Optical gain at 1.5µm in nanocrystal Si sensitized, Er-doped silica waveguide using top-pumping 470 nm LED

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Abstract: We demonstrate optical gain at 1.5µm in Si nanocrystal-sensitized, Er-doped silica waveguide using a commercial, low-cost 470nm LED in top-pumping configuration. Experimental evidence of full inversion with maximum possible gain of 3dB/cm is presented.

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OCIS codes: (140.4480) Optical Amplifiers, (060.2330) Fiber Optics Communications

1. Introduction

Optical amplifiers form the basis on which the optical telecommunication networks are built. While there are many different varieties (e.g., EDFA, EDWA, TDFA, Raman), they 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. This strongly limits the design flexibility and the overall device functionality, as different functionalities can only be integrated in a topologically 1-dimensional way. Thus, it can be said that solving these two problems represents a critical step toward developing low-cost, multi-functional optical devices that can enable the next generation optical networks.

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 waveguides [1]. 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 allows use of low-cost LEDs instead of an expensive laser tuned to a specific wavelength. Second, the effective excitation cross section of nc-Si is 4 orders of magnitude larger than that of Er in silica due to the high absorption cross section of Si nanocrystals [2,3,4], 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 [2,5,6], enabling high gain without the need for high Er concentration.

However, the necessity of nano-scale engineering of the material composition and structure [7], 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. In this paper, we demonstrate for the first time overcoming these past problems to obtain optical gain at 1.5µm in an nc-Si sensitized Er waveguide using an optimized material and recently introduced high-power 470nm LEDs in a top-pumping configuration. We also present experimental evidence of full inversion with the maximum possible gain of 3dB/cm, and discuss implications for future device applications.

2. Experimental set up

2 µm thick silica thin films with 1 at. % excess Si and 0.05 at. % Er were deposited on a Si wafer with 10 µm thick thermal oxide layer using PECVD process. After deposition, a 5 min, 950 °C anneal was used to precipitate nc-Si and to active Er\(^{3+}\) [8]. The presence of nc-Si increases the refractive index of the film to 1.46, thereby providing the refractive index contrast necessary for waveguiding. Afterwards, 1.1 cm long, single-mode ridge-type waveguides with 9 µm wide ridge were defined using photolithography and wet etching process, followed by mechanical polishing. Tapered fibers were used to couple signal from a tunable laser into and out of the waveguide. A 5 mm long linear array consisting of 5 commercially available 1mm×1mm 470 nm diodes was used to pump the waveguide from the top. 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. 1. Note that 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 2mm away from the waveguide,
and pump less than half of the waveguide. For cases requiring much higher pump power, the 477 nm line of an Ar laser was also used.

Figure 1: Schematic diagram of the experimental setup (left) and the actual pictures of the coupling setup and the pump LED array (right, under on / off condition)

3. Results and Analysis

Figure 2 shows the Er$^{3+}$ photoluminescence spectra at 1.5 µm obtained from the film with either the 477 nm line of an Ar laser or a 980 nm laser diode as the pump source, both at the same nominal pump power of 200 mW. It should be stressed here that the optical absorption cross section of Er$^{3+}$ at 477 nm is orders of magnitude less than that at 980 nm, as it does not coincide with any of the transition levels of Er$^{3+}$. However, 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 observe 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 msec, which is comparable to those observed from nc-Si free glasses.

Figure 2: The 1.5 µm Er$^{3+}$ photoluminescence spectra of the film obtained with either 477 nm or the 980 nm pump beam, demonstrating the effectiveness of nc-Si sensitization. The inset shows the PL decay trace

Figure 3 (a) shows the OSA traces of the transmitted signal at 1.533 µm, both with and without the LED pumping. A signal enhancement of nearly 2 dB is clearly evident, even with only a 5 mm long portion of the 1.1 cm long waveguide pumped. The inset shows the effect of LED pumping on the transmission of a 1.294 µm signal under identical conditions. In contrast to the 1.533 µm 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 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 – and that such power density can be provided by the latest commercial high power LED chips (e.g., 20 W/cm$^2$ from Cree XT18$^\text{TM}$ series LEDs) with proper alignment. Figure 3 (b) 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 increased across the entire wavelength under investigation. The amount of enhancement increases with increasing signal wavelength, as is expected for Er$^{3+}$ in low-pumping condition. Note, however, that the change in the signal intensity at 1545 nm has become positive, indicating optical gain. With the increased pump power, the change in the signal intensity becomes positive for all wavelengths. In fact, the maximum enhancement of 3 dB/cm at 1533 nm matches the maximum absorption, showing near full inversion has indeed occurred, and demonstrating the feasibility of fabricating an nc-Si sensitized, Er-doped silica waveguide top-pumped using low-cost, visible LEDs.

Simulations show that higher gain figures can be achieved by properly designing the waveguide structure and optimizing the coupling. For instance, the total pump power needed for 10 dBm power and 10 dB gain is $8.4 \times 10^{16}$ photons sec$^{-1}$, or 36 mW of 470 nm light for a 10 $\mu$m wide, 4 cm long waveguide – which is a very modest requirement since a single LED chip provides 18 mW of pump power at 3.2 V and 20 mA.

4. Conclusion

In conclusion, we have demonstrated optical gain at 1.5 $\mu$m 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 3dB/cm, and simulations show that this device has strong promise of providing commercially viable performance in a very cost-effective manner. This work was supported by NRL project from Ministry of Science and Technology of Korea.

5. References

[1] See, for example, L. Pavesi, S. Gaponenko, and L. dal Negro, Towards the First Silicon Laser, NATO Science Series II 93