CMOS Compatible High Power Erbium Doped Distributed Feedback Lasers

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Abstract: On chip, high power (75mW), erbium-doped distributed feedback lasers are demonstrated in a CMOS compatible fabrication flow. The laser cavities consist of silicon nitride waveguide and grating features defined by wafer-scale immersion lithography and a top erbium-doped aluminum oxide layer deposited as the final step in the fabrication process.

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

1. Introduction

Efficient, low noise and stable on chip lasers are essential for a number of important applications ranging from integrated analog photonics and microwave generation to coherent communications and laser detection and ranging (LADAR). Several methods have been applied to realize integrated lasers, including Germanium-on-Silicon heterojunctions [1], hybrid integration with III-V semiconductor materials [2–4], stimulated Raman scattering [5], and erbium-doped glass on silicon [6,7]. Despite demonstrating high efficiency lasing with electrical pumping, III-V hybrid lasers tend to exhibit broad linewidth and corresponding high phase noise levels due to their limited internal quality factors and large thermo-optic coefficients [8]. Moreover, integration of III-V chips or wafers to silicon is a complicated fabrication process that can lead to low yields. And, while there has been impressive progress in the development of directly integrated germanium on silicon lasers [1], germanium lasers currently exhibit large threshold currents, even lower internal quality factors, and broad spectral linewidth.

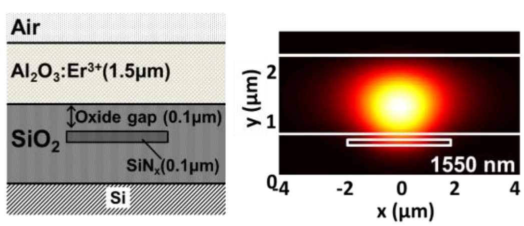

Figure 1. (left) Cross section view of the laser waveguide structure (Right) The calculated electric field distribution at x-axis for fundamental TE mode for the signal/laser wavelength (λ_s = 1550 nm)..

Rare earth (RE) doped glasses, if deposited at the end of a CMOS compatible wafer scale process, offer a versatile, low cost, and reliable alternative, appropriate for low phase noise microwave photonics sources, wavelength division multiplexed (WDM) communications, and sensing and imaging applications. Amongst RE atoms compatible with CMOS processing, erbium (with a quasi-three level system pumped at 1480 nm and lasing in the 1530-1610 nm range [9]) is a perfect candidate for silicon integrated, communication wavelength applications. A variety of glasses can be utilized to host the Er ions. Although the highest reported gain for on-chip devices was achieved in phosphate glass [10], enhanced deposition techniques and control over film stoichiometry make a metal-oxide film more desirable. We chose aluminum oxide due to its reliably low loss, ease of co-sputtering, high refractive index (n=1.65 at 1550 nm), and moderate acceptance of erbium ions without clustering. In order to avoid the necessity of incorporation of Er in the standard CMOS process, an inverted ridge waveguide design is used in which the high resolution patterns including the waveguide ridge and gratings are lithographically defined in a PECVD frontend silicon nitride (SiN). The Al_2O_3:Er glass layer can then be deposited as a backend process step without further etching or processing required (Fig. 1). This approach enables large-scale production of erbium-doped waveguide lasers and integration with silicon nitride passive components on silicon photonic chips.

2. Fabrication

The laser cavities were fabricated within a 300 mm line in a standard CMOS foundry. A 6 μm-thick plasma-enhanced chemical vapor deposition (PECVD) SiO_2 layer was grown, followed by deposition of a 0.1 μm-thick PECVD SiN layer. Both PECVD layers were chemically mechanically polished (CMPed) to reduce losses due to surface roughness. The silicon nitride layer was subsequently annealed at 1050°C for 72 min to reduce absorption due to Si─ H and N─ H bonds around 1.52 μm [11]. The nitride layer was then patterned using 193 nm immersion lithography and reactive ion etching. After patterning, a PECVD SiO2 layer was deposited and CMPed to a final height of 0.1 μm above the silicon nitride layer. 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 Al_2O_3:Er layer was deposited by reactive co-sputtering using a process similar to that reported in [12]. Using the prism coupling method to measure the planar losses around 1550 nm, we determine the background loss and dopant concentration in the Al_2O_3:Er film to be <0.1 dB/cm and 1e20 cm^{-3}, respectively.

3. Laser Design

A series of distributed feedback grating structures with variation in grating strength and cavity length were fabricated. The SiN ridge width was 4 μm; the grating period was 489 nm; and a quarter wavelength phase shift in the center created the cavity. The grating depth variation on each side of the waveguide was δW=100,123,145 nm and the DFB length was varied between 15 to 23 mm. The choice of 1e20 cm^{-3} for Er ion concentration ensures lasing in the cavities with longer photon lifetimes (larger quality factors) without an excess of quenched ion pairs increasing the threshold [13]. The chips were pumped with a 1480 nm wavelength fiber laser using an SM980 (6 μm core diameter) at one edge and the emitted photons are collected from the other edge. The fiber to chip coupling introduced approximately 10 dB loss both for the pump and the emitted signal. DFBs with stronger width modulation (δW=123,145 nm) demonstrated single mode lasing at 1563 nm wavelength while the best slope efficiency of 7 percent was achieved with the strongest cavity design. Figure 2 depicts two sample pump-signal efficiency curves for 145 nm width modulation (κ=300) with two different grating lengths. The longer DFB demonstrates 75 mW of on-chip laser power when pumped with 1.1 W, which is to our knowledge the greatest power achieved on an Al_2O_3:Er laser chip.

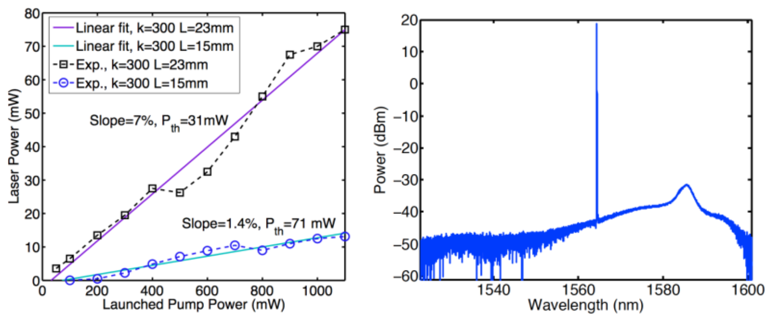

Figure 2. (Left) The laser (1563 nm) power as a function of launched pump power at 1480 nm for two DFBs with the strongest gratings (κ=300). The cavity with the longer grating shows higher slope efficiency and a lower threshold. (Right) Single mode emission from the DFB with more than 60 dB suppression of the amplified spontaneous emission (ASE).

3. Laser Stability

Laser output intensity fluctuation is a well-known phenomenon in highly doped RE based fiber lasers and is usually attributed to a combination of self pulsating due to fast decaying ion pairs [14] and resonant amplification of pump noise at relaxation frequency [15]. Several methods proposed for spiking suppression, such as secondary pumping [16], semiconductor amplification [17], or very long cavity lifetime filtering [18] are not applicable to on chip, waveguide based devices. Our rate equation model based on a small percentage of very fast quenched ions (spontaneous emission lifetime τ=1 μs as opposed to 7.5 ms for unquenched ions [13]) predicts more stable operation when the laser is excited with a more intense pump. As shown in Fig. 3(a), the measured laser output stability has a strong dependence on pump power. When pumped slightly above threshold (P=300 mW) the laser with κ=300 and L=15 mm demonstrated nearly full-scale pulsing with a frequency of 822 kHz. As the pump intensity was increased the oscillation frequency increased and pulsing behavior was suppressed. Figure 3 also shows the intensity of the laser monitored for 0.5 ms at different pump levels. The low pumping case demonstrates sustained pulsing while the highest pump provides a more stable output.

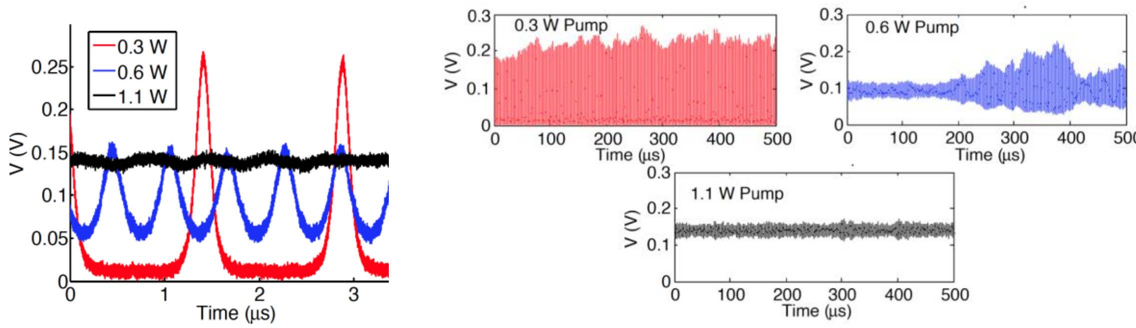

Figure 3. The effect of pump rate on intensity fluctuations of the laser output power. (Left) Self-pulsing behavior is suppressed when the launched pump power is increased from 0.3 W (red) to 1.1 W (black). (Right) Laser intensity fluctuation monitored for a 0.5 ms. Low pumped case (red) demonstrates sustained self-pulsing behavior while moderately pumped laser (blue) is susceptible to instabilities. The highest pumping setting (black) is stable for a longer period.

4. Conclusion

In this work we demonstrated high power, stable, CMOS compatible Er doped distributed feedback lasers with highest reported on chip power in Al_2O_3 material system. Pumping at 1480 nm wavelength leads to a 7% slope efficiency for the highest Q cavities and 75 mW of on chip lasing power at 1563 nm. Highly doped material is susceptible to intensity fluctuations at lower pump powers but the laser achieves stable operation when pumped with 1.1 W pump power. Longer cavity lifetimes, higher photon density, and elimination of resonant noise from the pump can lead to even more stable laser operation in future. This work was funded by 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.

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