Widely Wavelength-selective $Al_2O_3:Er^{3+}$ Ring Laser

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***Abstract*—Integrated $Al_2O_3:Er^{3+}$ channel waveguide ring lasers were realized on thermally oxidized silicon substrates. High pump power coupling into- and low output power coupling from- the ring is achieved in a straightforward design. Wavelength selection in the range 1532 to 1557 nm was demonstrated by varying the length of the output coupler from the ring.**

Keywords—waveguide laser; ring laser; erbium-doped laser; aluminum oxide

I. INTRODUCTION

Er-doped waveguide lasers are of interest for their emission at wavelengths around 1.55 µm in the third telecommunication window. A ring resonator laser offers a simple and straightforward solution with a low number and complexity of processing steps. Previously rare-earth-ion-doped ring lasers have been demonstrated in SiO_2 [1,2] and $LiNbO_3$ hosts [3]. $Al_2O_3:Er^{3+}$ offers several advantages compared with these materials. Compared to silica, it has a larger emission bandwidth, increasing the potential for tunability and generation of ultrashort pulses. In addition, its larger refractive index of ~ 1.65 (as compared to 1.45 in silica) allows for more compact devices and potentially reduces the threshold pump power due to a more tightly confined optical mode. As opposed to lithium niobate, it can be deposited on a number of substrates, including thermally oxidized silicon. This flexibility of deposition allows for monolithic integration of $Al_2O_3:Er^{3+}$ with other common integrated optical materials. Recently optical gain over a large bandwidth of 80 nm has been demonstrated in $Al_2O_3:Er^{3+}$ channel waveguides [4], opening the possibility for a tunable ring laser in this material.

We report on an integrated ring laser in $Al_2O_3:Er^{3+}$. By varying the degree of output coupling several laser wavelengths in the range 1532-1557 nm were demonstrated, exploiting the broad emission spectrum of this material.

II. FABRICATION AND DESIGN

A 500-nm-thick $Al_2O_3:Er^{3+}$ layer was deposited on an 8-µm-thick thermally oxidized 10-cm-wide standard Si wafer by reactive co-sputtering from high-purity metallic targets [5]. The resulting Er concentration was approximately 1×10^{20} cm^{-3}. Subsequently, 1.5-µm-wide channel waveguides were defined in the $Al_2O_3:Er^{3+}$ layer using standard lithography and reactive ion etching [6]. A 5-µm-thick SiO_2 top-cladding layer was deposited by plasma-enhanced chemical vapour deposition and end facets were prepared by dicing. The resulting channel waveguides were single-mode around 1550 nm for both TE and TM polarization and multimode at the 980-nm pump wavelength.

A schematic of the $Al_2O_3:Er^{3+}$ ring laser is shown in Fig. 1. The ring cavity was designed such that a high Q-factor of the ring resonator is obtained when the ring coupler (Coupler 1 in Fig. 1) permits strong coupling. Such a directional coupler exhibits stronger coupling for longer wavelengths, i.e. for the laser wavelength in a Stokes-shifted emitting laser, while coupling at the shorter pump wavelength can be minimized in order to launch a significant part of the pump power into the ring. The coupler lengths were varied from 350 to 600 µm in increments of 50 µm. The resonator length was varied from 2.0 to 5.5 cm.

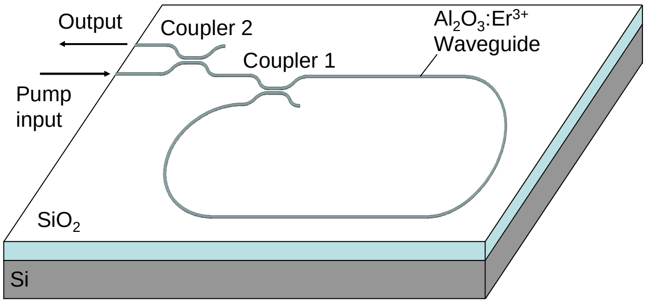

Figure 1. Schematic of $Al_2O_3:Er^{3+}$ ring laser.

A fiber array unit (FAU) was aligned simultaneously to the input and output ports of the chip. Pump light from a 980-nm diode laser was coupled to the chip through one fiber of the FAU. The output signal was collected in a second fiber of the FAU and the optical power and spectral behavior was measured.

III. LASER PERFORMANCE

The laser output power is shown as a function of launched pump power for devices with coupler lengths ranging from 400 to 550 µm in Fig. 2. The coupler length and main lasing wavelength are indicated. The highest slope efficiency of 0.11% was observed in a 5.5-cm-long resonator, with a TE-polarized output power of up to 9.5 µW measured at 19 mW launched pump power. The threshold pump power varied from 6.4 to 15.5 mW. This threshold power is significantly lower than those reported in previous Er-doped ring lasers [1,3].

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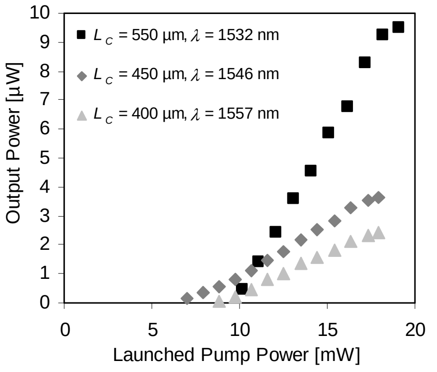

Figure 2. On-chip integrated laser output power vs. pump power launched into the chip for varying output coupler length. The coupler length and main lasing wavelength are indicated.

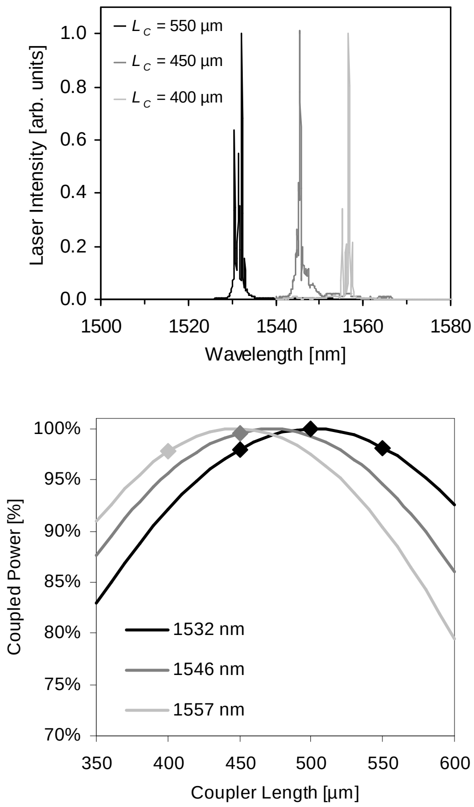

Figure 3. (a) Laser output spectra for coupler lengths L_C of 550, 450, and 400 µm.; (b) simulated coupled power in Coupler 1 vs. coupler length for the observed laser wavelengths and TE polarization. The coupler lengths for which lasing was observed are indicated by the diamonds on the curves.

Laser output spectra for three devices with different wavelengths are shown in Fig. 3a. Because of the long resonator length, which results in a free spectral range of between 0.3 and 0.8 pm, the spectra include many longitudinal modes. The laser selects the wavelength and polarization with lowest threshold power, which is directly affected by the resonator roundtrip losses and the percentage of coupled power at Coupler 1. A greater amount of coupled power results in a lower total roundtrip loss and a lower lasing threshold. Accordingly, in Fig. 3b the predicted percentage of coupled power is shown versus Coupler 1 length for the three observed main laser wavelengths and TE polarized light. At a coupler length of 400 µm a significantly higher percentage of coupled power is predicted at 1557 nm where lasing was observed. When the coupler length is increased to 550 µm, greater coupling is predicted at 1532 nm, and the laser output shifts to this wavelength.

Besides the outcoupling degree, the emission cross section also determines the roundtrip gain. The most common lasing wavelength was close to 1532 nm, at the peak emission cross section of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ Er^{3+} transition [4]. The high gain per unit length at this wavelength makes it more likely that round-trip net gain is achieved in the cavity, and lasing is possible even for a lower degree of coupling at Coupler 1. This effect is apparent for a coupling length of 450 µm (Fig. 3b). Besides the primary laser output around 1546 nm where the predicted coupling efficiency was 99.6%, a second set of laser lines around 1532 nm, where the coupling efficiency was 97.9%, is emitted.

The wavelength variation of the laser output is supported by the broadband gain observed [4]. By adjusting the coupling length of Coupler 1 in a single device, it would be possible to change the lasing wavelength. This concept could be applied to achieve a tunable on-chip ring laser.

IV. CONCLUSIONS

We have demonstrated an $Al_2O_3:Er^{3+}$ laser based on a ring-resonator design which allows strong coupling of pump light into the ring while simultaneously allowing only a small percentage of output coupling at the signal wavelength. Due to the broad gain spectrum in $Al_2O_3:Er^{3+}$, the output wavelength varied between 1532 to 1557 nm, over a large section of the telecom C-band, in devices with different output coupler lengths. Design enhancements will lead to wavelength tunability.

V. REFERENCES

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