High-Power CMOS-compatible Photonic Integrated Thulium-Doped Distributed Feedback Laser

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***Abstract* – We report a high power CMOS-compatible thulium-doped distributed feedback laser with single-mode output power up to 267 mW, 14% slope efficiency, and >70dB side mode suppression ratio.**

***Index Terms* – Solid State Laser, Thulium, Distributed Feedback, Silicon Photonics**

I. Introduction

Laser sources around 2 µm wavelength have many applications such as light detection and ranging (LIDAR), spectroscopy, optical waveform generation and synthesis, material processing, communication, and trace-gas detection systems. The high water absorption at 2 µm also makes such lasers good candidates for medical applications [1]. Furthermore, pulsed 2 µm wavelength lasers could be used as pumps for nonlinear processes in silicon [2]. Silicon is the material of choice for both microelectronic circuits and integrated photonic components around 1.31µm and 1.55µm. To extend the applicability of silicon photonic devices to 2µm wavelength region, complementary metal-oxide semiconductor (CMOS) compatible integrated laser sources around 2µm are required and will enable more compact devices that can perform the task of current complex bulky laboratory setups.

Prior to this work, we have reported a thulium-doped microcavity laser with sub-milliwatt output power and multi-mode operation in ref. [3]. However, high output power and single-mode operations are desired. In this paper, we demonstrate a high-power thulium-doped laser on a silicon chip, which is fabricated in a 300-mm CMOS foundry. A $Al_2O_3:Tm^{3+}$ thin film is deposited as a gain medium on top of a buried Si_3N_4 rib in SiO_2 that defines a rib waveguide on a silicon substrate. The narrow reflection bandwidth of a distributed feedback (DFB) structure enables a single-mode output. The maximum on-chip lasing power achieved was 267 mW, with a 14% slope efficiency.

II. Design

The DFB laser gain waveguide cross-section is shown in Fig. 1 (a). The inverted rib waveguide is defined by a diluted Si_3N_4 rib consisting of five closely spaced Si_3N_4 bars with 300 nm by 200 nm cross section separated by 350 nm gap embedded in SiO_2 to ensure enough mode confinement within the gain medium. The oxide gap between the Si_3N_4 layer and Al_2O_3 is 100 nm. Fig. 1(b) shows the transverse electric (TE) field intensity of the fundamental mode. The perspective view of the DFB laser is illustrated in Fig. 1(c). The gap between the grating and gain waveguide is designed to be 450 nm, and the grating width is chosen to be 260 nm in order to provide enough feedback at the designed laser wavelength. The cavity length is chosen to be 2 cm to ensure sufficient gain. The effective refractive index (n_{eff}) of the gain waveguide is calculated using a 2D mode solver, considering the grating as perturbations on both sides of the diluted Si_3N_4-rib to provide feedback. The grating period (Λ) can be obtained using the following equation: $\Lambda = \lambda/(2n_{eff})$, where λ is the designed laser wavelength.

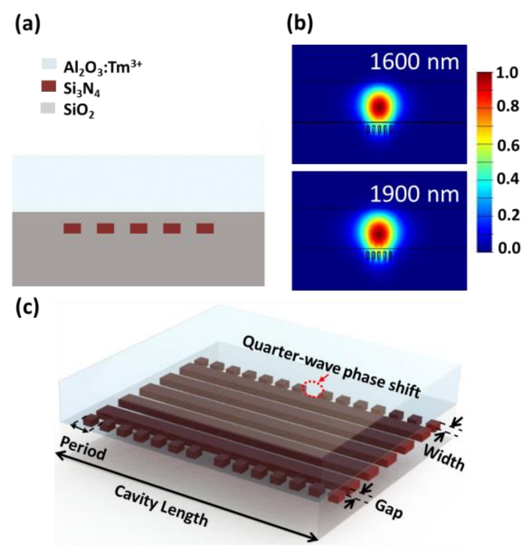

Fig. 1 DFB laser design: (a) The cross-section of the laser gain waveguide with 5 pieces of Si_3N_4. (b) The fundamental transverse electric field intensity for pump (1600 nm) and signal (1900 nm). (c) Perspective view of a DFB laser, showing different layers of material (not to scale).

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III. Characterization

The measurement setup for characterizing the DFB laser is illustrated in Fig. 2(a) below. A high power CW laser source at 1612 nm was used for optical pumping. A polarization controller was used to ensure that the pump light is coupled into the fundamental TE mode of the gain waveguide. A cleaved SMF-28 fiber was used to couple the pump light onto the chip, and another cleaved SM-2000 fiber was used to collect the output signal out of the laser from the chip. The coupling losses for fiber-to-chip and chip-to-fiber were measured to be 7.1 dB and 7.9 dB for SMF-28 and SM-2000 respectively. The output signal goes directly into an optical spectrum analyser to capture the spectrum. The grating period design variations are 581 nm, 587 nm, 594 nm, 601 nm, 608 nm and 625 nm. They are calculated using grating period equation in section II, with corresponding wavelengths at 1820 nm, 1840 nm, 1860 nm, 1880 nm, 1900 nm and 1950 nm respectively. The measured optical spectra of the corresponding laser designs are plotted in Fig. 2(b). Within the broad gain bandwidth of the $Al_2O_3:Tm^{3+}$, we are able to precisely control the laser wavelength by choosing a proper grating period.

Among all the DFB laser design variations, we picked the one that operates near the peak of the thulium emission spectrum for the lasing slope efficiency measurement. The slope efficiency curve is shown in Fig. 3(a). The maximum on-chip laser output power was measured to be 267 mW from single side of the DFB laser. With linear curve fitting, the slope efficiency was found to be 14%, with a laser threshold at 96 mW with pump wavelength at 1612 nm. The peak laser wavelength at 1861 nm with 2W on-chip pump power was recorded by a spectrum analyser, as shown in Fig. 3(b). Single-mode operation was enabled by the narrow bandwidth DFB grating. The side mode suppression ratio was more than 70 dB.

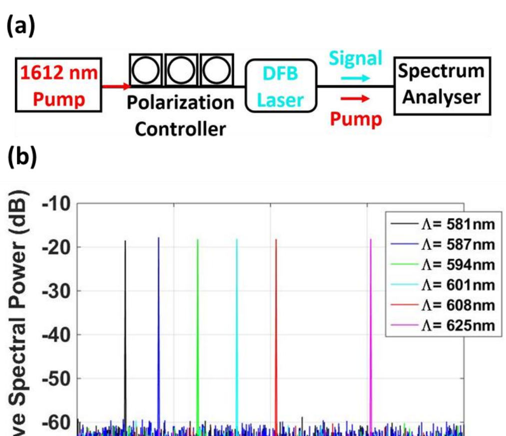

Fig. 2 (a) Measurement Setup: 1612 nm high power pump source, followed by the polarization controller to ensure the fundamental TE mode is coupled into the gain waveguide of the laser. (b) Output spectrum of DFBs with different grating period designs. Designed laser wavelength from left to right: 1820 nm, 1840 nm, 1860 nm, 1880 nm, 1900 nm, and 1950 nm.

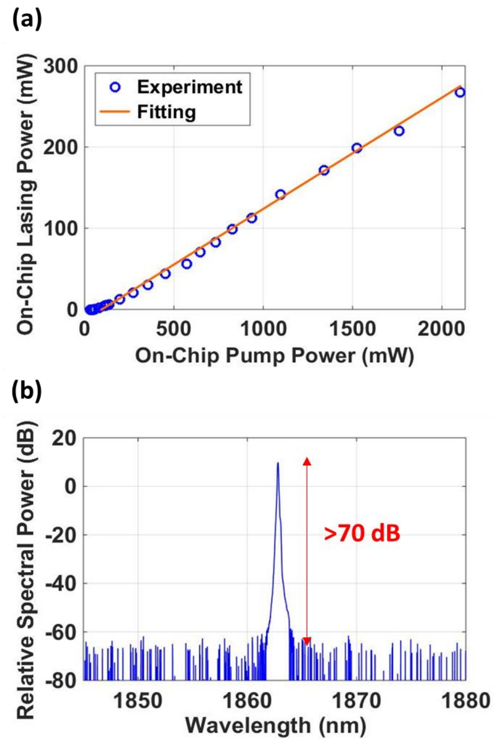

Fig. 3 (a) DFB laser slope efficiency curve: 14% slope efficiency, 267 mW maximum output power and 96 mW lasing threshold. (b) The output spectrum of DFB at 1861 nm with 2W on-chip pump power: side mode suppression ratio >70 dB.

IV. Conclusion

We have demonstrated a CMOS-compatible high-power DFB laser built on a silicon wafer. A diluted Si_3N_4 rib-wavevguide was used for mode confinement in the gain waveguide for both pump and laser modes. Gratings were added on both sides of the diluted Si_3N_4 rib waveguide to provide feedback. Thulium-doped Al_2O_3 glass was used as the gain medium. By varying the grating period, single-mode lasers have been demonstrated within the thulium gain bandwidth. The highest output power of 267 mW under 1612 nm pumping was measured for 1861nm central wavelength with a slope efficiency of 14%, and more than 70 dB side mode suppression.

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