Performance Optimization of nanocrystal-Si sensitized Er-doped Waveguide Amplifier

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Abstract: We analyze the performance of nanocrystal-Si sensitized Erbium doped waveguide amplifier, and suggest novel structures / operation methods which can be used to enhance its performance figures. With modest assumptions on the design parameters including currently available pump LED power, we show that the performance target of 10dB of gain with 0dBm input signal can be achieved.

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I. Introduction

Out of many approaches developed so far to achieve low-cost micro amplifiers (ampllets) for the access / metro network, Erbium doped waveguide amplifier (EDWA) has been considered to the most promising candidate due to its well known characteristics inherited from its relative, the EDFA. Unfortunately, there also exist two main drawbacks for EDWA/EDFA which hinders the ultimate performance / cost optimization for ampllet application: the need of an expensive pump laser tuned precisely to the narrow absorption band of Er ion, and long interaction length between pump and signal resulting from the small pump absorption cross section. As a possible solution mitigating these obstacles, the recently proposed technique of nanocrystal Si (NC-Si) sensitization of Er ion has received great attention [1-5]. NC-Si as a co-dopant to Er ions, acts as efficient sensitizer, which absorbs pump photons, creates photo-carriers, and finally transfers energy to nearby Er ions through the Auger-excite process. As confirmed by numerous experimental reports, NC-Si differ from the common type of sensitizer for Er - in the sense that it has a strong, continuous, broad absorption band for the pump [1, 4, 5], and that it gives orders of magnitude larger effective excitation cross-section for the Er ion [2-5] enabling the top pumping of the pump. Additional advantage from the co-doping of NC-Si also comes from the enhanced Er emission cross-sections at 1.5µm, enabling high gain without the need of high Er concentration – thus avoiding the performance degradation from the quenching effect [3, 8, 10]. Following these observations, the possibility of achieving positive optical gain has been demonstrated / assessed in terms of both experimental [6, 7] and theoretical means [8, 9]. Still, the analysis so far has remained in the fundamental domain confirming the optical gain in top-pumped NC-Si sensitized Er waveguide, not yet scrutinized targeting for the real device applications.

In this paper, for the first time, we provide the detailed performance analysis of NC-Si codoped, Er waveguide amplifier (NC-EDWA) targeting for the real application. Saturation output power, required pump density, optical gain and noise figure has been assessed in terms of the device structure and input signal strength. Results show the positive feasibility of achieving 10dBm of output power with 0dBm of signal input signal, using commercially available high-power LED array as its pump sources.

II. Set-up

Rate and propagation equation describing the top-pumped NC-EDWA has been developed and checked with the previous study [9]. To concentrate on the net effect from the device structure variation rather than negligible [3, 9, 10] quenching / backward Auger effect (~10^{-4} – 10^{-2}), the rate equation has been reduced to a coupled 2-level system both for the NC-Si energy states and Er energy states (below we show the rate equation of Er ion only):

\[
\frac{dN_1}{dt} = \frac{\sigma_{pa} I_p \text{eff}}{\hbar \nu_p} N_1 - N_2 \frac{\tau_{21}}{\tau_{21}} - (\sigma_{sa} N_2 - \sigma_{se} N_1) \frac{\Gamma_s I_s}{\hbar \nu_s}, \quad \frac{dN_2}{dt} = -\frac{\sigma_{pa} I_p \text{eff}}{\hbar \nu_p} N_1 + N_2 \frac{\tau_{21}}{\tau_{21}} + (\sigma_{sa} N_2 - \sigma_{se} N_1) \frac{\Gamma_s I_s}{\hbar \nu_s},
\]

where \( N_1, N_2, \sigma_{pa}, \sigma_{sa}, \sigma_{se}, I_p \text{eff}, I_s, \tau_{21}, \Gamma_s, \hbar \) are ground state Er ions density, meta stable state Er ions density, pump effective excitation cross-section, signal absorption cross-section, signal emission cross-section, effective pump
intensity, signal intensity, metastable state lifetime and overlap factor between erbium ions and signal mode envelope, respectively. Worth to note, to accommodate the top-pumping configuration, we constructed a two-dimensional propagation equation set for pump and signal/ASE beams (figure 1). All of the simulation parameters listed in table 1 were obtained/checked with the previous publications [6, 8, 10]. Profiles of emission, and absorption cross-section were also obtained from the photoluminescence spectrum and applying the McCumber relation to the emission cross-section. Mode envelope of the waveguide was calculated using Kumar’s method, and 10x10x400 segments of spatial slots have been assigned to cover the entire volume of doped core for the numerical calculation of inversion, signal and pump powers at each point. Simulation has been carried out over the spectral range of 1500 to 1610 nm with 1 nm resolution, including the amplified spontaneous emission. Comparison of the simulation result to previous experimental reports [6, 8] showed reasonable agreement in the behaviors of performance factors, considering the measurement errors including the misalignment of pump beam, and coupling of the signal to the air-clad ridge waveguide used in the experiment.

III. Performance analysis

To test the feasibility of the NC-EDWA for amplet application, we started with a waveguide structure with core dimension of 7 x 7 \( \mu m^2 \). Targeting a modest gain of 10 dB, we set the length of the waveguide to 4 cm, allowing enough margins considering the measured signal absorption from the Erbium ion in the waveguide (~4 dB/cm, with incomplete mode overlap factor). Figure 2 shows the result of the numerical analysis obtained with this waveguide structure (type A) using the parameters listed in table 1. Though 10 dB or even higher small signal (< -10 dBm) gain can be easily achieved with commercially available pump LED (37.5 W/cm\(^2\) from Cree), it was estimated that three times larger intensity (100 W/cm\(^2\)) was required for LED to accomplish 10 dB of gain with 0 dBm input signal. Even if the easiest resolution for the NC-EDWA gain enhancement is increasing the (Er : NC-Si) doping concentration, in order to see the effect of structure optimization, we plot in figure 3(a) the gain values obtained from the same structure but with pump reflector at the bottom (100% reflection). The gain improvement from the reuse of unabsorbed (estimated ~65%) pump was evident, now requiring lower pump intensity (60 W/cm\(^2\)) to achieve the same performance when compared to that of plain NC-EDWA without mirror. Another non-trivial but novel approach for the performance enhancement can be found along the width of the waveguide, utilizing the adiabatic expansion technique for the single-mode waveguide (see the propagation of a signal wave in a tapered, adiabatic waveguide - inset of figure 3(b)). Roughly speaking, with the expansion of the waveguide width increasing the pump-collection area, the type B (adiabatic, parameters listed in table 1) NC-EDWA can be considered as a parallel integration of amplet arrays, with enhanced saturation characteristics - while lowering the requirement on the pump intensity. As shown in figure 3(b), with type B EDWA, only 12 W/cm\(^2\) of pump intensity was required to meet the target operating condition. Additional gain we get comes from the increase in the mode overlap factor for the signal - due to the increased core width - with inverted Er ions. Increase in the small signal gain, about 3.5 dB (when compared to type A NC-EDWA) has been observed from this effect. As an another key performance factor, we also calculated noise figures for each NC-EDWA structure at the identical operating condition (0 dBm input and 10 dB gain). 4.36 dB, 4.36 dB and 4.90 dB of NF have been obtained for type A, mirrored type A and type B, respectively.

### Table 1. Parameters for NC-Si EDWA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index of core</td>
<td>1.46</td>
</tr>
<tr>
<td>Refractive index of cladding</td>
<td>1.44</td>
</tr>
<tr>
<td>Doping concentration</td>
<td>3e25 m(^{-3})</td>
</tr>
<tr>
<td>Peak emission cross-section</td>
<td>6e-24 m(^2)</td>
</tr>
<tr>
<td>Effective excitation cross-section</td>
<td>2e-21 m(^2)</td>
</tr>
<tr>
<td>Meta stable state lifetime</td>
<td>8.5 ns</td>
</tr>
<tr>
<td>Background loss of signal bund</td>
<td>20 dB/m</td>
</tr>
<tr>
<td>Core dimension (type A)</td>
<td>7 x 7 ( \mu m^2 )</td>
</tr>
<tr>
<td>Core dimension (type B)</td>
<td>100 x 7 ( \mu m^2 )</td>
</tr>
</tbody>
</table>
Finally to explore the other dimension of NC-EDWA engineering, we plot in figure 3 (c) the example of inversion distribution control. Different from the common types of EDF/WA employing co-/counter-propagation of pump waves inside the waveguide, the inversion distribution of NC-EDWA can be adjusted with much larger degree of freedom, as it utilizes top-pumping configuration. The pump intensity distribution can be easily adjusted to desired curve with the control of individual LEDs in the pump array on the top, to shape arbitrary inversion distribution or signal evolution profiles. For example, the EDFA-equivalent Booster / Pre amplifier, or multi-stage amplifier design can be achieved for NC-EDWA with much less efforts, and it shows the additional distinctive features of NC-EDWA for future applications.

IV. Conclusion

To summarize, we have analyzed the performance of NC-EDWA in terms of their device structure, and suggested also novel means of increasing its performance factors. For 3 types of EDWA (square, mirrored square and extended rectangular waveguide structure), 105 W/cm$^2$, 63 W/cm$^2$ and 11.7 W/cm$^2$ of pump intensity was required to achieve 10dB of gain with 0 dBm of input signal power. The noise figure stayed well below 5dB for all the structures. Considering the pump intensity / pump cost available from a commercial LED, it is expected that the NC-EDWA has good feasibility to work as a future cost-effective, small form factor amplet arrays for metro application.

References