Prospect for compact on-chip lasing with hybrid erbium-doped silicon integration

(Student Paper)

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ABSTRACT

Taking advantage of our recently demonstrated erbium-doped Al_2O_3/Er_2O_3 thin film with large gain up to 52 dB/cm at 1533 nm, we investigate the feasibility for realizing compact on-chip lasers in the near infrared spectral region with the silicon on insulator photonic platform.

Keywords: Integrated silicon photonics, Erbium material, On-chip lasing.

1. INTRODUCTION

Silicon integration photonics has drawn a great interest in the past decades, and now it already plays an important role in modern photonics and optoelectronics [1,2]. Nevertheless, there are still a few key points to be resolved, including the issue of the light source. Due to the silicon's indirect band gap, one of the biggest challenges is indeed to realize compact, highly efficient, low power consumption and low cost on-chip lasers and amplifiers [3]. Several methods have been investigated to address the problem. Introducing hybrid integration of III/V based lasers on silicon can achieve highly efficient integrated lasing and is considered as the present dominant approach [4-6]. It nevertheless requires a heterogeneous integration, which is not COMS compatible with complex fabricating process and high cost. Any direct monolithic integration of materials deposited at temperatures compatible with a back-end CMOS process (<500°C) is therefore preferable. In this way, introducing rare-earth doped materials that were wildly employed in developments of optical fiber communications may be of interest [7]. Recently, progresses on the integration of rare-earth-doped amorphous aluminum oxides in silicon nitride waveguides have been reported by several research groups [8]. These works have opened up very interesting prospects by proposing integrated structures leading to laser emission in various configurations, the most interesting one is probably that of optically pumped integrated DFB lasers. However, the demonstrated obtained devices have typical lengths of more than 2 cm [8-9], which are significantly larger than the typical waveguides, micro-resonators, and active components. An effort to shrink erbium optical amplifiers and lasers is therefore required. Another limitation that is not addressed by the previous works is the choice of the pump wavelength. In previous works, the erbium-doped active matrix is pumped at 980nm. Although this pump wavelength is the most effective wavelength to get population inversion in the erbium-based medium, it is clearly not compatible with a light propagation in silicon in the near infra-red.

Our study is based on the active Erbium doped material we have recently developed [10-11]. With a 1470 nm pump source, up to 52.4 ± 13.8 dB/cm material gain per unit length at 1533 nm wavelength was realized, which, to the best of our knowledge, is among the highest gain achieved from erbium-based planar waveguides. Given such erbium-doped material properties, in order to get lasing, a proper optical cavity, which owns not only high mode confinement in the active material region but also low losses meanwhile, is worth being investigated. Inspired by the wise tiny multi-segment waveguide structure proposed before in Ref. [8] and taking advantage of our Erbium-doped material platform relying on the atomic layer deposition (ALD) technique, we investigate here the feasibility for realizing compact Erbium-doped on-chip lasers based on the SOI platform through the design of quarter-wave shifted (QWS) distributed feedback (DFB) cavities.

2. WAVEGUIDE STRUCTURE

Recently, based on silicon nitride platform, rare-earth doped material DFB lasers composed of several segment waveguides were explored [8]. This kind of structure presents a high light field confinement factor in the active material, which can perfectly meet our needs. As a result, we adopt here a similar waveguide structure, but after transposing it to SOI optical waveguides to target more compact designs. The waveguide structure cross section view is shown in Fig. 1(a). Based on a 220 nm thickness silicon core SOI wafer, fabrication can be carried out by etching five silicon segments, then planarizing the waveguide with depositing a thin SiO2 layer, and finally depositing a Al_2O_3:Er stack on top through an atomic-layer deposition (ALD) process. This thin SiO_2 layer can reduce the impact of the high refractive index Si stripe on the optical mode distribution and improve wavelength insensitivity to get a higher overlap between the pump and signal mode fields. The 3D schematic diagram of the full waveguide structure is shown in Fig. 1(b), and Fig. 1(c) shows the front view.

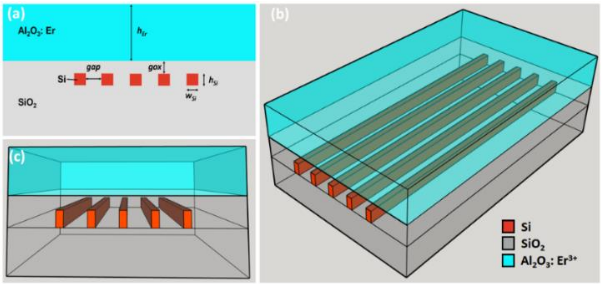

Figure 1. (a) Waveguide structure cross section view.
(b) 3D schematic diagram of full waveguide structure. (c) Front view of waveguide structure.

Mode analysis was conducted through *COMSOL Multiphysics*, with the parameters of the waveguide structure as follows: h_{Er} = 500 nm, w_{Si} = 100 nm, h_{Si} =100 nm, *gap* = 300 nm, *gox* = 100 nm. Fig. 2(a) and Fig. 2(b) show the mode solution results of the pump and signal modes, respectively. Clearly, we can see that electric field distributes mainly inside the active material region, for both the pump and the signal. An ideal confinement factor of 0.05 is obtained in silicon, which makes it reasonable to neglect the Two Photon Absorption (TPA) effect.

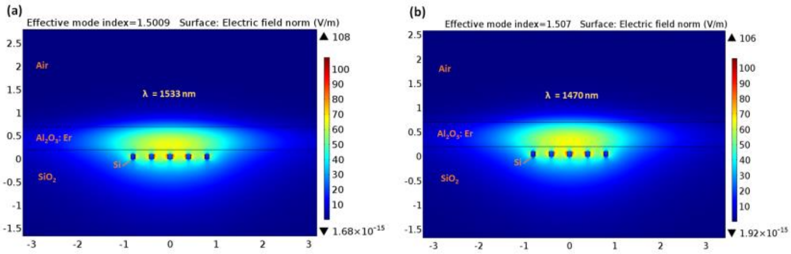

Figure. 2. Mode analysis results when the parameters of the waveguide structure are as follows: h_{Er} = 500 nm, w_{Si} = 100 nm, h_{Si} =100 nm, gap = 300 nm, gox = 100 nm. (a) Light electric field at the signal wavelength, λ = 1533 nm.
(b) Light electric field plot at the pump wavelength, λ = 1470 nm.

3. COMPACT DFB LASERS

Based on the waveguide structure mentioned above, quarter-wave shifted (QWS) distributed feedback (DFB) lasers can be designed, as it contains several parallel rails and that patterning some of them with slits allows to realize Bragg mirrors with controlled and widely adjustable mirror strengths. A QWS-DFB laser structure is composed of two distributed Bragg reflectors (DBR), which are back to back with zero gap. The 3D schematic diagram of designed QWS-DFB structure is shown in Fig. 3(a), and Fig. 3(b) is the 2D counterpart diagram from the top view. Two rails of silicon segment structures next to the central strip is used as gratings. Through this way,

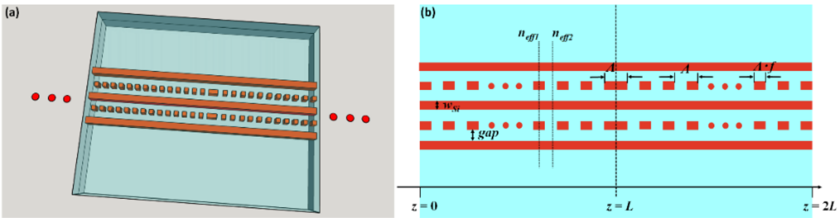

Figure. 3. Designed QWS-DFB structure. (a) 3D schematic diagram. (b) 2D structure diagram from the top view.

appreciable grating coupling coefficient ($|\kappa|$) can be obtained without huge effect on the target waveguide guided modes. The length of each DBR in each side is L. The grating period is Λ, and the filling factor f (defined as the ratio of single silicon grating length to the grating period) is 0.5, which provides the highest coupling coefficient [12].

To estimate the distribution level of the light electric field in the active material, the following confinement factor is considered. The confinement factor in active material is indicated by Γ_a, with its definition as: the ratio of the optical dielectric power confined in the active region to the total optical power flowing through the structure:

$$\Gamma_a = \frac{\iint_A \varepsilon |E|^2 \, dxdy}{\iint_\infty \varepsilon |E|^2 \, dxdy} \tag{1}$$

With this confinement factor, the threshold of the QWS-DFB laser can be further studied. The lasing threshold and mirror loss level (external loss)/ material absorption loss (cavity internal loss) are represented by g_{th} and α_m/α, respectively. Mirror loss level (α_m) is basically dominated by the grating coupling coefficient ($|\kappa|$) once the gain material is chosen and constrains the lasing through condition:

$$\Gamma_a g_{th} = \alpha_m + \alpha \tag{2}$$

In our case, the material absorption loss is α = 8.06 cm^{-1} [10]. According to the simulation and analysis carried out by exploring the design space of the waveguide and active layer parameters, we find that only when the value of Γ_a is larger than 0.714 (meanwhile for $|\kappa|L$ larger than 4) that lasing can be achieved. In other words, in the case of ensuring that Γ_a > 0.714 and $|\kappa|$ > 8000 m^{-1}, a compact on-chip QWS-DFB laser with no longer than 1 mm footprint size can be obtained; even close to 0.5 mm long size when $|\kappa|$ > 16000 m^{-1}. Supported by numerous analysis, we can conclude that using our design, it is feasible to fulfil the requirement for a compact on-chip DFB laser. More information will be given during the conference.

4. CONCLUSION

In summary, we investigate the feasibility of realizing compact on-chip DFB lasers relying on composite silicon multiple-rail waveguides coated with a highly erbium doped concentration active Al_2O_3/Er_2O_3 materials. Supported by our proposed structure and good luminescent materials grown by the atomic layer deposition technique (ALD), sub-mm footprint size (even as short as 0.5mm) laser optically pumped at 1470nm wavelength can be achieved theoretically. This work opens up interesting prospects for integrating and combining these sources to create optical links or more complex on-chip functions.

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