Optical Gain at 1.5 μm in Nanocrystal Si-Sensitized Er-Doped Silica Waveguide Using Top-Pumping 470 nm LEDs

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Abstract—This paper demonstrates optical gain at 1.5 μm in Si-nanocrystal-sensitized, Er-doped silica waveguide using a commercial, low-cost 470 nm LED in top-pumping configuration. Experimental evidence of full inversion with maximum possible gain of 3 dB/cm is presented. Possible application of Si-nanocrystal-sensitized, Er-doped silica for silicon-based microphotonics is also presented.

Index Terms—Erbium, microphotonics, optical amplifier, silicon nanocrystal.

I. INTRODUCTION

AMPLIFICATION is an integral part of any network. In particular, optical amplifiers, with their advantages of low noise, transparency, and built-in ability for wavelength division multiplexing, has been critical in enabling establishment of the all-optical telecommunication network that has powered the information revolution [1].

In principle, the essential role of an optical amplifier is conversion of a pump photon into a signal photon. In this regard, the exact nature of the pump photon and the conversion mechanism should be immaterial. However, the many different kinds of optical amplifiers—e.g., erbium-doped fiber amplifiers (EDFAs), erbium-doped waveguide amplifiers (EDWA), thulium-doped fiber amplifiers (T DFA), and Raman fiber amplifiers—all rely on expensive lasers for the pump source. This presents a formidable barrier against price reduction, as the pump lasers constitute the major, fixed portion of the final amplifier cost. Furthermore, all optical amplifiers share the fundamental principle of co/counter propagating signal and pump waves in the same waveguide. This does not present much of a problem for fiber-based optical amplifiers. However, when trying to integrate optical amplifiers into small, planar photonic circuits, it can strongly limit the design flexibility and the overall device functionality, as different functionalities can only be integrated in a topologically one-dimensional (1-D) way. This problem is shown schematically in Fig. 1, which shows the limitation of such 1-D “integration.”

Thus, it can be said that solving these two problems represents a critical step toward developing low-cost, multifunctional optical devices that can enable the next generation optical networks. Unfortunately, these two problems arise from the fundamental operational physics of optical amplifiers. For example, EDFAs rely on atomic-level, intra-4f transitions of Er3+ ions for both pumping (e.g., 4I15/2 → 4I11/2) and amplification (4I13/2 → 4I15/2). However, these are parity-forbidden intra-4f transitions that occur due to the parity mixing effects of the crystal field. This gives rise to the stable and low-noise amplification properties of EDFAs, but at the same time, also requires a laser beam tuned precisely to such an atomic level and a long interaction distance due to the small absorption cross sections associated with such forbidden transitions.

A novel approach that has attracted a great deal of research interest due to its potential for solving these problems is nanocrystal Si (nc-Si) sensitization of Er doped silica [2]–[4]. In such a case, nc-Si absorbs a pump photon, thereby creating photocarriers. The photocarriers then recombine, and in the process Auger-excite nearby Er3+ ions. A schematic description of this process is shown in Fig. 2.

Originally proposed for Er-doped crystalline Si [4], this mechanism has since been shown to apply to nc-Si-sensitized Er3+ as well [5]–[7]. Similar in principle to other well-known sensitizers such as Yb, nc-Si has the following crucial differences. First, it has a continuous absorption band, which obviates the need for a laser tuned to a specific wavelength, and allows use of low-cost LEDs instead. Second, the effective excitation cross section of nc-Si-sensitized Er3+ is orders of magnitude larger than that of optical excitation cross section of Er3+ in pure silica due to the high absorption cross section of nc-Si [8]–[10], allowing the waveguide to be pumped from the top—as sufficient pump photons are absorbed within the thickness of the core layer (≈ 2–10 μm) with this much larger
pump absorption. Finally, nc-Si sensitization greatly enhances the emission cross section of Er$^{3+}$ at 1.5 μm [9], [11], [12], enabling high gain without the need for high Er concentration. We note that such carrier-mediated excitation mechanism can work in reverse, quenching the Er$^{3+}$ [13]. In the case of nc-Si, however, the strong quantum confinement effects and matrix effects suppress such quenching mechanisms such that efficient Er$^{3+}$ luminescence efficiency can be obtained under practical conditions [5]–[7].

However, the necessity of careful nanoscale optimization of material composition and structure [14] as well as the lack of suitable high intensity pump LED sources has prevented demonstration of top-pumped optical gain from this material with an LED [15]. In this paper, we demonstrate for the first time overcoming these past problems to obtain optical gain at 1.5 μm in an nc-Si-sensitized Er waveguide using an optimized material and recently introduced high-power 470 nm LEDs in a top-pumping configuration. We also present experimental evidence of full inversion with the maximum possible gain of 3 dB/cm, and discuss implications for future device applications.

II. EXPERIMENTAL CONDITIONS

A. Sample Preparation

A 2-μm-thick Er-doped SiO$_2$($x < 2$) film was deposited on a Si wafer with a 10-μm-thick thermal oxide by electron-cyclotron resonance plasma enhanced chemical vapor deposition with concurrent sputtering of Er using SiH$_4$ and O$_2$ as source gases [3]. Prior to deposition, the substrate was cleaned by ultra-sonic cleaning in acetone and methanol, followed by RCA cleaning and dipping in DI water. The base pressure, the microwave power, and the deposition pressure were 1 μtorr, 1, and 20 mtorr, respectively. The flow rate of SiH$_4$, O$_2$, and Ar was 1, 2, and 3.5 sccm, respectively. Rutherford backscattering spectroscopy showed the Si and Er content to be 34 at. % and 0.05 at. %, respectively (data not shown). After deposition, the samples were rapid thermal annealed at 950 °C for 5 min in order to precipitate the excess Si atoms into nc-Si. Previously, we had shown this set of fabrication conditions to result in the optimum for Er$^{3+}$ luminescence properties [16].

The presence of nc-Si raises the refractive index of the material to 1.46, automatically providing the refractive index contrast necessary for waveguiding. Thus, ridge-type, single-mode waveguides were formed by defining 1.1-cm-long, 9-μm-wide, 0.3-μm-high ridges using photolithography and buffered oxide etching process, followed by mechanical polishing. A scanning electron microscope (SEM) image of a finished waveguide is shown in Fig. 3. Note that due to the isotropic etching of the wet chemical process, the ridge actually has a trapezoidal cross section rather than a rectangular cross section. The presence of nc-Si raises the refractive index of the material to 1.46, automatically providing the refractive index contrast necessary for waveguiding. Thus, ridge-type, single-mode waveguides were formed by defining 1.1-cm-long, 9-μm-wide, 0.3-μm-high ridges using photolithography and buffered oxide etching process, followed by mechanical polishing. A scanning electron microscope (SEM) image of a finished waveguide is shown in Fig. 3. Note that due to the isotropic etching of the wet chemical process, the ridge actually has a trapezoidal cross section rather than a rectangular cross section. Using the effective index method, the core-mode overlap is estimated to be < 45%.

B. Optical Characterization

Photoluminescence spectra of the deposited films were measured using the 477-nm line of an Ar laser, a 1/4-m grating monochromator, and a thermoelectrically cooled InGaAs detector, and employing the lock-in technique. We note that no direct optical absorption line coincides with the 477 nm pump beam, resulting in very little (more than an order of magnitude smaller [4]) optical absorption. Thus, excitation of Er$^{3+}$ ions is dominated by nc-Si. For comparison, a 980 nm laser was also used to obtain the PL spectra of the film. In all cases, the pump beam was incident onto the film surface at an angle of about 30°, and the PL spectra were obtained normal to the film surface.

For optical characterization of the waveguides, tapered fibers were used to couple signal beam into and out of the waveguides. Transmitted signal was analyzed with an optical spectrum analyzer. For top-pumping, a 5-mm-long array of five 1 mm × 1 mm commercially available 470 nm GaN LEDs (Cree X-Bright, is a trademark of Cree, Inc., 4600 Silicon Drive, Durham, NC 27703) was placed on top along the waveguides. The nominal output of the LED arrays is 600 mW with an input of 3.6 V and 200 mA per LED die. The schematic diagram of the LED pump setup along with the pictures of the actual coupling setup and the pump LED arrays are shown in Fig. 4. Note that the actual length of the waveguide pumped by the LED array is less than a half of the total waveguide length. Furthermore, the presence of the cover glass for the LED array and the need to clear the coupling fibers required the LED
arrays to be about 2 mm away from the waveguide, resulting in strong reduction of the pump power actually incident on the waveguide.

III. RESULTS AND DISCUSSION

A. Film Properties

Fig. 5 shows a typical photoluminescence excitation spectrum of nc-Si-sensitized, Er-doped silica obtained using a tungsten-halogen white light source. We find that we can obtain 1.5 $\mu$m Er$^{3+}$ luminescence for all pump energies in the visible and UV range, demonstrating the feasibility of using a broadband pump source such as an LED. More importantly, we do not observe any peaks corresponding to the direct, resonant optical excitation (e.g., peaks at 2.38 and 2.53 eV due to direct, resonant optical absorption by $^2\text{H}_{11/2}$ and $^4\text{F}_{9/2}$ Er$^{3+}$ levels), showing the efficiency of the nc-Si sensitization.

Fig. 6 shows the 1.5 $\mu$m Er$^{3+}$ PL spectra of the nc-Si-sensitized, Er-doped silica film, obtained using either the 477 nm line of an Ar laser or a 980 nm diode laser, both at the same nominal pump power density of 2 W/cm$^2$. It should be stressed here that the optical absorption of the 477 nm pump beam by Er$^{3+}$ ions is negligibly small, as it does not coincide with any of the transition levels of Er$^{3+}$. On the other hand, 477 nm pump beam is readily absorbed by nc-Si. In contrast, the 980 nm pump beam is readily absorbed by Er$^{3+}$ ions, as it corresponds to the $^4\text{I}_{11/2}$ optical absorption band of Er$^{3+}$, but is only weakly absorbed by nc-Si due to the enlarging of the bandgap by the quantum confinement effect. We find that the PL intensity obtained with the 477 nm line is 2 orders of magnitude greater than that obtained...
with the 980 nm diode laser even with only half the photon flux. This demonstrates the effectiveness of the nc-Si sensitization of Er$^{3+}$, and ensures that all effects we report henceforth are due to nc-Si mediated pumping of Er$^{3+}$. The inset shows the time-resolved decay trace of the Er$^{3+}$ luminescence. We find a single exponential decay with a lifetime of 8.5 ms, which is comparable to those observed from nc-Si free glasses.

B. Er$^{3+}$ Absorption

The experimental nature of the waveguide fabrication and the lack of a mode converter results in strong surface scattering and coupling losses. Such external losses, however, can easily be corrected by more advanced fabrication techniques, and do not represent fundamental properties of nc-Si sensitized, Er-doped silica waveguides. Thus, the waveguides were analyzed using the relative changes in the transmitted beam intensity. The absorption spectrum of the waveguide was obtained by measuring the transmitted intensity of the signal beam from a tunable laser diode. A clear dip in the transmitted intensity near the 1.53 $\mu$m is observed, indicative of Er$^{3+}$ absorption. As the external losses can be approximated to be constant over such a narrow wavelength range, the relative changes in the intensity were converted to Er$^{3+}$ absorption by fitting the data to the expected Er$^{3+}$ absorption spectrum calculated from the Er$^{3+}$ luminescence spectrum using the McCumber theory. Best fit was obtained when a value of about 3 dB/cm at 1535 nm was used, as is shown in Fig. 7. Given the noise in the data and the uncertainties in fitting, however, we estimate the possible error to be quite large—about $\pm$1 dB/cm absorption.

C. Optical Gain

Fig. 8 shows the OSA traces of the transmitted signal at 1.533 $\mu$m, both with and without the LED pumping. A signal enhancement of nearly 2 dB is clearly evident, even though only a 5 mm long portion of the 1.1 cm long waveguide was pumped. The inset shows the effect of LED pumping on the transmission of a 1.294-\mu m signal under identical conditions. In contrast to the 1.53 $\mu$m signal, the 1294 nm signal does not show any effect of the LED pumping. This shows that the enhancement we observe is due to Er$^{3+}$ and not due to other spurious effects.

Obtaining higher signal enhancement, and ultimately full inversion, requires higher pump densities. However, the unoptimized distance between the LED arrays and the waveguide and the poor efficiency of manual alignment limited the pump power density achievable with LED. Therefore, higher LED pump power densities were simulated by focusing the 477-nm laser beam from an Ar laser into a thin line of approximately 4 mm $\times$ 0.1 mm using a cylindrical lens, and then pumping the waveguide along its length from the top. Again, we stress that all physical processes under 477 nm laser pumping are identical to that under 470 nm LED pumping, and that the Ar laser here simply serves as a convenient source of the necessary power.
density. In fact, the maximum possible power density achievable by butt-coupling the present LED array onto the waveguides already exceeds 10 W/cm$^2$, and the latest commercial high power LED chips can provide power densities comparable to the highest ones used here (e.g., > 20 W/cm$^2$ from Cree XT21 (Cree XT21 is a trademark of Cree, Inc., 4600 Silicon Drive, Durham, NC 27703) series LEDs). Fig. 9 shows the full, wavelength-dependent changes in the signal intensity. Without any pump, we observe the typical Er$^{3+}$ absorption spectrum centered at 1533 nm, with a maximum loss of 3 dB/cm. With the LED on, the transmitted signal is increased across the entire wavelength under investigation. The maximum enhancement of 3 dB/cm at 1533 nm matches the maximum absorption, indicating near full inversion.

D. Performance Analysis

Fig. 9 clearly demonstrates that we obtain optical gain using an nc-Si-sensitized, Er-doped silica waveguide top-pumped using low-cost, visible LEDs. Furthermore, we have not observed the 980-nm luminescence which would indicate excited state absorption or upconversion (data now shown). This allows us to model the Er$^{3+}$ population as a two-level system [15]. In such a case, the increase in the transmitted beam intensity is written as $I_L = I_0 \exp[(\Gamma L)/\sigma]$, where $\Gamma$ is the core-mode overlap, $L$ is the length, and $I_0$ is the excited Er$^{3+}$ population, given by $F \Sigma N/(\Phi \Sigma + w)$, where $\Phi$ is the photon flux, $\Sigma$ is the effective excitation cross section, $N$ is the total Er density, and $w$ is the Er$^{3+}$ decay rate. From the maximum gain of 3 dB/cm at a pump power density of 24 W/cm$^2$, we obtain effective excitation cross section and emission cross section of $\sim 2 \pm 1 \times 10^{-17}$ cm$^2$ and $\sim 6 \pm 2 \times 10^{-20}$ cm$^2$, consistent with the previous reports of great enhancement of the cross sections by nc-Si sensitization [8–12]. The enhancement of the effective excitation cross section is easily explained by the large absorption cross section of nc-Si and efficient energy transfer from nc-Si to Er$^{3+}$. The enhancement of Er$^{3+}$ $\sim 1.5 \mu$m emission cross section may be due to the large crystal field fluctuations present in the nc-Si/silica composite matrix, but is so far difficult to explain. However, it is quite promising for amplifier applications, as it implies that we may get high gain without having to resort to high Er$^{3+}$ concentrations that can result in lower amplification efficiencies due to upconversion.

For true amplification, the gain due to Er$^{3+}$ needs to be larger than all other intrinsic losses combined. For possible losses, we can identify: insertion loss, surface scattering loss, carrier absorption loss, and material scattering due to nc-Si and other inhomogeneities. The first two loss mechanisms do not present fundamental limitations, since they can be reduced to very small values using advanced fabrication techniques. The carrier absorption loss is due to absorption of the signal beam by photocarriers that need to be generated inside nc-Si in order for nc-Si sensitization to work. If the free carrier lifetime is too long, then they can act as strong absorbers of signal light. Such carrier-induced absorption has been reported previously [11], and we have also observed such losses in un-optimized films. However, the lack of such effect on the 1294 nm signal seen in Fig. 8 shows that with careful optimization, this carrier absorption loss can be reduced nearly completely. The nc-Si scattering loss, on the other hand, cannot be eliminated in any way since the presence of nc-Si is essential. However, both theoretical and experimental [17] results indicate that the nc-Si scattering losses at 1.5 $\mu$m region is much less than 1 dB/cm—smaller than the 3 dB/cm Er$^{3+}$ gain demonstrated in Fig. 9. Finally, we note that because the waveguide is pumped vertically, it is possible to excite Er$^{3+}$ ions independent of the mode size and shape. Simulations indicate that by taking advantage of this ability, it is possible to achieve near 100% core-mode overlap, greatly increasing the possible Er$^{3+}$ gain figures. Therefore, we conclude that with better fabrication methods, net optical gain is possible with nc-Si sensitization.

For a typical requirement of 10 dB gain, we can conservatively estimate the necessary waveguide length to be about 4 cm, requiring a total pump power of 80 mW incident on a 10-$\mu$m-wide, 4-cm-long waveguide. This pump power requirement corresponds to 4 LEDs consuming < 300 mW of electrical power. The amplified signal power is more difficult to estimate, since it depends strongly on the actual device geometry. Simulations with different geometries show, however, that total signal power of 10 dBm is easily within reach. Therefore, we conclude that a properly designed nc-Si-sensitized, Er-doped silica waveguide amplifier with top-pumping LEDs can meet the commercially required specifications.

Finally, we note that apart from Er, the entire film consists of silicon and silica only, and that the entire fabrication process does not require any special manufacturing equipment or processes. Thus, it is possible to leverage the astronomical, well-established silicon CMOS processing technology and infrastruc-
ture. This, coupled with the ever-increasing performance/cost ratio of visible LEDs and the ease of aligning such LED pump arrays, suggest that nc-Si-sensitized amplifiers can be mass-produced in a very cost-effective manner.

E. Vertically Coupled Planar Amplifying Circuit (VCPAC)

The advantage of nc-Si sensitization extends beyond the waveguide amplifier applications. With the reduced cost and footprint of amplifying circuits, and the ability to locally pump arbitrary locations on chip without the need for pump beam circuit and coupling/decoupling multiplexers, we can envision planar optical circuits with integrated amplifying sections, pumped vertically from the top. A demonstration of such a concept is shown in Fig. 10, which shows a dense array of nc-Si-sensitized, Er-doped silica microdisk resonators, produced with the standard Si lithography and wet etching. They are all optically active, and in principle, can be pumped individually from the top. Such ability to incorporate the amplifying function virtually anywhere in a planar optical circuit, we believe, is unprecedented and holds a great promise for developing highly functional, low-cost integrated optical devices for the next-generation optical networks.

IV. CONCLUSION

In conclusion, we have demonstrated optical gain at 1.5 μm in optimized nc-Si-sensitized, Er-doped silica waveguide using commercial 470 nm LEDs in a top-pumping configuration. Experimental evidence indicates full inversion with the maximum possible gain of 3 dB/cm, and simulations show that this device has strong promise of providing commercially viable performance in a very cost-effective manner.

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