Cooperative upconversion in erbium-implanted soda-lime silicate glass optical waveguides

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Soda-lime silicate glass has been locally doped with 0.2-at. % erbium by 3.0- and 5.0-MeV ion implantation. Single-mode fiber-compatible optical waveguides were then fabricated by use of $Na^+ \leftrightarrow K^+$ ion exchange. Characteristic photoluminescence (PL) of Er^{3+} centered at 1.54 μm is observed on excitation at 1.48 μm. For low pump intensity the PL decay is nearly single exponential with a lifetime of 7.2 ms. At high intensity it becomes nonexponential as a result of cooperative upconversion, an interaction between excited Er ions. Self-consistent modeling of the PL intensity and decay data yields an upconversion coefficient of $3.2 \pm 0.8 \times 10^{-24}$ m^3/s. The effect of upconversion on optical gain is shown and discussed. An extrapolation of measured optical gain shows that 1 dB/cm of net gain is possible in the present Er-implanted soda-lime glass.

1. INTRODUCTION

Erbium-doped materials have become of great interest because of their use as optical gain media.[1,2] Er shows an optical transition centered at 1.54 μm, a standard wavelength in silica-based optical fiber communication systems. Optical fibers have been doped with Er to fabricate lasers, and in 1987 Er-doped fiber amplifiers operating centered at 1.54 μm were reported.[3] More recently a need has arisen for planar amplifiers that can be integrated with planar optical devices such as optical switches and multiplexers.[4] For example, a planar amplifier with a moderate gain of 3 dB could compensate for the intensity decrease in a Y splitter. To obtain such a gain in a few-centimeters-long waveguide, as opposed to the meter lengths used for Er-doped fiber amplifiers, the Er concentration needs to be of the order of an atomic percent. However, high Er concentrations can give rise to undesirable effects like reduction of the fluorescence lifetime and cooperative upconversion,[5–7] leading to an increase in the pump power required for optical gain. We showed previously that the luminescence lifetime of Er in soda-lime silicate glass is higher than 10 ms for Er concentrations as high as 0.2 at. %.[8] Above 0.2 at. %, significant concentration quenching was observed owing to energy migration that results from a resonant interaction between excited and nonexcited Er ions.

In this paper we will focus on cooperative upconversion effects. Cooperative upconversion is a process by which two Er ions that are both excited to the $^4I_{13/2}$ manifold (see Fig. 1) interact. One Er ion transfers its energy to the other, leaving itself in the ground manifold ($^4I_{15/2}$) and the other ion in the $^4I_{9/2}$ manifold. The remaining excited Er ion rapidly decays back to the $^4I_{13/2}$ state through nonradiative decay channels, producing heat, or it decays directly to the ground state by emission of a photon. The upconversion process is (nearly) resonant, and therefore the upconversion rate depends on the absorption and emission spectra of Er^{3+} manifolds in the host and on the phonon spectrum of the host. Cooperative upconversion effects are observable only when the pump intensity is high enough to maintain a high concentration of excited Er ions. One can achieve high pump intensities (as high as 10^5 W/cm^2) by using a cw laser confining the light in an optical waveguide with a 1–10-μm mode diameter. Although upconversion is an important process in planar amplifiers, little quantitative information concerning upconversion coefficients of Er in silica is available in the literature.

In this study we use ion implantation to dope soda-lime silicate glass with Er.[8] By selection of the implantation energy the Er depth profile can be accurately tuned to the optical mode profile. Also, in the lateral direction, Er can be localized in the waveguides by implantation through a mask that can subsequently be used to define waveguides. The advantage of tuning the Er profile to the mode profile is that lower pump powers are required to obtain optical gain. On a microscopic scale, ion implantation may lead to a locally homogeneous distribution of Er without clustering. Low-loss fiber-compatible channel waveguides can be easily fabricated in soda-lime glass by use of a $Na^+ \leftrightarrow K^+$ ion-exchange process.[9] A further advantage of this multicomponent glass is that

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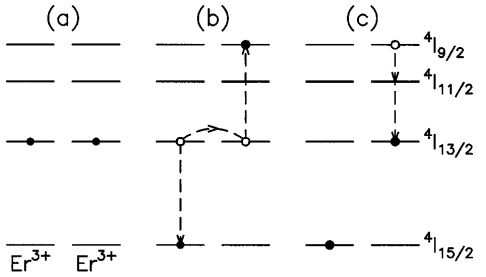

Fig. 1. Schematic representation of two-particle cooperative upconversion. The horizontal lines represent Stark manifolds of the $4f$ levels of Er^{3+}. The filled circles indicate to which of the four states the Er^{3+} ions are excited. The dashed arrows indicate nonradiative transitions. (a) Two ions are excited to the metastable $^4I_{13/2}$ manifold. (b) Energy transfer from one Er ion to the other. (c) Remaining excited Er ion rapidly decays back to the $^4I_{13/2}$ manifold.

it can accommodate high concentrations of Er without clustering.[2,8]

Here we determine the cooperative upconversion coefficient of Er implanted into soda-lime glass, using measurements of the 1.54-μm photoluminescence (PL) intensity and decay in Er-doped waveguides, following excitation with a 1.48-μm source. This pump wavelength, with which Er is directly excited to the metastable $^4I_{13/2}$ manifold, provides the most simple pump scheme for a study of upconversion. The effect of upconversion on optical gain is shown and discussed.

2. EXPERIMENT

Commercially available 1-mm-thick soda-lime silicate glass[10] was successively implanted on one side with 0.6×10^{16} Er ions cm^{-2} at 3.0 MeV and 1.2×10^{16} Er ions cm^{-2} at 5.0 MeV while the sample was kept at 300 °C to avoid surface roughening.[11] The sample was then annealed at 512 °C for 1 h in air. Subsequently, a thin Al film was deposited, and by use of photolithographic techniques, 5-μm-wide channels were etched in the Al. Channel waveguides were then defined by $Na^+ \leftrightarrow K^+$ ion exchange in the Er-implanted glass as well as in unimplanted glass for reference. In this process the samples were immersed in molten KNO_3 at 375 °C for 3.5 h. After etching off the Al mask we deposited a transparent silicone resin cladding (refractive index, 1.43) and polished the end faces of the sample. The length of the resulting Er-implanted channel waveguides was 3.0 cm. Single-mode optical fibers were aligned with the polished end faces of the waveguides and fixed by use of UV-hardening acrylate. The fiber-to-sample coupling loss was estimated to be 2–3 dB at 1.5 μm.

The geometry of the Er-implanted waveguide is shown in Fig. 2. The open circles show the Er concentration profile as a function of depth in the waveguide. We determined the profile by using Rutherford backscattering spectrometry, using 4.0-MeV $^4He^+$ and a scattering angle of 160°. The profile consists of two overlapping Gaussian distributions, resulting in an average Er concentration of 0.2 at. % (1.4×10^{20} cm^{-3}) at a depth ranging from ~1.0 to 2.1 μm. The solid curve shows the typical refractive-index profile after $Na^+ \leftrightarrow K^+$ ion exchange relative to the index of bulk soda-lime glass (1.50). Mode angle spacing measurements on ion-exchanged soda-lime glass show that the typical index increase at the surface is ~0.8%.[12] A calculated intensity distribution of the guided optical mode at 1.5 μm (through the center of the channel waveguide) as a function of depth is shown in Fig. 2 by the dashed curve,[13] for the case in which a cladding layer is deposited. The lateral width of the mode, which depends on the width of the channels on the Al mask during the ion-exchange process, was ~10 μm, comparable with that for standard silica optical fibers. A schematic cross section of the waveguide and the Er doping profile is shown in the inset of Fig. 2.

We performed PL spectroscopy by pumping the waveguides with powers ranging from 18 μW to 23 mW, using a Philips InGaAsP laser operating at 1.48 μm. The pump light is absorbed high in the $^4I_{13/2}$ manifold of Er^{3+} (see Fig. 1), from which the energy almost instantaneously thermally equilibrates over the $^4I_{13/2}$ sublevels. The Er PL signal was collected perpendicular to the direction of the waveguide with a lens, was spectrally analyzed with a 48-cm monochromator, and was detected with a liquid-N_2-cooled Ge detector or a cooled (−30 °C) photomultiplier tube. The pump light was mechanically chopped at 12 Hz, and spectra were recorded with a lock-in amplifier. We performed time-resolved luminescence decay measurements by switching off the pump light when the PL signal was in steady state. Decay data were recorded with the Ge detector (time resolution 30 μs) and averaged with a digital storage oscilloscope.

We performed signal gain measurements, using a continuous pump source (at 1.48 μm), while a signal from a tunable external-cavity laser (in the range of 1.523–1.558 μm), chopped at 1 kHz, propagated in the opposite direction. Fiber wavelength demultiplexers were used to mix and separate pump and signal wavelengths, and signal transmission change data were recorded by use of an InGaAs detector and lock-in detec-

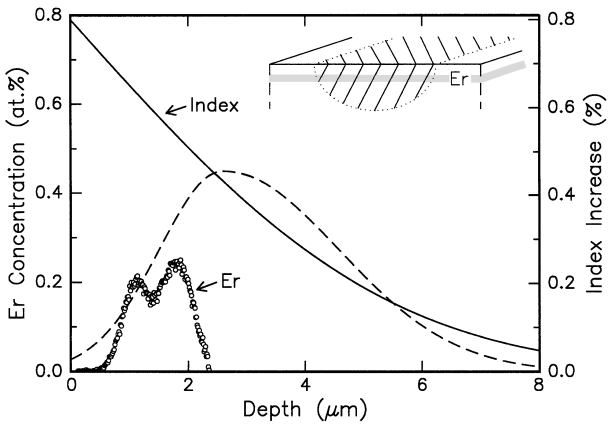

Fig. 2. Erbium concentration as a function of depth, measured by use of Rutherford backscattering spectroscopy (open circles). The average concentration in the waveguide is 0.2 at. %, corresponding to 1.4×10^{20} cm^{-3}. For comparison a typical refractive-index profile for $Na^+ \leftrightarrow K^+$ ion-exchanged waveguides is included (solid curve). The dashed curve is a calculated normalized optical intensity profile for a wavelength of 1.5 μm in the center of the channel waveguide. The inset shows a cross-sectional view of the waveguide: the shaded area shows the Er-implanted region; the hatched area is enclosed by the surface; and the dotted ellipsoid indicates the ion-exchanged region, i.e., the waveguide.

tion. The signal power was varied between 6 nW and 60 μW.

3. COOPERATIVE UPCONVERSION

A. Results and Analysis

Figure 3 shows the PL spectrum between 1.50 and 1.65 μm of the Er-implanted channel waveguide. The spectrum of the 1.48-μm excitation laser is also included (dotted curve). The PL spectrum peaks at 1.537 and 1.545 μm. This emission spectrum is characteristic for intra-4f transitions between the $^4I_{13/2}$ and $^4I_{15/2}$ manifolds of Er^{3+} (Ref. 14) and is consistent with our earlier study on Er implantation in soda-lime glass.[8] The shape of the spectrum near 1.54 μm was independent of pump power, and for none of the employed powers[15] (as high as 23 mW, i.e., 30 kW/cm^2) was luminescence detected near 800 or 980 nm which would be associated with the $^4I_{9/2} \rightarrow {}^4I_{15/2}$ and $^4I_{11/2} \rightarrow {}^4I_{15/2}$ transitions[14] (see Fig. 1). No green or other visible emission was observed either.

Figure 4 shows PL decay measurements at 1.537 μm following pumping to steady state by use of different pump powers in the range from 18 μW to 22.6 mW. As can be seen, almost single exponential decay with a lifetime τ of 7.2 ms is observed for powers as high as 1 mW. When the pump power is increased further, a faster component becomes visible in the decay curve. After 22.6-mW excitation the e^{-1} decay time is 25% lower than after low-power excitation, whereas the slow component in the decay remains at 7.2 ms.

The fast components in the PL decay after pumping at high intensities are explained in terms of cooperative upconversion,[6] in which one excited Er ion is promoted to the $^4I_{9/2}$ state at the cost of the $^4I_{13/2}$ excitation of another Er ion (see Fig. 1). Subsequently, either the $^4I_{13/2}$ level will be repopulated by means of nonradiative relaxation from the $^4I_{9/2}$ manifold, or a direct (radiative) transition in the ground manifold will occur, resulting in 800- or 980-nm emission. Because no 800- or 980-nm emission is observed, the lifetimes of the $^4I_{9/2}$ and $^4I_{11/2}$ manifolds are thought to be short. In that case, rate equations for a two-level system can be used to describe the fraction n_2 of Er^{3+} ions in the $^4I_{13/2}$ level[16]:

$$\frac{dn_2}{dt} = R_\uparrow(1 - n_2) - R_\downarrow n_2 - \frac{n_2}{\tau} - \rho C {n_2}^2 . \qquad (1)$$

Here τ is the spontaneous decay time resulting from radiative and nonradiative decay for the case without upconversion, $R_\uparrow$ and $R_\downarrow$ are the rates of absorption and stimulated emission of 1.48-μm pump light, ρ is the Er density, and C is the homogeneous upconversion coefficient. The effect of amplification of spontaneous emission on n_2 is neglected. Upconversion is described by a quadratic term because it involves two excited Er ions. The following relations were used: $R_\uparrow = I_p\sigma_a/h\nu_p$ and $R_\downarrow = I_p\sigma_e/h\nu_p$, where $h\nu_p$ is the pump photon energy, σ_a and σ_e are the absorption and emission cross sections at 1.48 μm,[17] and I_p is the pump intensity, which is estimated by use of an average mode diameter of $\sim$10 μm.[13] Note that the stimulated emission term $R_\downarrow n_2$ of pump light has to be included because the pump laser spectrum partly overlaps with the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ emission spectrum of Er^{3+}. The measured PL signal is proportional to n_2. We the find time evolution of the PL signal after switching off the pump source ($R_\uparrow = R_\downarrow = 0$) at $t = 0$ by solving Eq. (1):

$$n_2(t) = \frac{1}{\tau}\left[\left(\frac{1}{\tau n_2(0)} + \rho C\right)\exp(t/\tau) - \rho C\right]^{-1}, \qquad (2)$$

where $n_2(0)$ is the fraction of Er^{3+} that is excited in the $^4I_{13/2}$ manifold at $t = 0$. At low pump powers, upconversion effects become negligible, and Eq. (2) reduces to a single exponential with lifetime τ, which was determined to be 7.2 ms. Equation (2), with τ fixed at 7.2 ms, can now be used to fit the decay curves in Fig. 4 for all pump powers, with C as a free parameter, if $n_2(0)$ is

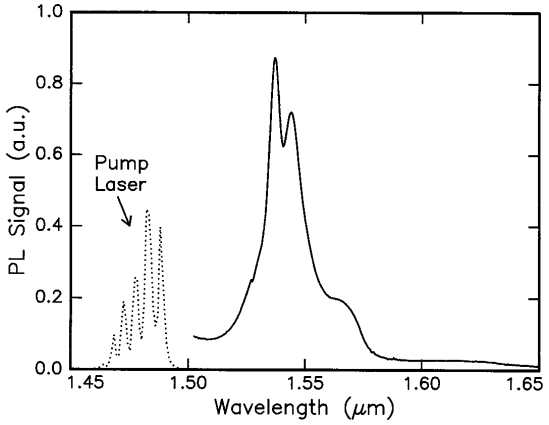

Fig. 3. Room-temperature PL spectrum of an Er-implanted soda-lime silicate glass channel waveguide (solid curve), measured with a resolution of 0.4 nm. The spectrum of the excitation laser (dotted curve) is shown on a greatly reduced scale.

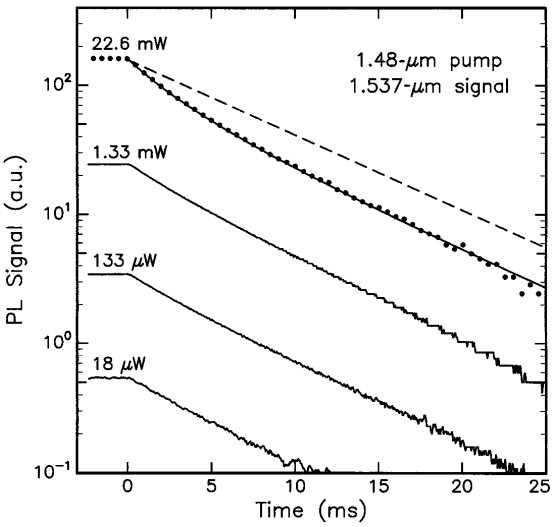

Fig. 4. PL decay curves following pumping to steady state by use of 1.48-μm excitation at 0.018, 0.133, and 22.6 mW in an Er-implanted soda-lime silicate channel waveguide, measured at 1.537 μm. The pump was switched off at $t = 0$. The luminescence signal is plotted on a logarithmic scale versus time. A power of 22.6 mW corresponds to an intensity in the waveguide of $\sim$30 kW/cm^2. A calculation according to Eq. (2), yielding $C = 3.2 \times 10^{-24}$ m^3/s, is shown as the solid curve. The dashed curve shows a single exponential decay with $\tau = 7.2$ ms.

known at each pump power. The decay measurements in Fig. 4 were made after the Er was pumped to steady state. Therefore $n_2(0)$ can be obtained as a function of pump power from measurements of the steady-state PL intensity.[15] These data are shown in Fig. 5 (open circles) and clearly show a sublinear behavior resulting from the combined effect of cooperative upconversion and depletion of the $^4I_{15/2}$ ground manifold. In our two-level description we can derive $n_2(0)$ from Eq. (1) by setting $dn_2/dt = 0$. This yields

$$n_2 = \frac{R_\uparrow + R_\downarrow + 1/\tau}{2\rho C}\left\{\left[1 + \frac{4\rho C R_\uparrow}{(R_\uparrow + R_\downarrow + 1/\tau)^2}\right]^{1/2} - 1\right\} \equiv n_2(0). \quad (3)$$

A value for the upconversion coefficient C can now be found so that relations (2) and (3) consistently describe the PL intensity (Fig. 5) and PL decay curves (Fig. 4) for all pump powers. The solid curves in Figs. 4 and 5 are calculated by use of $C = 3.2 \times 10^{-24}$ m^3/s. A constant scaling factor was used to convert from n_2 to the arbitrary PL units in Figs. 4 and 5. As can be seen, good agreement with the data is obtained. The estimated accuracy of the value for C found in this way is ~25%. The calculated fraction of excited Er ions, $n_2(0)$, is shown on the right-hand axis of Fig. 5. For comparison the dashed curve in Fig. 4 shows a single exponential decay with $\tau = 7.2$ ms in the absence of upconversion ($C = 0$). The dashed curve in Fig. 5 shows a calculation of the PL intensity for the case $C = 0$. The sublinear behavior is then due only to depletion of the ground manifold; the effect of upconversion is clearly visible in the data.

B. Discussion

Other research, in which Er-doped soda-lime glass waveguides were fabricated with rf sputter deposition,[18] yielded a homogeneous upconversion coefficient of 3×10^{-24} m^3/s, similar to the value we find here. This implies that the local environment and distribution in Er-implanted soda-lime glass is the same as that in the sputtered glass. Er-implanted phosphorous silicate glass (P-glass) yielded an upconversion coefficient of 9×10^{-23} m^3/s,[18] 30 times higher than that of Er-implanted soda-lime glass. A similar high upconversion coefficient of $\sim 10^{-22}$ m^3/s was reported for highly Er-doped Ge/Al-doped fused-silica P-fibers.[19] The difference in upconversion coefficients may be explained by a difference in overlap between the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ emission and $^4I_{13/2} \rightarrow {}^4I_{9/2}$ absorption spectra, which is higher in these doped P-glasses than in soda-lime glass. The upconversion transition to the $^4I_{9/2}$ manifold (~800 nm) is not resonant, with twice the peak emission wavelength from the $^4I_{13/2}$ manifold (~1537 nm). Therefore the relative intensity of the long-wavelength tail of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ emission spectrum is important. Indeed, the room-temperature PL spectrum of Er in P-glass[20,21] shows a more intense shoulder near 1.600 μm than is the case for Er in soda-lime glass.[8] Such a difference is also observed in low-temperature spectra.[22]

We can explain the data presented in this paper by using the assumption that the Er is distributed uniformly on the atomic scale (i.e., homogeneous upconversion). Previously we showed that all ions remained optically active for an implanted Er concentration of at least as high as 2 at.%,[8] meaning that no Er precipitation occurs. The data for the rf sputtered waveguides were also explained with the assumption of a uniform Er distribution.[18] However, in Er-implanted P-glass the analysis of upconversion effects shows that 20% of the Er ion is bound as ion pairs.[18] Paired ions undergo much stronger upconversion than homogeneously distributed Er ions. This comparison indicates that, with respect to upconversion, the soda-lime glass is a much better host for high concentrations of Er than is P-glass.

4. OPTICAL AMPLIFICATION

A. Results and Analysis

Optical amplification measurements were performed by coupling of a signal beam at 1.536 μm in the (3-cm-long) waveguide, in addition to the pump beam at 1.48 μm. Figure 6 shows the signal transmission change as a func-

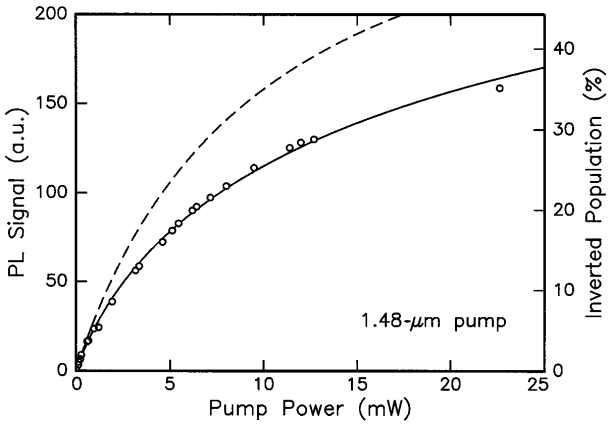

Fig. 5. PL intensity at $\lambda = 1.536$ μm measured as a function of pump power inside the waveguide. The highest measured power corresponds to an intensity of ~30 kW/cm^2. The solid curve is a calculation based on Eq. (3); the fraction of excited Er ions that follows from the calculation is shown on the right-hand axis. For comparison the dashed curve shows a calculation using the same parameters, but with $C = 0$ (no upconversion).

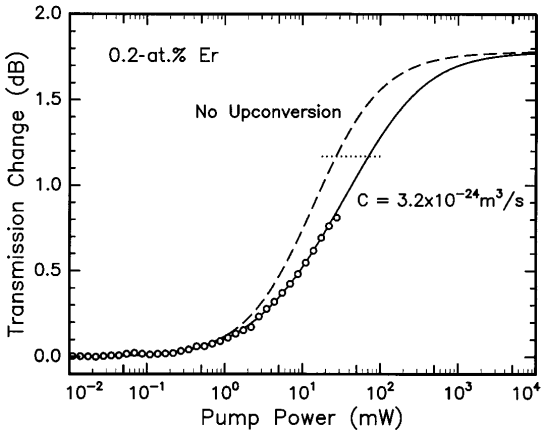

Fig. 6. Measured transmission change of a 1.536-μm signal as a function of 1.48-μm pump power in the waveguide (open circles). The solid curve is a calculation using the measured upconversion coefficient. The dotted line indicates the point at which the signal absorption rate equals the stimulated emission rate. The dashed curve shows the calculated gain curve in the absence of upconversion.

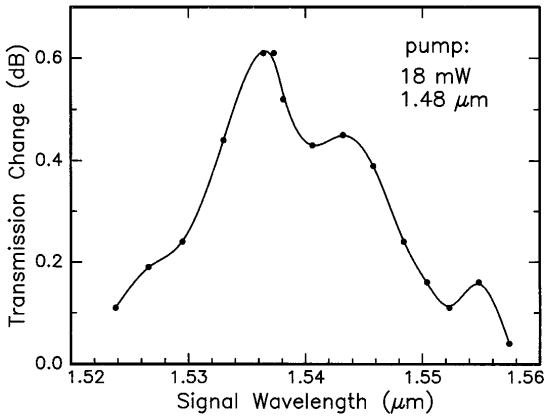

Fig. 7. Transmission change as a function of signal wavelength. The pump power at 1.48 μm was 18 mW. The filled circles are measured data, and the curve is a guide for the eye.

tion of pump power in the waveguide. The output signal with the pump on is plotted relative to the output signal intensity without pumping. By use of ~1 mW of pump power a small signal transmission change is measurable, and at 28 mW a transmission change of 0.8 dB is observed. We measured a gain spectrum (Fig. 7) by varying the signal wavelength between 1.523 and 1.558 μm. The spectrum peaks at 1.536 μm, and the full width at half-maximum is 17 nm. The transmission change at 1.536 μm (with 28 mW of pump power) was independent of input signal power in the range of 6 nW–60 μW, indicating that the $^4I_{13/2}$ manifold is not measurably depleted by the stimulated emission owing to the signal beam. Note that, without pumping, the total signal loss through the sample is 7.9 dB, consisting of waveguide loss (2–3 dB), coupling losses from fiber to sample (2–3 dB) and from sample to fiber (2–3 dB), and Er absorption (≈1.2 dB). Therefore no net signal gain is achieved with the pump powers that were used.

A numerical model was developed with which the evolution of both a pump and a small-signal beam through the Er-doped waveguide were calculated. The parameters C, τ, ρ, determined in the previous section, were used in the model. The overlap between the Er and the pump intensity distribution is taken to be the same as in Section 3. The overlap between the Er and the signal intensity distribution was a free parameter in the calculation, thus allowing for differences in guided pump and signal mode diameters. Cross sections for absorption and emission at pump and signal wavelengths were taken from Ref. 17, and a typical value of 1.0 dB/cm was assumed for the intrinsic waveguide loss.[9] Excited-state absorption was neglected. A small-signal approximation was made, meaning that the pump intensity fully determines the fraction n_2 of inverted Er ions. The calculations were performed with a constant (average) fraction of inversion over the cross section of the waveguide.

The solid curve in Fig. 6 shows the result of the numerical calculation. The calculation fits the measured data well, consistent with the results from the previous section that we obtained from the same waveguide. The unwanted effect of cooperative upconversion becomes clear from comparison with a calculation using the same parameters but without upconversion ($C = 0$, dashed curve). Also indicated in the figure (dotted line) is the point at which the rate of the signal absorption equals the rate of stimulated emission. The extrapolated pump power that is needed to reach that point is 70 mW, but this was not available from the pump laser used. Without upconversion this point would be reached at a power of 25 mW.

B. Discussion and Possible Design Improvements

The gain calculation in the previous section shows that the overlap between the signal mode and the Er profile—the only free parameter in the amplification model—is 0.4 times the overlap between the pump mode and the Er profile. This means that the signal mode is not well confined in the waveguide. Indeed, optical loss measurements as a function of wavelength in this waveguide (not shown) indicate that the cutoff wavelength in the Er-implanted ion-exchanged waveguides is at 1.540 μm, close to the signal wavelength. This results in bad confinement of the light. The cutoff wavelength of the waveguides fabricated simultaneously in unimplanted soda-lime glass was greater than 1.6 μm. Apparently the ion-exchange parameters have changed as a result of the Er implantation. This may be due to selective outdiffusion of Na during implantation,[23] which results in a lower K concentration after ion exchange and therefore a lower refractive-index increase. We may therefore improve the Er-implanted waveguides by simply performing the ion exchange for longer times, extending the cutoff to a longer wavelength. We estimate that the overlap between the signal mode field and the Er profile doubles in waveguides with appropriate cutoff wavelengths, resulting in an increased gain.

A second possible improvement that can be made is to increase the amount of Er in the waveguide. An increase in concentration leads to an undesirable reduction in the PL lifetime.[8] However, the amount can be increased threefold without increasing the Er concentration by extension of the Er profile into the depth, as can be seen in Fig. 2.

As a third suggestion for improvement it is interesting to consider the pump wavelength. In the 1.48-μm resonant pumping scheme that was used here the high-power limit of Eq. (3) shows that the maximum degree of inversion is ~0.67, which is due to stimulated emission by pump photons. This is a serious limitation for optical gain, despite advantages of this pump wavelength, such as low coupling and propagation losses. With 980-nm pumping (i.e., excitation to the $^4I_{11/2}$ manifold) near-full population inversion can be reached. However, there may be additional depletion of the $^4I_{13/2}$ manifold owing to excited-state absorption of 980-nm photons, leading to excitation of the $^4F_{9/2}$ level.[14] In our case, since the lifetime of the levels above the $^4I_{13/2}$ manifold are thought to be low, we assume that such depletion is negligible.

We can now use the numerical model to study gain prospects of the Er-implanted soda-lime channel waveguides, taking into account the three design improvements suggested above: extending the Er profile three times deeper in the waveguide, having better overlap between pump and signal mode, and pumping at 980 nm. Figure 8 (dashed curve) shows the result of the calculation of net signal gain for an Er concentration of 0.20 at. % and a measured lifetime of 7.2 ms. The calculation takes into account a waveguide loss of 1.0 dB/cm (indicated by the

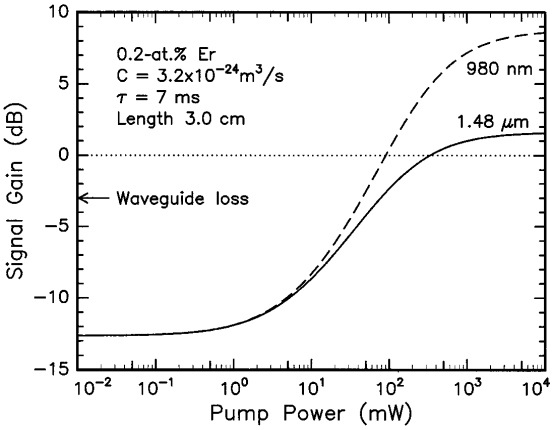

Fig. 8. Calculated gain at 1.536 μm as a function of pump power in a 3-cm-long waveguide, based on the design specifications given in the text. The waveguide loss (no Er) of 1.0 dB/cm is indicated by the arrow. The Er concentration is 0.2 at.%. The upconversion coefficient (3.2×10^{-24} m^3/s) and PL lifetime (7.2 ms) were determined in Section 3. The solid curve shows the result for a 1.48-μm pump, and the dashed curve for a 980-nm pump. With 200 mW, a net gain of 3.0 dB can be achieved.

arrow); furthermore, cooperative upconversion is included by use of $C = 3.2 \times 10^{-24}$ m^3/s, as obtained in Section 3. As Fig. 8 shows, with 200 mW of 980-nm pump a modest net gain of 3.0 dB (1.0 dB/cm) is achievable, enough to compensate the intensity loss in, for instance, a Y splitter. The negative gain of nearly −12 dB at zero pump power is due to the waveguide loss (3 dB) and the absorption by Er (9 dB). A calculation using a pump wavelength of 1.48 μm (solid curve) is also shown; no net gain is achievable in this way for pump powers less than 300 mW.

Recently Er-doped P-glass waveguides were made by flame hydrolysis[24] and plasma-enhanced chemical-vapor deposition[20] and yielded 0.65 and 0.33 dB/cm net gain, respectively, by use of ~400 mW of pump power at 980 nm. These gain numbers—slightly lower than the ~1-dB/cm value that would be achievable in our soda-lime waveguides—were obtained with only ~0.07 at.% Er, which was used to avoid concentration quenching and to reduce cooperative upconversion.[24] Net gain was still feasible in those experiments because of the extremely low waveguide loss of only 0.2 dB/cm, as opposed to ~1 dB/cm in our ion-exchanged waveguide.

Measurements on Er-doped soda-lime glass waveguides made by use of rf sputter deposition[25] showed a net signal gain of 3.3 dB/cm at 280 mW, three times higher than calculated here. In the sputtered glass, Er concentrations as high as 1.5 at.% were incorporated with PL lifetime as high as 10 ms.[7] In this case, the deexcitation rate owing to upconversion [$\rho C n_2$, see Eq. (1)] is as high as 2100 s^{-1} for a 70% excited fraction of Er ions. Such a high deexcitation rate can only be compensated for by use of a high pump intensity (i.e., a high power in a narrow waveguide).

5. CONCLUSIONS

Ion-exchanged optical waveguides have been fabricated in million-electron-volt Er-implanted soda-lime glass. Using excitation at 1.48 μm, we measured both the PL intensity and PL decay as functions of time in a channel waveguide by using pump intensities as high as ~30 kW/cm^2. The decay for low pump intensity is almost single exponential, with $\tau = 7.2$ ms, whereas for high pump intensities a faster nonexponential decay is observed. This is explained in terms of a homogeneous upconversion effect; the upconversion coefficient is found to be $3.2 \pm 0.8 \times 10^{-24}$ m^3/s. This value is 30 times less than that observed for Er in P-doped silicate glasses, which is partly attributed to the difference between the spectral shapes of the Er^{3+} manifolds of the two materials. Upconversion is unavoidable, and therefore it determines a fundamental limit to the optical gain per unit length in Er-based amplifiers. An extrapolation of measured optical signal gain shows that 1 dB/cm of net gain is achievable in the present Er-implanted soda-lime glass.

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