C- and L-Band Erbium-Doped Aluminum Oxide Lasers with Silicon Nitride Distributed Bragg Reflector Cavities

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Abstract: We demonstrate erbium-doped waveguide lasers with lithographically-defined silicon nitride distributed Bragg reflectors. We measure output powers of up to 5 mW and show emission over a wide wavelength range (1536, 1561 and 1596 nm).

OCIS codes: (130.3120) Integrated optics devices; (140.3500) Lasers, Erbium

1. Introduction

Recently, erbium-doped aluminum oxide ($Al_2O_3:Er^{3+}$) lasers have been demonstrated on silicon chips with potential applications in communications [1], microwave signal generation and sensing [2]. For production-level fabrication of integrated lasers on silicon, it is desirable to define the laser cavities using standard silicon processing methods. Since rare-earth-doped materials are incompatible with silicon production lines, a process flow in which the erbium-doped layer can be deposited in a back-end manner would be highly beneficial.

Silicon nitride (Si_3N_4) is a silicon-compatible material which is used to fabricate low-loss, high-refractive-index-contrast photonic features [3]. We propose an approach whereby the laser waveguide and gratings are defined in a thin Si_3N_4 layer, while a blanket $Al_2O_3:Er^{3+}$ active layer is deposited on top. This approach enables wafer-scale production of erbium-doped waveguide lasers and integration with other Si_3N_4 passive components on silicon chips.

In this paper, we demonstrate integrated $Al_2O_3:Er^{3+}$ lasers with high-resolution, lithographically-defined Si_3N_4 distributed Bragg reflector cavities. We obtain up to 5 mW of output power and show lasing in both the C- and L-bands, covering a wavelength range more than two times larger than that previously shown using $Al_2O_3:Er^{3+}$.

2. Laser Design and Fabrication

The laser waveguide design is depicted in Fig. 1a. It consists of a 0.1 μm × 4.0 μm nitride ridge with SiO_2 cladding and a top 1.4-μm-thick $Al_2O_3:Er^{3+}$ layer. A thin (0.1 μm) SiO_2 layer between the Si_3N_4 ridge and the $Al_2O_3:Er^{3+}$ film reduces the guiding effect of the higher-refractive-index silicon nitride, and results in high confinement factor of the pump and laser intensity within the active medium (0.89 and 0.87 at 980 and 1550 nm, respectively). In addition, it results in large overlap (93%) of the pump and signal modes (also shown in Fig. 1a). Therefore, our design allows either efficient pumping resonantly at 1480 nm or pumping at 980 nm where enhanced Er-ion sensitization by Yb-co-doping is feasible.

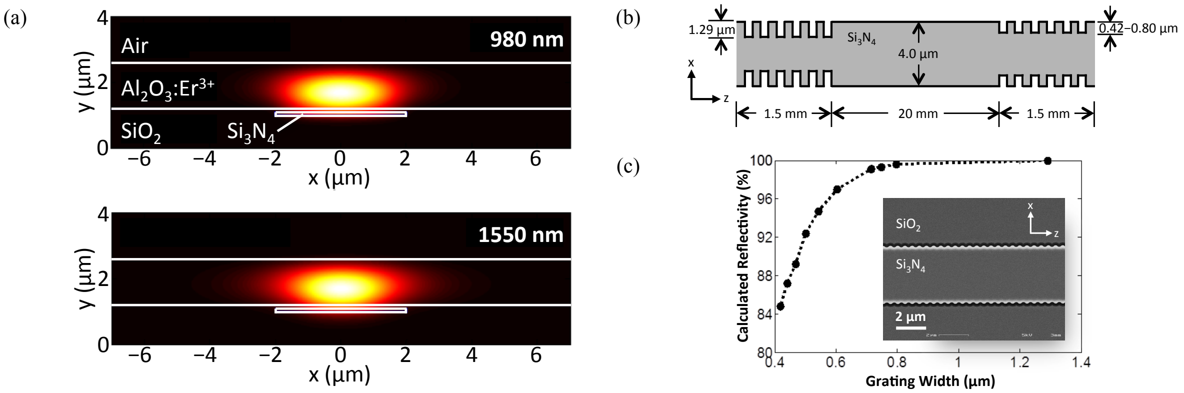


Fig. 1. (a) Laser waveguide cross-section with calculated TE-polarized optical intensity profiles at 980 nm (top) and 1550 nm (bottom); (b) top-view schematic of the silicon nitride DBR laser cavity; (c) grating reflectivity calculated using coupled mode theory and scanning electron micrograph top-view image of the grating region (inset).

The silicon nitride distributed Bragg reflector (DBR) cavity consists of a straight waveguide of length 20 mm and width 4.0 μm confined by two reflection gratings (Fig. 1b). The gratings are formed by waveguides of length 1.5 mm with corrugated sidewalls (duty cycle = 50%). The sidewall gratings have widths of 1.29 μm at one end and

0.42 µm to 0.80 µm at the other end, resulting in theoretical reflectivities of 100% and 85% to 99.6%, respectively (see Fig. 1c). The grating period was varied between lengths of 0.478, 0.487 and 0.498 µm, which correspond to Bragg wavelengths of 1536, 1561 and 1596 nm, respectively.

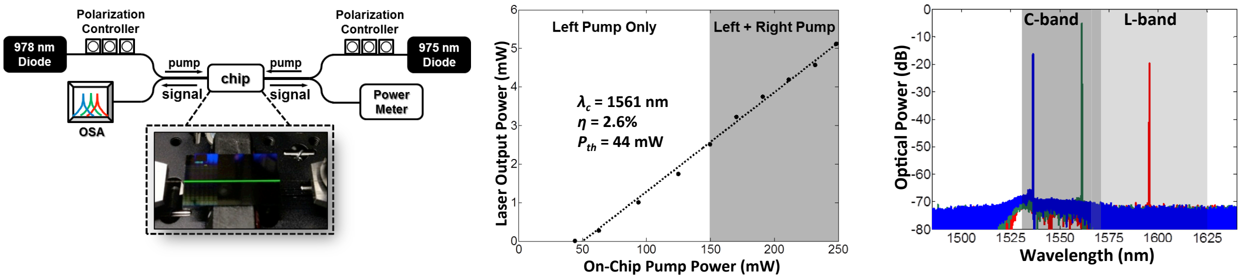
We fabricated the integrated laser cavities using a state-of-the-art 300-mm silicon wafer line. A 6-µm-thick plasma-enhanced chemical vapor deposition (PECVD) SiO_2 layer was grown on a 300-mm Si wafer, followed by deposition of a 0.1-µm-thick PECVD Si_3N_4 layer. The nitride layer was patterned using 193-nm optical immersion lithography followed by reactive ion etching. After patterning, a PECVD SiO_2 layer was deposited on top and planarized to a height of 0.1 µm above the nitride ridge. Trenches for dicing and fiber end coupling were then etched into the edges of the dies by deep oxide and silicon etching. The wafers were then transferred from the silicon foundry and diced into individual ~2.5 × 2.5 cm^2 dies. Finally, an $Al_2O_3:Er^{3+}$ layer (doping concentration ≈ 1.4×10^{20} cm^{-3}) was deposited by reactive co-sputtering using a similar process to that reported in [4].

3. Results

Figure 2a shows the experimental setup used to characterize the lasers. Transverse electric (TE) polarized pump light from 978 nm and 975 nm laser diodes was coupled into the chip on each side using fiber-based 980/1550 nm wavelength division multiplexors (WDMs), respectively. The laser output was collected from the 1550 nm port of the WDM and the power was measured using a power meter, while the spectrum was recorded by an optical spectrum analyzer (OSA).

We obtain the maximum output power from the DBR laser with center wavelength, λ_c, at 1561 nm and theoretical grating reflectivities of 100 and 95% (Fig. 2b). With single-side pumping we observe a threshold pump power, P_{th}, of 44 mW and an on-chip output power of up to 2.5 mW (taking into account fiber-chip coupling losses of 5 and 7 dB at 980 and 1550 nm, respectively). We obtain maximum on-chip output power of 5.1 mW with double-sided pumping, corresponding to a slope efficiency, η, of 2.6%. In addition, we obtain maximum output powers of 2.5 mW at λ_c = 1536 nm and 0.5 mW at λ_c = 1596 nm. These output powers are obtained from cavities with output DBR reflectivities of 86% and 95%, respectively. We attribute the difference in the optimum reflectivity for the DBR cavities to the wavelength-dependence of both the gain threshold and the small signal gain.

Figure 2c shows the spectra of the three DBR lasers recorded by the OSA. The emission peaks span a wavelength range of more than twice that shown in previous $Al_2O_3:Er_{3+}$ lasers [1]. The laser emission at 1596 nm is a consequence of low grating scattering loss, low background losses in the $Al_2O_3:Er^{3+}$ film (≤ 0.1 dB/cm, determined by prism coupling) and the wide gain spectrum of $Al_2O_3:Er^{3+}$ [5]. By simply modifying the period of the gratings in the silicon nitride layer, it is feasible to fabricate arrays of lasers spanning both the C and L communication bands.



(a) (b) (c)

Fig. 2. (a) Setup used to characterize DBR lasers; (b) laser power vs. launched 980-nm pump power for single- and double-sided pumping; (c) measured laser spectra for DBRs centered at 1536, 1561 and 1596 nm.

4. Conclusions

We have demonstrated erbium-doped waveguide lasers fabricated using 300-mm wafer-scale technology. We realize high-quality silicon nitride gratings and lasing at wavelengths separated by up to 60 nm in the C and L bands.

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5. References

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