Highly Efficient Distributed Feedback Waveguide Laser in $Al_2O_3:Yb^{3+}$ on Silicon

E. H. Bernhardi, K. Wörhoff, R. M. de Ridder and M. Pollnau
*Integrated Optical MicroSystems Group, MESA+ Institute for Nanotechnology, University of Twente,
P.O. Box 217, 7500 AE Enschede, The Netherlands*

Abstract: An ytterbium-doped aluminum oxide distributed feedback channel waveguide laser is reported. The laser has a 5 mW threshold and emits 34 mW in single-frequency operation at 1022.2 nm wavelength with a slope efficiency of 67%.
OCIS codes: (140.3615) Lasers, ytterbium; (140.3490) Lasers, distributed-feedback; (230.7380) Waveguides, channeled

1. Introduction

Ytterbium-doped waveguides are suitable for realizing compact and highly efficient lasers due to the relatively high absorption and emission cross-sections and high quantum efficiency of ytterbium. Monolithic, ytterbium-doped channel waveguide lasers have been demonstrated in a variety of cavity configurations and materials, which include Fabry-Pérot cavities in YAG [1] and KYW [2], as well as one previous report of a distributed feedback (DFB) cavity which was realized in phosphate glass [3].

Due to its favorable optical properties, rare-earth-ion-doped amorphous aluminum oxide (Al_2O_3) has been recognized as a very promising gain material for a variety of integrated optical structures [4-6]. The relatively high refractive index of 1.65 and the resulting high refractive-index contrast between waveguide and cladding allow for the fabrication of compact integrated optical structures and smaller waveguide cross sections. Al_2O_3 can be deposited on a number of substrates, including thermally oxidized silicon, which allows for integration with existing silicon-on-insulator waveguide technology [7].

Here we present, to the best of our knowledge, the first ytterbium-doped laser in Al_2O_3, which is also the first ytterbium-doped DFB channel waveguide laser on a silicon substrate. Above a threshold of 5 mW, the single-polarization, single-longitudinal-mode emission at a wavelength of 1022.2 nm produced up to 34 mW of output power, which resulted in a slope efficiency of 67% versus launched pump power.

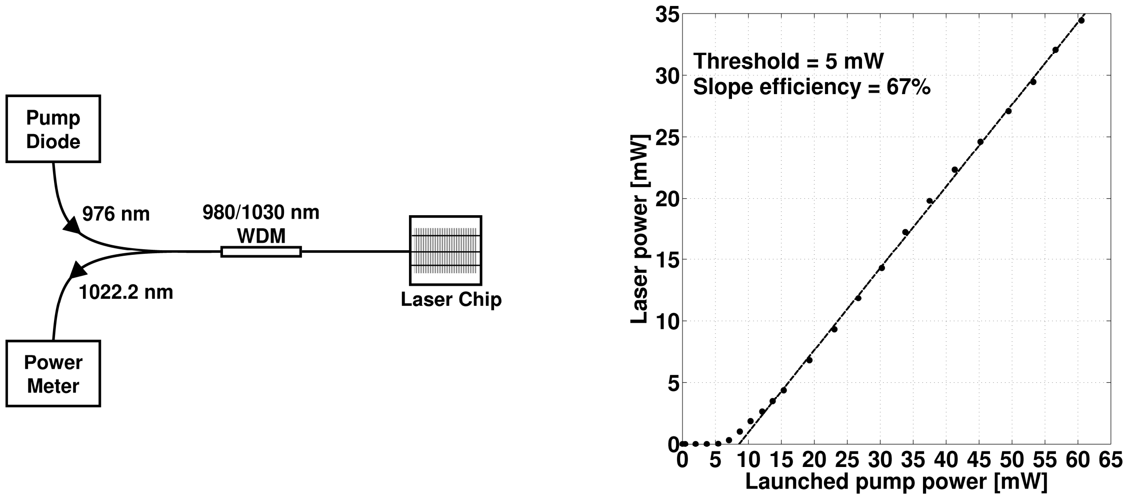
2. Fabrication

Channel waveguides were fabricated in a 1 µm thick $Al_2O_3:Yb^{3+}$ layer with an ytterbium concentration of 5.8×10^{20} cm^{-3}. The waveguide layer was deposited onto an 8 µm thick thermally oxidized standard silicon wafer by means of reactive cosputtering [8]. The single-transverse-mode ridge waveguides were 1 cm long, 2.5 µm wide, and were etched 90 nm deep via standard lithography and a chlorine reactive ion etching process [9]. A 340 nm thick SiO_2 cladding layer was deposited on top of the ridge waveguides using plasma enhanced chemical vapor deposition.

A grating pattern was defined in a negative resist layer on top of the SiO_2 cladding by means of laser interference lithography. The grating was etched 80 nm deep into the SiO_2 using a $CHF_3:O_2$ reactive ion plasma, after which the residual resist was removed by an O_2 plasma. The resultant Bragg gratings have a period of 316 nm and a duty cycle of ~ 50%. In order to ensure single-longitudinal-mode operation, a distributed quarter-wave phase shift was introduced to the cavity by means of a 2 mm long adiabatic tapering of the waveguide width in the central region of the cavity [10,11]. Defining the phase shift in this manner does not require any additional fabrication steps.

3. Characterization

The experimental setup that was used to measure the power characteristics of the laser is shown in Fig. 1a. The laser was optically pumped with a 976 nm laser diode via a 980/1030 nm wavelength division multiplexing (WDM) fiber where a maximum pump power of 61 mW was launched into the waveguide. The measured power characteristics of the laser are shown in Fig. 1b. The laser emission was collected from the pumped side of the cavity via the WDM fiber and sent to a power meter. The DFB laser threshold occurs at a launched pump power of only 5 mW. The low laser threshold as compared to the threshold performance of the previously realized ytterbium-doped DFB laser [3] emphasizes the strong light confinement due to the relatively high refractive index of Al_2O_3 as well as the low losses which are present in this waveguide geometry. The maximum laser power emitted from the pumped side of the cavity is more than 34 mW, which results in a slope efficiency of 67% versus launched pump power. This value of the slope efficiency is, to our knowledge, the highest slope efficiency of any rare-earth-ion-doped DFB laser. No saturation of the output power was observed and further power scaling is only limited by the amount of available pump power.

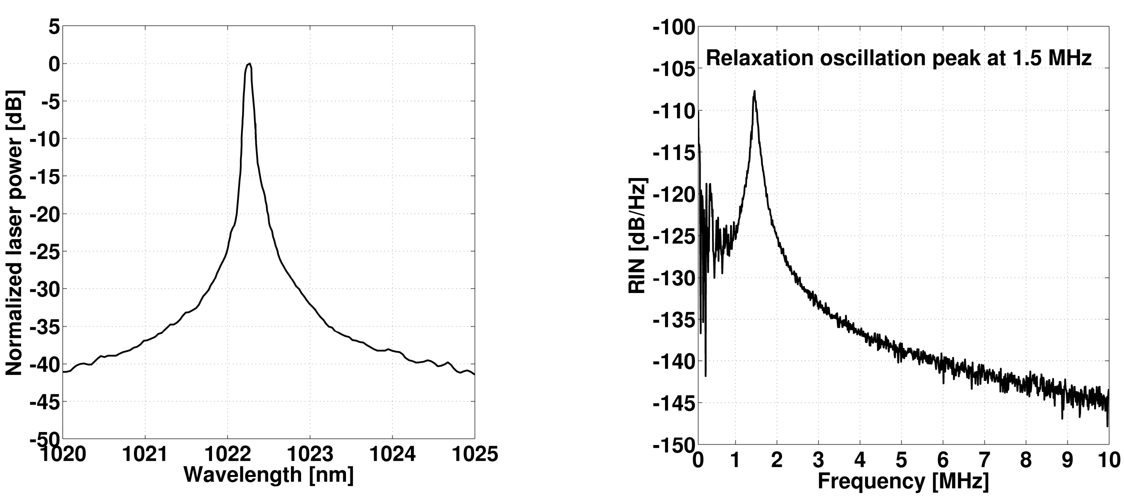


(a) (b)

Fig. 1. (a) Experimental setup for measuring the power characteristics of the laser; (b) output power of the DFB laser as a function of launched pump power.

The emission spectrum of the laser was measured with an optical spectrum analyzer (OSA) which has a resolution of 0.1 nm. The laser operated at a wavelength of 1022.2 nm and exhibits an emission peak with an optical signal-to-noise ratio of more than 40 dB (see Fig. 2a). Although single-longitudinal-mode behavior could be confirmed with this measurement, the measured linewidth was limited by the resolution of the OSA. High-resolution heterodyning linewidth measurements are currently under way. This laser shows more than one order-of-magnitude improvement in output power as compared to our previously demonstrated 1.7-kHz-linewidth erbium-doped channel waveguide DFB laser operating at 1.55 μm [6]. Since the fundamental linewidth is inversely proportional to the laser output power [12], we expect the linewidth to be about one order of magnitude narrower. Since mode calculations and measurements of the previous DFB cavities showed that the grating strength for the TM mode is not sufficiently strong to reach threshold, it was concluded that the laser emission was TE polarized at all times [6].

The relative intensity noise (RIN) of the laser was also investigated (see Fig. 2b). The RIN is dominated by a peak value of -108 dB/Hz at 1.5 MHz, which is the relaxation oscillation frequency of the laser, after which it falls to -145 dB/Hz for frequencies near 10 MHz. This RIN is comparable to that obtained by other rare-earth-ion-doped channel waveguide DFB lasers [13,14].



(a) (b)

Fig. 2. (a) Normalized laser emission spectrum; (b) Measured relative intensity noise spectrum.

4. Summary

The first ytterbium-doped distributed feedback channel waveguide laser in Al_2O_3 was presented. The laser operates in a single longitudinal mode and single polarization (TE) at a wavelength of 1022.2 nm. The laser exhibits a low threshold of 5 mW launched pump power and emits a maximum laser output power of more than 34 mW. This results in a slope efficiency of 67%, which is, to our knowledge, the highest value reported to date for rare-earth-ion-doped DFB lasers. To our knowledge, this is also the first ytterbium-doped DFB laser that is fabricated on a silicon substrate.

5. References

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