Erbium-Doped Laser with Multi-segmented Silicon Nitride Structure

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Abstract: We report on DFB and DBR lasers formed from a wavelength insensitive multi-segmented silicon nitride waveguide. Using a five-segment waveguide, we obtain lasing in erbium-doped DBR (-3.6 dBm) and DFB (-7.3 dBm) cavities.

OCIS codes: (130.0130) Integrated optics; (130.2790) Guided waves; (130.3120) Integrated optics devices; (140.3460) Lasers.

1. Introduction

Lasers on a silicon platform have generated substantial interest due to the numerous important applications ranging from integrated communications to optical sensors. Several methods have been developed to realize on-chip lasers, including germanium-on-silicon lasers [1], III-V hybrid lasers [2, 3], and erbium-doped glass lasers [4, 5]. Of these approaches, only erbium-doped glass lasers have been shown to achieve both ultra-narrow linewidth [4] and CMOS-compatibility [3]. Thus, the next step is to demonstrate integration with other photonics devices. In particular, silicon nitride based waveguides provide robust, low-loss and compact devices for a wide range of optical wavelengths [6, 7]. Erbium laser resonators have been demonstrated by patterning silicon nitride structures beneath the erbium host material (Al_2O_3) to form an inverted ridge waveguide [4, 5]. In a traditional waveguide design, the relatively high index contrast of these materials (n_{SiN_x} = 1.99 and $n_{Al_2O_3}$ = 1.65) requires that the silicon nitride layer be very thin so that the mode overlaps strongly with the gain medium. However, a thin silicon nitride layer prevents the layer from being effectively reused to form other important integrated devices such as microring-resonators.

Here, we solve this problem by implementing a multi-segmented silicon nitride waveguide [8] to achieve strong overlap with the active region while maintaining a thick silicon nitride layer for passive component integration. Additionally, the resulting design facilitates broadband, high confinement and overlap factors across the entire near-infrared wavelengths (0.9 μm – 2.0 μm) offering potential for amplifier and laser operation across an extremely broad bandwidth, a result that will become of increasing importance as the S, C, and L bands become saturated. We demonstrate multi-segmented waveguide Er_{3+}:Al_2O_3 lasers in distributed Bragg reflector (DBR) cavities with maximum output powers of -3.6 dBm and distributed feedback (DFB) cavities with maximum output powers of -7.3 dBm at a wavelength of λ~1565nm.

2. Design and Simulation

Figure 1 a) shows the schematic of the multi-segmented waveguide designs for Er_{3+}:Al_2O_3 lasers. The waveguide consists of a silicon (Si) substrate, a five segment SiN_x waveguide buried in SiO_2 (n_{SiO_2} =1.445), and a SiO_2 gap between the top surface of the SiN_x and the Er_{3+}:Al_2O_3. The distance between the Si to the bottom layer of SiN_x (>2.5μm) was chosen so that the fundamental TE mode is not affected by the substrate. The parameters of the SiN_x waveguide consist of a waveguide thickness t = 200 nm, width w = 600 nm, and gap g = 400 nm. A layer of oxide (SiO_2) filling the gap with thickness of 200 nm was deposited in between the erbium glass and SiN_x to help reduce the guiding effect of high index SiN_x [5]. Lastly, an Er_{3+}:Al_2O_3 of thickness of 1500 nm was put on top of the structure.

The intensity distributions of the fundamental TE mode at different wavelengths were calculated by a finite difference mode solver. Figure 1 b) and c) show the intensity distribution for pump wavelength at 980 nm and signal wavelength at 1550 nm. If we define the confinement factor (γ) and overlap factor (Γ) in the active medium by the following,

$$g_{s/p} = \frac{\int_A I_{s/p}\,dA}{\int_{\infty} I_{s/p}\,dA} = \frac{\sum_{active(ij)} I_{ij}^{(s/p)}}{\sum_{ij} I_{ij}^{(s/p)}}$$

$$\Gamma_{sp} = \frac{\int_A I_p I_s dA}{\sqrt{\int_A I_p^2 dA \int_A I_s^2 dA}} = \frac{\sum_{active(ij)} I_{ij}^{(p)} I_{ij}^{(s)}}{\sqrt{\sum_{active(ij)} I_{ij}^{2(p)}} \sqrt{\sum_{active(ij)} I_{ij}^{2(s)}}}$$

then we obtain $\gamma_{1550nm} = 90\%$, $\gamma_{980nm} = 89\%$, and $\Gamma_{980-1550} = 99\%$.

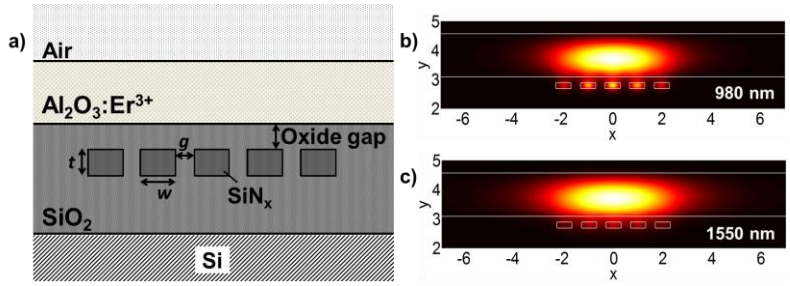

Figure 1 a) Schematic of the vertical five-segment waveguide design. The calculated intensity of fundamental TE mode at b) 980 nm (pump) and c) 1550 nm (signal).

We extended our analysis of the multi-segmented structure to broader wavelength selections; 950 nm and 980 nm (InGaAs pump diode), 1050 nm (Ytterbium/Yb and Neodymium/Nd doped laser), 1300 nm (Nd doped laser), 1550 nm (Er doped laser), and 2000 nm (Thulium/Tm and Holmium/Ho doped laser). The confinement and overlap factors (with 980 nm as the reference pump) of these wavelengths are shown in Figure 2. We obtained >85% confinement factor for all wavelengths longer than 950 nm and >98% intensity overlap factor with 980 nm pump over the entire near-infrared wavelength light sources, demonstrating insensitivity of mode profiles at various wavelengths. We note that the calculation has ignored the variation of the refractive indices at various wavelengths.

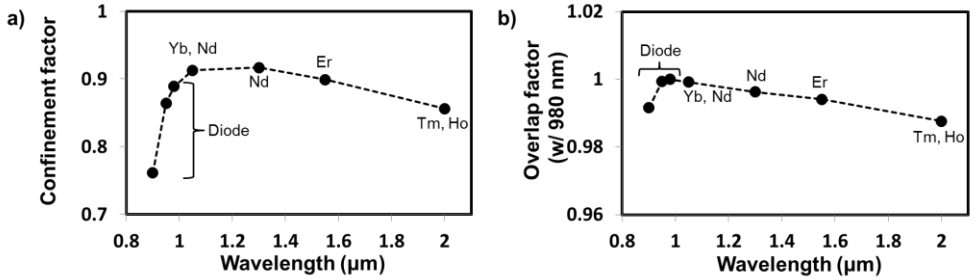

Figure 2 a) Confinement factor of different light sources. b) Intensity overlap factor of different wavelength with 980 nm.

3. Er_{3+}:Al_2O_3 Laser based on VMS waveguide

We designed DBR and DFB resonators for Er_{3+}:Al_2O_3 lasers. Periods of both DBR and DFB are the same Λ = 504 nm. The DBR cavity consists of a straight multi-segmented waveguide of length L_{gain} = 13.8 mm confined by two similar reflection gratings. Each grating is formed by periodic additional side pieces on both sides of the multi-segmented waveguide (adding to total of 7 SiN_x segment waveguides), with each additional pieces having widths of w_{DBR} = 600 nm and separated from the multi-segmented waveguide by a gap of g_{DBR} = 400 nm. The total length of each of the gratings is given by L_{DBR} = 5 mm. The DFB cavity consists of grating across the entire gain region, with the grating also formed by periodic additional side pieces with w_{DFB} = 300 nm and g_{DFB} = 550 nm. The total length of the DFB is L_{DFB} = 20 mm. The quarter-wave phase shift of the DFB was designed to be slightly off from the center of the cavity (0.6 L_{DFB}) so as to ensure lasing out of a single facet.

The laser cavities were fabricated within a 300mm CMOS foundry. A 6 μm-thick plasma-enhanced chemical vapor deposition (PECVD) SiO_2 layer with 0.2 μm-thick LPCVD SiN_x layer was first purchased from vendor. The nitride layer was then patterned using 193 nm immersion lithography and reactive ion etching. After patterning, a PECVD SiO_2 layer was deposited and chemically mechanically polished (CMP)-ed to a height of 0.1 μm above the silicon nitride layer. A second nitride layer was then deposited and patterned with a thickness of 0.2 μm and buried

under additional 4 μm SiO_2 layer. The second nitride layer is a part of process for other devices, however in the case of laser structures, we utilized this layer as an etch stop for erbium trench. After the nitride was etched away, we deposited another 0.1 μm SiO_2 to make the total oxide gap to become 0.2 μm. Trenches for dicing and fiber end coupling were then etched into the edges of the dies by deep oxide and silicon etching. Finally, the wafers were transferred from the CMOS foundry, diced into individual dies, and an Er_{3+}:Al2O3 layer was deposited by reactive co-sputtering using a process similar to that reported in [9]. Using the prism coupling method to measure the planar losses around 1550 nm, we obtained background loss, dopant concentration, and thickness of the film to be < 0.1 dB⁄cm, 1.0×10^{20} cm−3, and 1 μm respectively. The confinement and overlap factors for 1 μm-thick Er_{3+}:Al_2O_3 are given by $\gamma_{1550nm} = 75\%$, $\gamma_{1550nm} = 66\%$, and $\Gamma_{980-1550} = 99\%$ respectively.

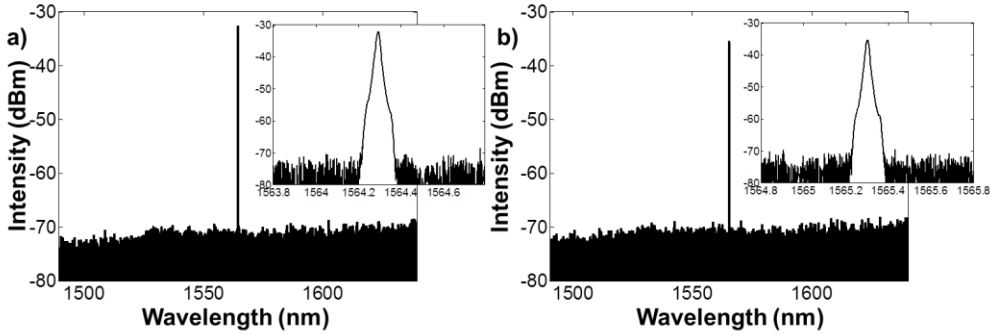

Figure 3 Spectrum of a) DBR and b) DFB lasers.

The DBR and DFB lasers were pumped by using two 978 nm diode lasers. By transmission measurement, we measured the coupling losses. For the DBR laser, we estimated maximum on-chip power of P_{max} = 0.44 mW (-3.6 dBm) and slope efficiency of η = 1.4%. The threshold pump power is P_{th} = 64 mW. For DFB laser, we estimated maximum on-chip power of P_{max} = 0.18 mW (-7.3 dBm) and slope efficiency of η = 2.7%. The threshold pump power is P_{th} = 14 mW. Figure 3 shows the spectrum of the DBR and DFB lasers at ~1565 nm.

4. Conclusion

We report on a wavelength insensitive design for the near-infrared range by using a multi-segmented waveguide design. The design allows for high confinement and intensity overlap between the pump and signal wavelengths. We use a five-segmentwaveguide design to demonstrate Er_{3+}:Al_2O_3 in DBR and DFB cavities. We obtained maximum power of -3.6 dBm for DBR laser and -7.3 dBm for DFB laser. The waveguide design allows operation of lasers at different wavelengths and due to the increased layer thickness, a further integration of compact silicon nitride devices.

This work was funded by the Defense Advanced Research Projects Agency Electronic Photonics Integration (DARPA-EPHI) program, grant no. HR0011-12-2-0007 and the Samsung Global Research Outreach (GRO) program.

5. References

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