Practical Method for engineering Erbium-doped fiber lasers from step-like pulse excitations

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Abstract. A simple method, known as ‘easy points’, has been applied to the characterization of Erbium-doped fibers, aiming for the engineering of fiber lasers. Using low-power flat-top pulse excitations it has been possible to determine both the attenuation coefficients and the intrinsic saturation powers of doped single-mode fibers at 980 and 1550 nm. Laser systems have been projected for which the optimal fiber length and output power have been determined as a function of the input power. Ring and linear laser cavities have been set up, and the characteristics of the output laser have been obtained and compared with the theoretical predictions based on the ‘easy points’ parameters.

1. Introduction
Erbium-doped fiber lasers (EDFLs) have received much attention from the telecommunication industry due to their compact size and facility of integration to all-optical fiber communication systems [1], beyond other reasons. Nowadays, commercially available Erbium-doped fiber devices such as EDFLs, amplifiers (EDFAs), and amplified spontaneous emission sources (ASE) have already established their key role for a wide range of communication and sensing applications at the 1.5 µm wavelength region [1,2].

In an EDFL, the design of the cavity strongly influences the output power: it is essential to attain a suitable combination of low loss and high gain to obtain laser emission with low pump power. Since the laser performance is affected by a large number of factors such as the intrinsic parameters of the fiber and its length, the intracavity loss, and the output coupling ratio, a careful optimization procedure is necessary for the proper engineering of EDFLs cavity. In the literature, many papers regarding the design of single line [3-4], pulsed [2,5], multiline [6], and broadly tunable [7,8] lasers can be found. However, few papers report on optimization methods [9,10]. In general, the small signal gain, the slope efficiency, the threshold, and the wavelength emission of the fiber lasers are a function of intrinsic fiber parameters such as the optical mode distribution, the doping level and its distribution along the fiber cross section, the emission and absorption cross sections. These parameters are normally difficult to be directly measured, and the experimental results are often achieved by fitting procedures [11]. On the other hand, a good description of Erbium-doped fiber devices can also be obtained in terms of the attenuation coefficients, $\alpha$, the intrinsic saturation powers, $P_{IS}$, at the pump and laser wavelengths ($i=p, L$) and the excited state lifetime, $\tau$, [12]. The $P_{IS}$ can be obtained from non-linear transmission measurements, which are time consuming, often destructive, and limited by saturation [2,11], or alternatively, through a simple, nondestructive method, known as ‘easy points’
method [13]. With this method, the intrinsic parameters of the fibers can be retrieved from measurements of the waveform distortions that a step-like excitation pulse suffers upon propagation through the doped fiber.

The present work regards the engineering of EDFLs. We exploit the ‘easy points’ method to characterize the doped fiber and simplify the laser design, estimating the optimum value of the fiber length and predicting the maximum output signal, as a function of the input pump power. We set up linear and ring EDFLs and evaluate the performance of the output signal in comparison to the theoretical predictions based on the ‘easy points’ method results.

2. Theory of fiber laser

Fig. 1 represents the two types of cavity that are typical for fiber lasers. The linear cavity is made of two reflectors with reflectivities $R_1$ and $R_2$ at the laser wavelength, $\lambda_L$. Two counter propagating laser beams circulate in the cavity. The reflectors are transparent at the pump wavelength, $\lambda_p$, so the pump passes only once through the laser cavity. In the ring laser, a WDM is employed to couple the pump laser into the cavity. An optical isolator forces the unidirectional propagation of the laser radiation inside the cavity. The output coupling is provided by a directional fiber coupler. In both systems, $\varepsilon_1$ and $\varepsilon_2$ are loss terms that take into account intracavity components, splices, and coupling losses.

The single-line output power of a fiber laser above threshold is found by evaluating the amplification process through one cavity round-trip in terms of the input pump power $P_p^\text{in}$ [9,12]:

$$P_L^\text{out} = \eta(P_p^\text{in} - P_p^\text{th}).$$

(a)

(b)

Figure 1. Fiber laser configurations for (a) linear laser and (b) ring laser.

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(1)
This fiber-laser linear-output equation is valid up to pump-level saturation. For a properly designed laser, this saturation is not observed since pump-level saturation is only significant for fiber lengths much shorter than the optimum length. Therefore, the linear solution equation (1) can be taken as exact for all practical cases. In (1), $\eta$ and $P_p^{th}$ are the slope efficiency and pump power threshold, which for a two-level atomic model are given by:

Linear laser:

$$\eta = \frac{\lambda_p (1 - R_2) \varepsilon_2}{\lambda_c [1 - \varepsilon_2^2 R_2 + (1 - \varepsilon_1^2 R_1) \varepsilon_2^2 / (\varepsilon R)]} \left[ 1 - (eRG_{max})^{-\delta} \right]$$

(2)

$$P_p^{th} = \frac{\gamma_p P_{L}^{IS} \alpha_l L - \ln(\varepsilon R)}{\lambda_p 1 - (eRG_{max})^{-\delta}}.$$  

(3)

Ring laser:

$$\eta = \frac{\lambda_p \varepsilon_2 (1 - K)}{\lambda_c (1 - K \varepsilon)} \left[ 1 - (K \varepsilon G_{max})^{-\delta} \right]$$

(4)

$$P_p^{th} = \frac{\lambda_p P_{L}^{IS} \alpha_l L - \ln(K \varepsilon)}{\lambda_p 1 - (K \varepsilon G_{max})^{-\delta}}.$$  

(5)

Here $G_{max} = \exp[(\alpha_p / \delta - \alpha_c) L]$ describes the maximum gain at $\lambda_c$. $L$ is the doped fiber length, $R = (R_1 R_2)^{1/2}$ is the effective reflectivity, $\varepsilon = \varepsilon_1 \varepsilon_2$ is the effective cavity transmission, and $\delta = P_{L}^{IS} / P_p^{IS}$ denotes the saturation power ration. The two-level model is true for 1.48-$\mu$m pump wavelength, where only upper level $^4I_{13/2}$ and bottom level $^4I_{15/2}$ of the Erbium ion are involved, as shown in Fig 2. For 0.98-$\mu$m pumps, Erbium ions are more accurately described by a three level model. However a two-level model is a good approximation since the number of atoms on the pump level $^4I_{11/2}$ is small due to its short lifetime. It has been demonstrated that the two-level model is valid for pump powers less than 1 W at 0.98 $\mu$m [14].

It is noteworthy that the theoretical model used to derive the expressions (2)-(5) uses some simplifying assumptions. First, although spontaneous decay is accounted for, amplified spontaneous emission (ASE) is neglected. This is valid for fiber lasers above threshold. Second, it is assumed that there is no excited-state absorption (ESA) at the pump wavelengths, which should be expected a small difference between the theoretical predictions with the experimental evidence.
3. The ‘easy points’ method

Traditionally, $P_i^{IS}$ and $\alpha_i$ have been found from one beam transmission measurements in which the transmission is measured as a function of the input power for a doped fiber of length $L$ [12]. In the present work we apply the fast and nondestructive ‘easy points’ method. As described in [13], upon excitation of the Er$^{3+}$ ions, if a flat-top pulse with power amplitude $P_0$ is launched into the fiber, its temporal profile at the exit of the fiber will be distorted as depicted in Fig. 3. $P_1$ and $P_2$ are the power amplitudes at the front ($t=0$) and at the end of the exit pulse ($t>>\tau$), respectively. The time evolution of the power amplitude is characterized by the time constant $\Delta t$.

Using the expressions below, both $P_i^{IS}$ and $\alpha_i$ can be directly obtained from a single measurement in which $P_1$, $P_2$, and $\Delta t$ are obtained:
The factor $\xi$ in (6) accounts for the coupling efficiency between the fiber output and the detector. The life time $\tau$ can be found by measuring the counter propagating ASE decay, as discussed in [2,11].

4. Experimental set-up and results

Table 1 shows the characterization results for the Erbium doped fiber used in this work (ER20-4/125, Liekki) at relevant wavelengths 980 nm and 1550 nm. The parameter reported by the manufacturer is the attenuation coefficient at 1530 nm which has a value of 2.0 m$^{-1}$. This value is very close to that obtained experimentally at 1550 nm, which shows that the method yields satisfactory results.

Table 1. Attenuation coefficients and intrinsic saturation powers established by the ‘easy points’ method for the Erbium doped fiber used in this work.

| Parameter                        | Liekki ER20-4/125 fiber |
|----------------------------------|-------------------------|
| Attenuation coefficien@980 (m$^{-1}$) | 1.13                    |
| Intrinsic saturation power@980 (µW)   | 230.42                  |
| Attenuation coefficien@1550 (m$^{-1}$) | 1.56                    |
| Intrinsic saturation power@1550 (µW)   | 43.77                   |

The configuration of the realized lasers is shown schematically in Fig. 4. For the ring laser we have included an optical-fiber connectorized Fabry-Perot filter (F-P) to control the emission wavelength of the laser with a voltage source. We found that losses in the cavity at 1550 nm are 5 dB. In the case of linear laser, the cavity is defined by two fiber Bragg gratings (FBGs) that act as mirrors. The spectral response of FBGs in this experimental setup has the reflection peak around 1584.9 nm and a 3-dB bandwidth of 0.21 nm. Unlike the ring cavity, the optical isolator in this case avoids possible instabilities in the pump signal by reflections in the optical circuit. Although the reflection peak of the FBGs is around 40%, which is little low for this type of lasers, we could obtain slope efficiency around 20%.

Taking into account the losses that occur in each configuration of fiber laser, especially the insertion loss in each incorporated device and the losses that occur at each required splice, together with the data reported in Table 1, we can estimate the optimum length of doped fiber and predict the output power of each laser. We used doped fiber lengths of 9.7 m and 9.57 m for the ring laser and the linear laser, respectively, both optimized for an optical pumping power of 150 mW.

Fig. 5 shows the comparison of theoretical and experimental results for the output power of the ring laser at wavelength $\lambda_L=1582$ nm. As can be seen, the theoretical data fit very well with the experimental results. The difference between the values of slope efficiency is 2.53%, which validates the model based on the ‘easy points’ parameters. The maximum difference between the results is 2 mW, which is due to the ESA associated with pumping at 980 nm.

Fig. 6 shows the comparison of theoretical and experimental results for the output power of the linear laser at wavelength $\lambda_L=1585$ nm. Again we can see how the theoretical results fit very well with the experimental. The difference between the values of slope efficiency is 4.08%, which is quite satisfactory. The maximum difference in the results is about 4 mW, twice as recorded in the ring laser.
This result is explained by the fact that in this case the insertion losses are lower, thus achieving greater efficiency.

**Figure 4.** Schematic diagram of the realized lasers: (a) ring laser, (b) linear laser.

**Figure 5.** Ring laser output power at wavelength $\lambda_L = 1582$ nm versus pump power.
5. Conclusion
In conclusion, we have exploited the easy-points method to simplify the Erbium-doped fiber laser design by predicting the optimum values of variables with great effect on the fiber laser performance. The output power, the slope efficiency and threshold of ring and linear lasers were given in terms of directly measurable quantities with this method. To prove the proposed methodology, ring and linear lasers were designed and constructed. The agreement between theory and experiment is good, so the method is an appropriated tool for engineering two-level fiber lasers.

6. Acknowledgment
This work was supported in part by the National University of Colombia through the Bicentenario program, Grant 90201022, and Darwin-DIME program, Grant 90202046.

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