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Alexandre Fafin, J. Cardin, Christian Dufour, Fabrice Gourbilleau

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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^{3+} or with Er^{3+} ions

A. Fafin¹, J. Cardin², C. Dufour² and F. Gourbilleau²

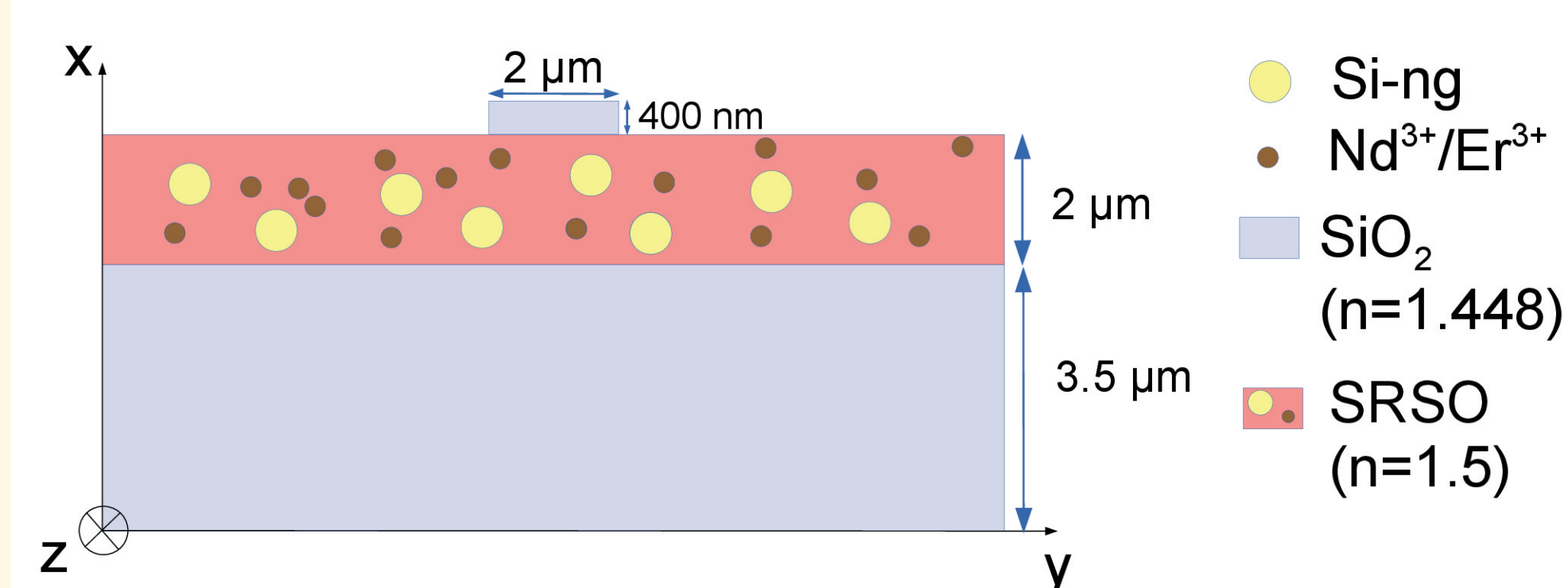
¹ Institut Pprime, Département Physique et Mécanique des Matériaux, UPR 3346 CNRS, Université de Poitiers, SP2MI, 11 Bvd. M. et P. Curie, BP 30179, 86962 Futuroscope Chasseneuil Cedex, France

²CIMAP, UMR CNRS/CEA/ENSICAEN/UCBN, Ensicaen, 6 Bvd Maréchal Juin, 14050 Caen Cedex 4, France, EU

e-mail: alexandre.fafin@univ-poitiers.fr

INTRODUCTION

Goal: Compare the optical gain in a waveguide containing silicon nanograins (Si-ng) and doped with either neodymium ions (Nd^{3+}) or erbium ions (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 Δt imposed by the FDTD method. (In visible spectral range $\Delta t \approx 10^{-17}$ s).

➔ **10⁶ years of calculation to reach steady state of \mathbf{N}_i on a such waveguide.**

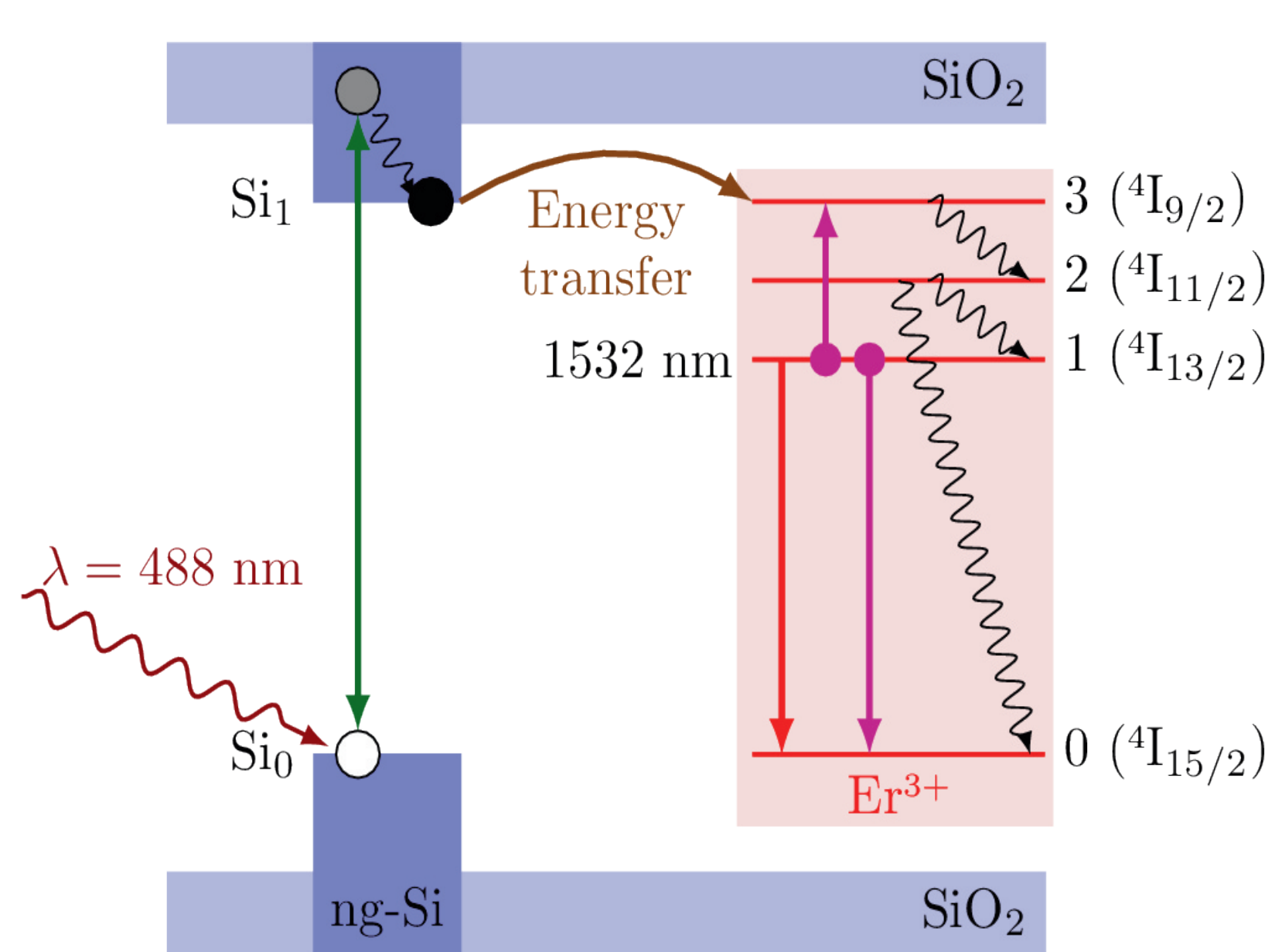
New ADE-FDTD algorithm¹: separate loops for \mathbf{E} , \mathbf{H} and \mathbf{P} on the one hand and populations \mathbf{N}_i on the other hand.

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

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

- ω_{nr} : Non radiative transition

- \downarrow : Radiative transition

- \uparrow : Up-conversion

Erbium ions

Signal at 1532 nm :

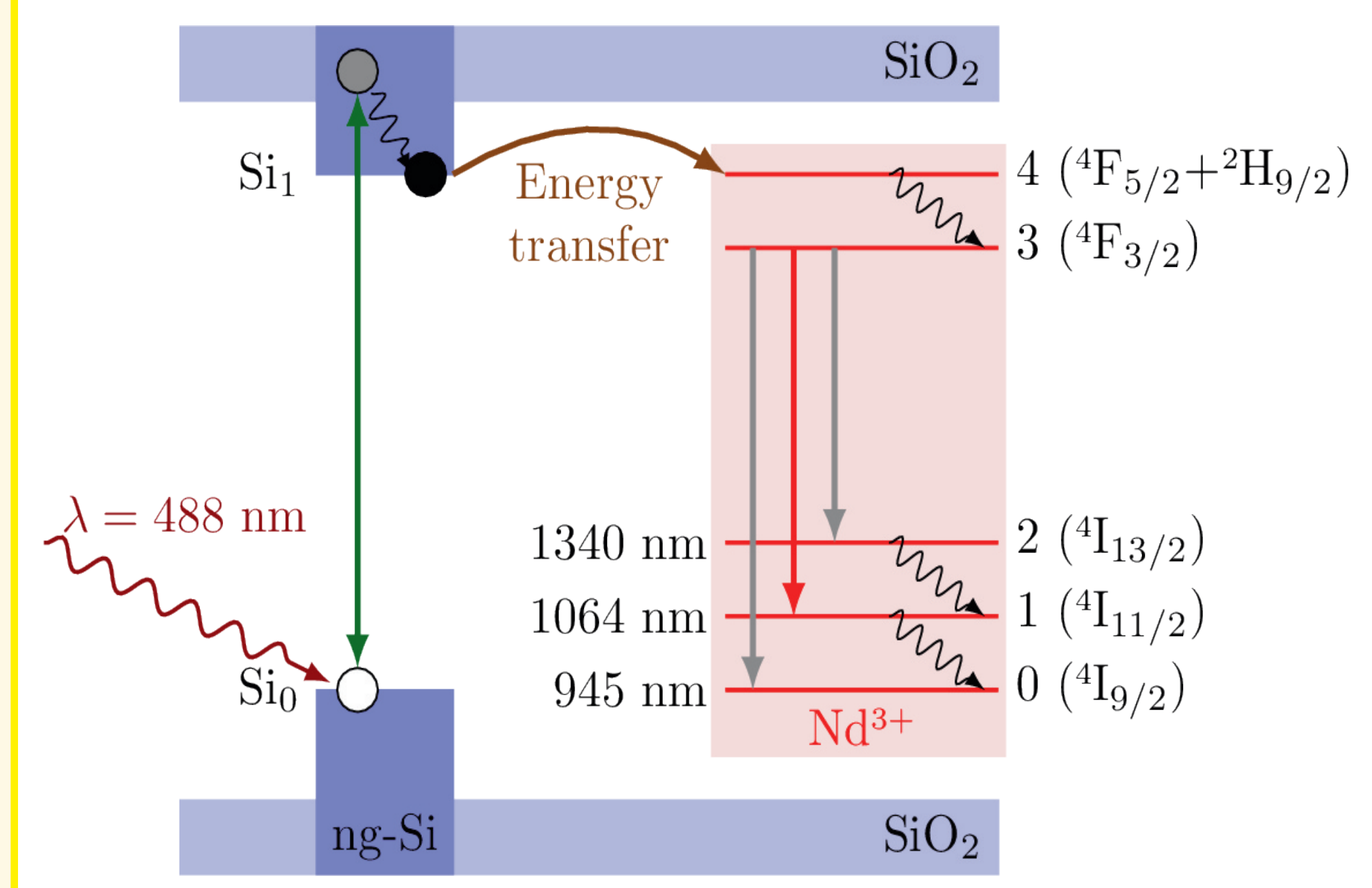
➔ Transition between \mathbf{N}_1 and \mathbf{N}_0

Neodymium ions

Signal at 1064 nm :

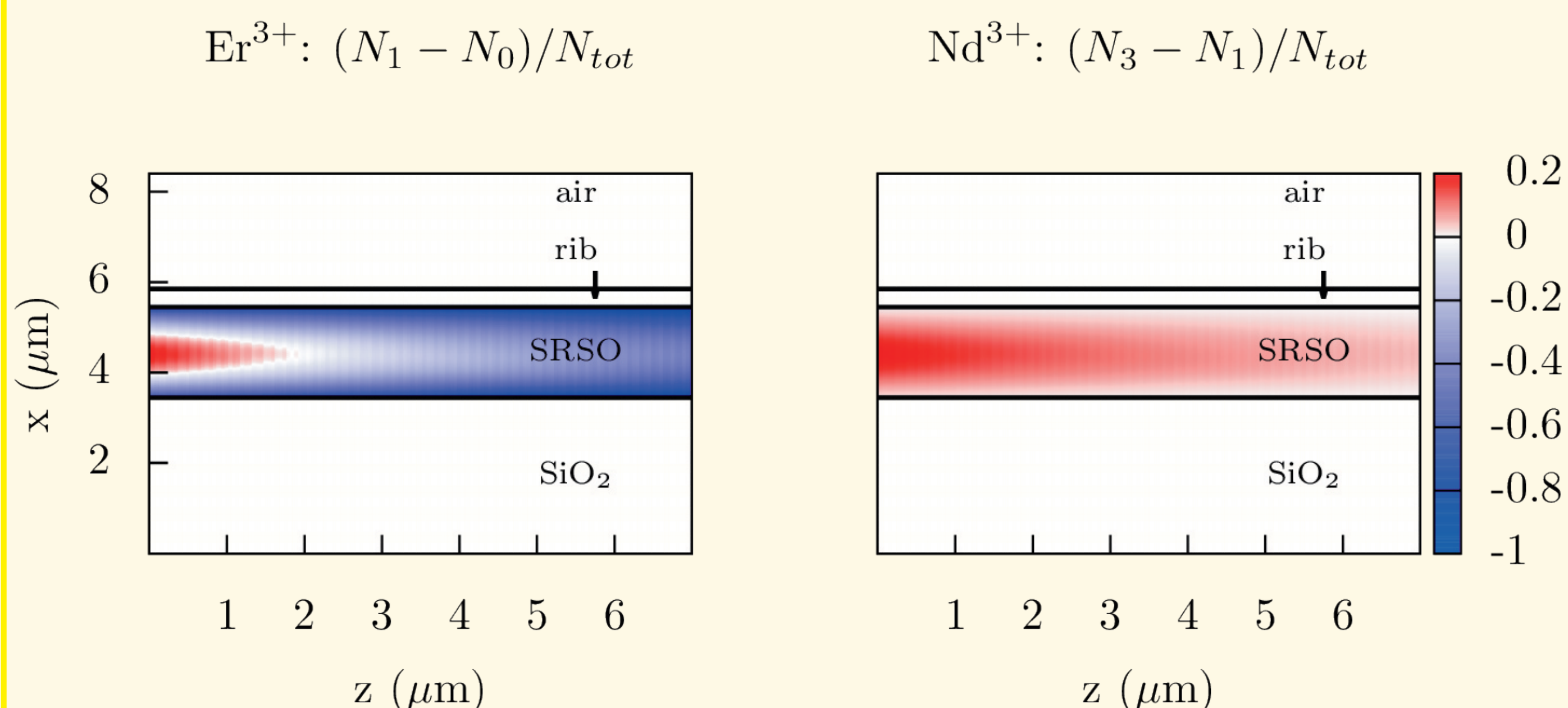
➔ Transition between \mathbf{N}_3 and \mathbf{N}_1

Neodymium excitation mechanisms



RELATIVE POPULATION DIFFERENCE

For a pump power of 1000 mW/mm²



Relative population difference reach population inversion only over a length of 1.5 μm .

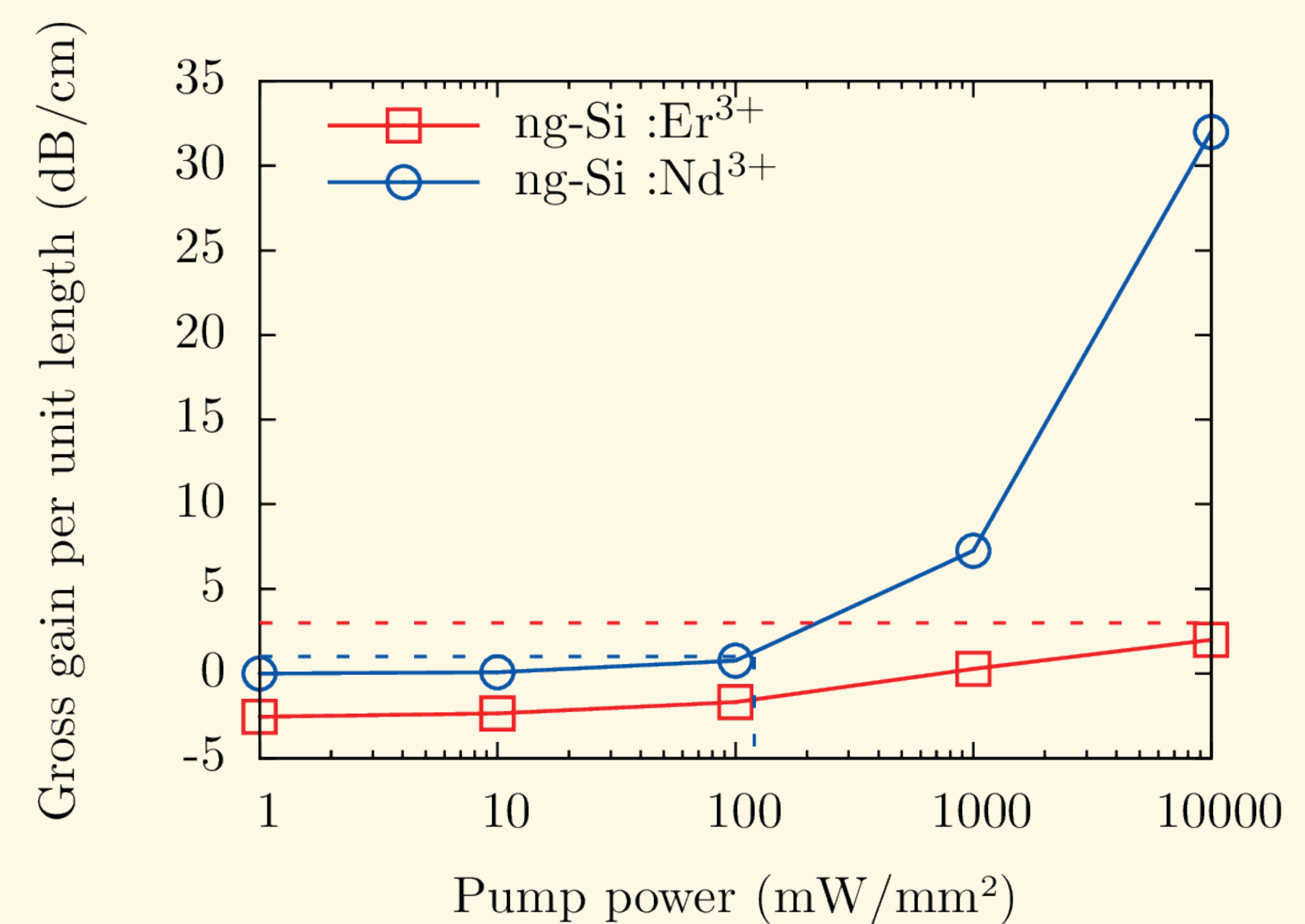
➔ Er^{3+} is a 3-level system

Relative population difference reach population inversion along the whole structure.

➔ 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 Er^{3+} and J. Appl. Phys. 114, 014906, 2013 for Nd^{3+}). **No positive net gain with Er^{3+} . Positive net gain with Nd^{3+} for a pump power higher than 120 mW/mm².**

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 Nd^{3+} or Er^{3+} ions. A positive optical gain is reached only with Nd^{3+} ions. For a pump power of 10⁵ mW/mm² the optical gain is over 30 dB/cm. For more details see Opt. Express **22**, 12296 (2014).

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