# Optimization of an Er-Doped Silica Glass Optical Waveguide Amplifier

Edwin Snoeks, Gerlas N. van den Hoven, and Albert Polman

*Abstract*—**The optical gain performance of a highly Er-doped waveguide amplifier is affected by concentration quenching and cooperative upconversion effects. Based on materials parameters, which were previously determined for Er-doped sodalime-silicate glass, we calculate how the gain performance can be improved by reducing these limiting processes. For amplifiers with an Er concentration exceeding 0.1 at.%, the Er de-excitation rate is dominated by cooperative upconversion rather than radiative decay or nonradiative decay due to coupling to defects. The effect of lowering the waveguide loss and reducing the optical mode diameter is also demonstrated.**

## I. Introduction

MUCH ATTENTION is being devoted to the development of erbium-doped optical amplifiers operating at 1.5 $\mu$m that can be integrated on planar waveguide structures. Compact amplifier devices that can be fully integrated with other components on the optical chip require the length of the amplifying waveguide to be as short as possible. This leads to a desire to increase the Er concentration as much as possible. This paper will discuss the effects of high Er concentration on the achievable optical gain.

Various methods to fabricate Er-doped planar optical waveguides have been reported, and in some cases optical gain has been demonstrated [1]–[7]. We used ion implantation to incorporate optically active Er into bulk sodalime-silicate glass, in which optical waveguides are fabricated by $Na^+ \leftrightarrow K^+$ ion exchange. The optical properties of Er-implanted sodalime glass have been investigated experimentally, as is described in [8]–[11]. The radiative decay rate of the 1.54-$\mu$m transition in $Er^{3+}$ was determined to be $45s^{-1}$ [9], corresponding to a luminescence lifetime of 22 ms. Two Er-concentration dependent photoluminescence (PL) quenching mechanisms which lower the PL lifetime were found to be significant in these implanted specimens: 1) concentration quenching due to excitation migration from excited Er ions to unexcited Er ions, followed by quenching at hydroxyl impurities [12], [13], and 2) cooperative upconversion, in which two Er ions in the first excited state interact nonradiatively [12]–[14]. In this interaction, one Er ion is promoted to a higher lying state, leaving the other in the ground state. This phenomenon becomes significant when the concentration of excited Er ions in an optical waveguide is high [11], [15], [16]. Both quenching mechanisms increase the decay rate of the metastable first excited state, thereby lowering the optical gain efficiency.

In this article, a model to calculate optical amplification characteristics is presented. The model is based on previously measured materials parameters of sodalime-silicate glass and includes the effects of concentration quenching and cooperative upconversion. Calculations show that a maximum gain of ~1.0 dB/cm is achievable in an Er-implanted sodalime glass waveguide amplifier using 200-mW pump power at 980 nm. The gain performance is limited mainly by the effects of cooperative upconversion and not by nonradiative decay due to the presence of quenching sites. It will be demonstrated how the optical gain can be improved by reducing the upconversion and by further optimizing the waveguide.

## II. Rate Equations for Optical Propagation

The optical gain in Er-doped waveguides depends on the amount and fraction of excited Er ions and the optical loss along the waveguide. The former is determined by the pump intensity which itself suffers from waveguide losses and absorption by Er. To accurately calculate the optical gain as a function of pump power for a certain waveguide length, it is therefore important to first calculate the pump evolution in the Er-implanted waveguides as a function of distance along the waveguide. Our calculations are based on the derivation of Digonnet [17], which we extended to account for cooperative upconversion.

It is assumed that the decay rates from all the higher lying levels to the metastable $^4I_{13/2}$ manifold are high compared to the de-excitation rate of the $^4I_{13/2}$ manifold to the ground manifold [11]. Under this assumption, the rate equations for a quasi-two-level system are sufficient to describe the populations of the two levels. For the case in which the signal intensity is low compared to the pump intensity, the fraction $n_2$ of $Er^{3+}$ in the metastable $^4I_{13/2}$ level anywhere in the optical waveguide is given by

$$\frac{dn_2}{dt} = R_{\uparrow}(1 - n_2) - R_{\downarrow}n_2 - \frac{n_2}{\tau} - \rho_{\mathrm{Er}}Cn_2^2. \qquad (1)$$

Here, $\tau$ is the luminescence lifetime resulting from radiative and nonradiative decay to the ground state (i.e., without upcon-

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TABLE I
EXPERIMENTAL PARAMETERS USED IN THE MODEL

| | | | Ref. |
|---|---|---|---|
| Density of sodalime glass | $\rho_{sls}$ | $0.67 \times 10^{23}$ at./cm$^3$ | |
| Density of OH in sodalime glass | $\rho_{OH}$ | $0.8 \times 10^{19}$ OH/cm$^3$ | 9 |
| Density of implanted Er | $\rho_{Er}$ | $1.4 \times 10^{20}$ Er/cm$^3$ | 11 |
| PL lifetime | $\tau$ | $(42\,s^{-1} + \rho_{Er}\rho_{OH} \cdot 5.75 \times 10^{-50} m^6 s^{-1})^{-1}$ | 9 |
| Upconversion coefficient | $C$ | $3 \times 10^{-24}$ m$^3$/s | 11 |
| Cross section absorption 980 nm | $\sigma_p^a$ | $1.0 \times 10^{-21}$ cm$^2$ | 14, 18 |
| Cross section emission 980 nm | $\sigma_p^e$ | 0 | 14, 18 |
| Cross section absorption 1.536 $\mu$m | $\sigma_s^a$ | $4.1 \times 10^{-21}$ cm$^2$ | 14, 18 |
| Cross section emission 1.536 $\mu$m | $\sigma_s^e$ | $5.0 \times 10^{-21}$ cm$^2$ | 14, 18 |
| Waveguide length | | 1.0 cm | |
| Optical loss in waveguide | $\alpha$ | 1.0 dB/cm | |
| Optical mode size | | $6 - 10\,\mu$m | 19 |

version), $\rho_{Er}$ is the Er density, $C$ the cooperative upconversion coefficient, and $R_\downarrow$ and $R_\uparrow$ are rates of stimulated emission and absorption, both at the pump wavelength. The excited fraction in steady state is

$$n_2 = \frac{R_\uparrow + R_\downarrow + 1/\tau}{2\rho_{Er}C}\left(\sqrt{1 + \frac{4\rho_{Er}CR_\uparrow}{(R_\uparrow + R_\downarrow + 1/\tau)^2}} - 1\right). \tag{2}$$

Using $R_\uparrow = I_p\sigma_p^a/h\nu_p$ and $R_\downarrow = I_p\sigma_p^e/h\nu_p$, with $\sigma_p^a$ and $\sigma_p^e$ the pump absorption and emission cross sections, $I_p$ the pump intensity, and $h\nu_p$ the energy of a pump photon, (2) can be used to calculate $n_2$ as a function of $I_p$.

Note that all variables $n_2, R_\uparrow, R_\downarrow$, and $\rho_{Er}$ in principle depend on the position inside the waveguide. However, in our case [11], the Er concentration is uniform and localized only in the center of the cross section of the waveguide where the pump light intensity is higher than 70% of its maximum.[1] In calculating $n_2$, we therefore assume that $R_\uparrow$ and $R_\downarrow$ are constant over the entire cross section of the doped region of the waveguide, so that $n_2$ is uniform over the doped cross section of the waveguide.

The evolution of the pump intensity $I_p$ along the light-propagation direction in the waveguide (the $z$ axis) is determined by absorption and stimulated emission due to $Er^{3+}$ and by the waveguide loss ($\alpha$, in units of cm$^{-1}$) as

$$\frac{dI_p}{dz} = -\alpha I_p - \sigma_p^a(1 - n_2)I_p \int \rho_{Er}(x,y)p_0(x,y)\,dx\,dy + \sigma_p^e n_2 I_p \int \rho_{Er}(x,y)p_0(x,y)\,dx\,dy \tag{3}$$

[1]This assumption can be made for Er-implanted waveguides, because implantation enables the waveguides to be doped locally in the core of the waveguide.

in which $p_0(x,y)$ represents the pump-intensity distribution across the waveguide and is normalized such that $\int p_0(x,y)\,dx\,dy = 1$. After inserting (2)—which provides $n_2(I_p)$—in (3), the solution $I_p(z)$ may be found by numerical integration. From $I_p(z)$, the fraction $n_2$ of excited $Er^{3+}$ can then be determined everywhere along the length in the waveguide.

It is then possible to determine the signal evolution along the waveguide. Starting from the differential equation for the normalized signal intensity $s(z)$, which is similar to (3), using in this case the emission and absorption cross sections at the signal wavelength, and the signal intensity mode $s_0(x,y)$, the gain function $g(z) \equiv \ln[s(z)]$ is found

$$\frac{dg(z)}{dz} = \frac{ds(z)/dz}{s(z)} = -\alpha - \sigma_s^a(1 - n_2)\int \rho_{Er}(x,y)s_0(x,y)dx\,dy + \sigma_s^e n_2 \int \rho_{Er}(x,y)s_0(x,y)\,dx\,dy. \tag{4}$$

Equation (4) can be solved numerically, making use of the evolution of $n_2(z)$ along the waveguide as derived above.

## III. RESULTS AND DISCUSSION

Calculations will be presented for Er-implanted sodalime-silicate glass waveguide amplifiers. Previously determined parameters, most of which are measured for Er in commercially available Fisher Premium sodalime glass, are shown in Table I. Unless differently stated, the calculations in the following sections were done using these values. The overlap integrals in (3) and (4) were determined using optical intensity distributions as shown in [19]. The Er concentration distribution is taken to be a constant within the area of the waveguide where the pump intensity is above

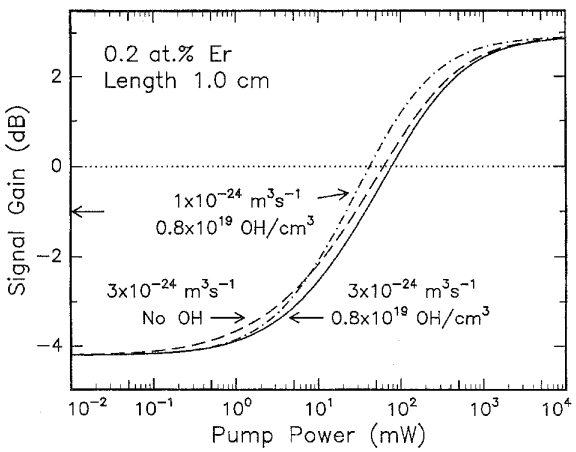


Fig. 1. Calculated gain as a function of pump power at 980 nm in a 1-cm-long waveguide in Fisher Premium sodalime glass. The solid line shows the result for sodalime glass with $0.8 \times 10^{19}$OH/cm$^3$ ($\tau = 8.5$ ms). The dashed line corresponds to the case in which no quenching sites are present in the glass ($\tau = 22$ ms). The arrow on the left axis indicates the waveguide loss (1 dB/cm). The Er concentration is 0.2 at.% ($1.4 \times 10^{20}$at./cm$^3$). In both cases, the measured upconversion coefficient $C = 3 \times 10^{-24}$ m$^3$/s is used [11]. The dot-dashed (- · -) line is calculated for the case that $C = 1 \times 10^{-24}$ m$^3$/s (and $0.8 \times 10^{19}$OH/cm$^3$).

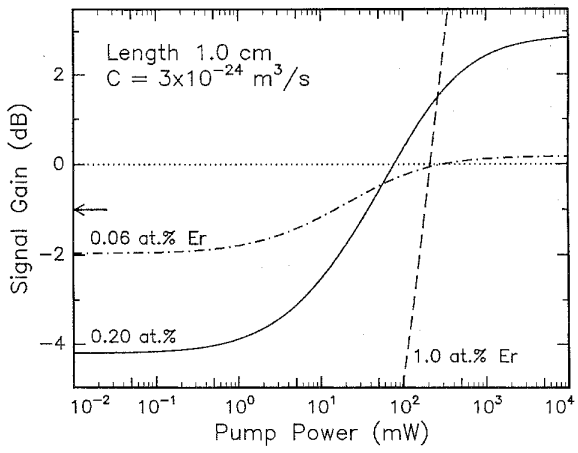


Fig. 2. Calculations of net optical signal gain as a function of pump power at 980 nm, based on known measured parameters. Three cases are shown, for three Er concentrations: 0.06 at.% (- · - line), 0.20 at.% (solid line), and 1.0 at.% (dashed line). The other parameters are fixed, except for $\tau$, which depends on the Er concentration because of quenching at OH impurities. The arrow indicates the waveguide loss.

70% of the maximum intensity. The above model has been shown to describe previously measured data quite accurately [11].

In the following sections, the influence of several important parameters on the optical gain is demonstrated. All calculations are performed for a pump wavelength of 980 nm.

### A. Effect of Removing Nonradiative Decay Sites

Fig. 1 shows calculations of the optical gain in a waveguide implanted with a constant Er concentration (see Table I). The full line is a calculation for the case that $0.8 \times 10^{19}$/cm$^3$ OH quenching sites are present, which is the case in commercially available Fisher Premium sodalime glass [9]. The PL lifetime then is 8.5 ms. The dashed line corresponds to the case that all OH is removed from the silica, in which case the lifetime is expected to be ~22 ms [9], [10], [20]. The waveguide loss (no Er) is indicated by an arrow. As can be seen in Fig. 1, removal of OH has only a very small effect on the gain curve. The gain threshold (the minimum pump power to reach net gain) is reduced from 76 to 62 mW (−0.9 dB). At 200-mW pump power, the net optical gain improves from 1.2 to 1.4 dB/cm.

The effect of the removal of OH is small due to the fact that for Er concentrations above $\sim 2 \times 10^{19}$at./cm$^3$, the de-excitation rate is dominated by cooperative upconversion. It is more important to focus on achieving low upconversion than to attempt to remove quenching impurities.

### B. Reduction of Upconversion

Fig. 1 also shows a gain calculation for the case that the upconversion coefficient is reduced from $C = 3 \times 10^{-24}$ m$^3$/s to $C = 1 \times 10^{-24}$ m$^3$/s (- - - line). As can be seen, this three-fold reduction of $C$ has a large effect on the gain threshold power, which reduces from 76 to 43 mW (−2.5 dB). The net gain at 200-mW pump power increases from 1.2 dB/cm to 1.9 dB/cm.

It is important to find host materials that show as low as possible cooperative upconversion. The upconversion coefficient is hard to control; it depends on the spectral overlap between the $^4I_{13/2} \rightarrow ^4 I_{15/2}$ and $^4I_{13/2} \rightarrow ^4 I_{9/2}$ transitions of $Er^{3+}$ as well as the phonon spectrum in the host. The spectral overlap may be minimized if a glass is used in which the emission spectra are narrow. The effect of upconversion can also be reduced by lowering the Er concentration.

### C. Effect of Er Concentration on Optical Gain

In this section, we will investigate the effect of increasing or decreasing the Er concentration on optical gain and gain threshold power. Fig. 2 shows three gain calculations, using three different Er concentrations (0.06, 0.2, and 1.0 at.%). All other parameters were kept fixed, except for the PL lifetime, which depends on the Er density $\rho_{Er}$ due to concentration quenching as shown in Table I. In Fig. 2, it can be seen that the maximum achievable gain increases for increasing Er concentration, which is expected under the condition that enough pump power is available to excite all Er. The gain threshold, however, shows a more complicated behavior as a function of Er density. For low Er concentration (0.06 at.%), the gain threshold is high (300 mW) because almost all Er must be inverted in order to produce sufficient signal gain to overcome the waveguide loss of 1.0 dB/cm. When the Er concentration is increased to about 0.2 at.%, net gain may be reached for a lower degree of inversion, resulting in a lower gain threshold power (76 mW). At even higher Er concentration (1.0 at.%) the luminescence lifetime $\tau$ decreases strongly due to concentration quenching, and upconversion becomes more effective as well [see (1)]. Therefore, more pump power is required to reach a certain degree of inversion, and the threshold increases to 215 mW.

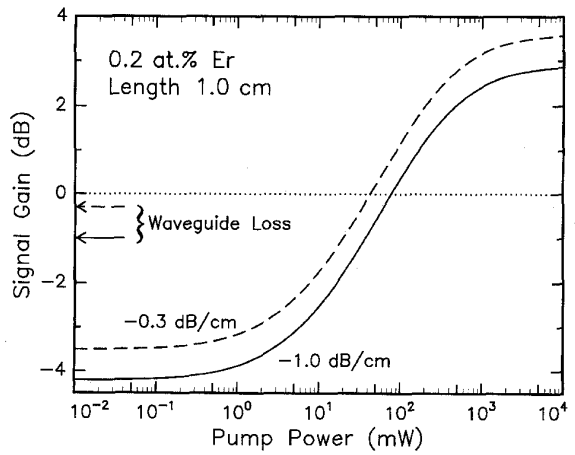


Fig. 3. Calculation of net optical gain in an Er-doped planar waveguide with 1.0 dB/cm loss (full line) or 0.3 dB/cm loss (dashed line). All other waveguide parameters were the same as those used for the solid line in Fig. 1.

### *D. Optical Confinement and Waveguide Loss*

The optical gain and gain threshold of an Er-doped planar waveguide amplifier may also be improved by reducing the optical losses in the waveguide. Indeed, in ion-exchanged silicate glass, optical losses well below the 1.0-dB/cm loss used in our calculation have been demonstrated. To first order, any reduction in optical waveguide loss results in an equally large improvement in net gain. This is shown in Fig. 3. The solid line from Fig. 1 is replotted together with the result of a calculation in which the waveguide loss was reduced from 1.0 dB/cm to 0.3 dB/cm loss. Net gain is now achieved at 43 mW. The net gain increases over the entire pump power range. All above calculations were performed for 1-cm-long waveguides. Note that for longer waveguides, the total gain is limited by the strong pump loss in the waveguide.

Another way to improve the optical gain performance is to reduce the dimensions of the optical modes, thereby increasing the pump intensity for a given pump power. This may be achieved by defining waveguides with a higher refractive-index contrast, leading to stronger optical confinement. In the ion exchange process, a higher core index may be reached by using silver ions [21] instead of the lighter potassium ions used here. $Ag^+$ ion-exchanged waveguides, however, are reported to show more optical loss than $K^+$-exchanged waveguides, due to precipitation of Ag. More research is required to develop alternative low-loss high-index ion-exchanged waveguides. If the optical modes could be shrunk to a diameter of 3 $\mu$m rather than the $\sim$10 $\mu$m which is presently the case, all pump power scales in Figs. 1–3 would be reduced by a factor of 10.

## IV. Conclusion

The optical gain performance of an Er-doped sodalime-silicate glass waveguide amplifier is limited by de-excitation of Er due to cooperative upconversion if the Er concentration exceeds $\sim$0.1 at.% ($5 \times 10^{19}$at./cm$^3$). A reduction of the upconversion coefficient, e.g., by choosing a different host for the Er, can lead to a large reduction of the pump threshold for net gain. Further improvements may be possible by reducing the waveguide propagation loss as well as by reducing the optical mode dimensions. The Er concentration that results in the highest possible optical gain is determined by the trade-off between: 1) more signal gain at a higher Er concentration, and 2) a higher pump threshold for gain due to more cooperative upconversion at high Er concentrations. The optimum Er concentration, therefore, depends on the amount of available pump power.

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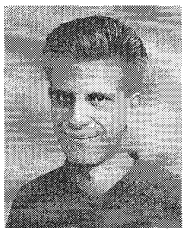

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