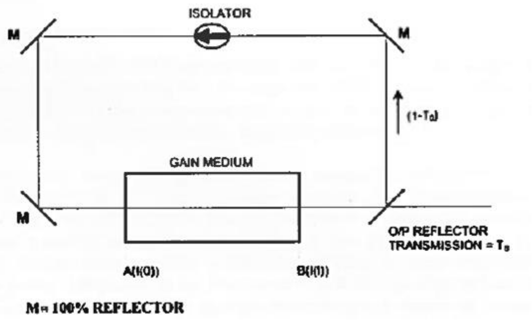


Fig. 3 - Schematic diagram of bulk optic ring laser [5]

A mathematical analysis of the above laser produces the following equations [5]:

The output intensity at point B is given by:

$$I(l) = \frac{[\gamma_0(v)l + \ln L_i(1-T_0)]I_s}{1-L_i(1-T_0)} \qquad (17)$$

Where: $\gamma_0(v)l$ is the small signal gain coefficient
L_i is the intra-cavity loss
I_s is the saturation intensity
T_0 is the transmittance of the output coupler
l is the length of the gain medium

The input intensity at point A is given by:

$$I(0) = \frac{T_0[\gamma_0(v)l + \ln L_i(1-T_0)]I_s}{1-L_i(1-T_0)} \qquad (18)$$

By multiplying by the cross sectional area we get the output power, P_0:

$$P_0 = \frac{T_0[\gamma_0(v)l + \ln L_i(1-T_0)]L_i P_s}{1-L_i(1-T_0)} \qquad (19)$$

Where P_s is the saturation power

This can be rearranged to give:

$$P_0 = \frac{T_0 P_s \gamma_0(v)l}{1-L_i(1-T_0)} + \frac{\ln[L_i(1-T_0)]T_0 P_s}{1-L_i(1-T_0)} \qquad (20)$$

Since $\gamma_0(v)l$ is proportional to the pump power P_p the output power can be written as:

$$P_0 = \left(\frac{T_0 P_s C}{1-L_i(1-T_0)}\right) \cdot P_p + \frac{\ln[L_i(1-T_0)]T_0 P_s}{1-L_i(1-T_0)} \qquad (21)$$

Where C is the constant of proportionality. This equation is the equation of a straight line intersecting the pump power axis at the laser threshold point. At this point the pump power provides a small signal gain which exactly offsets the intrinsic loss.

The gradient of this line is known as the slope efficiency SE:

$$SE = \frac{T_0 P_s C}{1-L_i(1-T_c)} \qquad (22)$$

2. **Equipment**

The equipment used is the Erbium Doped Fibre Amplifiers Educator Kit (ED-AMP). This kit consists of two units: A signal source and receiver unit and an EDFA unit.

The signal source and receiver unit is a two part instrument. The signal laser module allows the input signal to be controlled. Modulation setting is used to provide a sinusoidally varying output.
The receiver unit measures signals either in average or lock-in mode. Lock-in mode means the unit only measures the modulated amplified signal power. In average mode, the receiver

measures the total averaged incident power, including the contribution from ASE. The input signal power and output signal are displayed in dBm accurate to ±0.1dBm.
The EDFA unit is pumped by a 980nm laser via a 980nm/1550nm wavelength division multiplexer (WDM). The WDM allows optical signals of a range of wavelengths to be transmitted together. The pump power is controlled by this unit, and displayed in mW to one decimal place.
Also used in this section was a fixed attenuator, operating at 16.8dB, 2 patchcords and a digital real-time oscilloscope and BNC.

The general setup for the gain and noise investigations was to connect the signal laser output to the amplifier input using a patchcord, and the amplifier output to the photoreceiver using either a patchcord or the fixed attenuator.

For the investigation of Use of an EDFA as a Laser Gain Medium, the ED-LASE unit was used in addition to the ED-AMP apparatus. The setup used is shown in fig. 4:

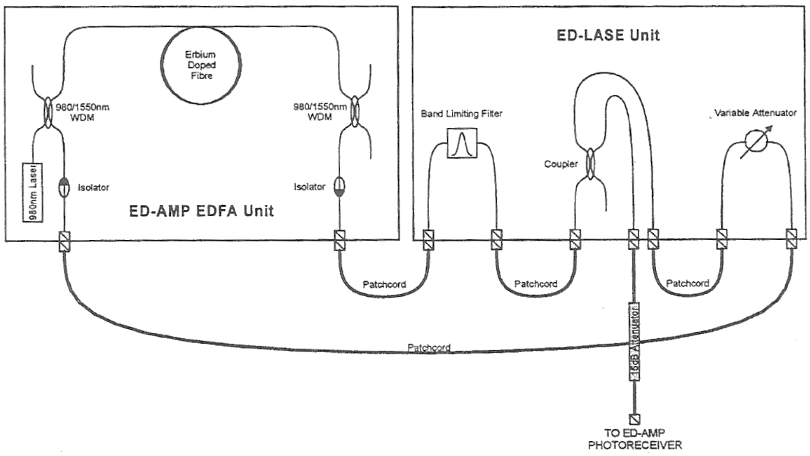


Fig. 4- Experimental setup used to investigate use of EDFA as a laser gain medium [5]

The ED-LASE unit uses the EDFA of ED-AMP as the laser gain medium. The optical feedback is provided by a fibre coupler, band limiting filter and a variable in-line attenuator. The EDF ring laser is formed by connecting the two units with four patchcords as shown above. The fixed 16.8dB attenuator was used to connect the output arm of the coupler to the photoreceiver unit.

3. **Procedure**

The procedure followed was based on that outlined in the Erbium Doped Fibre Amplifiers Educator Kit (ED-AMP) Student Manual [4].

A. Gain Characteristics

The signal output was connected to the amplifier input using a patchcord, and the amplifier output was connected to the photoreceiver using a fixed attenuator of 16.8dB.
Initially the signal output power was investigated as a function of the input power for fixed pump power values of 10mW, 15mW, 20mW, 40mW and 60mW. This allowed the gain to be measured using the ratio of the values, according to equation (1).
Gain was plotted as a function of input power and output power, allowing the saturation input power and saturation output power to be estimated. The saturation output power was then plotted as a function of pump power.

In order to investigate gain as a function of pump power, the output power of the EDFA was measured at input signals of -15dBm, -20dBm, -25dBm,-30dBm and -35dBm for pump powers of 7mW, 10mW, 20mW, 30mW, 40mW, 50mW and 60mW. The gain was calculated as before (eq (1)). The input powers were chosen in order to span the range from low signal gains to the region of gain saturation. This plot allowed calculation of the point of transparency, the gain efficiency and the gain gradient under small signal conditions.

B. Noise Characteristics

The experiments were carried out in order to investigate the different forms of noise- thermal noise at the receiver, ASE noise, ASE-ASE beat noise and Signal-ASE beat noise.

Thermal noise at the receiver was measured by connecting a digital real-time oscilloscope to the receiver unit using a BNC connector. With no signal present, the amplitude of the noise level was estimated using cursors on the oscilloscope display. This was then divided by 5 to find the rms noise voltage.

In order to investigate amplified spontaneous emission (ASE), the output is connected to the receiver using the 16.8dB fixed attenuator. With no signal, the receiver (in average mode) displays the ASE power emitted by the amplifier. The ASE power is measured as a function of pump power. This type of noise is ASE-ASE beat noise.

The noise amplitude was measured as a function of ASE power. The attenuator was replaced by a patchcord. The oscilloscope is again used to observe the noise. The pump power is increased until the amplitude of the optical noise is greater than receiver noise. The pump power is used to increase the ASE level and the corresponding increase in noise level is measured from the oscilloscope.

The ASE level is measured as a function of signal power at fixed pump powers of 15mW, 35mW, 50mW and 70mW. The ASE level is the total average power (read using average mode) minus the average signal level (using lock-in). This is measured for input signals in the range of -5dBm to -40dBm.

The Signal-ASE noise was then investigated. The amplifier output was connected to the photoreceiver using a patchcord. Initially the signal level was set to a low level, -35dBm, and the pump power was increased until the ASE-ASE beat noise amplitude exceeded the receiver noise. The pump power was then fixed at this value and the signal level was increased and the noise amplitude was read from the oscilloscope display as Signal-ASE noise began to dominate. Then with the same pump power, the signal is set to a value at which Signal-ASE noise is dominant. The Signal-to-Noise ratio and Noise Figure could then be estimated and compared with theory.

C. Use of an EDFA as a Laser Gain Medium

Initially the variable attenuator was calibrated. With no signal present the EDFA output was connected to the photoreceiver using a patchcord and the pump power was adjusted to give an output reading on the photoreceiver of 800μW, which is -31.0dBm. The variable attenuator was then connected between the EDFA and the photoreceiver and the dial was turned to give signals of 400μW, 200μW, 100μW and 50μW, which correspond to losses of 3dB, 6dB, 9dB and 12dB respectively.

The apparatus was then set up as shown in fig.4.

For each output coupling ratio- 20%, 40%, 60% and 80%, the ring laser output power is measured as a function of pump power for excess losses of 0dB, 3dB, 6dB, 9dB and 12dB.

From these values, plots could then be made of the laser output power as a function of pump power for different values of excess intra-cavity loss and coupling ratio.

The threshold power, small signal gain at threshold and the slope efficiency could then be determined from the plots.

4. Experimental Data and Discussion

A. Gain Characteristics

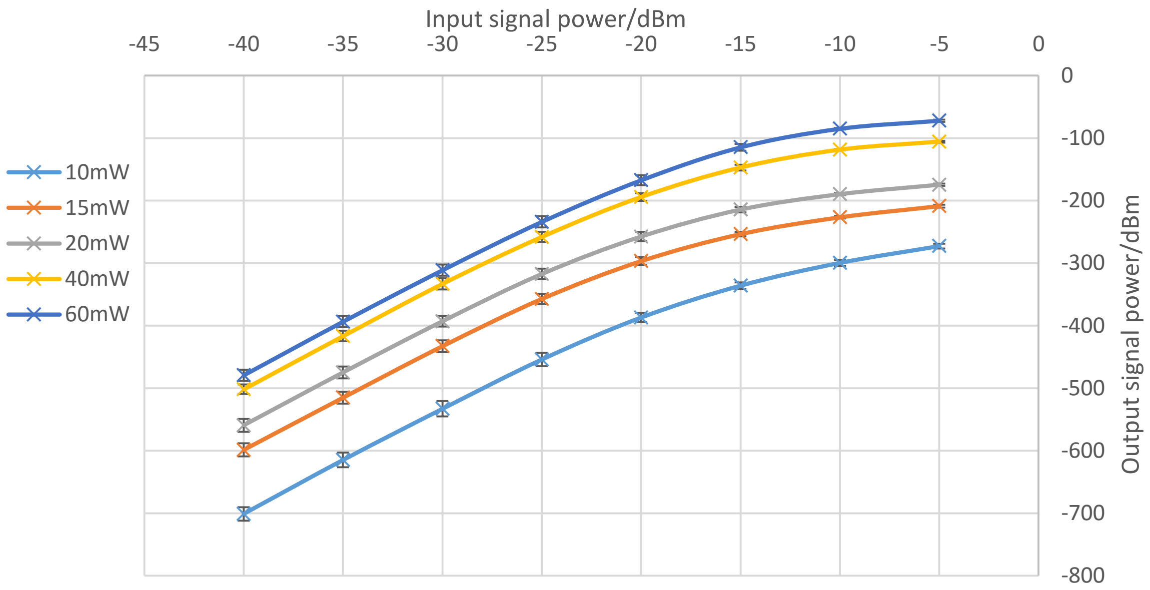


Fig.5- output signal as a function of input signal power for various pump powers

This graph shows that the output power initially increases linearly with input power. However the graph begins to flatten at around -25dBm, as the increase in output power reduces. This is because the amplifier begins to enter gain saturation. The increasing signal begins to reduce the population inversion due to increasing stimulated emission, reducing the increase in output power.

The signal power and output power can be read from the displays accurate to 1 decimal place, meaning the uncertainties in all values read from the display is ±0.1dBm.

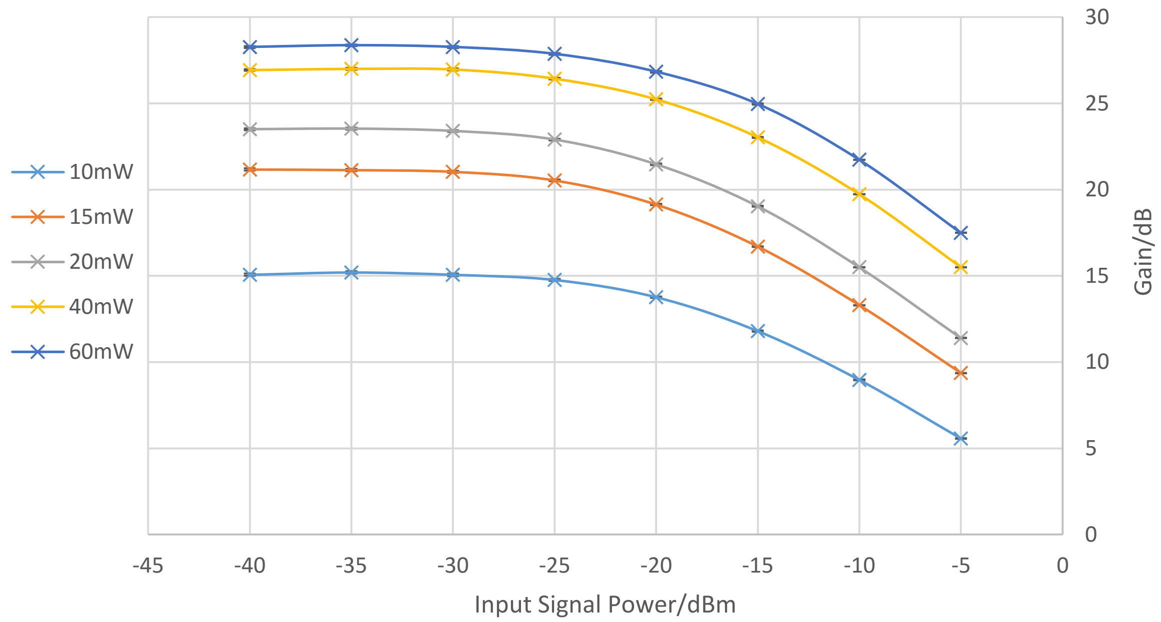


Fig. 6 Gain as a function of input signal power at various pump powers

Fig.6 shows that as the input signal increases the gain initially remains constant as the output power initially increases linearly with the input power. As the amplifier enters gain saturation the population inversion is reducing, resulting in a drop in the gain.
The signal level becomes large enough to significantly deplete the population inversion due to increased stimulated emission and the amplifier gain falls off in agreement with equation (8). The saturation input power is the signal power for which the signal gain drops 3dB relative to the small signal gain. This was measured from the point at which the gain falls away in the graph, and was found to be (-25±5) dBm. The uncertainty in this value arises because the gain was calculated for signal powers in steps of 5dBm.

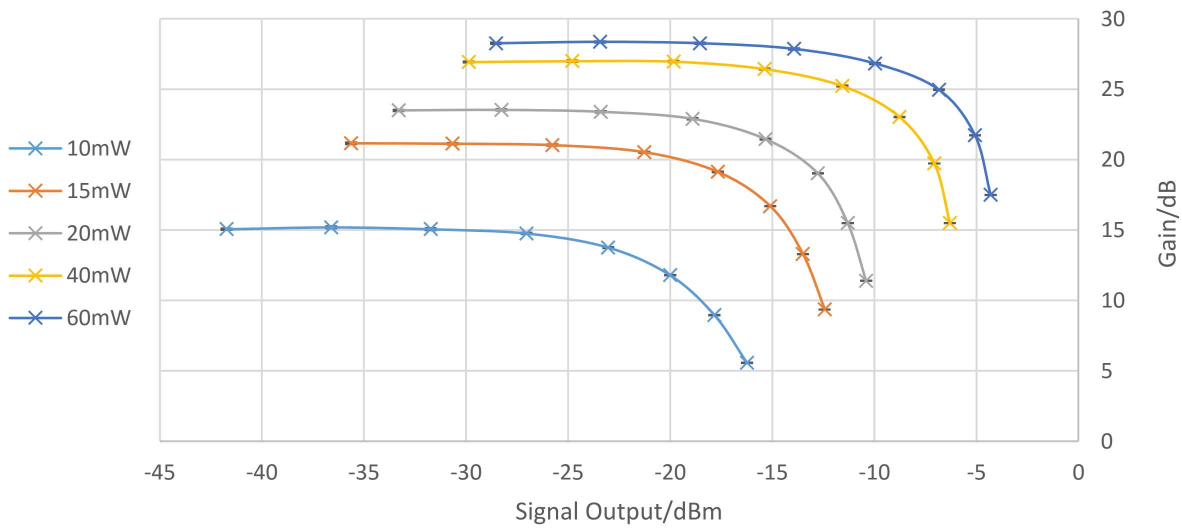


Fig.7- Graph of gain as a function of output signal power at various pump powers

As the input signal power increases from low values, the output also increases with almost constant gain. As the input increases further the population inversion starts to reduce due to increased stimulated emission, so the increase in output is lower and the gain drops.

From this graph the saturation output power was estimated for each pump power and plotted.

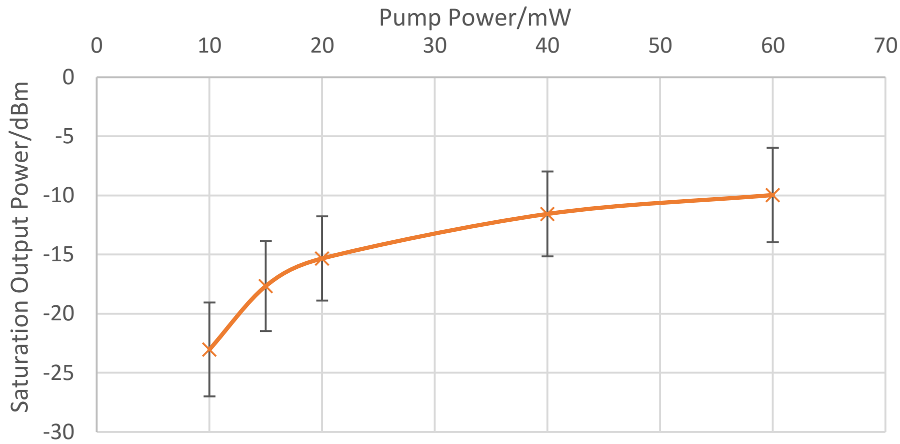


Fig.8- saturation output power as a function of pump power

Fig.8 shows a trend which is roughly linear at low pump powers and then flattens in a similar trend to fig.5. At low pump powers the saturation output power increases linearly with the pump power as the amplifier has not reached saturation. As the amplifier moves toward saturation the output power reduces due to a drop in gain. At higher pump powers the population inversion increases until no more ions can be pumped to a higher energy level, which places a limit on the output power.

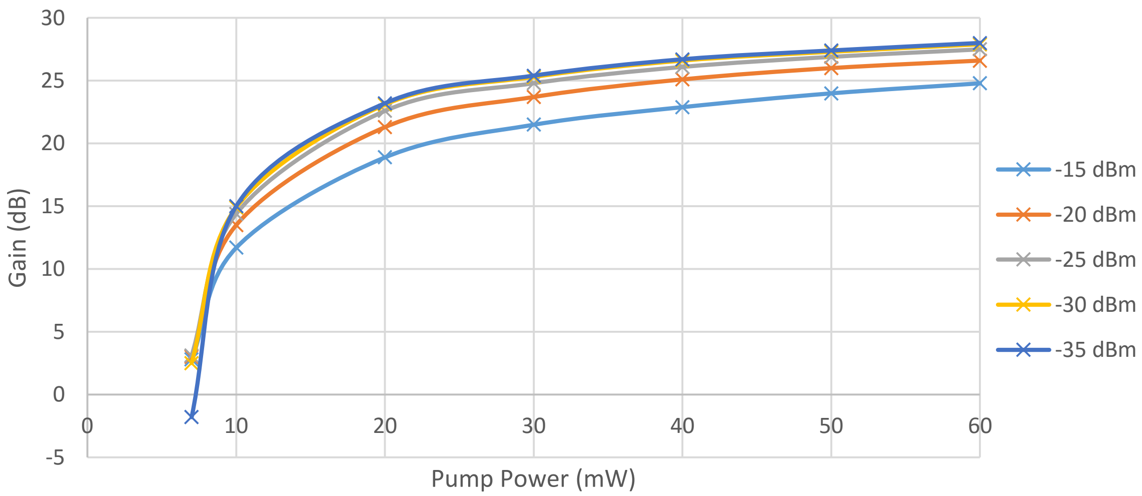


Fig.9- Graph of gain as a function of pump power for signal levels of -15, -20,-25,-30 and -35dBm

For low pump powers the gain is negative, the fibre is absorbing. With increasing pump power the EDFA passes through the point of transparency. Initially the gain increases linearly with pump power (eq.(7)) until the effects of pump saturation become evident as the high level of pumping depletes the ground state population so that the population inversion can no longer increase as all ions are inverted, leading to the graph flattening as the gain can only increase minimally and saturates (equation (8)).

From the graph at -15dBm, the lowest input signal used:
The point of transparency was found to be (7.3±0.6) mW
The gain gradient, the gradient of the linear part of the graph, was found to be (7.4±1.9) $dBmW^{-1}$
The gain efficiency, the gradient of a line through the origin tangent to the curve was found to be (1.47±0.10) dB mW^{-1}

The uncertainties arose from the maximum and minimum gradient of the linear part of the graph. Only two points were taken in the range of pump powers for which the graph is linear, which meant the gradient could not be found using a least squares fitting method. The results could have been improved by taking more results at lower pump powers.

B. Noise Characteristics

With no signal present and zero pump power, the receiver noise level due to thermal noise was estimated to be (2.1±0.2) mV from the oscilloscope display, giving an rms noise of (0.42±0.04) mV.
The uncertainty in this result arose from the maximum and minimum value of the amplitude read from the oscilloscope due to fluctuations in the waveform displayed.

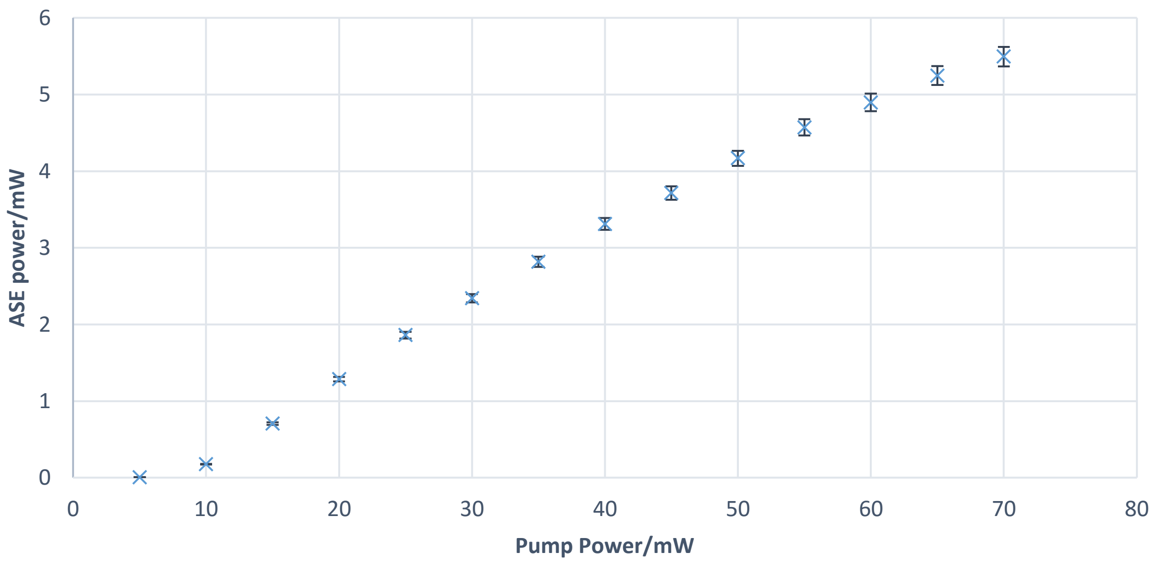


Fig.10- Graph of average ASE power as a function of pump power

With no signal present, the receiver in average mode displayed the ASE power emitted by the amplifier. This is because any optical signal detected must be due to spontaneous emissions in the amplifier. As the pump power was increased the ASE power also increased because increasing pump power causes an increase in population inversion so the probability of an ion being spontaneously emitted also increased. The graph appears to show that the amount at which the ASE power increases with each step reduces at higher pump powers. This is consistent with the fact that the population inversion reaches a maximum at higher pump powers so the ASE power can no longer increase linearly with pump power.

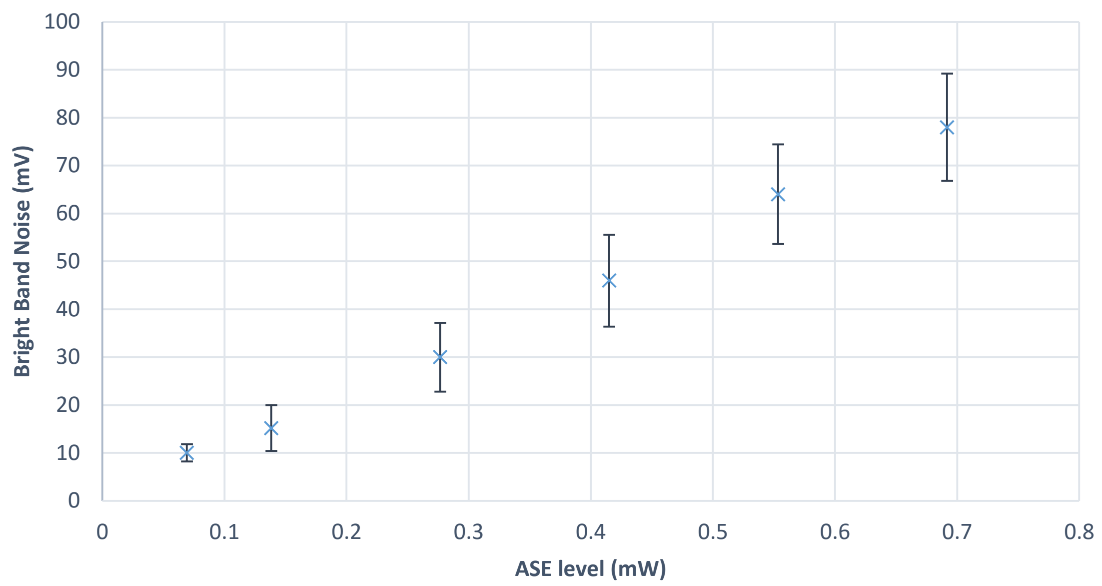


Fig.11- Graph of bright band noise voltage as a function of ASE level

As we increase the pump power, the ASE level increases and ASE-ASE beat noise begins to exceed the thermal noise. The noise amplitude was read from the oscilloscope display.

The noise amplitude increases roughly linearly with the ASE power. This is consistent with equation (11) which shows the noise power increases with the square of the ASE power. The uncertainties are calculated using the maximum and minimum values for amplitude as measured using cursors on the oscilloscope.

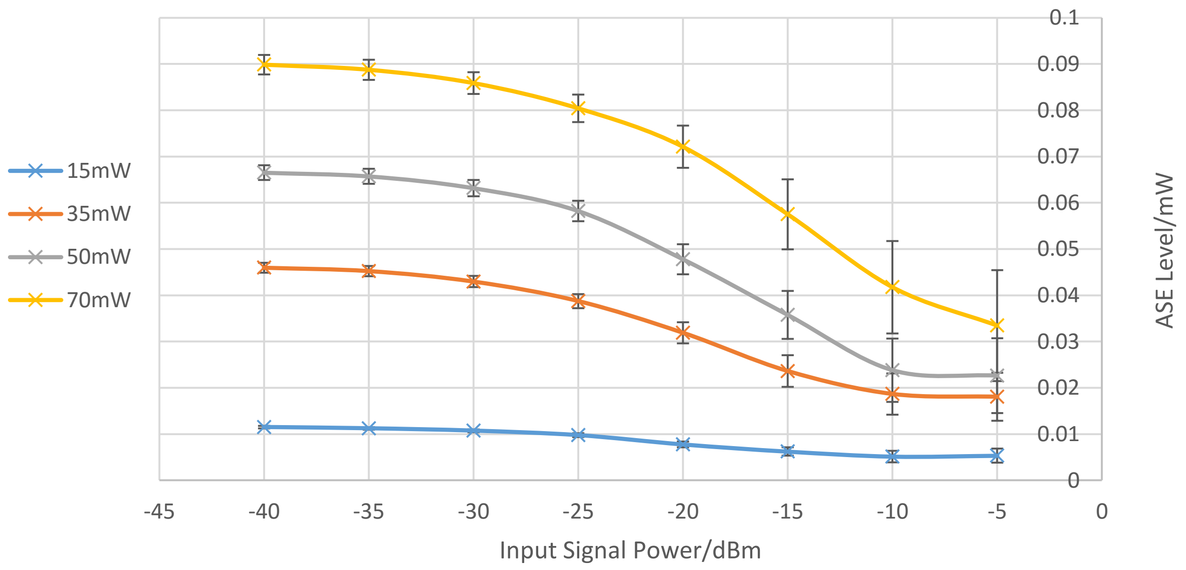


Fig.12- Graph of ASE power as a function of input signal power for pump powers of 15mW, 35mW, 50mW and 70mW

The ASE levels begin to fall dramatically as the input signal level increases into the gain saturation region. The population inversion of the amplifier falls at higher signal powers as the ions are emitted by the signal. There is a corresponding decrease in spontaneous emission and gain.

The uncertainties were calculated from the uncertainty in the ASE level read from the display in dBm, which had an uncertainty of ±0.1dBm. The uncertainty in mW was found by calculating the maximum and minimum values in the ASE level when converting from dBm to mW.

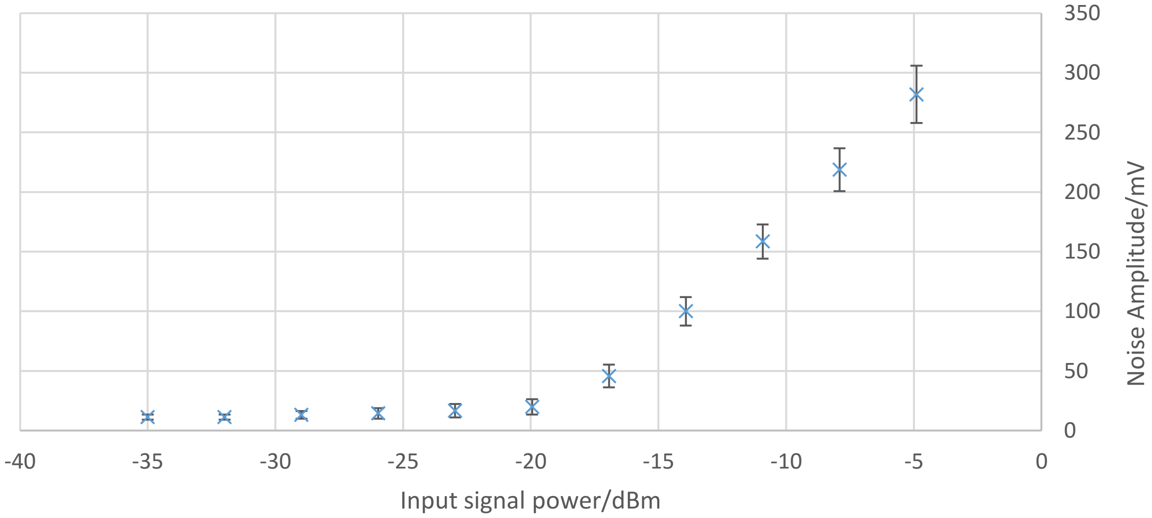


Fig.13- Graph of Signal-ASE noise amplitude as a function of input signal at 12mW pump power

To observe the signal-ASE beat noise, the pump power is fixed at 12mW to provide an ASE power of 43.7μW when no signal is present. Under these conditions the observed ASE-ASE beat noise is just greater than the receiver thermal noise. Initially as we increase the input signal power from low levels, the noise remains constant as the ASE-ASE beat noise is much greater than the signal-ASE beat noise. At signal levels greater than (-15±5) dBm, the noise begins to increase (equation (10)). The uncertainties in the readings were found from the maximum and minimum possible values of the amplitude using the oscilloscope cursors.

At a pump power of 12mW and a signal of -16.9dBm, the Signal-ASE noise dominates and the Signal-to Noise ratio was estimated, as shown below:

Bright band noise voltage= (2.1±0.2) mV
Rms noise voltage= (0.42±0.04) mV
Using DC coupling, the signal out= (3.6±0.4) V

$\frac{Signal}{Noise} = \frac{(3.6\pm0.4)}{(0.42\pm0.04)\times10^{-3}}$ = 8571±1254

In terms of the mean square noise current:

$$SNR_{out} = (8571 \pm 1254)^2 = (7.35 \pm 2.15) \times 10^7$$

The input SNR is calculated from equation (14):

Where: the bandwidth of the receiver is 350 kHz, P_0 is (2.04±0.476) ×10^{-5} W and the photon energy $h\nu$ equals 1.27×10^{-19} J.

Giving
$$SNR_{in} = \frac{(2.04\pm0.476)\times10^{-5}W)}{2(1.27\times10^{-19}\,J)(350\times10^{3}Hz)} = (2.30 \pm 0.05) \times 10^8$$

So from direct noise and SNR measurements, the noise figure can be estimated:

$$NF = \frac{SNR_{in}}{SNR_{out}} = \frac{(2.30 \pm 0.05) \times 10^8}{(7.35 \pm 2.15) \times 10^7} = (3.1 \pm 0.9)$$

This can be compared with values for SNR_{out} and NF calculated from spectral density measurements:

Using equation (13) SNR_{out} can be calculated.

$$P_{ASE}^{B_e} = \rho_{ASE} B_e$$

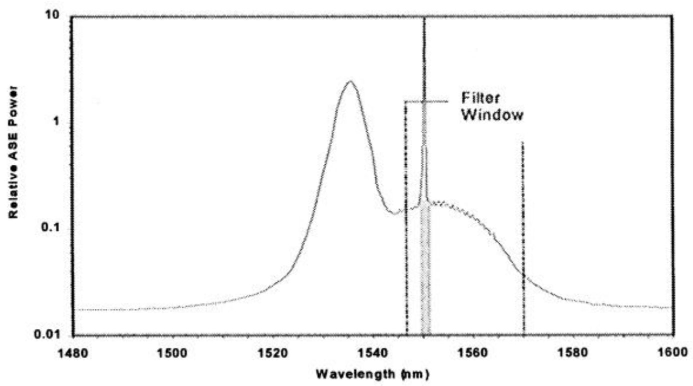


Fig.14- Relative variation of ASE power with wavelength from the EDFA, the fraction of the total power in a 1nm bandwidth around the signal is 0.008

Gain = (11.7±0.14547)
Input signal = (20.4±0.4755)μW = (-16.9±0.1) dBm
The total measured ASE power = (-13.6±0.1) dBm= (4.37±0.144) ×10^{-5} W
Spectral power density=0.008 x (4.37±0.144) ×10^{-5} W nm^{-1} = (3.50±0.1156) × 10^{-7} W nm^{-1}

Using $\quad \Delta v = \frac{c}{\lambda^2} \Delta\lambda$

Where: c is speed of light, 3×$10^8$$ms^{-1}$
λ=wavelength, 1550nm
$\Delta\lambda$ =band of wavelengths=1nm

$$\Delta v = \frac{(3 \times 10^8 ms^{-1})(1 \times 10^{-9} m)}{(1550 \times 10^{-9} m)^2} = 1.249 \times 10^{11}$$

This value has no uncertainty as it was calculated from given values.

Giving $\rho_{ASE} = \frac{spectral\ power\ density}{\Delta v} = \frac{(3.50 \pm 0.1156) \times 10^{-7} Wnm^{-1}}{1.249 \times 10^{11}} = (2.80 \pm 0.0926) \times 10^{-18} WHz^{-1}$

$$P_{ASE}^{B_e} = 350 \times 10^3 Hz \times (2.80 \pm 0.0926) \times 10^{-15} WHz^{-1} = (9.765 \pm 0.324) \times 10^{-13} W$$

And therefore $SNR_{out} = \frac{GP_0}{4P_{ASE}^{B_e}} = \frac{(11.7 \pm 0.14547)(2.04 \pm 0.04755) \times 10^{-5} W}{4 \times (9.765 \pm 0.324) \times 10^{-13} W)} = (6.09 \pm 0.215) \times 10^7$
The calculated voltage SNR=$\sqrt{(SNR_{out})} = 7806 \pm 137$

This value is in agreement with the value estimated directly from noise measurements on the oscilloscope to within the stated uncertainty.

If we assume that the input SNR is limited as before, using a value of SNR_{in}= 2.24×10^{8}, the noise figure is:

$$NF = \frac{SNR_{in}}{SNR_{out}} = \frac{(2.30 \pm 0.05) \times 10^8}{(6.09 \pm 0.215) \times 10^7} = (3.79 \pm 0.16)$$

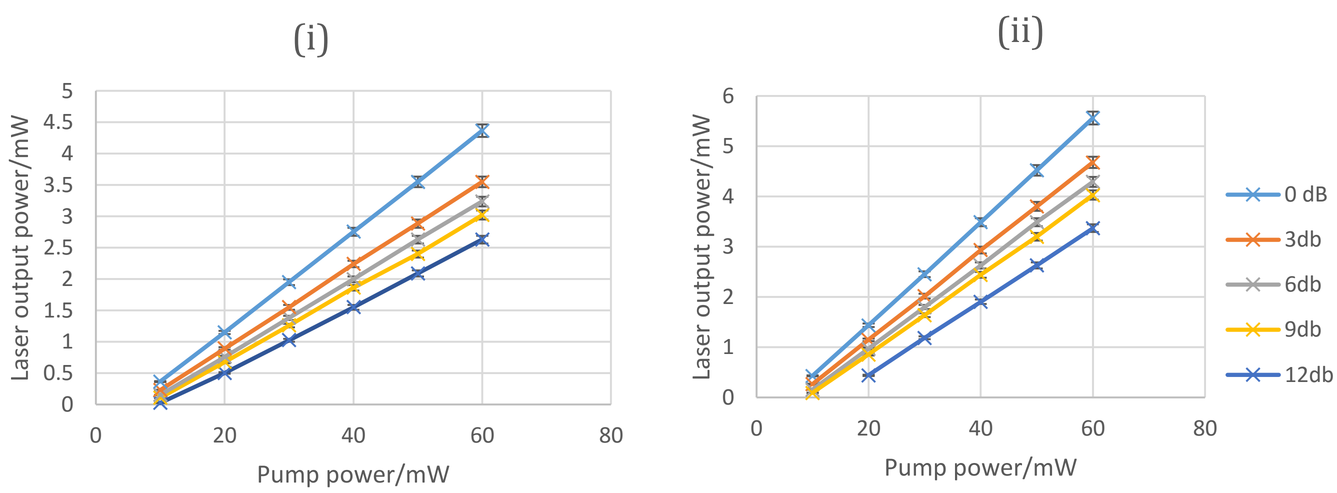
The values of signal-to-noise ratio and noise figure directly from the experimental noise data agree with the calculated values to within the stated uncertainties.

C. Use of an EDFA as a Laser Gain Medium

The variable attenuator was calibrated by finding the settings which resulted in losses of 3dB, 6dB, 9dB and 12dB.
The table below shows the dial settings used:

Excess Intra-Cavity Loss/dB	Variable Attenuator Dial Setting
3	1.23
6	4.89
9	6.24
12	7.36

Table 1-Variable attenuator setting for each excess intra-cavity loss



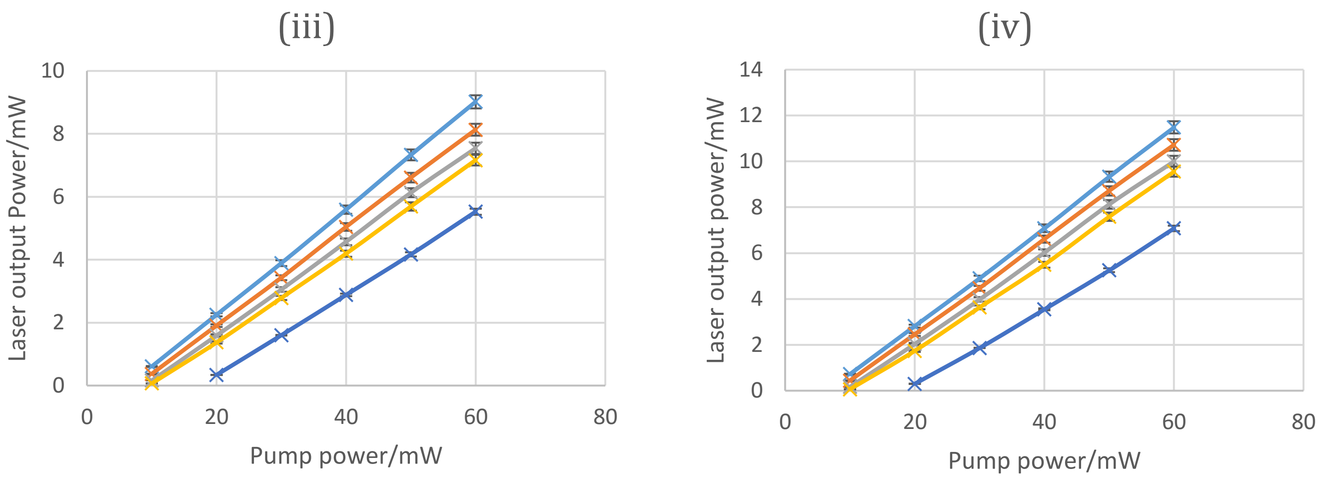


Fig.15- Laser output power as a function of pump power at various levels of excess intra-cavity loss for output coupling ratios of (i) 20%, (ii) 40%, (iii) 60% and (iv) 80%.

The graphs show a linear relationship between the output power and pump power as predicted by equation (21).
The gradient, the slope efficiency, increases as the output coupling ratio increases.
For high loss, the denominator of equation (22) varies only weakly with the intra-cavity loss which predicts a weak variation in slope efficiency, so the gradient is largely independent of the increasing loss. This can be seen in fig.15(i)-(iv), as the gradients of the lines only vary slightly at high losses and coupling ratios.

By extrapolating these graphs to the pump power axis, the threshold pump power was determined which was then used to find the small signal gain at threshold.

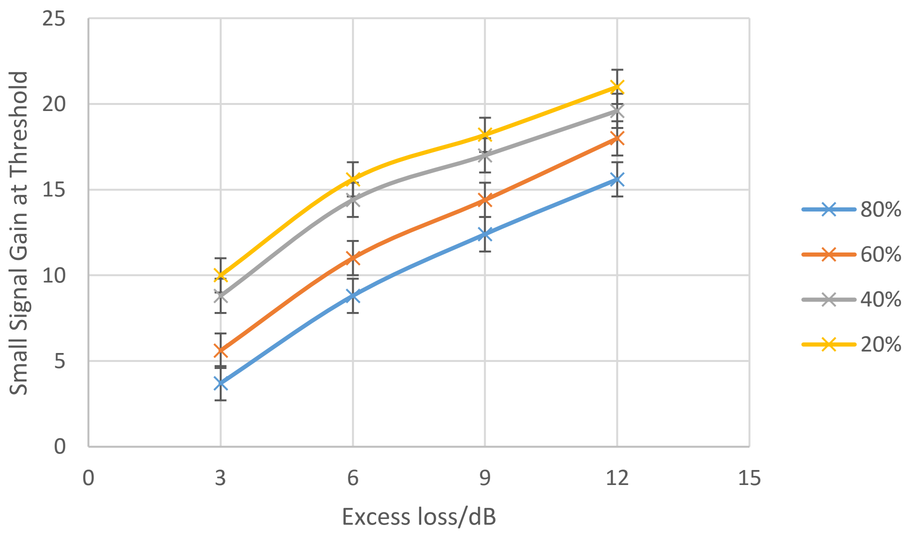
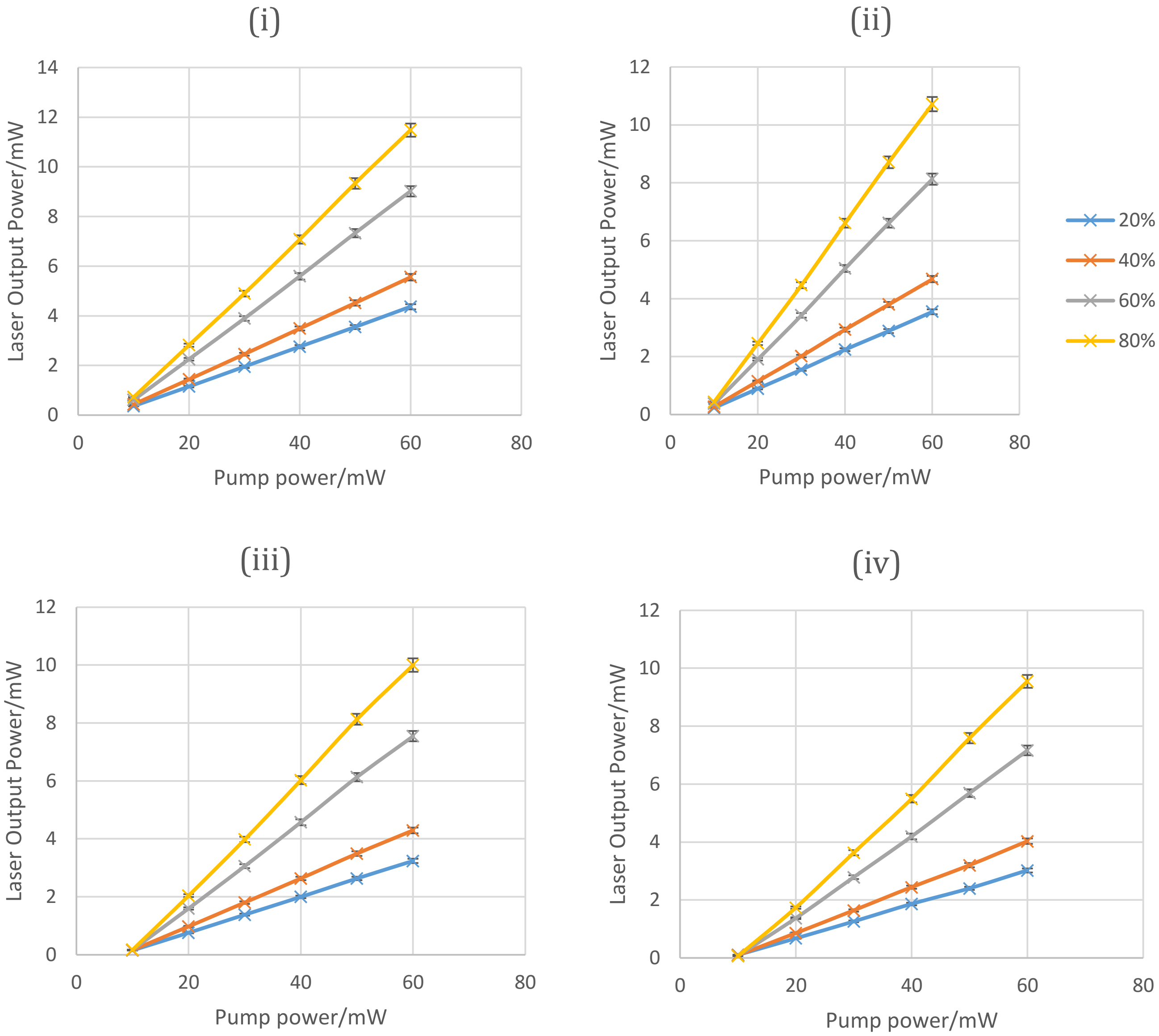


Fig.16- Graph of small signal gain at threshold as a function of excess intra-cavity loss for each output coupling ratio

The threshold gain increases at each coupling ratio to offset the increasing intra-cavity loss, as predicted. The uncertainty in these values come from the uncertainty in the gradients of the plots in fig.15 used to determine the threshold pump power. 20% output coupling ratio produces the highest small signal gain because it produces the highest percentage of feedback in the cavity.



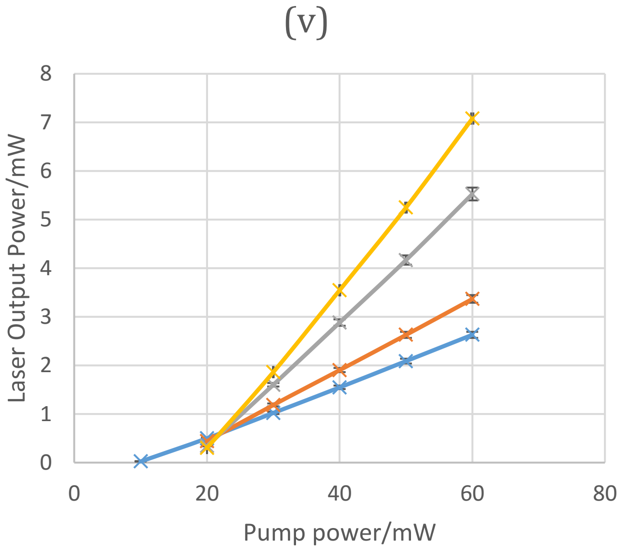


Fig.17- Laser output power as a function of pump power for each output coupling ratio at excess losses of (i) 0dB, (ii) 3dB, (iii) 6dB, (iv) 9dB and (v) 12dB.

Each plot shows a linear relationship between the laser output power and the pump power as before. The threshold and slope efficiency increases with output coupling ratio. This is because a higher output coupling ratio means a lower percentage of feedback so the amplifier reaches its threshold at higher pump powers.

5. **Conclusions**

Overall the results did agree with theoretical expectations. The investigation of the EDFA gain characteristics demonstrated the nature of amplification due to population inversion. The graphs produced showed that the amplifier gain is eventually reduced at higher signal powers due to stimulated emission.
It was also demonstrated that as pump power is increased, the gain increases linearly until gain saturation, at which point the gain cannot increase further as no more ions can be inverted.
The saturation input power was found to be (-25±5) dBm.
The point of transparency was found to be (7.3±0.6) mW.
The gain gradient was found to be (7.4±1.9) dBmW^{-1}.
The gain efficiency was found to be (1.47±0.10) dB mW^{-1}.

The investigation of EDFA noise demonstrated that the dominant noise term varies as the signal power increases from thermal noise to ASE-ASE beat noise and to Signal-ASE beat noise. It was found that the ASE power increases with pump power at low signals. As the signal power increases the ASE power decreases rapidly as ions are emitted by stimulated emission leading to a drop in spontaneous emission.
At a signal power when Signal-ASE noise is dominant, the Signal-to-Noise Ratio and Noise Figure were estimated from experimental readings and compared with theoretical results.
The experimental NF was found to be (3.1 ± 0.9) and the theoretical NF was found to be (3.79 ± 0.16).
These values agree with each other to within the stated uncertainties and agree with theory as theoretically a noise figure must be greater than 2.

The investigation of the EDFA as a laser gain medium demonstrated the operation of a ring laser. The variation of the laser output with pump power at various output coupling ratios and excess intra-cavity losses agreed with theory. From these plots the small signal gain at threshold was calculated and was found to increase with the excess intra-cavity loss as expected. The threshold and slope efficiency were found to increase with output coupling ratio as expected.

The experimental equipment and procedure were sufficient to gain an insight to the characteristics of the erbium doped fibre amplifier. However, improvements which could have been made would have been using equipment with a higher resolution, greater than the accuracy of one decimal place on the ED-AMP kit. More results could have been taken in the linear region for the plot of gain against pump power. The readings on the oscilloscope were highly inaccurate due to fluctuations in the displayed waveform.

Characteristics not under investigation were the effect of length of the fibre and the wavelength of the optical signal on the gain and noise. This was due to the apparatus used. The length of the fibre would place a limit on the number of erbium ions present and therefore the population inversion, and therefore could also be used as a variable.
An ASE reduction filter could have been used in this investigation but was not available.

Overall the experiment provided a clear demonstration of the characteristics of the EDFA, and the principles of optical amplifiers in general. Knowledge of these amplifiers is very valuable as they are important components in laser systems and optical communications.

6. References

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