Signal amplification and laser oscillation in Er-doped fiber

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Compiled March 21, 2015

We investigate the properties of an Er-doped fiber amplifier (EDFA) pumped at 980 nm for signal wavelengths between 1520 nm and 1570 nm. We quantify its performance in terms of net gain and noise figure at the essential wavelength of 1550 nm for various pump powers, signal levels, and signal propagation directions. By closing the loop, we realize a fiber laser using the EDFA as its active gain medium. The laser shows tunable operation from 1520 nm to 1570 nm and a slope efficiency of 0.72 % at 1550 nm. Relaxation oscillations are observed, with a characteristic timescale $\sqrt{\tau_c \tau_2} = 12\,\mu\mathrm{s}$.

OCIS codes: (060.2410) Fibers, erbium; (060.2320) Fiber optics amplifiers and oscillators

1. Introduction

Modern communications infrastructure is based on light: the bandwidth afforded by optical frequencies simply cannot be matched by any electronic communication scheme. However, the commercial viability of long-haul, high-capacity fiber optic links requires the availability of robust and cost-effective optical amplifiers for use as repeaters. Presently, this need is fulfilled by the invention of the erbium-doped fiber amplifier in the 1990s, which can be pumped with low-cost semiconductor diode lasers and operates around 1.55 µm, corresponding to the low-loss, low-dispersion window of silica fibers. [1]

The Er^{3+} ions in glass forms a quasi three-level system, so it absorbs light at the lasing transition but can also amplify light when pumped above transparency. The ground state of the Er^{3+} ions is $^4\mathrm{I}_{15/2}$, and we focus on the 980 nm pumping transition to the $^4\mathrm{I}_{11/2}$ level, for which high power diode lasers are readily available. There is a relatively fast, non-radiative decay from $^4\mathrm{I}_{11/2}$ to $^4\mathrm{I}_{13/2}$ (about 20 µs). After that, the transition from $^4\mathrm{I}_{13/2}$ back down to $^4\mathrm{I}_{15/2}$ is radiative with a lifetime of about 10 ms and occurs at the key wavelength of 1.55 µm. It is worth noting that due to the amorphous structure of the glass medium, these transitions are significantly broadened, and this fact is what gives rise to the broad gain and emission spectrum of the EDFA. [1, 2]

The Er-doped fiber we use in this experiment is an 8 m long, 8 µm diameter bare fiber coil, pumped at 980 nm with a temperature controlled JDS Uniphase diode laser (threshold 14.4 mA, output 0.64 mW/mA, 100 mA max). Wavelength-division multiplexers (WDMs) on the two ends of the fiber separate the pump and signal light for pump and signal inputs/outputs to the EDFA. For maximal stability, the EDFA and the WDMs are enclosed in a box, and the system is configured by mating fiber patch cords to these four available ports.

In Sec. 2, we operate the Er-doped fiber as an optical amplifier (as in a telecomm repeater) and use a signal probe to characterize its gain and noise. In Sec. 3, we close the loop to realize an Er-doped fiber laser (EDFL) tunable across the gain bandwidth of the EDFA, and we characterize its output properties as a function of pump.

2. Fiber amplifier

To measure amplification properties, we use as our signal source an external-cavity diode laser (New Focus 6428) tunable from 1520 nm to 1570 nm, with variable output from 6.9 dBm to −3.0 dBm nominally. A fiber isolator is used after the laser, which has a high measured insertion loss of 10.4 dB at 1550 nm and maximum laser power.

The isolator output is sent into the EDFA via the input WDM, co-propagating with the pump. On the output WDM, the residual pump is sent to a power meter for monitoring, and we perform spectral measurements of the EDFA output at signal wavelengths using a fiber-coupled optical spectrum analyzer (OSA) (Agilent 86140B). The OSA settings used here are as follows: RBW 0.1 nm; VBW 19.3 kHz; sensitivity −55.00 dBm; scan time 449 ms; noise floor ∼ −65 dBm/RBW.

Fig. 1 shows the amplified spontaneous emission (ASE) spectrum of the EDFA output for no signal input, at various pump powers. The mere presence of pump light results in significant broadband power in the signal wavelength range of interest, and we expect that the shape of the ASE is related both to the absorption as well as gain spectrum of the EDFA.

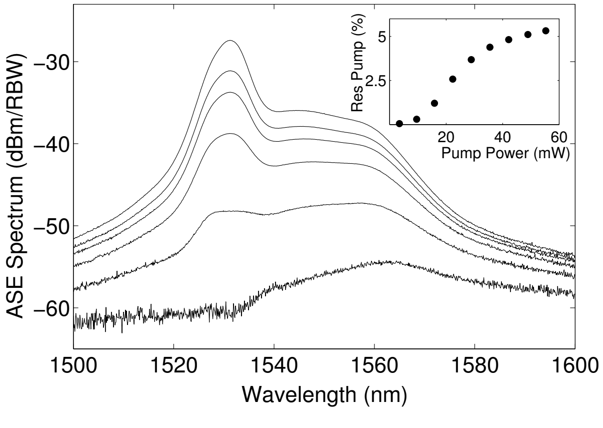


Fig. 1: ASE spectra of EDFA for various pump powers, without signal probe. From bottom to top: 9.6 mW, 15.9 mW, 22.4 mW, 28.9 mW, 35.5 mW, and 55.3 mW. Inset: Residual pump power vs. pump input power.

Because the EDFA exhibits both absorptive loss α and amplification g when pumped, we need to measure both to determine the net gain $G = g\alpha$. To find g, we calculate the integrated signal power using the OSA spectrum over the signal band $\Delta\lambda_s = \text{peak} \pm 0.5\,\text{nm}$ with the pump on, and then divide that by the same calculation for an OSA spectrum taken with the pump off.

To determine α, we turn off the pump and use an InGaAs power meter to measure the signal power out of the EDFA divided by the signal power going in (measured after the isolator). Performing this measurement at various wavelengths, we derive an absorption spectrum $\alpha(\lambda)$ for the EDFA, shown as part of Fig. 2 below.

Unfortunately, we had initially assumed the signal absorption is a function only of wavelength and not input power. Consequently, we only have absorption data at the highest power setting of the probe, and just one data point at a lower power setting, for 1550 nm. Comparing this value (23.5 dB loss at −12.8 dBm in) to the data in Fig. 2 (19.9 dB loss at −3.0 dBm in), it is in retrospect evident there is a power dependence.

Subsequent reflection tells us the absorption α goes as $\alpha = \alpha_0/(1 + P_{\text{sig}}/P_{\text{sat}})$, in accordance with signal saturation in a two-level (i.e., not pumped) system. [3] Interpolating using the two data points we have at 1550 nm, we infer $\alpha_0 = 24.0\,\text{dB}$ and $P_{\text{sat}} = 2.43\,\text{mW} = 3.86\,\text{dBm}$. We henceforth use this interpolation for the absorptive loss of the EDFA at 1550 nm, given input powers.

The above procedure allows us to determine the net gain empirically. Theoretically, on the other hand, net gain in the three-level system is related to the population inversion ΔN, which goes as [4]

$$\log G \propto \Delta N \propto \frac{W_{\text{pump}} - \gamma_2}{W_{\text{pump}} + \gamma_2 + 2W_{\text{sig}}}, \tag{1}$$

where W_{pump} is the pump rate, W_{sig} is the signal stimulated emission rate, and γ_2 is the decay rate of the upper state ($\gamma_2 \sim 1/10\,\text{ms}$).

Also of interest is the noise figure (NF) of the EDFA, which we define to be $\text{NF} = \text{SNR}_{\text{in}}/\text{SNR}_{\text{out}}$. To determine SNR_{out}, we take an OSA spectrum with the pump on and divide the integrated power within $\Delta\lambda_s$ by the integrated power outside of $\Delta\lambda_s$. We assume that the ASE dominates the broadband noise of the output.

Ideally, we should have taken spectra of the input signal and defined SNR_{in} similarly, but we neglected to do so. As an alternative, therefore, we utilize the following formula based on the properties of the ASE-dominated output noise, assuming a shot-noise limited input: [1]

$$\text{NF} \approx \frac{1}{G}\left(1 + \frac{\Delta P_{\text{ASE}}(\lambda_s)}{h\nu_s \Delta\nu_s}\right),$$

where $\Delta P_{\text{ASE}}(\nu_s)$ is the integrated ASE power (inferred from the ASE floor under the peak) within the signal band $\Delta\nu_s \approx c\Delta\lambda_s/\lambda_s^2$. It is noted in the literature that the noise figure defined this way exhibits a fundamental limit of at least 3 dB. [1]

Fig. 3a and 3b show the net gain and SNR_{out} and NF at 1550 nm as a function of signal power, for fixed high (48.9 mW) and low (15.9 mW) pump power. Because the power output of the signal source has limited range, we use a 10 % splitter (8.6 % measured) to continue signal power down to −23.5 dBm.

As predicted by Eq. 1, the small-signal gain (proportional to $W_{\text{pump}} - \gamma_2$) is larger for higher $P_{\text{pump}} \propto W_{\text{pump}}$, from ∼7 dB at the low pump to ∼17.5 dB at the high pump. Then, for a fixed pump, G generally decreases as $P_{\text{sig}} \propto W_{\text{sig}}$ increases, eventually reaching unity gain at 0 dB for large signal inputs. This effect is pump-dependent gain saturation, and the −3 dB saturation point occurs around −14 dBm for high pump and −9 dBm for low pump. An interesting case (not explored here) is to pump below transparency so $W_{\text{pump}} < \gamma_2$.

In the noise measurements, we see that the output SNR rises very much like the shot noise of the input, and this is confirmed by the NF measurements, which show roughly constant NF with signal power for fixed pump. The data suggests that a lower noise figure, near the 3 dB limit, can be achieved with higher pumping.

Fig. 3c and 3d show the net gain and SNR_{out} and NF at 1550 nm as a function of pump power, for fixed high (−3.0 dBm) and low (−12.8 dBm) signal power.

As predicted by Eq. 1, the gain levels off at large $P_{\text{pump}} \propto W_{\text{pump}}$ when $P_{\text{sig}} \propto W_{\text{sig}}$ is fixed, with the curvature being more pronounced for low P_{sig}. Furthermore, we see evidence of the unity gain/transparency point at $\log G = 0$ where $W_{\text{pump}} = \gamma_2$ in Eq. 1. This point occurs a little over 10 mW of pump power in the data, independent of signal power as expected from Eq. 1.

We see low output SNR at low pump powers, which improves and clamps past the transparency point. In terms of the NF, the EDFA performance generally increases towards the limit of 3 dB with increasing pump, and small signal performance improves faster than for large signals, presumably due to signal saturation.

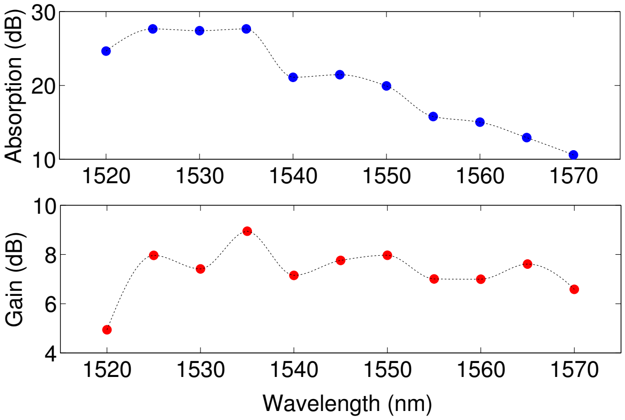


Fig. 2: EDFA gain and absorption as a function of wavelength. Absorption is measured without pump at −3.0 dBm P_{sig}, and gain is measured at 48.9 mW P_{pump} and −3.0 dBm P_{sig}. Cf. the ASE spectrum in Fig. 1.

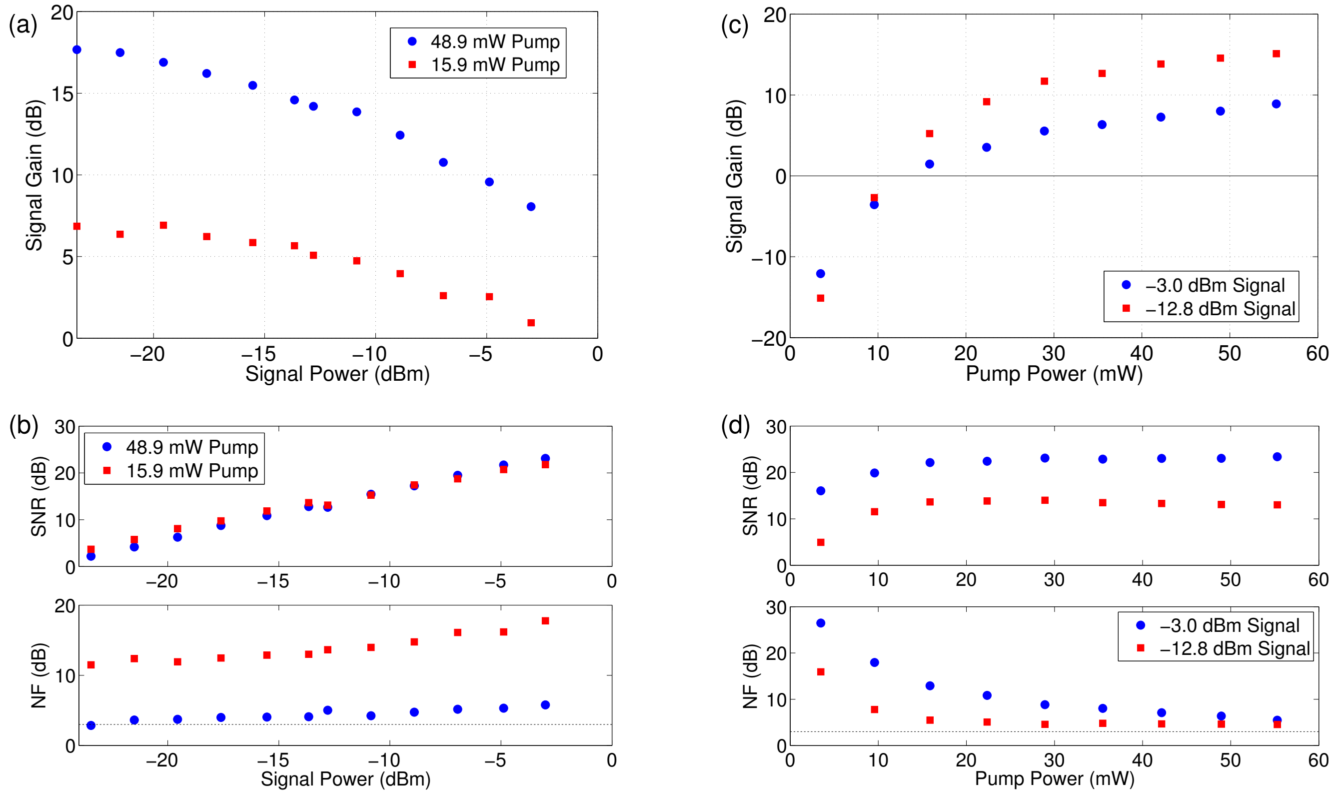


Fig. 3: Gain, output SNR, and NF of the EDFA. In (a) and (b), pump power is fixed, while signal power is varied (lower six values taken with a 10 % splitter). In (c) and (d), signal power is fixed and pump power varied. Line in (c) denotes unity gain/transparency point. Dotted lines in (b) and (d) denote the so-called quantum NF limit at 3 dB.

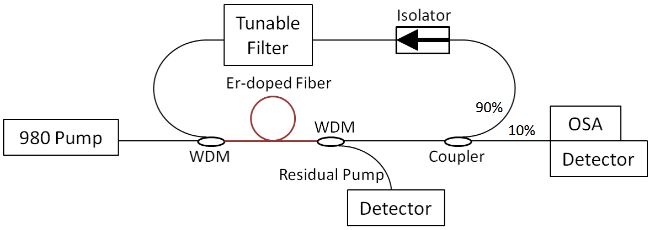
Finally, we reverse the direction of the pump, so that pump is high when signal is low and vice-versa. At $P_{\mathrm{pump}} = 48.9\,\mathrm{mW}$ and $P_{\mathrm{sig}} = -3.0\,\mathrm{dBm}$, we measure $G = 8.8\,\mathrm{dB}$ and $\mathrm{SNR}_{\mathrm{out}} = 21.2\,\mathrm{dB}$, compared to $G = 8.0\,\mathrm{dBm}$ and $\mathrm{SNR}_{\mathrm{out}} = 23.0\,\mathrm{dB}$ for the co-propagating pump at the same settings. Hence G improves by $\sim$0.7 dB, but the SNR decreases.

3. Fiber laser

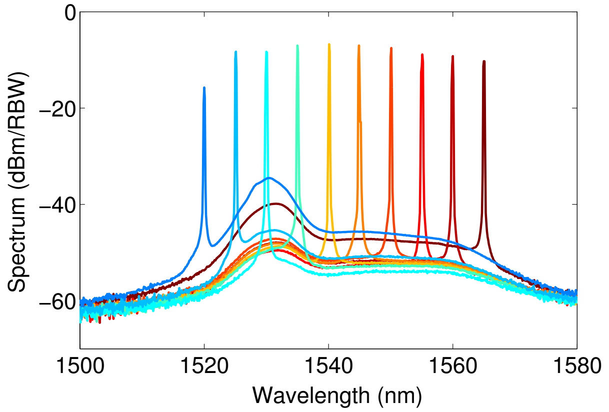
To construct a resonator around the EDFA (see Fig. 4a), we take the output signal port and send it into a 90/10 fiber-based splitter acting as an output coupler. The 90 % port is then connected through an isolator and a tunable filter back into the signal input port. This creates a unidirectional, fiber-based cavity, which is then pumped in a single pass configuration as before.

We are unable to obtain an accurate estimate of the cavity lifetime τ_c, since we did not measure the total fiber length used in the resonator (though we can estimate $\sim$10 m). It is worth noting, however, that the cavity is extremely lossy: the isolator exhibits a loss of 10.4 dB = 91 %, and we measure the loss at the bandpass filter to be 30.7 % at 1550 nm. Furthermore, it turns out one of the patch cables used in the cavity is damaged, with a loss of 20.1 %. Finally, the measured output from the 90 % port of the splitter is in fact only 74 %, indicating a loss of 36 % (with 8.6 % actual output coupling).

Fig. 4: Configuration and operation of a tunable EDFL.



(a) Schematic of EDFL configuration, adapted from [5].



(b) Tunable operation of EDFL. Center wavelengths from 1520 nm to 1565 nm, in steps of 5 nm. Pump power set to 55.3 mW for all traces.

Despite this high loss (approximately 14 dB), the high gain of the EDFA nevertheless supports lasing. Shown in Fig. 4b is a collection of the EDFL output spectra for various settings of the bandpass, at maximal pump power. This demonstrates that the EDFL can be widely tuned within the gain bandwidth of the Er-doped fiber.

Fig. 5 shows the output power of the EDFL as a function of pumping at 1550 nm, which exhibits a slope efficiency of 0.72 % and threshold at 22.6 mW of pump. It is possible to drastically improve these values by switching to better fiber components in the laser. From the inset, we also see that the laser output includes broadband noise associated with the presence of ASE.

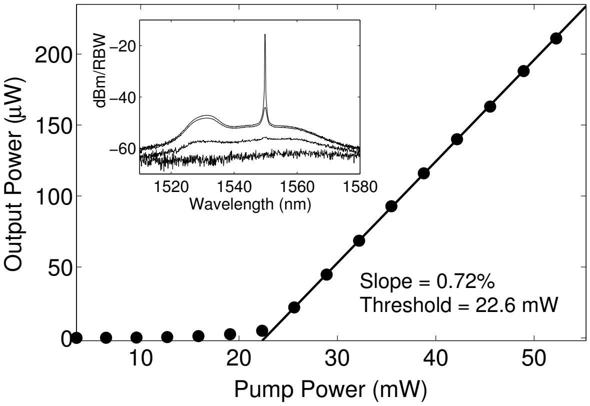


Fig. 5: Output power of EDFL as a function of pump power, operating at 1550 nm, ∼10 % output coupling. Inset: EDFL output spectrum at various pump powers. Bottom to top: 9.6 mW, 15.9 mW, 22.4 mW, 28.9 mW.

As a solid-state laser with a relatively long upper-state lifetime of $\tau_2 = 10$ ms, the EDFL is expected to exhibit relaxation oscillations (RO), driven by small fluctuations in the resonator or pump power. We can observe these noise-driven ROs by sending the output of the EDFL into a fast InGaAs detector and recording the output spectrum using an RF spectrum analyzer (Agilent 4395A). The settings used are as follows: RBW 10 Hz, VBW 3 Hz, and noise floor ~ -120 dBm/RBW). A sample trace of the RO peak is shown inset in Fig. 6.

The relaxation oscillation frequency f_{RO} goes as [3]

$$(2\pi) f_{\mathrm{RO}} = \sqrt{(r-1)/\tau_2\tau_c}, \tag{2}$$

where $\tau_2\tau_c$ is the product of the upper state and cavity lifetimes, respectively, and $r = P_{\mathrm{pump}}/P_{\mathrm{th}}$ is the number of times above threshold.

The data shown in Fig. 6 confirms this behavior, and a linear fit according to Eq. 2 yields a slope of approximately 13.5 kHz, which gives us a measurement of $\sqrt{\tau_2\tau_c} = 12\,\mu\mathrm{s}$. From Eq. 2, the intercept should be zero; as expected, the fit intercept is small. Based on our estimates of cavity length and losses, $\tau_c \sim 10$ ns very roughly. [6] Assuming $\tau_2 = 10$ ms as in the literature, we would have expected $\sqrt{\tau_2\tau_c} \sim 10\,\mu\mathrm{s}$, consistent with the measured result.

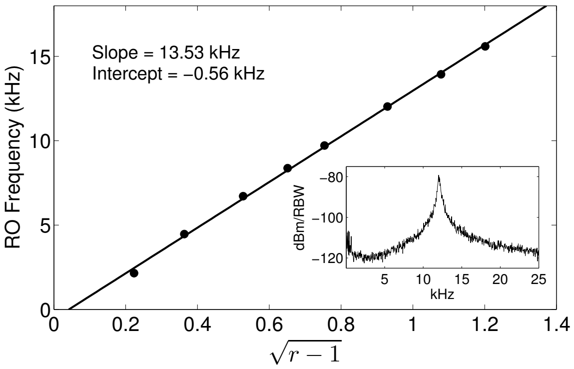


Fig. 6: Laser RO frequency vs. square root of times above threshold, for 1550 nm and ∼10 % out coupling. Inset: RF spectrum analyzer trace of RO peak, taken at 42.2 mW pump ($r = 1.86$); RO peak ∼12 kHz.

4. Conclusions

We observe high optical gain in excess of 15 dB around the practically important 1550 nm band in the EDFA, using modest pump powers up to 60 mW. We measure this signal gain along with the amplifier's intrinsic ASE noise (in particular, the output SNR and NF) for various regimes of low and high signal and pump powers, which qualitatively matches well with theoretical predictions. SNR values up to 20 dB are observed after amplification, and the 3 dB intrinsic limit to the NF of the EDFA is realized at high pump and low signal.

Taking advantage of the high gain, we build a fiber-based laser using the EDFA. Tunable operation of the EDFL from 1520 nm to 1570 nm is achieved using a bandpass filter, with a slope efficiency of 0.72 % at 1550 nm. Relaxation oscillations in the EDFL are observed, and we measure $\sqrt{\tau_2\tau_c} = 12\,\mu\mathrm{s}$, consistent with estimations based on fiber component losses and the natural lifetime of the Er^{3+} ions in the glass fiber.

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