Absorption bleaching by stimulated emission in erbium-doped silicon-rich silicon nitride waveguides

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Stimulated emission from sensitized erbium ions in silicon-rich silicon nitride is demonstrated by pump–probe measurements carried out in waveguides. A decrease in the photoinduced absorption of the probe at the wavelength of erbium emission is observed and is attributed to stimulated emission from erbium excited indirectly via localized states in the silicon nitride matrix.

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The quest for complementary-metal-oxide-semiconductor-compatible light sources and amplifiers continues to drive research in the emerging field of silicon photonics [1–5]. Potential material platforms must be electrically pumped and should preferably emit at the technologically relevant 1.55 μm telecommunications wavelength.

Erbium-doped silicon-rich silicon nitride (Er:SRN) is a promising material candidate for integrated light sources on silicon [6]. Localized trap states [7–9] as well as small nanometer-sized silicon nanocrystals [10,11] in a silicon nitride host act as highly efficient sensitizers for erbium ions. The excess silicon permits electrical access [12,13], while the erbium ions serve as emitters at 1.54 μm. Sensitized stimulated emission, erbium population inversion, and, ultimately, gain, must be achieved in an integrated waveguide, toward the end of demonstrating lasing with Er:SRN as the active material.

Achieving population inversion of erbium ions via Si nanocrystals embedded in SiO_2 is challenging, and an excited Er fraction of ~20% is the demonstrated state of the art [14]. Efficient photoluminescence [10,11], electroluminescence [12], and even optical gain under intense pulsed conditions [15] have been demonstrated in silicon nanocrystal-based systems without erbium. In addition, while sensitized stimulated emission from erbium in silicon-rich silicon oxide was reported in [16,17], photoinduced absorption was reported in [18]. Thus, engineering the optimal silicon-rich matrix for obtaining sensitized stimulated emission and gain remains an important task to be resolved before lasing can be demonstrated [19].

Here we present evidence of stimulated emission from indirectly sensitized erbium ions in a silicon-rich silicon nitride host matrix and show a 50% suppression of the expected carrier related losses. This suppression corresponds to a 6.5% excited Er fraction.

We fabricated waveguides based on 400-nm-thick Er:SRN films. The films were deposited on a 4-μm-thick SiO_2 layer grown on Si substrate by reactive sputtering, as detailed elsewhere [7,8]. The sputtered film has a relative Si atomic concentration of 47%, as compared to 43% in stoichiometric silicon nitride, indicating an excess silicon of 4% [7,8]. The erbium concentration was measured from Rutherford backscattering measurements to be $\sim 4.6 \times 10^{20}$ cm^{-3} [7]. We have not observed Er clustering by high resolution transmission electron microscopy at these concentrations in our previous work [7]. Er ions are sensitized in the SRN matrix by the localized states in the band-tails of the silicon nitride host [7,8]. To verify the optical activity of the erbium and the sensitizing matrix, erbium photoluminescence was obtained from the films by nonresonant pumping at 457 nm (Fig. 1). The Er:SRN was subsequently patterned via electron beam lithography and reactive ion etching. In the final step, the waveguides were clad with a 2 μm layer of SiO_2 by plasma-enhanced chemical vapor deposition. Figure 1 shows a schematic cross section of the fabricated

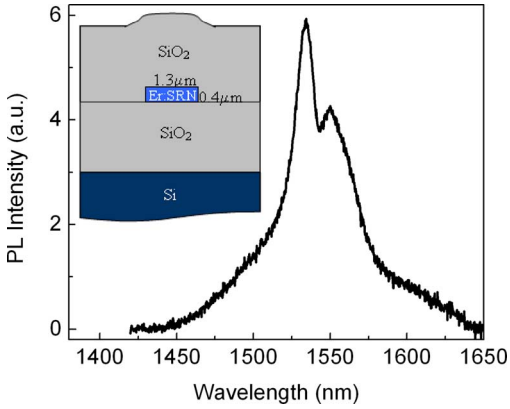

Fig. 1. (Color online) Er photoluminescence from 0.4-μm-thick Er:SRN pumped nonresonantly at 457 nm. Inset, schematic cross section of the fabricated Er:SRN waveguides (1.3 μm in width) with a refractive index of 2.23 at 1.55 μm on top of a 4 μm SiO_2 grown on an Si substrate. Devices were clad with 2 μm SiO_2.

devices. In these devices, scattering limited waveguide losses of ~20 dB/cm were achieved. The losses were determined by measuring the transmission through near identical waveguides of different lengths. Reduction of the scattering losses is essential in order to achieve net amplification, and this goal will be pursued further in the future.

In a pump–probe setup, we extract the dependence of the photoinduced losses on the probe wavelength. A cw at 455 nm was used to pump the Er:SRN waveguides. The pump beam was focused with a cylindrical lens into a line directly on top of the waveguide. The pump intensity was varied over a range from 1 to 186 mW/cm^2, while the probe (the output of a tunable laser of picometer precision) was coupled into the waveguides and scanned over a 1.5 to 1.6 μm range. In the presence of the pump, we observed a suppression of probe transmission for all wavelengths owing to photogenerated carriers in the SRN matrix.

We find evidence for stimulated emission of erbium from the photoinduced absorption as a function of wavelength for different pump powers (Fig. 2). The pump induced absorption, $\Delta\alpha$, is determined from the transmission in the pump-on and pump-off scenarios as

$$\Delta\alpha = -\frac{1}{L}\ln\left(\frac{P_{\text{on}}}{P_{\text{off}}}\right). \tag{1}$$

P_{on} and P_{off} represent the magnitude of the power transmitted through the waveguide with the pump on and off, while L denotes the length of the waveguide. Here, a positive $\Delta\alpha$ represents an increase in absorption. One can see that there is a dip around the 1.54 μm erbium emission peak against an overall background loss (Fig. 2). Such features are absent in waveguides with ~80% mode confinement, which were fabricated from a similar SRN material but were not cosputtered with erbium (Fig. 2). We suspect that the higher confinement and slight difference in the silicon content in the control film account for its photoinduced absorption being higher than the samples containing erbium. The important point is that the curve is featureless and lacks a clear dip in absorption

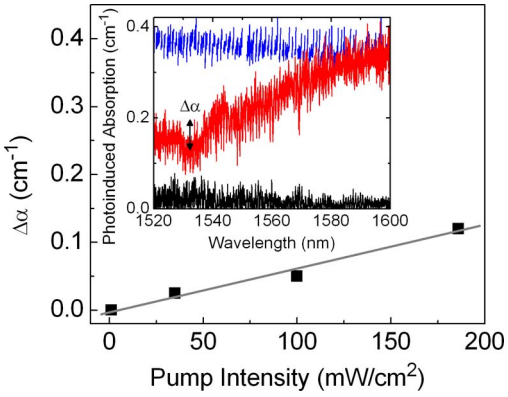

Fig. 2. (Color online) Increase of the dip located around 1.54 μm with pump. The straight line is a guide to the eye. Inset, the photoinduced absorption in 7.6-mm-long silicon-rich silicon nitride waveguides with Er ions (black lower curve, 1 mW/cm^2; red middle curve, 105 mW/cm^2) and without Er ions (blue upper curve, 50 mW/cm^2). Not all measurements are depicted for clarity.

at the erbium emission peak. The data are heavily modulated by Fabry–Perot features and, as shown in Fig. 2, the absorption dip is calculated using the mean value of these oscillations.

We attribute the dip in photoinduced absorption to stimulated transitions in the erbium population as detected by the probe beam. When the probe wavelength is varied, these stimulated transitions will follow the wavelength dependence of the erbium emission cross section. This picture is confirmed in our measurement and is manifested in the similarity between the dip in the absorption and the erbium emission spectrum (Fig. 3). We note that the transmitted probe was measured directly by an InGaAs photodetector with a flat response in the wavelength regime studied. Because the absorption here was measured as a function of probe wavelength, any spontaneous emission generated by the pump was detected as the same overall bias in the probe signal at all wavelengths.

We deduce a 6.5% inverted erbium fraction from the magnitude of the absorption dip. Considering that the origin of the dip in absorption is erbium stimulated emission, the inverted erbium population is estimated by assuming a two-level model where the populations of the ground state and excited states satisfy the condition

$$N_1 + N_2 = N, \tag{2}$$

where N_1 and N_2, respectively, are the ground and excited state erbium population densities and N is the total erbium density. The excited erbium fraction, N_2, is related to the magnitude of the dip in the absorption $|\Delta\alpha_{\text{dip}}|$ by

$$|\Delta\alpha_{\text{dip}}| = \Gamma\sigma_e N_2, \tag{3}$$

and the excited Er fraction, f, is thus given by

$$f = \frac{N_2}{N}, \tag{4}$$

where Γ is the modal confinement factor [20] and σ_e is the erbium emission cross section at 1.54 μm. By using the appropriate material parameters and waveguide dimensions, we obtain a value of $\Gamma = 0.67$ for the fundamental TM mode used in the experiment. To determine the excited Er fraction, we use the experimentally measured values of $|\Delta\alpha_{\text{dip}}| = 0.12$ cm^{-1} and $N_0 = 4.6 \times 10^{20}$ cm^{-3}. Given the small index difference between silicon nitride

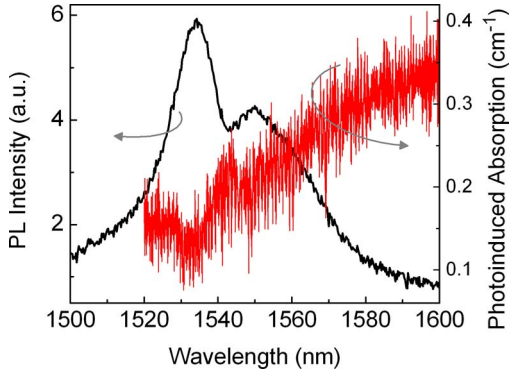

Fig. 3. (Color online) The dip in the photoinduced absorption shown alongside the measured Er emission peaked at 1.54 μm.

and silica, we use a value of $\sigma_e = 6 \times 10^{-21}$ cm^2, which is close to the highest measured value for erbium in silica [21]. By choosing a high value for σ_e and assuming 100% optically active ions, we obtain a lower excited Er fraction and thus a more conservative estimate. By using Eqs. (3) and (4), we get $f \approx 0.065$, corresponding to an ~6.5% excited Er fraction.

In this work, we fabricated Er:SRN waveguides and measured the excited Er fraction. The results demonstrate stimulated emission in an Er:SRN matrix related to a 6.5% erbium excited Er fraction. Recently, Clement *et al.* observed a dip in the photoinduced absorption with a similar spectral dependence and calculated a 15% excited fraction of Er in Er:SRO waveguides [17]. On the other hand, the transparency threshold (50% excited Er fraction) for Er:SRN photonic crystal nanobeam cavities excited at 980 nm has been observed [22]. Ultimately, a careful optimization over a range of silicon content must be carried out to demonstrate net optical gain in these waveguides structures under cw pumping conditions.

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