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# A theoretical investigation of the optical gain in waveguide based on a silica matrix containing silicon nanograins and doped either with Nd<sup>3+</sup> or with Er<sup>3+</sup> ions

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# A theoretical investigation of the optical gain in waveguide based on a silica matrix containing silicon nanograins and doped either with $\text{Nd}^{3+}$ or with $\text{Er}^{3+}$ ions

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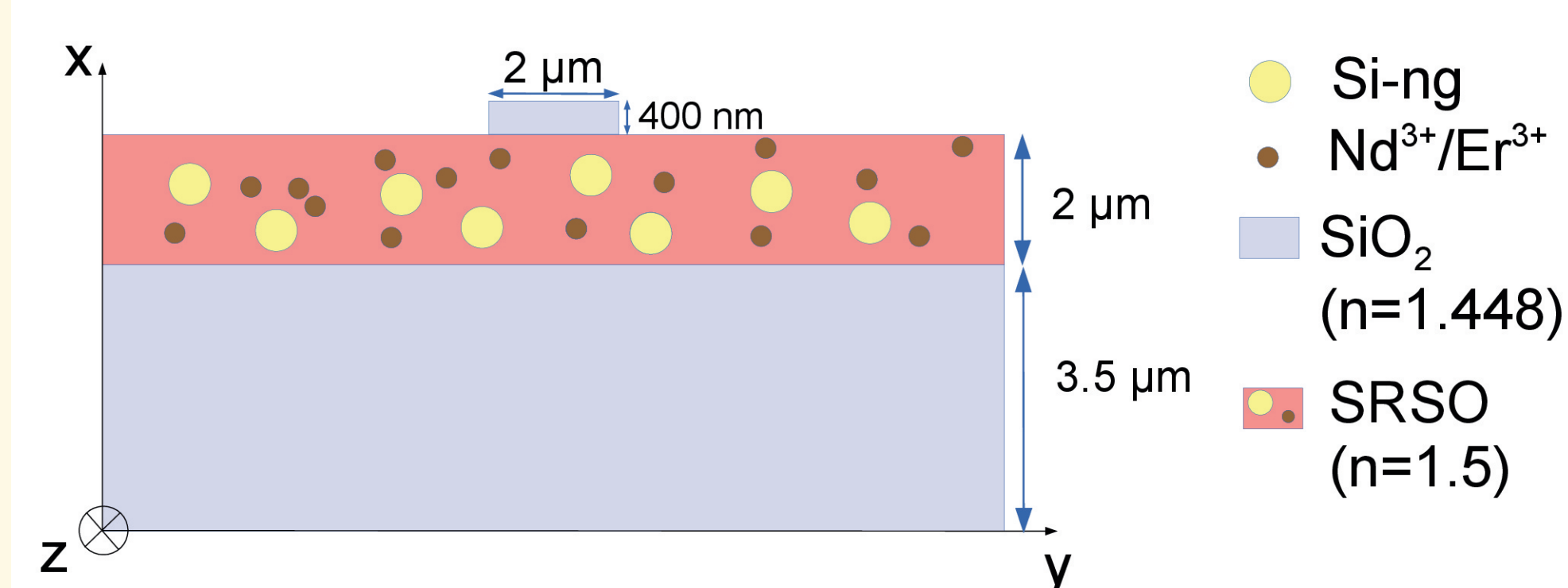
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## INTRODUCTION

Goal: Compare the optical gain in a waveguide containing silicon nanograins (Si-ng) and doped with either neodymium ions ( $\text{Nd}^{3+}$ ) or erbium ions ( $\text{Er}^{3+}$ ).



Transverse section view of the waveguide. Propagation of the pump and signal along z direction inside Silicon Rich Silicon Oxide (SRSO) layer.

## NEW ADE-FDTD ALGORITHM

**Classic ADE-FDTD algorithm:** Electric field  $\mathbf{E}$ , magnetic field  $\mathbf{H}$ , polarisations  $\mathbf{P}_{ij}$  and populations  $\mathbf{N}_i$  are calculated with a unique  $\Delta t$  imposed by the FDTD method. (In visible spectral range  $\Delta t \approx 10^{-17}$  s).

➔ **10<sup>6</sup> years of calculation to reach steady state of  $\mathbf{N}_i$  on a such waveguide.**

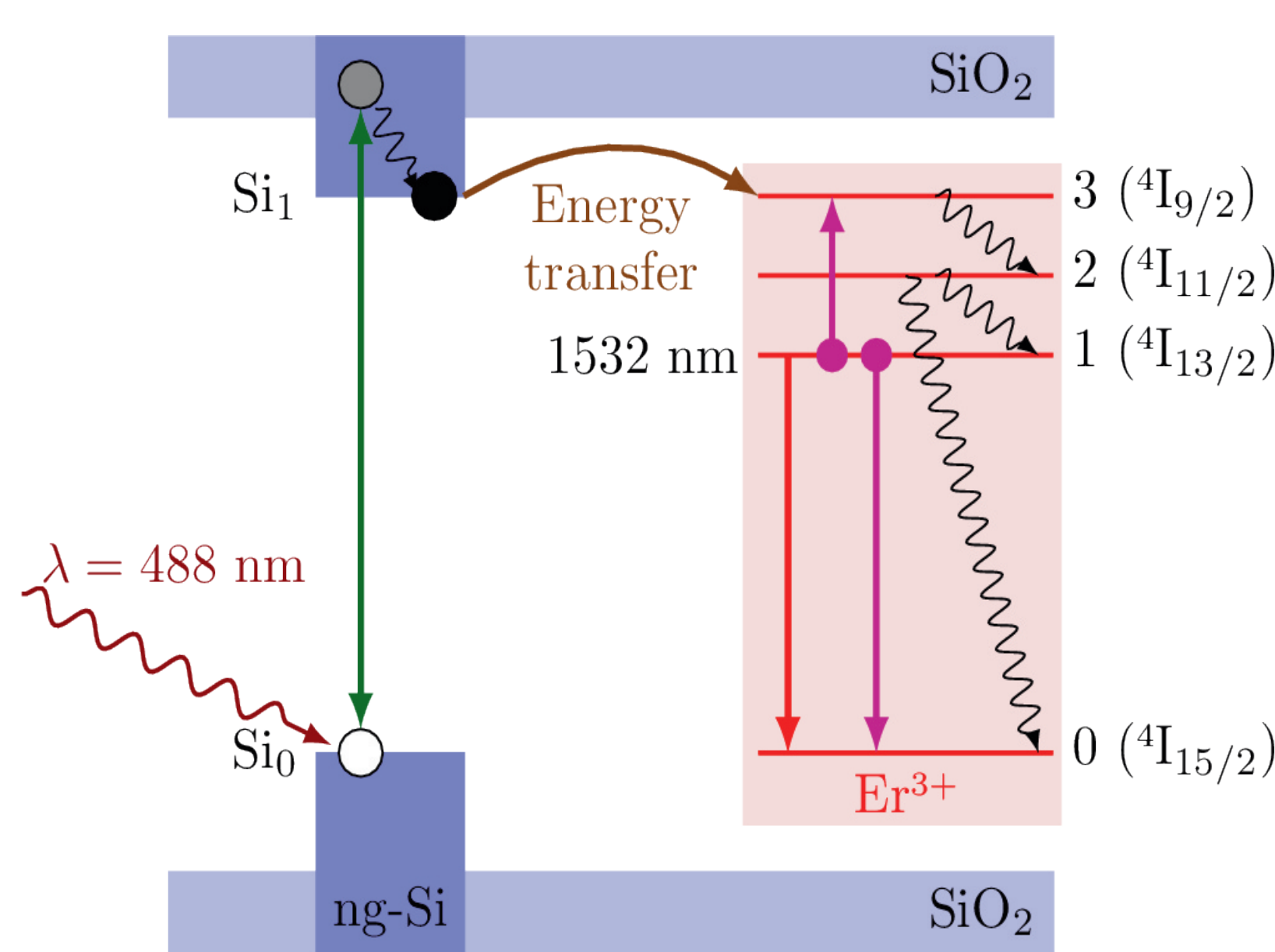
**New ADE-FDTD algorithm<sup>1</sup>:** separate loops for  $\mathbf{E}$ ,  $\mathbf{H}$  and  $\mathbf{P}$  on the one hand and populations  $\mathbf{N}_i$  on the other hand.

➔ **7 days of calculation to reach steady state of  $\mathbf{N}_i$ .**

(1) A. Fafin *et al.*, "Modeling of the electromagnetic field and level populations in a waveguide amplifier: a multi-scale time problem," Opt. Express **21**, 24171-24184 (2013).

## RARE EARTH EXCITATION

### Erbium excitation mechanisms



- Modeling rare earth ions ( $\text{Nd}^{3+}$  or  $\text{Er}^{3+}$ ) and silicon nanograins (si-ng) by a system of levels populations  $\mathbf{N}_i$ .
- Excitation of  $\text{Nd}^{3+}$  or  $\text{Er}^{3+}$  through the Si-ng by energy transfer.

- Si-ng are excited by a pump at 488 nm.

- $\rightsquigarrow$ : Non radiative transition

- $\downarrow$ : Radiative transition

- $\uparrow$ : Up-conversion

Erbium ions

Signal at 1532 nm :

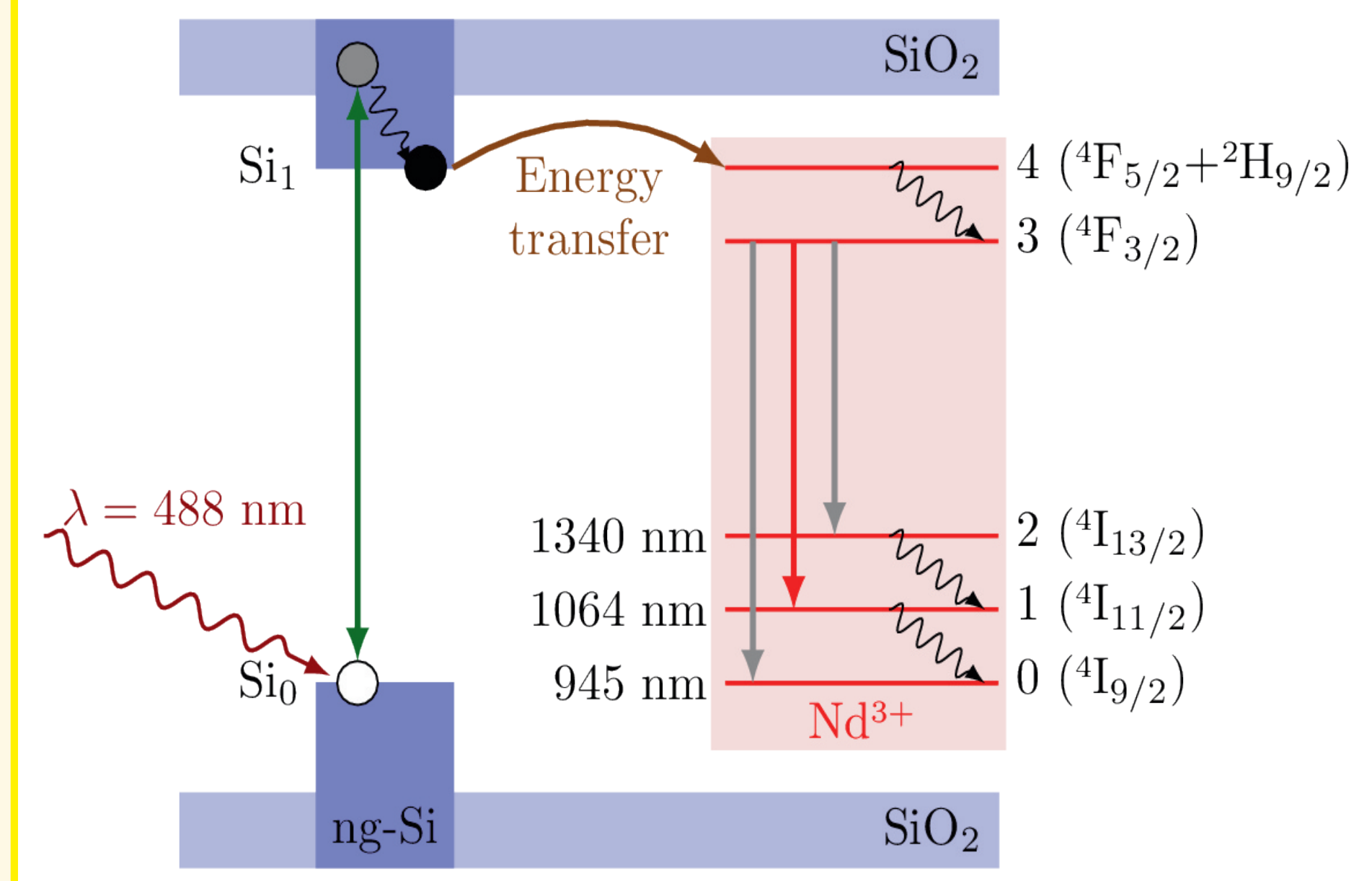
➔ Transition between  $\mathbf{N}_1$  and  $\mathbf{N}_0$

Neodymium ions

Signal at 1064 nm :

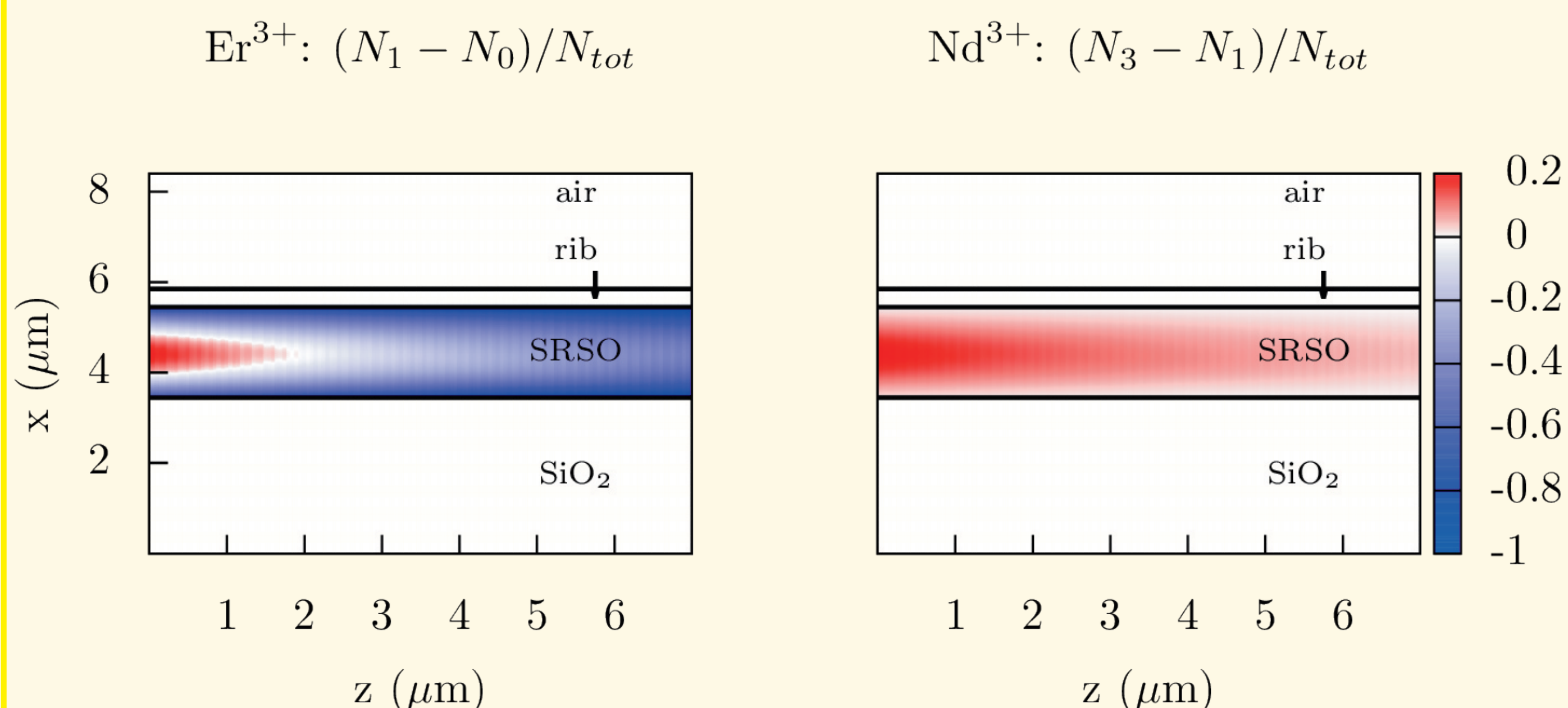
➔ Transition between  $\mathbf{N}_3$  and  $\mathbf{N}_1$

### Neodymium excitation mechanisms



## RELATIVE POPULATION DIFFERENCE

For a pump power of 1000 mW/mm<sup>2</sup>



Relative population difference reach population inversion only over a length of 1.5  $\mu\text{m}$ .

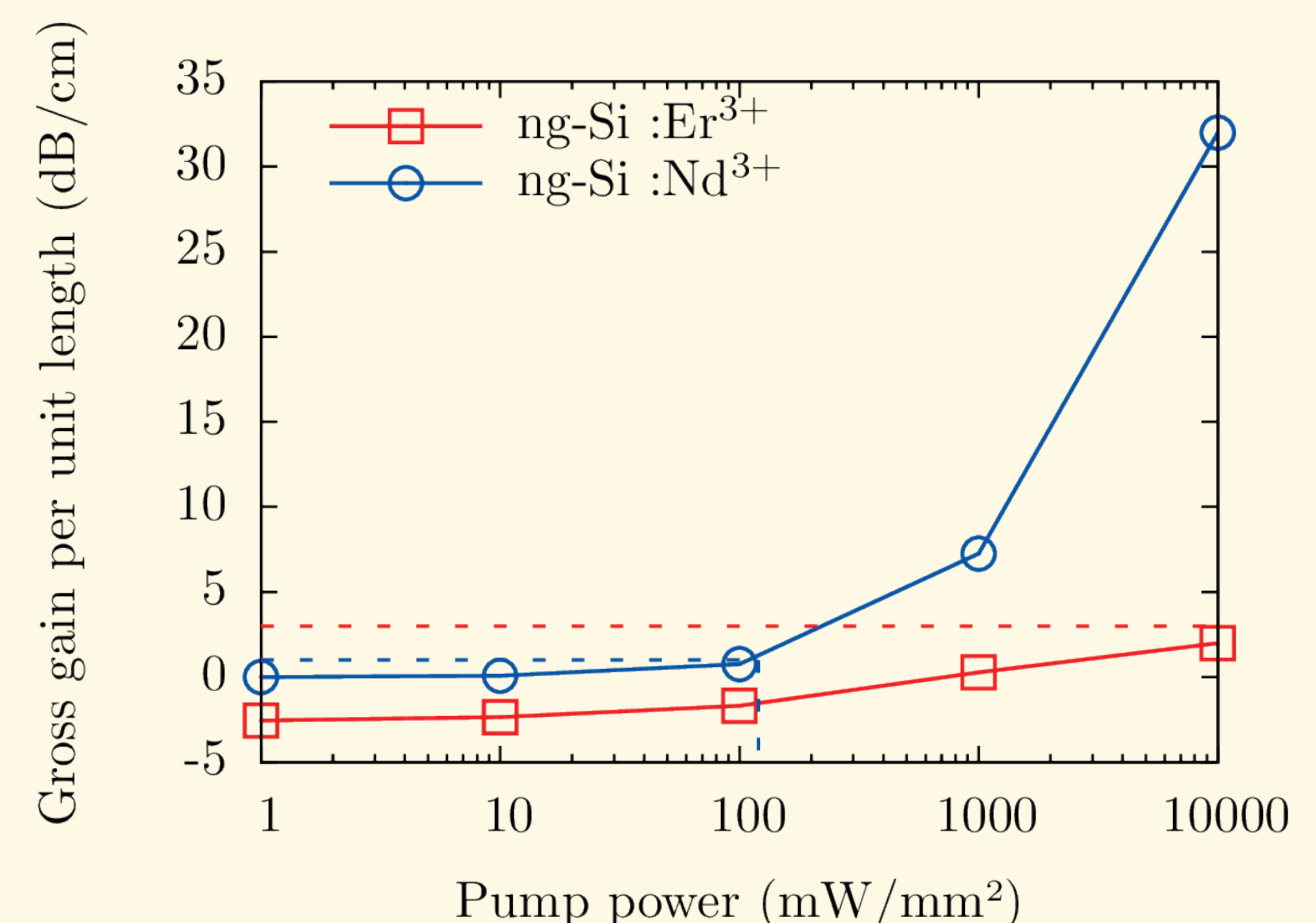
➔  $\text{Er}^{3+}$  is a 3-level system

Relative population difference reach population inversion along the whole structure.

➔  $\text{Nd}^{3+}$  is a 4-level system

## GAIN

At the beginning of the waveguide ( $z=0$ )



Levels populations in steady states allow to calculate the gross gain. Experimental background losses are represented in dashed line (see Appl. Phys. Letter 99, 231114, 2011 for  $\text{Er}^{3+}$  and J. Appl. Phys. 114, 014906, 2013 for  $\text{Nd}^{3+}$ ). **No positive net gain with  $\text{Er}^{3+}$ . Positive net gain with  $\text{Nd}^{3+}$  for a pump power higher than 120 mW/mm<sup>2</sup>.**

## ACKNOWLEDGMENT

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## CONCLUSION

Using an original ADE-FDTD method we reach steady state of fields and populations in SRSO waveguide doped with either  $\text{Nd}^{3+}$  or  $\text{Er}^{3+}$  ions. A positive optical gain is reached only with  $\text{Nd}^{3+}$  ions. For a pump power of 10<sup>5</sup> mW/mm<sup>2</sup> the optical gain is over 30 dB/cm. For more details see Opt. Express **22**, 12296 (2014).

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