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Monolithically integrated erbium-doped tunable laser on a CMOS-compatible silicon photonics platform

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Abstract: A tunable laser source is a crucial photonic component for many applications, such as spectroscopic measurements, wavelength division multiplexing (WDM), frequency-modulated light detection and ranging (LIDAR), and optical coherence tomography (OCT). In this article, we demonstrate the first monolithically integrated erbium-doped tunable laser on a complementary-metal-oxide-semiconductor (CMOS)-compatible silicon photonics platform. Erbium-doped Al2O3 sputtered on top is used as a gain medium to achieve lasing. The laser achieves a tunability from 1527 nm to 1573 nm, with a >40 dB side mode suppression ratio (SMSR). The wide tuning range (46 nm) is realized with a Vernier cavity, formed by two Si3N4 microring resonators. With 107 mW on-chip 980 nm pump power, up to 1.6 mW output lasing power is obtained with a 2.2% slope efficiency. The maximum output power is limited by pump power. Fine tuning of the laser wavelength is demonstrated by using the gain cavity phase shifter. Signal response times are measured to be around 200 µs and 35 µs for the heaters used to tune the Vernier rings and gain cavity longitudinal mode, respectively. The linewidth of the laser is 340 kHz, measured via a self-delay heterodyne detection method. Furthermore, the laser signal is stabilized by continuous locking to a modelocked laser (MLL) over 4900 seconds with a measured peak-to-peak frequency deviation below 10 Hz.

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Silicon photonics is a promising technology for integrated optical circuits [1–3]. The high refractive index contrast between silicon and a silicon dioxide cladding enables compact devices. The compatibility with mature complementary-metal-oxide-semiconductor (CMOS) fabrication technology can lead to low-cost and high-volume production of silicon photonics devices. Silicon photonics technology has enabled production of large-scale phased array devices [4, 5], ultralow-power and high-speed modulators [6, 7], band-pass filters [8, 9], supercontinuum generation [10, 11], as well as nonlinear optical data conversion [12–15]. In an integrated photonic circuit, a tunable laser source is a key component for a variety of applications, including spectroscopic measurements [16, 17], wavelength division multiplexing (WDM) [18, 19], frequency-modulated light detection & ranging (LIDAR) [20], optical coherence tomography (OCT) [21, 22], and grating-based beam steering [23]. Wide tunability is commonly obtained utilizing a Vernier effect based on two cavities with different free-spectral ranges (FSRs) [24–26]. The Vernier effect has been shown using Bragg grating reflectors or ring resonators [24–28], with ring resonators being commonly used for wide wavelength tuning purposes.

Compared to lasers using III-V semiconductor gain media, lasers based on erbium-doped gain media have a wide gain bandwidth across the C and L bands. Such wide emission spectrum enables a wide tuning range of the laser wavelength [29–31] as well as potential for mode-locking [31–34]. Additionally, erbium-doped lasers can achieve a narrow linewidth with large side mode suppression ratios (SMSRs) due to homogeneously-broadened gain [35, 36]. Since erbium can be co-sputtered with a host (e.g. silica, alumina or phosphate glass) [37–39], integration into a CMOS-compatible silicon photonics platform is straightforward as a back-end step. Monolithically integrated erbium-doped waveguide lasers have been
demonstrated with both continuous-wave and pulsed lasing using erbium co-sputtered with Al2O3 as a host [33, 40–45]. The low thermo-optic coefficient of Al2O3 enables robust operation of the laser over a wide temperature range [46, 47], important for control-free WDM systems [48]. However, previously demonstrated lasers could not be actively tuned. Lasers using erbium-doped fiber as gain media with integrated silicon microdisk cavities have been demonstrated with passive [49] and active [50, 51] wavelength tuning. However, these demonstrations were mostly fiber based and not fully integrated on-chip.

In this article, we present the first tunable monolithically integrated erbium-doped laser on a CMOS-compatible silicon photonics platform. Wavelength tunability is achieved by utilizing a Vernier structure, which is formed by two Si3N4 microring resonators. Erbium-doped Al2O3 is deposited as a back-end step and used as the gain medium, and metal layers for thermal tuning are deposited as heaters and contacts. Wavelength tuning over 46 nm (from 1527 to 1573 nm) with more than 40 dB SMSR is achieved. With 107 mW on-chip 980 nm pump power, up to 1.6 mW output lasing power is obtained with a 2.2% slope efficiency. The fine-tuning capability of the lasing wavelength is demonstrated by tuning a separate heater in the gain cavity that shifts the longitudinal cavity modes. The signal/heater response time is measured to be around 200 µs and 35 µs for coarse and fine tuning, respectively. In addition, the laser linewidth is measured to be 340 kHz by using a self-delay heterodyne method. Furthermore, the laser signal is stabilized by continuous locking to a mode-locked laser (MLL) over 4900 seconds. The peak-to-peak frequency deviation of the signal remains below 10 Hz during the measurement period. The system with stabilized tunable optical frequency can be further developed as an optical frequency synthesizer.

2. Integrated tunable laser design

A schematic perspective view of the tunable laser design is shown in Fig. 1(a), which includes all the layers used in the silicon photonics platform. It has a compact footprint of 0.23 cm2 (1 mm × 2.3 cm). Figure 1(a) includes the zoom-in view of the wavelength tuning components, which consists of two microring filters in a Vernier configuration and a gain-cavity longitudinal-mode phase shifter with metal heater layer on top. The rings are made of 200 nm thick and 1.6 µm wide Si3N4 with a radius of 100 µm and 104.6 µm, thereby giving a free spectral range (FSR) of 2.23 nm and 2.13 nm respectively. In a Vernier configuration, this gives a combined FSR of 50 nm for wide tuning within the erbium gain bandwidth. The coupling gap is designed to be 563 nm, resulting in 8.75% calculated power coupling for the signal wavelength while no 980 nm pump light couples. This is due to the large confinement of the pump in the Si3N4 bus waveguide, thereby obtaining a low-loss pump/signal combiner inside the laser cavity. Power coupling more than 8.75% leads to a wider bandwidth for each resonance of the microrings, and hence side mode extinction will be lower for the laser. In contrast, power coupling lower than the optimized value leads to more energy trapped in microring, and, hence, the intrinsic loss of the ring will dominate. Therefore, the 8.75% power coupling is chosen to balance between the side-mode extinction and intrinsic loss of the ring during the laser design.

The length of each gain-cavity longitudinal-mode phase shifter is 500 µm and a 2π phase shift can be readily achieved with about 200 mW electrical power applied on it. Both the gain cavity phase shifters and rings can be thermally tuned separately using a TiN/Al alloy metal layer above the waveguide. The heater layer has a width of 5 µm, and is located 2 µm above the Si3N4 layer to ensure optical isolation. The resistivity of the heater metal alloy is designed to be 15 Ω/sq. The heater layer is connected to the contact pads through vias. Both contact pads and vias form the M1 layer, which is made of a low resistance TiN/Al alloy for electrical routing.

The optical mode in the Si3N4 layer is coupled to the laser gain waveguide through an adiabatic transition. The transition loss is measured to be 0.3 dB/transition. The gain waveguide is formed by a 1.1 µm thick Al2O3:Er3+ film deposited within a 4 µm deep and 5
µm wide trench. The green color fluorescence due to the up-conversion in Er\textsuperscript{3+} under 980 nm pump is shown in Fig. 1(b). The electrical probe is in contact with the fabricated device for thermal tuning. Figure 1(c) shows a scanning electron microscopy (SEM) image of the gain waveguide cross-section. The depth of the trench is accurately controlled using the top Si\textsubscript{3}N\textsubscript{4} layer as an etch stop, as illustrated in Fig. 1(c). For the gain waveguide, the mode confinement factor within the Al\textsubscript{2}O\textsubscript{3}:Er\textsuperscript{3+} layer for the pump (980 nm) and signal (1550 nm) fundamental TE modes are calculated to be 90% and 80% respectively using a 2-D mode solver. The refractive indices used in the mode calculation are listed in Fig. 1(d). The gain waveguide is bent to allow for a >4 cm long waveguide to provide sufficient gain. Figure 1(e) shows the mode profile at the signal wavelength for several bending radii. The large bend mode mismatch between these modes is resolved by using an adiabatic Euler bend [52] which is simulated to be lossless with a minimum bending radius of 200 µm. From cutback test measurements, the Euler bend loss is estimated to be 0.6 dB per 180 degree bend.

The simulated response of two combined Si\textsubscript{3}N\textsubscript{4} rings is shown in Fig. 2(a), which provides an FSR of 50 nm. Figure 2(b) shows the simulation results of the combined ring filter response together with the laser cavity response. The simulated laser cavity longitudinal-mode spacing is 2.5 GHz, for a round trip cavity length of 4.6 cm. The selected lasing mode has 1.8 dB selectivity over the closest side mode.

Fig. 1. (a) 3D illustration of an integrated tunable laser, showing different material layers, heaters for microring and gain cavity phase shifters (not to scale), (b) Fabricated device on the test setup, showing Erbium green color fluorescence under 980 nm pump, (c) SEM image of the tunable laser gain waveguide cross section, (d) Refractive indices of the waveguide materials at both pump and signal wavelengths, (e) The transverse electric (TE) field intensity of the fundamental mode at the signal wavelength for different bend radii along the Euler bend.
The device is fabricated on a 300 nm silicon wafer with a 6 µm buried oxide. The fabrication process of the Si₃N₄ layer and laser trench is the same as previously reported [53–56]. An 1100-nm-thick Al₂O₃:Er³⁺ thin film is deposited via reactive co-sputtering. The deposition of Al₂O₃:Er³⁺ film is a single-step back-end-of-line process on the silicon wafer, allowing direct access to the laser design [57]. More details on this reactive co-sputtering process can be found in [57, 58]. The substrate temperature during deposition is measured to be 380 °C. The background loss of Al₂O₃:Er³⁺ film is measured to be <0.1 dB/cm. Deposition runs with different doping levels reveal an optimum Er³⁺ doping concentration of 1.5 × 10²⁰ cm⁻³, which is measured through Rutherford backscattering spectrometry (RBS) analysis. Given the same pump power, a lower doping concentration will suffer from lower gain while a higher concentration will result in lasing power degradation due to ion clustering and quenching [59, 60].

3. Wavelength tuning and slope efficiency

First, to find out the potential wavelength tuning range of the integrated laser, we obtain the spontaneous emission spectra of erbium-doped Al₂O₃ films, which emit near 1.55 µm (C-band). We deposit an Al₂O₃:Er³⁺ film on top of the SiO₂ layer. A low power pump at 980 nm (the Er³⁺ absorption peak) is used to generate spontaneous emission in the Al₂O₃:Er³⁺ film. The resulting spectrum recorded by an optical spectrum analyzer is shown in Fig. 3(a). It shows that the emission range is from 1524 nm up to 1574 nm, with a 3-dB bandwidth of 50 nm.

Next, to demonstrate the wide tuning capability of the tunable laser device within this emission range, both ring heaters are tuned using DC voltages. Lasing wavelength tuning from 1527 nm to 1573 nm is shown in Fig. 3(b), with relatively uniform output power (<1.5 dB difference) and more than 40 dB SMSR. Lasing at 1525 nm is also observed, but with less than 40 dB SMSR due to diminished gain of the erbium ions. Figure 3(c) shows the laser cavity resonance wavelength tuning by heating the two microrings simultaneously. For a given heating power P2 on ring 2, as the power P1 increases, the ring 1 resonance shifts, and, hence, the laser cavity resonance wavelength jumps to the next ring interference for two ring resonance peak matching. For a specific lasing wavelength setting, the heating power of both rings should be adjusted so that the ring 1 resonance peak matches with one of the ring 2 resonance peaks at the desired wavelength.

Laser devices with two different gain waveguide lengths (4.2 cm and 8.4 cm) are fabricated. The device with an 8.4 cm long gain waveguide is chosen for the following efficiency and power measurements as it gives relatively better performance due to the
increased gain. The laser power efficiency curve as a function of pump power at 1561 nm is shown in Fig. 3(d). The pump input port and lasing signal output port are marked in the laser schematic as shown in Fig. 1(a). Lasing power up to 1.6 mW is collected from the on-chip output port when 107 mW of on-chip pump power at 980 nm is used. A slope efficiency of 2.2% with respect to on-chip pump power at 980 nm is obtained.

4. Fine tuning demonstration

To characterize the fine-tuning capability of the erbium integrated tunable laser, a reference laser (Agilent 81600B) at a fixed wavelength is used to beat with the tunable laser through an optical combiner, as shown in Fig. 4(a). The beat signal is detected by a photodetector (PD) (EOT ET-3500F) and recorded by an electrical signal analyzer (ESA) (Advantest U3741). The gain cavity phase shifter, as shown in Fig. 1(a), is used for the fine tuning, as the FSR of the cavity (~2.5 GHz, for a round trip cavity length of 4.6 cm including the 4.2 cm gain waveguide) is much smaller than the FSR of the Si$_3$N$_4$ ring (~250 GHz). The beat frequency under different electrical powers supplied to the gain cavity phase shifter are shown in Fig. 4(b). As we increase the electrical power, the beat signal shifts continuously to higher frequencies, without mode hopping. Figure 4(b) shows the fine tuning over 2.5 GHz, with up to 170 mW electrical power delivery. The tuning efficiency can be obtained as 14 MHz/mW by fitting the data points to a linear curve.

Fig. 3. (a) Wide C-band spontaneous emission of Al$_2$O$_3$:Er$^{3+}$ film covering from 1524 nm to 1574 nm, pumped by a low power 980 nm pump source. (b) Laser output spectra showing 46 nm tuning range from 1527 nm to 1573 nm, with >40 dB SMSR. (c) Laser cavity resonance wavelength tuning for different heating powers applied on the heaters for both ring 1 and ring 2. (d) On-chip laser output power with respect to launched on-chip pump power, showing 2.2% slope efficiency and 1.6 mW maximum signal power achieved.
5. Signal time domain stability and response time measurement

The time domain of the laser signal is detected by a PD and monitored by an oscilloscope, as illustrated in Fig. 5(a). Strong dependence of time domain stability on pump power is observed. Under the condition that pump power is slightly above lasing threshold, the tunable laser device demonstrates self-pulsing behavior with a frequency of 0.125 MHz, as shown by the red curve in Fig. 5(a). This can be explained by the ion-pair formation in the gain medium [61, 62]. As the pump power is increased to beyond lasing threshold (>2 times higher than threshold), the relaxation oscillation frequency is increased and the pulsing behavior is suppressed, as shown by the green curve in Fig. 5(a). This is due to the fact that higher pump power causes population inversion and gain to be replenished rapidly [62, 63]. Small output fluctuations may be contributed by the noise from the PD, pump diode, and mechanical vibration of the fiber.

The time constant is measured with a 50% duty cycle square wave modulating the heaters for the microring and the gain cavity phase shifter. These two heaters are used for coarse tuning and fine tuning of the laser signal, as demonstrated in the previous two sections. The electrical resistance of the heaters for the microring and gain cavity phase shifter are measured to be 240 Ω and 25 Ω, respectively. The differences in resistivity are contributed by different heater lengths and wirings. The laser output power is detected by an external photodetector. The time response of the modulation is captured by an oscilloscope, as illustrated in Fig. 5(b) and 5(c). Figure 5(b) shows the response of the laser as one microring is modulated by a square wave signal with 200 Hz frequency. The rising curve and falling curve are fitted with an exponential function. The rise and fall times obtained are 200 μs and 230 μs, respectively. Figure 5(c) shows the response of the laser signal as the gain cavity phase shifter is modulated by a square wave signal with a 2.5 kHz frequency. After curve fitting, the rise and fall times obtained are 32 μs and 37 μs, respectively. Compared to the microring heater, the heater for the gain cavity phase shifter has a different response time due to the differences in thermal conductivity of the components. Furthermore, time-domain instability issues due to self-pulsing are not observed as the pump power is more than 2 times higher than the lasing threshold of the device.
In order to measure the linewidth of the integrated tunable laser, a delayed self-heterodyne detection method [64] is used. The setup is shown in Fig. 6(a). The laser signal at 1560.09 nm (after aligning the resonances of two SiN$_4$ rings as well as the gain cavity phase shifter) is split into two by a 3dB coupler. One signal goes through polarization controller 1 (PC1), and the other signal goes through a delay line. Here, the delay line is constructed in a circulating loop with an 80/20 splitter. An acousto-optic modulator (AOM) provides a frequency shift of 44 MHz. Since the erbium integrated laser has narrow linewidth, a fiber delay of 10 km is used. As the circulation number N increases, the total delay length increases. This circulating structure ensures that there are higher order harmonics of the 44 MHz beat note, which are incoherent with the signal propagating through PC1 after a sufficient number of roundtrips. As the circulating number N increases, the signal-to-noise-ratio (SNR) in the loop decreases. Hence, an erbium-doped fiber amplifier (EDFA) is used to compensate the loss of the circulating loop and maintain the SNR. A tunable filter (3-dB bandwidth of 1 nm) is tuned to the signal wavelength to suppress the amplified spontaneous emission of the EDFA. Beat signals are detected by an ESA. A stable and narrow linewidth of 340 kHz is observed with no coherence artifacts after an effective delay length of 400 km (400 km/10 km = 40th harmonic) for the tunable laser device with a 4.6 cm round-trip cavity length. The 40th harmonic at f = 40 × 44 MHz = 1.76 GHz and its Lorentzian fitting is shown in Fig. 6(b). The 340 kHz laser linewidth corresponds to a coherence length of 0.6 km, which is significantly shorter than the total 400 km fiber delay length. This verifies that the delay length used here is long enough to ensure incoherence. This is also verified by the absence of sidelobes in the ESA spectrum.
7. Laser frequency stabilization

In order to stabilize the signal frequency of the laser device for further applications (e.g., optical frequency synthesis), the laser signal is locked to one of the frequency comb lines generated by a commercial mode-locked laser (MLL, Menlo systems). The frequency locking setup is shown in Fig. 7(a) below. The signal from the integrated tunable laser (TL) is beat with the comb signal from the MLL through the balanced-photodetector (BPD). The beat signal is then filtered by a bandpass filter (BPF) with a 3-dB bandwidth of 40 MHz centered at 200 MHz. After division by 16 using a frequency divider, the signal-to-noise-ratio (SNR)-enhanced signal is compared with another RF synthesizer reference by a phase detector. The phase detector output serves as the error signal of a proportional-integral (PI) controller, which can lock the tunable laser frequency to the comb line of the MLL by generating the feedback signal to tune the gain-cavity longitudinal-mode phase shifter heater of the tunable laser. To evaluate the locking performance, the beat note is divided by 32 and then measured by a frequency counter. Both the RF synthesizer and frequency counter are referenced to the same 10 MHz clock, which ensures that the measurement results indicate the locking instability itself. The tunable laser is continuously locked to the MLL over 4900 seconds with a peak-to-peak frequency deviation below 10 Hz, as shown in Fig. 7(b). During this measurement time, the frequency instability (Allan deviation [65]) relative to the optical frequency at 1560 nm (Fig. 7(c)) is below $10^{-16}$ at 1 s and approaching $10^{-16}$ after 1000 s. The frequency instability can be further improved by introducing field-programmable gate array (FPGA)-based feedback with a much narrower bandwidth BPF. This system with a stabilized tunable optical frequency output can be further developed as an optical frequency synthesizer [66] or integrated with phased array for beam steering and LIDAR application [5].
Fig. 7. (a) Laser-to-comb locking setup, including an integrated tunable laser (TL), mode-locked laser (MLL), balanced photodetector (BPD), and band pass filter (BPF). (b) Frequency deviation relative to reference signal, showing a maximum frequency deviation of 10 Hz during the 4900 s measurement time. (c) Frequency instability of the locking after calculation based on Allan deviation algorithm.

8. Conclusion

In conclusion, we have demonstrated the first monolithically integrated erbium-doped tunable laser on a CMOS-compatible silicon photonics platform. Two Si3N4 microring resonators are used to form a Vernier cavity for wide-spectrum wavelength tuning, achieved with metal layers deposited for thermal tuning. Erbium-doped Al2O3 is deposited as a back-end step and used as a gain medium for lasing. The tuning range demonstrated is from 1527 nm to 1573 nm, covering the full C band and more. Within the 46 nm tuning range, a uniform lasing peak with >40 dB SMSR is achieved. With 107 mW on-chip 980 nm pump power, up to 1.6 mW output lasing power is obtained with a 2.2% slope efficiency. Fine tuning of the wavelength is demonstrated by tuning the gain cavity phase shifter. The laser signal response times are measured to be around 200 μs and 35 μs for coarse and fine tuning, respectively. The laser linewidth is measured to be 340 kHz via a delay self-heterodyne detection method. In addition, the laser signal is stabilized by continuous locking to a MLL over 4900 seconds and the peak-to-peak frequency deviation during this measurement period is below 10 Hz. This system with a stabilized tunable optical frequency output can be further developed as an optical frequency synthesizer.

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