Narrow Linewidth, Widely Tunable Integrated Lasers from Visible to Near-IR

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Principal Investigator(s): Michal Lipson

User(s): Xingchen Ji, Mateus Corato-Zanarella

Affiliation(s): Department of Electrical Engineering, Columbia University, New York City, NY 10027

Primary Source(s) of Research Funding: Defense Advanced Research Projects Agency

Contact(s): ml3745@columbia.edu, xj53@cornell.edu

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Abstract:

We demonstrate a chip-scale platform for narrow-linewidth lasers, tunable across the whole spectrum from blue to near-IR. We show powers up to 10 mW, intrinsic linewidth less than 8 kHz, tuning up to 12 nm and high side-mode suppression ratio up to 38 dB.

Summary of Research:

Integrated photonics platforms for light sources in the visible range are promising for applications including trapping, quantum photonics [1], biosensors [2], and spectroscopy. To date, narrow linewidth, tunable visible sources either rely on bulky external free-space cavities and components [3] or are limited to the long wavelength portion of the spectrum (red) and have large footprint [4].

Here, we demonstrate a chip-scale laser platform designed for lasing with narrow linewidth and tunability over a large spectral range covering the whole visible spectrum up to near-IR. We design the platform to be based on high confinement, high quality factor (Q) silicon nitride (Si_3N_4) resonators and commercially available Fabry-Perot (FP) laser diodes. We leverage the large transparency window of Si_3N_4 for high confinement low-loss light propagation at visible wavelengths and commercial FP laser diodes for robust self-injection locking [5]. We show that by coupling laser diodes to a low-loss ring resonator with an optical feedback path, self-injection locking causes the collapse of the multiple longitudinal modes of the diode into a single longitudinal mode, with further linewidth reduction induced by the high Q of the resonator. We achieve lasing at different wavelengths by tuning the resonator's resonance to align to different longitudinal modes of the laser.

We design our photonic components to operate over the whole visible to near-IR spectral range using a platform of 175 nm-thick Si_3N_4 waveguide core surrounded by silicon oxide (Figure 1a). We design a ring resonator with tapered dimensions from 300 nm to 1500 nm to ensure near-single mode operation and good coupling for all the wavelengths while maintaining high Q (Figure 1b) [6]. We leverage the high confinement to design the ring with small radius (10 μm). The resulting large free-spectral range (FSR) of several nm across the whole visible range allows the feedback of a specific wavelength within the gain bandwidth of the laser diodes without the need for a Vernier filter [4]. Such a frequency-selective feedback over a large range eliminates mode-hopping between longitudinal modes of the laser diodes when they are self-injection locked by our resonator. The feedback wavelength can be continuously tuned within the FSR by tuning the resonator. We optimize the feedback loop at the drop port for broad bandwidth, leveraging that the self-injection locking of FP laser diodes is robust to the amount of reflection [5]. We design inverse taper edge couplers to provide good laser-to-chip and chip-to-fiber coupling without inducing spurious reflections.

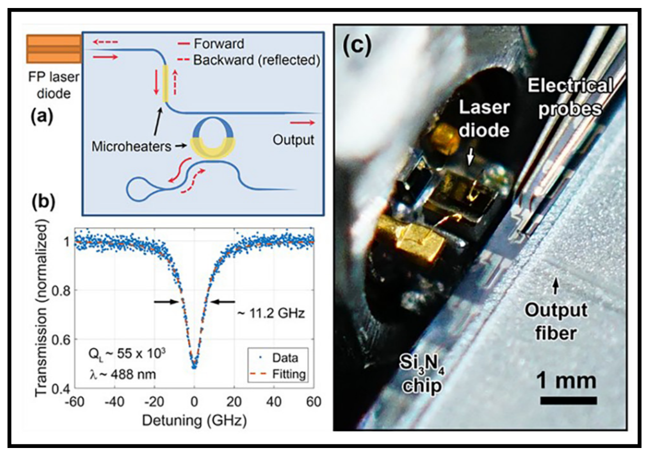

Figure 1: (a) Schematic of the integrated laser. An FP laser diode is butt-coupled to the chip, where a ring resonator with a feedback loop at the drop port acts as a wavelength selective reflector. (b) Ring resonance in blue measured with a Toptica DL Pro 488 nm laser. The loaded quality factor is ~ 5.5 × 10^4 and the extinction is ~ 50%. (c) Image of the laser setup.

We achieve broadband, narrow linewidth, tunable lasing by butt-coupling commercial FP laser diodes to our chip and controlling the position of the ring resonator's resonance using thermo-optic phase shifters (Figure 1c). We tune the lasing wavelength by tuning the resonator to different longitudinal modes of the laser diodes. When the resonator is detuned from the modes of the laser, the power dropped to the feedback loop is negligible and the laser diode lases with multiple longitudinal modes (Figure 2a). When we align the resonator to a mode of the laser, power is dropped to the feedback loop and then reflected back to the diode. We adjust the phase of the reflected light to cause the self-injection locking by using the phase-shifter on the bus waveguide in between the diode and the resonator. When the laser is locked, the longitudinal modes of the laser diode collapse into a single one (Figure 2b).

We show narrow linewidth, tunable integrated lasers covering blue (~492 nm), green (~522 nm), red (~660 nm) and near-IR (~785 nm) wavelengths with output fiber-coupled powers up to 10 mW, intrinsic linewidth < 8 kHz, wavelength tuning up to 12 nm and side-mode suppression ratios (SMSR) up to ~38 dB. We achieve coarse tuning ranges/SMSRs of ~3.21 nm/~30 dB in blue, ~3.2 nm/~30 dB in green, ~3.7 nm/~37 dB in red, and ~12 nm/~38 dB in near-IR (Figure 3).

We measure the intrinsic linewidths at the two extremes of the spectrum, blue and near-IR, and obtain (8 ± 2) kHz and (601 ± 227) Hz respectively, both limited by our instruments. We determine the linewidth in blue by measuring the RF beat note between our integrated laser and a commercial narrow-linewidth laser using a spectrum analyzer. The beat note represents the lineshape of our integrated laser, limited by the lineshape of the commercial laser. By fitting the beat note with a Voigt profile, we extract the Lorentzian contribution, which corresponds to the white noise that defines the intrinsic linewidth, and the Gaussian contribution, which corresponds to the flicker and technical noises that broaden the effective linewidth. The Voigt fitting of the lineshape (see Figure 4a) gives an intrinsic (Lorentzian) linewidth of (8 ± 2) kilohertz and a Gaussian linewidth of (250 ± 20) kilohertz. We measured the lineshape and frequency noise of our integrated near-IR laser with a linewidth analyzer. The Voigt fittings of the lineshapes (see Figure 4b) for different measurements give an intrinsic linewidth of (601 ± 227) hertz, limited by the linewidth analyzer sensitivity.

Our results show that chip-scale visible lasers can exhibit key specifications such as linewidth, tuning range, power, and SMSR comparable to bulky commercial laser systems. We envision our platform to be a key enabler for fully integrated visible light systems in applications including quantum photonics, trapping, AR/VR, biosensing, atomic clocks, and spectroscopy.

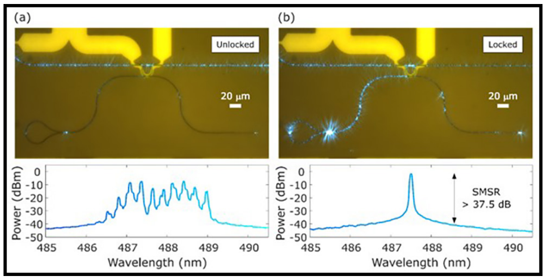

Figure 2: Microscope images of the ring resonator-based feedback loop and optical spectra of the chip output before and after self-injection locking. (a) Ring resonance is detuned from the Fabry-Perot (FP) laser diode modes, so no light is in the feedback loop (top). The chip output resembles the usual output of the FP laser with multiple lasing modes. (b) Ring resonance is tuned to one of the FP modes, so the feedback loop reflects part of the light back to the diode. Self-injection locking causes all the longitudinal modes to collapse into a single frequency, narrow linewidth lasing mode with high (> 37.5 dB) side mode suppression ratio (SMSR). The optical spectra are measured with an optical spectrum analyzer (Ando AQ6314A).

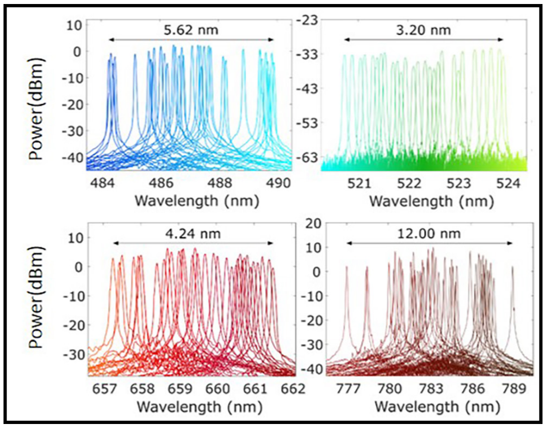

Figure 3: Coarse tuning ranges at blue, green, red and near-IR. The optical spectra are measured with an optical spectrum analyzer (Ando AQ6314A) and overlaid to show the tuning.

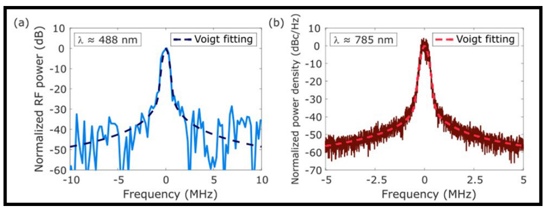

Figure 4: Linewidth characteristics of the blue and near-IR integrated lasers. RF beat note between our integrated blue laser and a commercial narrow-linewidth blue laser (Toptica DL Pro 488 nm). The beat note represents the lineshape of our integrated laser, limited by the lineshape of the commercial laser. By fitting the beat note with a Voigt profile, we extract the Lorentzian contribution, which corresponds to the white noise that defines the intrinsic linewidth, and the Gaussian contribution, which corresponds to the flicker and technical noises that broaden the effective linewidth. The Voigt fitting results in an intrinsic (Lorentzian) 8±2 kHz linewidth and Gaussian linewidth of 250±20 kHz.

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