Potential for sub-mm long erbium-doped composite silicon waveguide DFB lasers

Zhengrui Tu[1], Jianhao Zhang[1], John Rönn[2], Carlos Alonso-Ramos[1], Xavier Le Roux[1], Luarent Vivien[1], Zhipei Sun[2], Eric Cassan[1]

[1] Centre for Nanoscience and Nanotechnology, CNRS, Univ. Paris-Sud, Univ. Paris-Saclay, C2N – Palaiseau France .
[2] Department of Electronics and Nanoengineering, Aalto University, Tietotie 3, FI-00076 Espoo, Finland.

Background

Silicon photonics has drawn a great interest in the past decades. The maturity of this field is such that its transition to an industrialization stage has already been achieved with the most important applications in the field of telecommunications and datacom. However, Si is an indirect bandgap material, which can not produce effective stimulated emission for light emission and amplification. Compact and effective integrated on-chip lasers and amplifiers are urgently desired. In this context, the objective is to propose a possible approach for the realization of erbium-doped lasers on silicon, pumped at ~1.48 µm, directly integrated in silicon waveguides, with sub-mm dimensions.

Waveguide structure and analysis of confinement factor

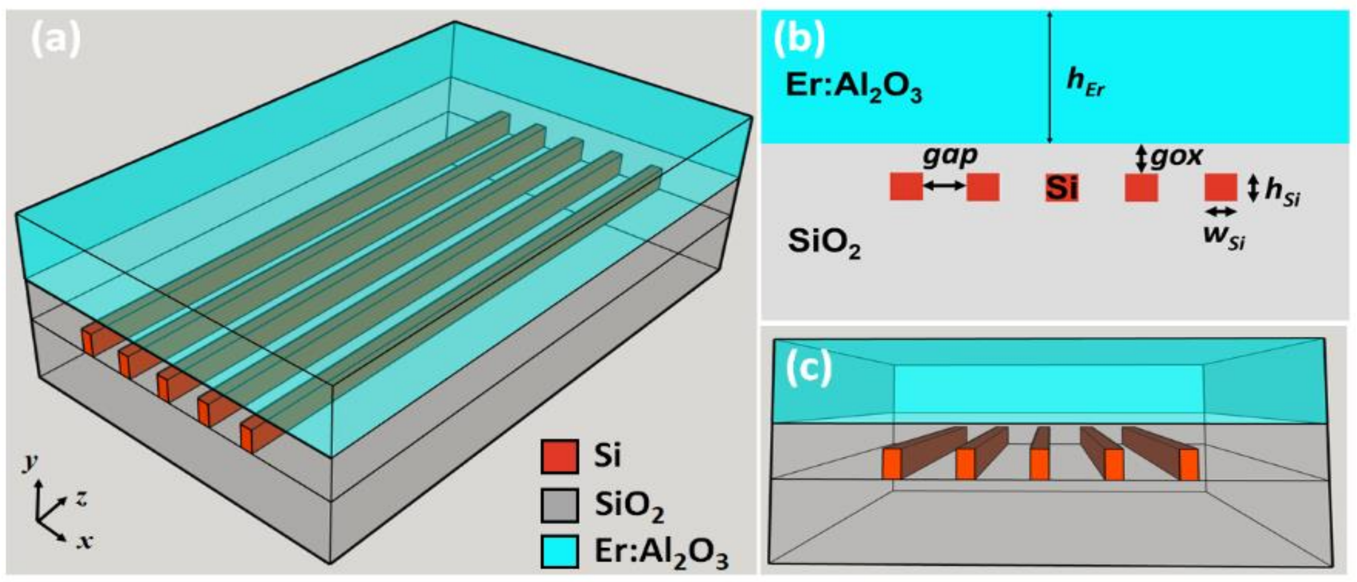

Fig 1. (a) 3D schematic diagram of the full waveguide structure. (b) Waveguide structure cross section view. (c) Front view of the waveguide structure.

Confinement factor definition

$$\Gamma_a = \frac{\iint_A \varepsilon |E|^2 \, dxdy}{\iint_\infty \varepsilon |E|^2 \, dxdy}$$

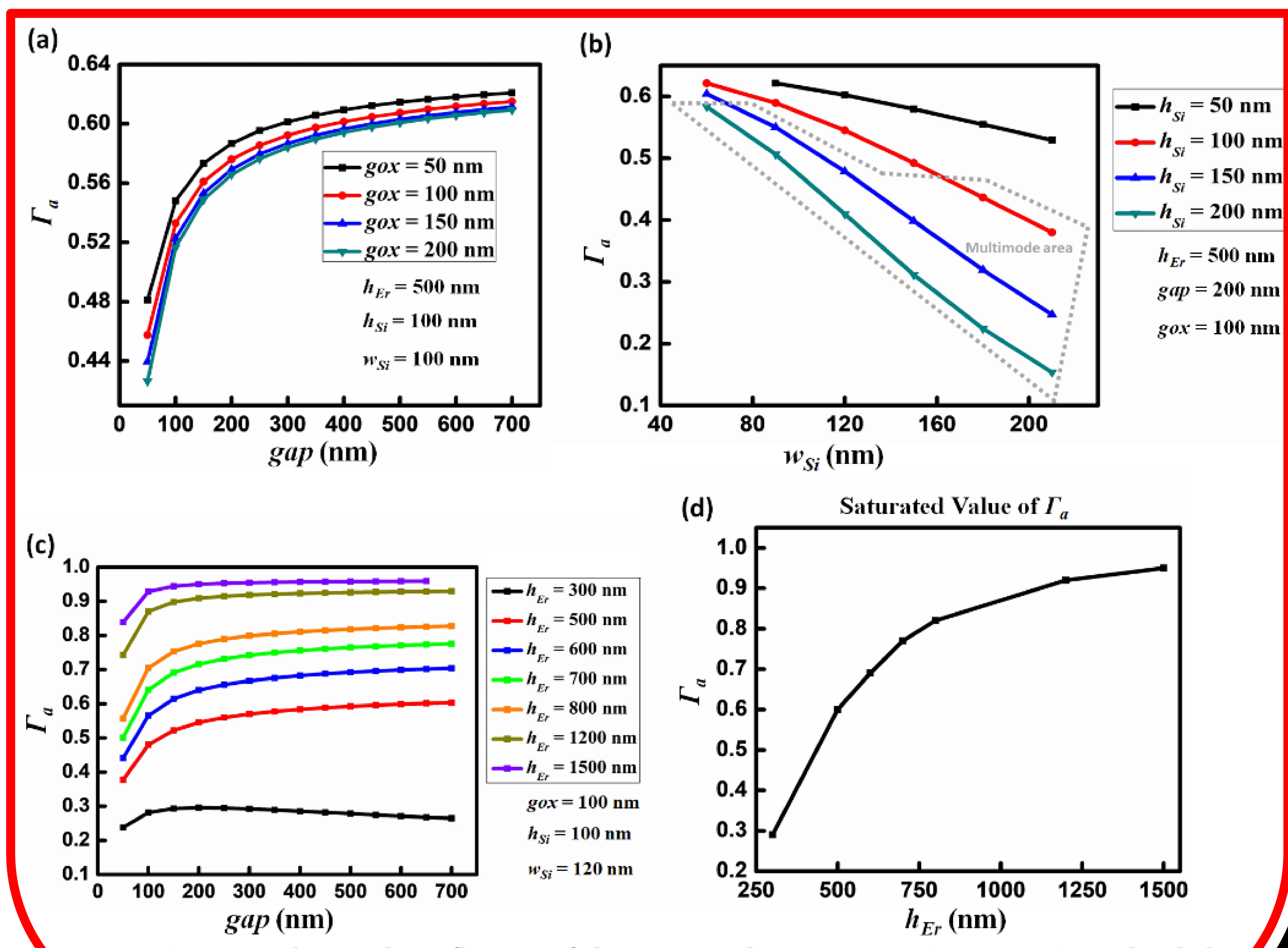

Fig 2. Exploring the influence of the waveguide parameters (see Fig. 1) on the dielectric energy confinement factor Γ_a in the active material.

Two conclusions can be drawn from the results reported in this section. Firstly, the mode confinement factor in the active material can be adjusted in a wide range and its value can reach up to 95%, which is a significant interest for achieving a strong laser effect. Secondly, the set of parameters leading to this confinement factor is only weakly sensitive to variations in the opto-geometric parameters of the multi-segment silicon waveguide, which induces a significant robustness of the investigated active structure to technological variations of the clean room fabrication processes.

Threshold analysis of compact QWS-DFB laser

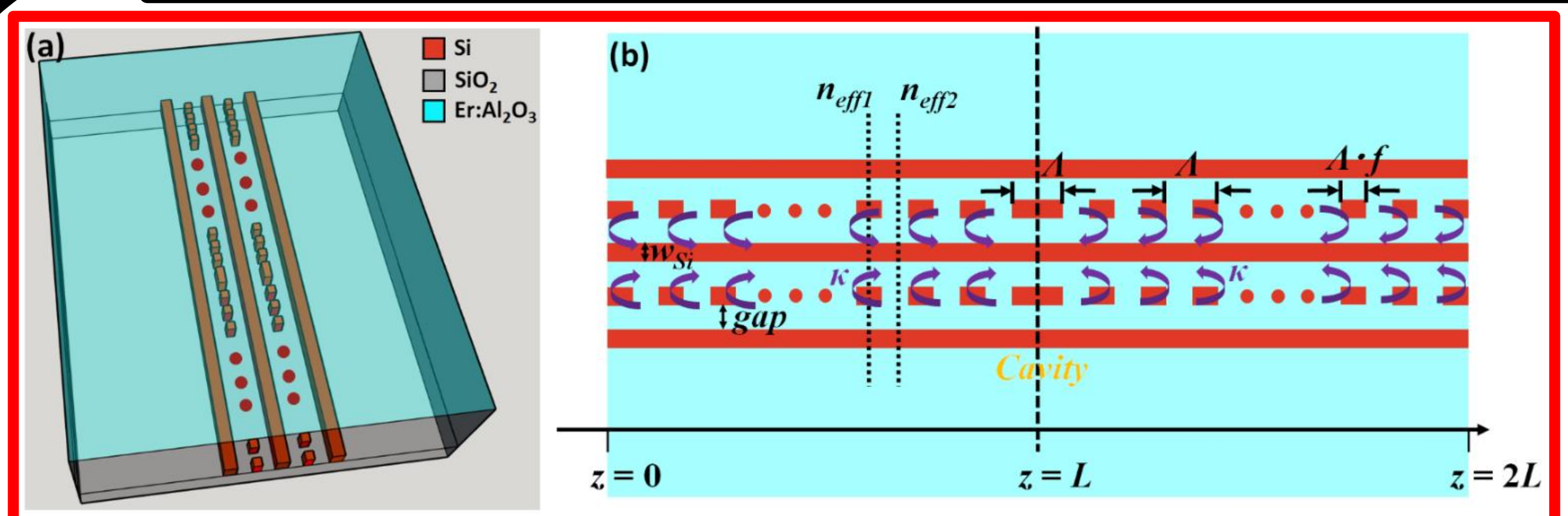

Fig 3. Designed QWS-DFB structure. (a) 3D schematic diagram. (b) 2D top view of the DFB cavity made of two identical DBR left and right mirrors and a quarter-wave intermediate section.

Threshold analysis formulas derived from coupled mode theory

$$\Gamma_a(g_{th} - \alpha) = \alpha_m + \alpha_s$$

$$|\kappa| = 2\frac{|n_{eff1} - n_{eff2}|}{2n_{eff}}\frac{1}{\Lambda} = \frac{2|n_{eff1} - n_{eff2}|}{\lambda_B}$$

$$\begin{cases} r = \dfrac{-\kappa^* \sinh(sL)}{\Delta\beta \sinh(sL) + is\cosh(sL)} \\ \Delta\beta = \beta - \beta_0 = \beta' - i\Gamma_a \dfrac{g}{2} - \beta_0 \\ s = \sqrt{|\kappa|^2 - \Delta\beta^2} \end{cases}$$

$$r^2 = \left[\frac{-\kappa^* \sinh(sL)}{\Delta\beta \sinh(sL) + is\cosh(sL)}\right]^2 = 1$$

This study is based on the gain material (Er:Al$_2$O$_3$) we have recently developed, which shows up to 52.4 ± 13.8 dB/cm (12.07 cm-1) net material gain per unit length at 1533 nm wavelength with 1470 nm pump source. Targeting at sub-mm long QWS-DFB laser, we have explored the values of Γ_a and $|\kappa|$ in different situations to distinguish if the situation is satisfied to the lasing condition. A higher Γ_a is primary for avoiding the TPA effect, then we have selected six different values of the active material thickness (h_{Er}): 700 nm, 800 nm, 900 nm, 1000 nm, 1100nm, and 1200 nm, respectively. For each h_{Er} value, many different parameters combinations have been scanned and studied. The cases situated around the lasing criterion have been readily retained. The related results in terms of Γ_a and $|\kappa|$ parameters are plotted in Fig. 4(a)-(f), according to the values of h_{Er}, respectively.

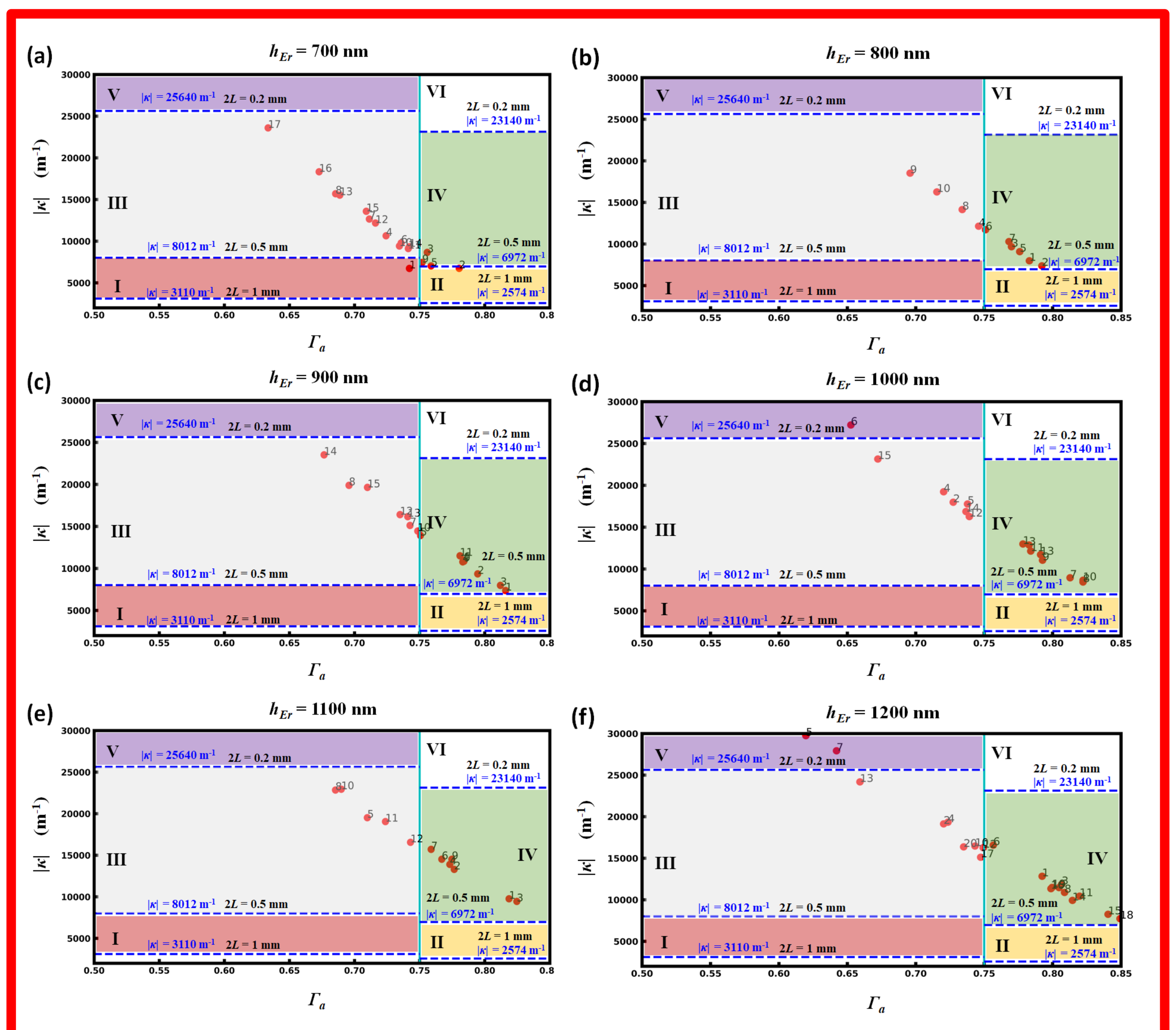

Fig 4. Exploration of the relationship between $|\kappa|$ and Γ_a in different situations. (a) h_{Er} = 700 nm. (b) h_{Er} = 800 nm. (c) h_{Er} = 900 nm. (d) h_{Er} = 1000 nm. (e) h_{Er} = 1100 nm. (f) h_{Er} = 1200 nm. For each plot of (a)-(f), the number labels stand for different combinations of the waveguide parameters (details are given in the supplementary material section).

Summary

We investigate the design of DFB lasers relying on composite silicon multiple-rail waveguides coated with a highly doped Er:Al$_2$O$_3$ layer grown by the atomic layer deposition (ALD) technique and optically pumped at 1470nm wavelength. The waveguide mode properties are investigated for exploring the influence of the structure's opto-geometrical parameters on the mode confinement factor in the active layer and on the Bragg mirrors' strength. This analysis reveals that the lasing threshold calculated through the coupled mode theory by considering realistic experimentally reported material gain levels at 1533 nm wavelength can be reached for sub-mm active structures, even 0.5 mm and 0.2 mm length footprint size. As a result, a wide range of parameters are available for the realization of lasers directly integrated into silicon-on-insulator waveguides. All the results show the very high potential of oxides doped with erbium and deposited at low temperature by ALD for the realization of integrated lasers pumped at 1470 nm by continuous sources of a few mW power. This opens up interesting prospects for integrating and combining these sources to create optical links or more complex on-chip functions and brings a contribution to the problem of sources and amplifiers for the silicon photonics platform.

References

- John Rönn, et al. Nature Comm. 10, 432 (2019)
- J. D. B. Bradley, et al. Laser Photonics Rev. 5, No. 3, 368–403(2011)
- F. Rana, "Semiconductor optoelectronics," Chapter 13, Cornell University.
- E. S. Magden, et. al. Optics Express, 25(15), 18058-18065 (2017)
- Michael Belt et al. Optics Express 22(9), 10655-10660 (2014)
- X. Wang, "Silicon photonic waveguide Bragg gratings," PhD thesis University of British Columbia (2013).