Gain and noise characteristics of an erbium doped fiber amplifier (EDFA) and ring laser

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We pump an EDFA at 980nm and drive the signal near 1550nm. Output power scaled up with signal power but eventually saturated while the gain dropped and approached unity. Higher signal powers also drove down amplified spontaneous emission and increased output SNR. The gain curve of the EDFA peaked near 1530nm, near which the output SNR improved as well. Finally, by feeding back the fiber output, we created a ring laser with a slope efficiency of 3%.

Applications and setup of the EDFA. EDFA was instrumental in enabling fiber optics communication over long distances. Telecom wavelength is around 1.5μ at which losses in silica fiber is minimal. Er^{3+} has a strong emission band near 1.5μ and also an absorption band near $980nm$, which can be pumped by diode lasers. EDFAs are thus used to amplify telecom signals, eliminating the need for electrical to optical conversions inside repeaters.

Here, we coupled our 980nm pump and ~1550nm signal through a wavelength domain multiplexer (WDM) to an EDFA (fig 1). We coupled the amplified signal to an OSA and thermal detector for spectral and power measurements.

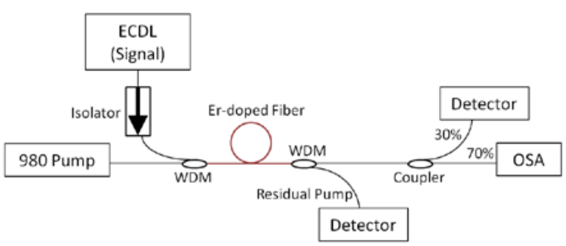

Fig 1 Setup of the EDFA

Output power vs. pump power and signal power. First we calibrated output power of pump laser against input current, obtaining a linear trend with a threshold. Then, we pumped the EDFA and measured the transmitted power. The power absorption was 95%, largely independent of pump power as expected from a Beer-Lambert law.

We now know the pump power (i.e. EDFA absorbed power) against pump current. Now, we inject an input signal of $-1dBm$ at $\lambda = 1548nm$ while varying the pump power. Fig. 2 shows a linear relationship between output signal power vs. pump power. If we pump at very high levels, we eventually expect the gain to saturate as full population inversion establishes.

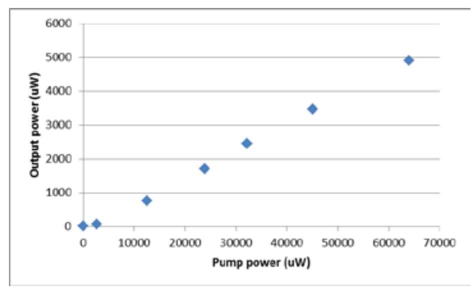

Fig 2 Output power scales with pump power

In another setup, we hold pump power constant at 18.5mW and instead vary the signal power (Fig. 2). In general, at steady state the normalized intensity along the fiber is governed by

$$\frac{d\tilde{I}}{dz} = \frac{\gamma_0 \tilde{I}}{1+\tilde{I}}$$

$$\rightarrow G = G_0 e^{\tilde{I}_{in} - G\tilde{I}_{in}} \qquad (1)$$

$\tilde{I}(z)$: Normalized intensity $\frac{I}{I_{sat}}$
G_0, G: Unsaturated and saturated total gain
$\gamma_0(z)$: Unsaturated gain per length

The self-consistent eqn. (1) predicts that at higher signal levels the overall gain drops and approaches unity. Physically, high light intensity depletes inversion and the local gain. Indeed, we find this in fig. 3.

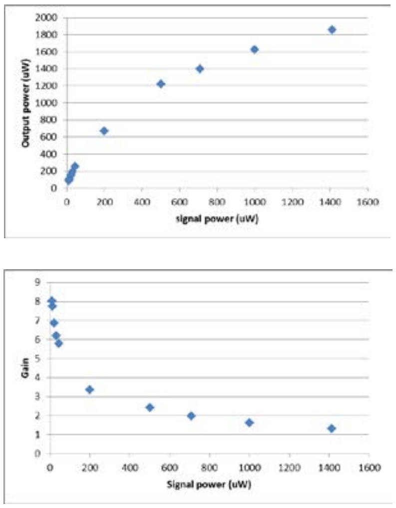

Fig 3 High signal power saturates down gain

Dependence of gain on wavelength. The lasing transition has a wavelength dependent lineshape function. We fixed pump current at 80mA and signal at 775uW while varying the signal wavelength (fig. AAA). The peak is around 1530nm (fig 4). Gain falls off fast outside of 1525nm to 1560nm. From 1540nm to 1555nm the gain is fairly flat. This is beneficial for amplifying telecom signals around 1550nm. Operation near the peak on the other hand improves SNR as we will explain next.

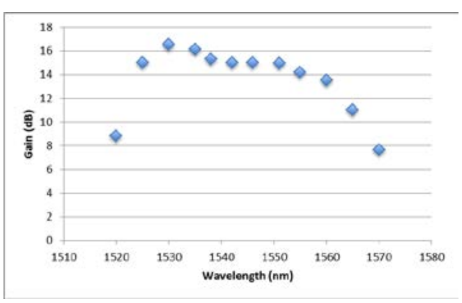

Fig. 4 Gain spectrum of EDFA

Amplified spontaneous emission (ASE). Noise is also amplified by the EDFA considering the broad bandwidth of the gain curve. Considering this, the SNR is

$$SNR = \frac{P_{sig}}{P_{noise}} = \frac{P_{sig}}{2hv\Delta f + P_{ASE}}$$

Where $2hv\Delta f$ is the shot noise arising from photons arriving in a Poisson process on a detector of bandwidth Δf and P_{ASE} is the ASE power. For $\lambda = 1535nm$, we saw ASE decreasing with input signal power as the signal saturates down the gain available to amplify noise (fig 5). Output SNR also increases, but this is expected as it's mostly due to the fact that the input SNR scales with input signal power (assuming pure shot noise from the signal source). As for wavelength dependence, the gain curve peaks at 1530nm meaning more gain is used to amplify signal than noise if we operate near there. Indeed, we observe at 1mW of input signal an output SNR of 31.5dB for 1535nm vs. 19.1dB for 1548nm.

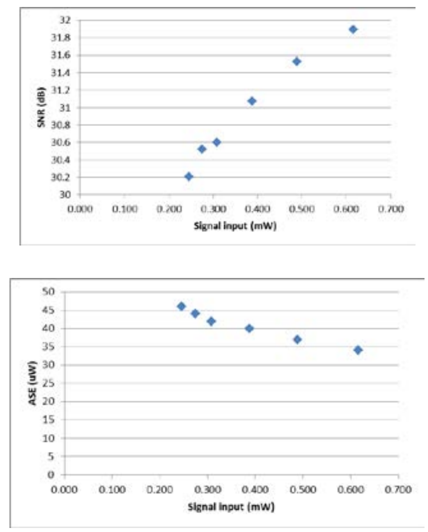

Fig 5 Noise dependence on signal input

Counter-propagation vs. co-propagation. We made all previous measurements using co-propagation where pump and signal travel in the same direction. When we switch to counter-propagation, we notice a drop in SNR but an increase in gain. In counter-propagation, the signal sees lower inversion first, giving it a chance to grow and extract more power from higher inversion regions later. However, the signal at first also grows slower, giving noise more space to extract power later.

EDFA laser. We now operate the EDFA as a laser by feeding the output back to the input and removing the signal source (fig 6). We also placed a fiber-coupled filter to induce a loss tunable over wavelength. We first got the laser to lase at 1547.14nm. Threshold is ~16mW and slope efficiency is ~3%. Theoretical quantum efficiency is $\frac{\lambda_{pump}}{\lambda_{laser}} \cong 63\%$. We thus see significant additional significant losses introduced by the tunable filter and isolator.

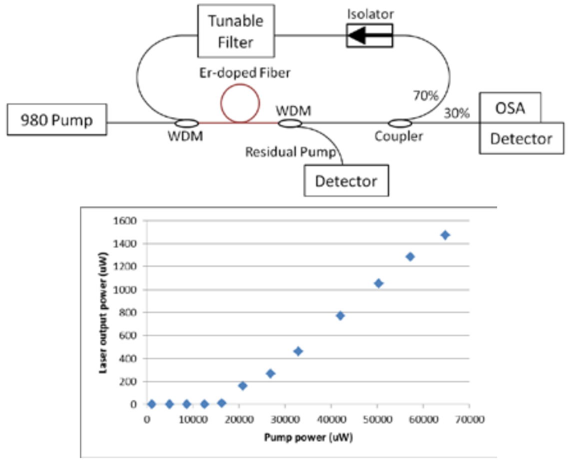

Fig 6 Lasing setup and threshold output for ring laser

Conclusion. Increased pump and signal powers scaled up extracted power. Eventually, large signal powers can saturate the inversion, causing the gain to drop and approach unity. Output SNR improves at higher signals and gain saturation as well as operation near 1530nm (gain spectrum peak) in a co-propagation fashion. Finally, we made a tunable ring laser with slope efficiency of 3%, with losses due to the tunable filter and isolator.

References

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