Electrical and Computer Engineering

EECS 539 - Lasers

Erbium-Doped Fiber Lasers and Amplifiers

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April, 2021

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1 Introduction

1.1 Optical Fibers

Optical fibers have made a remarkable impact on the optical technological advancements in society, particularly in communications. Its conceptual backbone, total internal reflection at the interface of media with differing refractive indices, was first demonstrated by Daniel Colladon and Jacques Babinet in the 1840s [1]. By the early 20th century, optical fibers were beginning to be used in dental applications as well as in image transmission, notably in applications related to internal medical examinations. To make a shameless plug to the university, in 1956, Basil Hirschowitz, C. Wilbur Peters, and Lawrence E. Curtiss of the University of Michigan patented the first fiber optic gastroscope [2]. This invention was the first time an optical fiber was made with glass cladding, instead of relying on air or oil/wax as the low-index cladding media. More specifically related to the field of optical telecommunications, the first optical fiber transmission system was demonstrated in the 1965 at Telefunken Research Labs. A few years later, NASA ended up using related fiber optic technology in their television cameras that were sent to the moon [3].

As it has been described so far, there is no doubt that optical fibers have played a rather expansive part in the advancement of technology. However, what is more in the scope of this paper is how these fibers, made out of materials such as silica glass, were used as the gain medium of lasers and amplifiers. This idea was first tested in the 1960s and subsequently led to the idea of using them telecommunication systems, as noted above. However, due to the large intrinsic losses of the glasses made for these fibers (around 4dB/m), this technology was largely delayed until the 1980s. Nonetheless, in the 1970s, Stone et al. realised the first silica-based fiber lasers [4]. These type of lasers were co-lineraly pumped with the signal by semiconductor diode lasers, continuously emitting at room temperature. A breakthrough in the optical fiber fabrication process (modified chemical vapor deposition) allowed the infusion of rare-earth ions in the core of a preform and subsequently the fabrication of a low background loss single-mode amplifier fiber [5]. In 1985, a group from Southampton University fabricated the first single-mode fiber lasers that were doped with neodymium in linear or ring structures, as has been discussed in a lecture this semester.

1.2 David Payne and his Rare-Earth-Doped Fibers

One of the researchers at Southampton University, David Payne, deserves to be highlighted for his pioneering work in the field of fiber optics communications. Not only are his experimental results seminal to the field of telecommunications, but they are particularly related to the gain medium of focus in this paper. The international society for optics and photonics, SPIE, has even written an entire article on him, emphasizing the impact of his contributions [6]. Leading up to his experimental work, the quest for all-optical amplifiers became a popular research topic in the 1980s. One common light source used in experimental pursuits were semiconductor diode lasers, as mentioned earlier, because they were small in size, cheap, and electrically powered; however, experimental efforts time and again fell short of producing an efficient amplifier. Some of the barriers faced were high loss, low gain, became linear at high speeds, and polarization sensitivity [6]. Many of these research labs were focused on purifying glass in order to reduce losses, thereby extending transmission distances. Southampton on the other hand, which included Payne, focused rather on producing special purpose fibers. This led to fabricating fibers doped with rare-earth elements, with the idea that since rare earths were known for their useful optical properties, they could provide an answer to this quest. As it turned out, their neodymium-doped silica-based fiber lasers increased light absorption only in the neodymium pump bands, but not at other wavelengths. Additionally, his group realized that pumping along the length of the fiber led to producing a high pump intensity, decreasing the laser threshold to very low levels [6]. This was a notable achievement because up to this point, neodymium fiber lasers were seen as impractical because they required being pumped from the side with a flash lamp, which was extremely inefficient as little light would end up propagating through the fiber.

After this accomplishment, Payne moved forward by concentrating on erbium as a potential dopant. The minimum loss of fibers is around 1550nm, and he knew that erbium emitted at this wavelength. Nevertheless, he decided to pursue other dopants such as thulium and ytterbium for fiber lasers because its laser transition was only a three-level system rather than a four-level system which is usually required for efficient lasing, also discussed in lecture. As it turned out, erbium surprisingly proved to be a much better laser than anticipated. Although erbium's 1550-nm wavelength was an obvious choice for amplifier demonstrations because this is where telecommunications fibers are the most transparent, it was expected to have low amplification because of its three-level process. After writing 26 papers on erbium-doped fiber lasers (EDFLs), Payne discovered to see a gain peak of 30dB, making this type of fiber a more realistic solution to long-distance data transmission. Even now in present time, Payne mentions that he "still finds it remarkable that desptie intense competition, no one has ever managed to supersede the EDFA at 1550 nm." [6] Queen Elizabeth gave notice to him and was therefore knighted by her in 2013, along with numerous awards for his accomplishments.

1.3 EDFLs and EDFAs

It is of high hopes that the impact of erbium-doped fiber amplifiers (EDFAs) and EDFLs in telecommunications has been emphasized clearly without much room for argument. Nevertheless, additional specifications regarding these erbium-doped systems will be presented here in order to prove that despite its downfalls, it is one of the best fiber amplifiers/lasers to implement in telecommunications systems.

As previously mentioned, one of the limiting factors of an erbium-doped fiber is that it approximates a three-level laser system. Despite this, though, the erbium ion in silica can be formed into a potent gain medium once put in fiber form. This guided-wave approach has a number of advantages over a bulk gain medium[5]:

- High pump intensity: Because these silica fibers are only a few microns in diameter, the waveguided light being pumped into the fiber core yields a much higher pump intensity than in a bulk medium, which therefore reduces the lasing threshold. This is a crucial feature for a three-level system to be a feasible option.
- Signal and pump light waveguiding: Efficient laser operation is possible because of the excellent mode overlap between the signal and pump beams along with their parallelism with each other down the fiber.
- Compact gain medium: The gain medium can be arbitrarily long due to being compact in fiber form. Additionally, silica fiber can be coiled compactly, allowing it to be packaged in a small space.
- Excellent heat dissipation: Heat-related problems such as thermal lensing, thermal gradien-induced stresses, and reduced fluorescence at high temperatures are greatly reduced since the small diameter of the fiber allows good heat dissipation.
- Robustness: A fiber laser cavity is much more robust to mechanical perturbations when compared to free-space laser systems, such as alignment issues.
- Independence of spot size and gain medium length: In bulk gain media, the pump beam is divergent and thereby follows a relation between the optimum gain medium length (L_{opt}) and pump spot size (w_0). For instance, for a TEM_{00} pump laser of wavelength λ,

  $$L_{opt} \approx 3\pi w_0/\lambda$$

  However, these two parameters are independent for a fiber laser. Also, having the ability to use an arbitrarily long gain medium in fiber-form allows for weak pump absorption lines to be utilized in exciting the lasing transition. This becomes important if this weak pump band coincides with the wavelength of available diode lasers described above.

Furthermore, as Payne has described, using EDFAs proved to be competitive relative to alternative optical amplifiers such as semiconductor fiber amplifiers (SOAs) and Raman fiber amplifiers. Some of its advantages are the possibility for simultaneous amplification of multi-wavelength signals, power efficiency, reliability, and cost. They also distinguish themselves from these other optical amplifiers by its compatibility with telecommunication optical fibers, having low crosstalk, its polarization independence, and its high output power and efficiency [5, 6].

2 Analysis of Erbium-Doped Optical Fibers

As mentioned multiple times, a three-level rate equation model can be adapted for the erbuium-doped optical fiber medium. However, it is sometimes necessary to include a fourth level to account for the effects of excited-state absorption, which is just simply the excitation of a system from one excited state to a higher one with the absorption of a photon [5, 7]. This can occur at either at the pump or signal wavelengths and reduces the overall amplification efficiency by exciting ions from the lasing level to an upper energy state, from which it may relax non-radiatively, eventually decaying to the lower energy level of the four-level system. Overall, this process wastes a pump photon each time it occurs, reducing the efficiency. Figure 1 illustrates this laser level system.

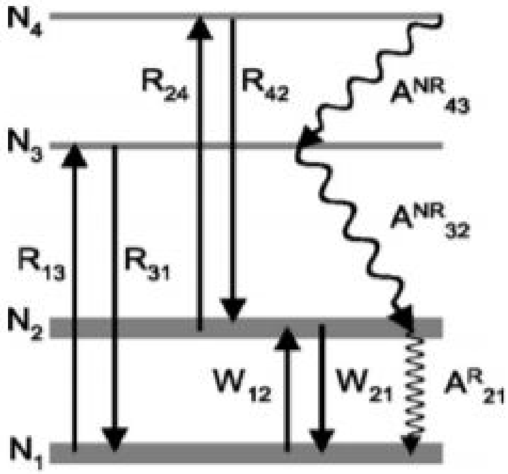

Figure 1: Erbium ion energy level system. The three-level erbium-doped system can be more accurately described using a fourth level to accomodate for the loss due to excited-state absorption. The lasing energy levels are N_1 and N_2, N_3 is the upper energy level, and N_4 is the excited-state absorption level. The pumping rates are denoted by R, the radiative and non-radiative relaxations by A^R and A^{NR}, and the stimulated signal transitions by W.

Another complication arises from the nonuniform nature of inversion along the length of the fiber [7]. Since, the fiber is pumped from one end, the pump power decreases along the fiber length; hence, it is important to include axial variations of the pump, signal, and the level populations. Therefore, in general, the set of coupled rate equations must be solved numerically.

Nevertheless, simplifying this model by ignoring the effects of spontaneous emission and excited-state absorption can lead to an intuitive and realistic model. For an EDFA, it is safe to assume that the pump level of the three-level system has a sufficiently short enough lifetime that we can state that this level remains approximately unpopulated (in other words, $\tau_{3,2} \ll \tau_{2,1}$). With these simplifications, we are able to readily describe the upper laser level rate equation as

$$\frac{\partial N_2}{\partial t} = -W_{2,1}N_2 + (W_{1,2} + R_p)N_1 - \frac{N_2}{T_1}, \tag{1}$$

$$\frac{\partial N_1}{\partial t} = -(W_{1,2} + R_p)N_1 + W_{2,1}N_2 + \frac{N_2}{T_1}, \tag{2}$$

where $N_{tot} = N_1 + N_2$ is the total number density as usual, while $W_{i,j}$ the transition rates for the pump and signal, and T_1 is the recovery time for the population difference. We have also defined the pumping rate as $R_p \equiv \eta_p W_p N_i$, where $W_p = W_{1,3}$ is the pumping transition rate and η_p is the quantum efficiency [8]. From lecture, as well as in Siegman's textbook, we know that in the absence of degeneracy, $W_s \equiv W_{1,2} = W_{2,1}$ and

$$R_p = \frac{\sigma_p}{\hbar\omega}\frac{P_p}{A_p}\Gamma_p \tag{3}$$

$$W_s = \frac{\sigma_s}{\hbar\omega}\frac{P_s}{A_s}\Gamma_s, \tag{4}$$

where P is the pump power, σ is the transition cross section, ω represent the pump and signal frequencies, A is the mode area of the pump and signal inside the fiber, and Γ is the overlap factor representing the fraction of the power within the doped region of the fiber. We can now rewrite Eqns (1) and (2) as, for convenience,

$$\frac{\partial N_2}{\partial t} = R_p N_1 - W_s(N_2 - N_1) - \frac{N_2}{T_1}, \tag{5}$$

$$\frac{\partial N_1}{\partial t} = -R_p N_1 - W_s(N_1 - N_2) + \frac{N_2}{T_1}. \tag{6}$$

If we wish to solve for the steady-state solution of Eq. (5), we need to set $\partial N_2/\partial t = 0$:

$$\frac{\partial N_2}{\partial t} = 0 = R_p N_1 - W_s(N_2 - N_1) - \frac{N_2}{T_1}.$$

Using the definition of N_{tot}, we obtain

$$\begin{aligned} 0 &= R_p(N_{tot} - N_2) - W_s\left[N_2 - (N_{tot} - N_2)\right] - \frac{N_2}{T_1} \\ &= -N_2\left(R_p + 2W_s + \frac{1}{T_1}\right) + N_{tot}\left(R_p + W_s\right) \\ \Rightarrow N_2 &= \frac{(R_p + W_s)N_{tot}}{\frac{1}{T_1} + 2W_s + R_p} \\ &= \frac{(R_p + W_s)T_1 N_{tot}}{1 + 2W_s T_1 + R_p T_1}, \end{aligned}$$

and therefore,

$$N_2 = \frac{(P'_p + P'_s)N_{tot}}{1 + 2P'_s + P'_p}, \tag{7}$$

where we defined $P' \equiv P/P^{sat}$ with the saturation powers defined as

$$P_p^{sat} \equiv \frac{A_p\hbar\omega_p}{\Gamma_p\sigma_p T_1}, \tag{8}$$

$$P_s^{sat} \equiv \frac{A_s\hbar\omega_s}{\Gamma_s\sigma_p T_1}. \tag{9}$$

The pump and signal powers vary along the length of the amplifier due to absorption and stimulated and spontaneous emission. Additionally, it also depends on whether the two beams propagate in the same or opposite directions through the fiber [7]. Neglecting spontaneous emission and assuming forward pumping, the pump and signal powers satisfy

$$\frac{dP_p}{dz} = -\Gamma_p \sigma_p N_1 P_p - \alpha' P_p, \tag{10}$$

$$\frac{dP_s}{dz} = -\Gamma_s \sigma_s (N_2 - N_1) P_s - \alpha P_s, \tag{11}$$

where α and α' account for the fiber losses at the given pump and signal wavelengths, which are clearly not assumed to be the same, respectively. Substituting in Eq. (7) into these, we obtain

$$\begin{aligned} \frac{dP_p}{dz} &= -\Gamma_p \sigma_p N_1 - \alpha' P_p \\ &= -\Gamma_p \sigma_p (N_{tot} - N_2) - \alpha' P_p \\ &= -\Gamma_p \sigma_p \left[N_{tot} - \frac{(P_p' + P_s')N_{tot}}{1 + 2P_s' + P_p'} \right] - \alpha' P_p \end{aligned} \qquad \begin{aligned} \frac{dP_s}{dz} &= -\Gamma_s \sigma_s (N_2 - N_1) - \alpha P_s \\ &= -\Gamma_s \sigma_s (2N_2 - N_{tot}) - \alpha P_s \\ &= -\Gamma_s \sigma_s \left[2\frac{(P_p' + P_s')N_{tot}}{1 + 2P_s' + P_p'} - N_{tot} \right] - \alpha P_s, \end{aligned}$$

which reduce to

$$\frac{dP_p'}{dz} = -\frac{(P_s' + 1)\alpha_p P_p'}{1 + 2P_s' + P_p'} - \alpha' P_p', \qquad \frac{dP_s'}{dz} = \frac{(P_p' - 1)\alpha_s P_s'}{1 + 2P_s' + P_p'} - \alpha P_s', \tag{12}$$

where we defined $\alpha_p \equiv \Gamma_p \sigma_p N_{tot}$ and $\alpha_s \equiv \Gamma_s \sigma_s N_{tot}$ as the pump and signal absorption coefficients at their respective wavelengths [7, 8]. This makes sense because absorption cross sections σ describe the strength of an atomic transition per atom, N_{tot} is the total number density within the medium, and Γ just represents the fraction of N_{tot} that are useful from the doped region of the fiber. Proceeding, these equations accurately describe the evolution of the pump and signal powers through the fiber, as long as the spontaneous emission remains small. They can be numerically solved, as explicitly shown in the Appendix. Figure 2 plots these coupled equations for a number of different initial parameters for the power and signal ratios with respect to the saturation powers for each. For fiber lengths under 1km, the losses α and α' in Eq. (9) can be set to zero and still represent an accurate model.

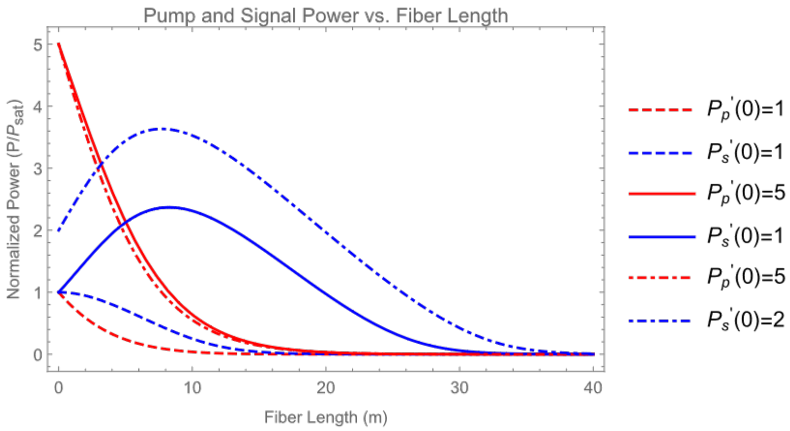

Figure 2: Normalized pump power (red curves) and signal power (blue curves) as they propagate through a fiber. This corresponds to the solutions of the coupled equations expressed in Eq. (9). Here, we have set different values for the initial conditions in order to observe their trends: $P'_p(0) = 1$ and $P'_s(0) = 1$, $P'_p(0) = 5$ and $P'_s(0) = 1$, and $P'_p(0) = 5$ and $P'_s(0) = 2$. The losses were set to $\alpha_p = 3$ dB/m and $\alpha_s = 3.3$ dB/m, as these are their typical values when $\lambda_p = 1480$nm and $\lambda_s = 1550$nm [9].

We can derive another expression that presents a different perspective of the equation for N_2 using the steady-state condition of Eq. (5) and the propagation equations shown in Eqns. (10) and (11). Again, assuming that $\alpha = \alpha' = 0$ for fibers shorter that 1km, we can write (10) and (11) as

$$P_p = -\frac{1}{\Gamma_p \sigma N_1}\frac{\partial P_p}{\partial z}, \tag{13}$$

$$P_s = -\frac{1}{\Gamma_s \sigma (N_2 - N_1)}\frac{\partial P_s}{\partial z}, \tag{14}$$

and substituting these into the steady-state condition of Eq. (5), along with the definitions presented in Eqns. (3) and (4), we obtain

$$\begin{aligned} 0 &= R_p N_1 - W_s(N_2 - N_1) - \frac{N_2}{T_1}, \\ &= \frac{\Gamma_p \sigma P_p}{A_p \hbar\omega_p} N_1 - \frac{\Gamma_s \sigma P_s}{A_s \hbar\omega_s}(N_2 - N_1) - \frac{N_2}{T_1}, \\ &= \frac{\cancel{\Gamma_p \sigma}}{A_p \hbar\omega_p}\frac{1}{\cancel{\Gamma_p \sigma N_1}}\frac{\partial P_p}{\partial z}\cancel{N_1} - \frac{\cancel{\Gamma_s \sigma}}{A_s \hbar\omega_s}\frac{1}{\cancel{\Gamma_s \sigma (N_2 - N_1)}}\frac{\partial P_s}{\partial z}\cancel{(N_2 - N_1)} - \frac{N_2}{T_1}, \\ &= \frac{1}{A_p \hbar\omega_p}\frac{\partial P_p}{\partial z} - \frac{1}{A_s \hbar\omega_s}\frac{\partial P_s}{\partial z} - \frac{N_2}{T_1}, \end{aligned}$$

and hence

$$N_2 = \frac{T_1}{A_p \hbar\omega_p}\frac{\partial P_p}{\partial z} - \frac{T_1}{A_s \hbar\omega_s}\frac{\partial P_s}{\partial z}. \tag{15}$$

Then, substituting this into Eqns. (13) and (14) and integrating over the length of the EDFA fiber, we get the powers P_s and P_p at the output. Also, we can consider the total amplifier gain G for an EDFA of length L is computed using [7]

$$G = \Gamma_s \exp\left[\int_0^L \sigma(N_2 - N_1)dz\right] \quad (16)$$

One of the limiting assumptions of this model is that we are assuming the absorption and emission cross sections are the same for the pump and signal beams. In fact, based on experimental work by C.R. Giles and E. Desurvire as well as B. Pederson et al., these differences are proven real, as shown in Figure 3 [7, 9, 10].

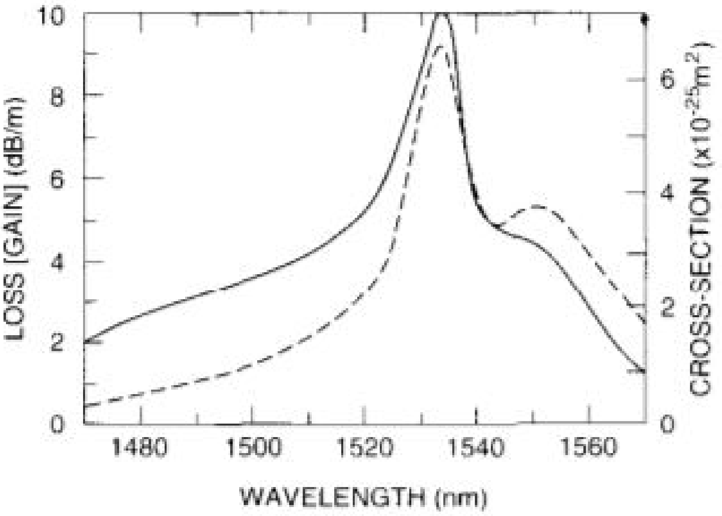

Figure 3: The absorption (solid) and gain (dashed) spectra of an EDFA with its core doped with germania.

We can see that the gain spectrum is particularly broad with two main peaks, while the absorption spectrum has one notable peak. In addition to this, the shape and width of each spectrum is notably sensitive to the core composition of the fiber. One experimental result by W. J. Miniscalco is shown in Figure 4, plotting four EDFAs with different core compositions.

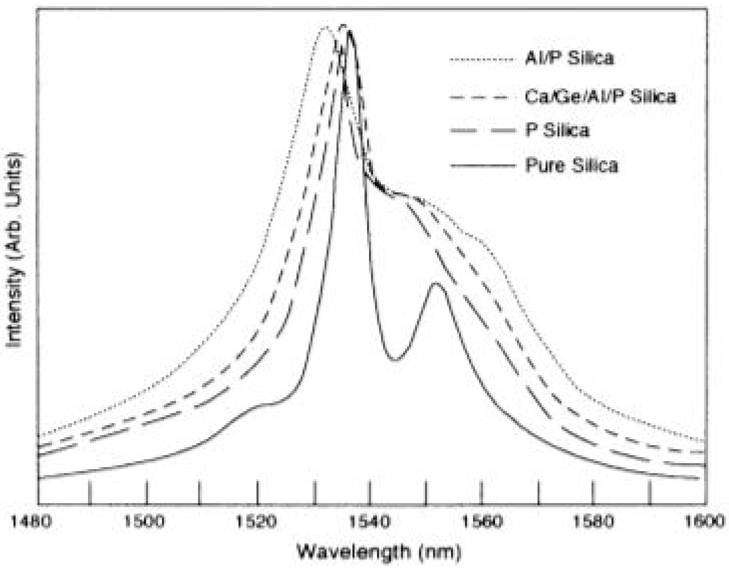

Figure 4: The gain spectra of four EDFAs with different fiber core compositions: Al/P silica, Ca/Ge/Al/P silica, P silica, and pure silica. As it can be seen, codoping the silica core with aluminum or phosphorus broadens the emission spectrum quite substantially.

This figure shows that the narrowest spectrum is when we have just pure silica, though it can be significantly broadened by doping the silica with other elements along with erbium.

Nevertheless, our model can be extended to include these differences in cross sections. Figure 5 shows how the small-signal gain gain at the optimal telecommunications wavelength of $\lambda_s = 1.55$µm changes as we increase the pump power P_p at $\lambda = 1.48$µm for various fiber lengths L, given an input power of 100nW [9, 13]. This plot is attained by using Eq. (16) with the respective cross sections σ_s and σ_p not assumed to be the same. For a given fiber length, the gain initially increases exponentially, but then comes close to levelling off when the pump power exceeds a certain value. Such a plot allows one to understand how much the fiber should be pumped not only to achieve a high gain, but also if increasing the pumping power beyond a certain point is worth it or not.

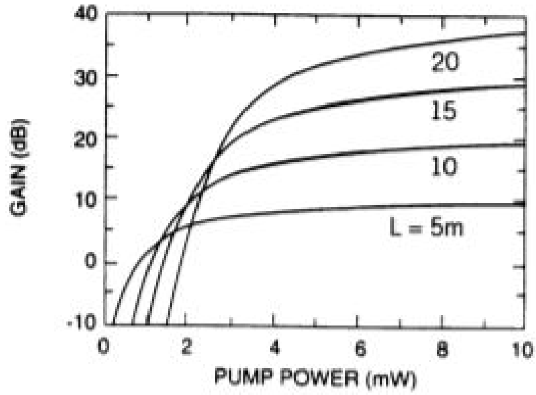

Figure 5: The small-signal gain at 1.55µm as a function of the pump power at $\lambda_s = 1.48$µm. The gain and loss of the pump and signal beams through the fiber were accounted for using the values seen in Figure 3 for their respective wavelengths.

Moreover, we can also consider what the optimal fiber length needs to be, given a specific pump power, in order to maximize the gain. This is a valid parameter to pay attention to because as the pump beam propagates down the fiber, it will be absorbed by the EDFA until being completely depleted, assuming an arbitrarily long fiber. This means that if the fiber is any longer than the point in which the gain becomes its maximum (given a specific pump power), then the fiber will begin to absorb the amplified signal, thus reducing the output signal power. So, since the optimum fiber length depends on the pump power, we need to be careful in choosing both of them. Figure 6 depicts the case where our pump power wavelength is $\lambda_p = 1.48$µm [9]. As it can be observed, a maximum gain of 35dB is obtained for a pump power of $P_p = 5mW$, corresponding to a fiber length of $L = 30m$. Interestingly, these qualitative features are shown to be observed in all EDFAs [11].

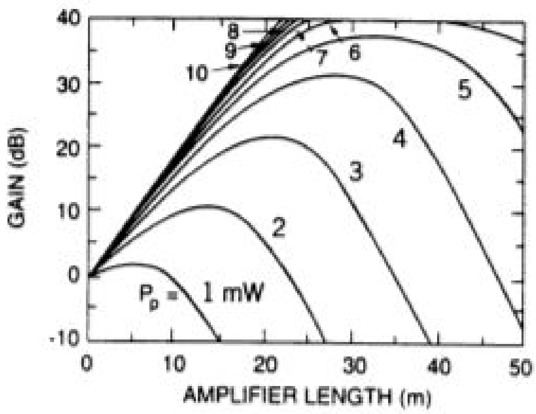

Figure 6: The small-signal gain as a function of the amplifier length when considering various pump powers at $\lambda_p = 1.48$µm. The plot in Figure 3 was used in Giles et al. in order to achieve this plot.

3 Applications

3.1 CW to Pulsed

Throughout the entire analysis, we have been focused on continuous-wave pump and signal beams. In telecommunication systems, EDFAs are normally pumped by using continuous-wave lasers, but the signal is generally pulsed. If the signal was not pulsed, it would make long-distance optical communication systems essentially useless as pulsed trains of beams are used to create sequences of 1 and 0 bits of information. Consequently, it is important to maintain a constant gain over all pulses that passes through an EDFA.

Fortunately, constant gain can be achieved as long as the temporal pulse widths are shorter than a few microseconds [7]. This can be reasoned by the relatively large lifetime decay T_1 that we see in Eq. (1), which is around 10ms. When the lifetime decay is much larger than the timescale of a given signal pulse, the erbium ions in the fiber are not able to follow such fast variations. If the fiber is not able to recover its initial, optimal gain in time before the next pulse in the train propagates through it, then there will be attenuation of the amplification of these following pulses. However, because signal pulse energies tend to be much lower than the saturation energy, which is approximately 10µJ, EDFAs respond to the average power. Consequently, the gain saturation of the fiber corresponds to the average signal power, resulting in a constant gain from pulse to pulse.

3.2 Wavelength-Division Multiplexing

On a different note, if we consider the application of wavelength-division multiplexing (WDM), one EDFA is used to amplify a large number of channels simultaneously [7]. Not only that, but a WDM signal is likely to pass through many EDFAs from the transmitter to the receiver. Therefore, in both cases of trained pulses and WDMs, if the gain is not flat, or even slight variations over the wavelengths of interest, there can be potentially large variations among each wavelength/channel once it reaches the receiver. One solution to this issue is using an optical filter that transmits more light in the wavelengths where the gain is lower. Another solution, which is primarily used now, are fiber bragg gratings [14], a topic to which has been briefly discussed in EECS 634 with Professor Winful.

With optical filters, they can provide flat gain over a bandwidth of up to 30nm; however, dense WDM systems which are designed to transmit 50 or more channels, have stricter requirements of a flat gain that is over 50nm [7]. This is quite difficult if looking to achieve this with a single EDFA. One design to satisfy this requirement is to use two EDFAs in which the second is codoped with ytterbium and phosphorus, resulting in a flat gain [15]. Another design that solves this problem is dividing the WDM signal into two bands, the conventional (C) band (1530-1560nm) and the long-wavelength (L) band (1570-1600nm). The incoming WDM signal into two branches containing optimized EDFAs for the C- and L-bands [7]. The L-band

EDFA requires long fiber lengths (¿ 100m) since the inversion is relatively low (see Figure 3 or 4 for reference). This design can produce a relatively uniform gain of 4 dB over 80nm when pumped using 980-nm semiconductor lasers [16].

3.3 Erbium-Doped Fiber Lasers

So far, we have mainly been focused on the amplifier aspect of using erbium-doped fibers. Even so, much of the analysis is the same as to when applying these fibers for lasing instead. These EDFLs can operate in several wavelength regions, from visible to infrared. Nonetheless, the most attractive wavelength region as previously mentioned is the 1.55µm region because it conveniently overlaps with the low-loss region of silica fibers. Also mentioned before is that because this fiber is approximated by a three-level lasing system, it requires at least half of the population to be in the upper laser level state, resulting in a high threshold [8]. On top of this, we know that excited-state absorption becomes an issue , eating away at the efficiency of the laser by excited valuable pump photons away from the lasing system. One notable pumping wavelength region in which this is a big problem is near 0.8µm, though the situation can be improved by codoping the fiber with elements such as ytterbium [17].

It turns out that the performance of EDFLs improve considerably when pumped at 0.98µm or 1.48µm because of the absence of this excited-state absorption [7]. Their utilization has resulted in commerical 1.55-µm fiber lasers. So, despite being a three-level system, EDFLs are too convenient to pass up when considering a telecommunications perspective.

One important property of operating EDFLs continuously is their ability to provide a tunable output over a wide range. According to a textbook by P. R. Morkel [18], there are many techniques to reduce the spectral bandwidth of a tunable EDFL. One experiment mentioned is creating an etalon formed between one of the ends of the fiber and the output mirror, as well as using an external grating. This resulted in a 620-MHz linewidth and was tunable over 70nm. The output power was over 250mW in the wavelength range 1.52-1.57µm [19]. Figure 7 shows the experimental setup along with the tuning curves for two different fiber lengths.

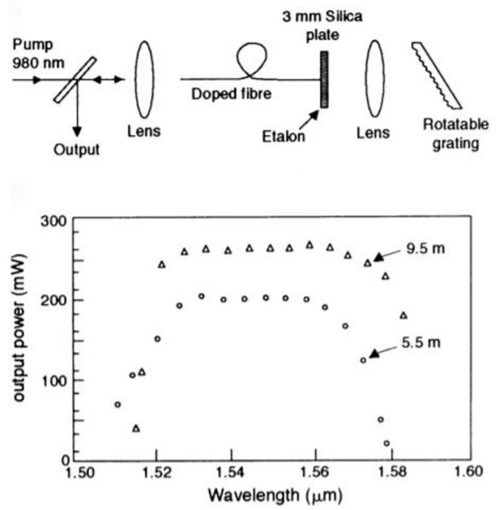

Figure 7: The experimental setup for a tunable EDFL using an etalon and a rotatable grating. The tuning curves are with respect to fiber lengths of 9.5m and 5.5m at 540mW input power.

As it is illustrated, the input beam is focused down to where it can enter the erbium-doped optical fiber. It then is incident on an etalon, controlling the wavelengths of light transmitted, which is then focused with another lens and passed to a rotatable grating. This grating is able to separate the various wavelengths that are incident on it, and rotating it allows one to tune to a specified wavelength that were transmitted though the Fabry-Perot.

3.4 The Ring-Cavity EDFL

The ring cavity is one of the more common designs for EDFLs in the literature, mainly because of its simplicity. One of the simpler designs is shown in Figure 8 [20]. Essentially, it utilizes an EDFA that was thoroughly discussed in the analysis in which its output is fed to its input using a coupler, creating a rind-cavity laser.

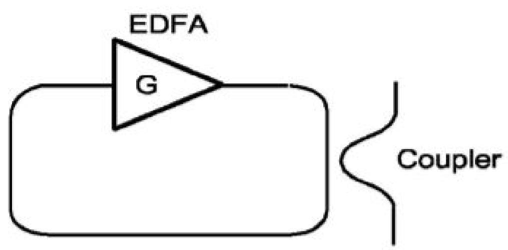

Figure 8: A general ring-cavity EDFL schematic.

This laser design has travelling-wave operation, in contrast to standing-wave operation which was the main focus in our lectures (apart from one homework assignment where we considered ring-cavity laser systems). A standing-wave architecture for EDFLs can form a gain grating in the fiber, which is why a travelling-wave architecture is preferred. Unlike in the pulsed scenario discussed earlier in this section, a continuous-wave operation, as discussed here, can saturate the gain within the fiber since the restoration rate of the erbium-doped medium may not be fast enough to allow its effects to be negligible. And since the signal is forced to travel back and forth in a standing-wave cavity, along with the pump beam, the gain will be saturated and replenished at various, periodic points along the fiber. This means that the beams that formed his grating will reduce the round-trip gain because of the locally saturated regions within the fiber. The possibility of mode-hopping is now a concern, which is a phenomenon in which the frequency of the signal may shift to another frequency due to external influences (e.g. gain saturation). This can occur due to neighboring modes having a higher gain (i.e. unsaturated gain). Such a phenomenon can make it difficult for frequency tuning, which was previously discussed.

In contrast, ring-cavity EDFLs use the gain in the fiber more efficiently [5]. Figure 8 depicts a typical setup for this kind of laser system [20].

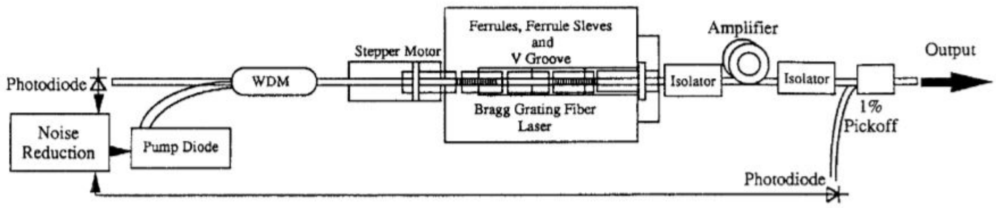

Figure 9: An EDFL ring laser. The pump light is a laser diode which is injected into an erbium-doped fiber through a WDM.

In this setup, a high-power compact fiber-pigtailed laser diode is used as the pump light. This is then sent through the erbium-doped fiber using a WDM, which is just a wavelength-dependent fused fiber coupler. The isolators depicted in the figure forces unidirectional travel of the laser light, as to prevent gain gratings forming. What makes this type of architecture more appealing is that they can integrate a wide variety of fiber optical components, such as Gragg gratings, modulators, stitches, etc. in sequence, even if any are prone to back-reflections, as the isolators ensure unidirectional travel. Consequently, ring cavities are great for broadlly-tuneable EDFL applications [5].

3.5 Erbium-Doped Fibers Today

Erbium-doped fibers continue contribute in massive ways in society today, just like it has in the few decades. One of the largest manufacturers of these fibers is Corning in Corning, NY. They have perfected and patented a manufacturing process for their fibers called Outside Vapor Deposition (OVD), which they claim makes the most consistent fiber in the world. In other words, the company states that it produces 100% synthetic glass, meaning no impurities in their fibers. As such, just like it was noted in the introduction, this leads to better fiber performance, which greatly reduces the variation in the gain spectrum using this manufactured fiber. [21]. Customers of their fibers use them in their state-of-the-art EDFAs. These amplifiers are typically used in long-distance optical communication systems today, such as in broadband optical networks cable television, optical coherence tomography, and biomedical illumination. This last application utilizes EDFLs that are pulsed in the femto-second range. This type of laser allows it to penetrate deeper into tissue without inflicting damage to it.

4 Conclusion

In this paper, we introduced a brief historical description of the advent of the optical fiber, beginning with one of optics' famous contributors: Jacques Babinet. We then discussed the qualitative reasoning behind why erbium-doped fibers deserve the amount of attention science and technology has given them, whether today or 30 years ago. Due to their attractive features for telecommunication systems, including having a relatively flat gain for a range of favorable long-distance communication wavelengths, a convenient and robust way of permitting lasing to occur, and its excellent mode overlap between the signal and pump beams to name a few, it does not appear that they will be considered outdated for years to come. Furthermore, we quantitatively analyzed these fibers by deriving its respective rate equations based off a three-level system, along with developing an understanding of its pump and signal power propagation equations. Moreover, we analyzed various parameter relationships from these derived equations, such the relationship of the output power down the length of the fiber, the gain and loss variations over the attractive telecommunication wavelengths and with various codopants, how the gain varies with respect to the pump power given different fiber lengths, and how the gain varies with respect to the fiber length given numerous pump powers. We then transitioned into a few applications of these fibers, discussing their use in continuous-wave or pulsed beams; in wavelength-division multiplexing; in EDFLs, including a description of the ring-cavity structure; and how these fibers are used today, outside of the scope of the rest of the paper. Even though these fibers have been deeply studied and tested, they are still of active research in the field of communications systems. In the future, perhaps the knowledge gained through intense study of these fibers will help in the development of other doped fibers that have not been created yet.

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