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# Versatile Chip-Scale Lasers : Bridging Near-Ultraviolet to Near-Infrared Spectra

**Amit Kumar Kolhe[1], Dr. Sunil Kumar[2]**
[1]Research Scholar, Kalinga University, Naya Raipur, Chhattisgarh, India
[2]Professor, Department of Electrical Engineering, Kalinga University, Naya Raipur, Chhattisgarh, India

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ABSTRACT

Narrow-linewidth lasers that are widely tunable in the visible spectrum are crucial for various applications such as quantum optics, optical clocks, and atomic and molecular physics. However, current laser systems are typically bulky and confined to laboratory settings, limiting their practical use beyond research environments. In this study, we introduce a chip-scale visible laser platform capable of producing tunable and narrow-linewidth lasers spanning from near-ultraviolet to near-infrared wavelengths.

By leveraging micrometer-scale silicon nitride resonators and off-the-shelf Fabry–Pérot laser diodes, we achieve significant coarse tuning capabilities of up to 12.5 nm, coupled with mode-hop-free fine tuning up to 33.9 GHz. Remarkably, our lasers exhibit intrinsic linewidths as low as a few kilohertz. Additionally, our platform demonstrates impressive fine-tuning speeds of up to 267 GHz per microsecond, alongside fiber-coupled powers reaching up to 10 mW and typical side-mode suppression ratios surpassing 35 dB.

These remarkable specifications of our chip-scale lasers rival those previously attainable only with large, state-of-the-art benchtop laser systems. This breakthrough positions our lasers as powerful tools poised to drive the next generation of visible-light technologies, enabling practical applications in various fields beyond the confines of traditional laboratory setups.

**Keywords :** Smart Grid, Chip, Power, Energy

## I. INTRODUCTION

To enable chip-scale technologies for quantum optics, optical clocks, and atomic and molecular physics, there's a pressing need for on-chip lasers that offer both wide tunability and narrow linewidths across visible wavelengths. Current experiments require multiple lasers emitting at various colors to manipulate species, such as those used in optical atomic clocks, which span from near-ultraviolet (near-UV) to near-infrared (near-IR) wavelengths. However, existing laser systems are bulky benchtop setups, primarily relying on Fabry–Pérot (FP) laser diodes that require external free-space cavities for linewidth narrowing and tunability.

To address this challenge, we present a chip-scale laser platform capable of achieving wide tunability, narrow linewidths, and robust lasing from near-UV (404 nm) to near-IR (785 nm) wavelengths. Our platform utilizes micrometer-scale silicon nitride (Si3N4) resonators with high quality factor (Q) and integrates commercial FP laser diodes. Leveraging a broadband and low-loss optical-feedback scheme based on ring resonators, we achieve tunable and narrow-linewidth lasing across the visible spectrum.

By confining resonators tightly and employing hybrid integration, we ensure mode-hop-free operation with a high side-mode suppression ratio (SMSR). Unlike previous approaches relying on Vernier filters, our method requires fewer phase shifters, reducing noise and thermal crosstalk while minimizing power consumption and footprint. Additionally, we achieve compact and low-loss single-mode operation by tapering the ring width, allowing broadband low loss critical for visible wavelengths.

Our choice of FP laser diodes ensures robust self-injection locking against coupling loss and unwanted reflections, contributing to the stability and scalability of our scheme. Unlike lasers based on reflective semiconductor optical amplifiers, our approach separates the main laser cavity from the photonic chip, enabling stable and tunable lasing from near-UV to near-IR wavelengths in a photonic integrated platform. This breakthrough represents a significant step towards realizing chip-scale technologies for a wide range of applications in quantum optics and beyond.

The demand for chip-scale lasers with wide tunability and narrow linewidths stems from the burgeoning field of quantum optics, where precise manipulation and control of individual quantum systems are paramount. Such lasers are essential for tasks like optical trapping and cooling of atoms and ions, quantum state engineering, and quantum information processing. Additionally, in the realm of optical clocks, which are crucial for precision timekeeping and fundamental physics research, stable and narrow-linewidth lasers are indispensable for interrogating atomic transitions with high precision.

Atomic and molecular physics also heavily relies on lasers for tasks such as spectroscopy, laser cooling, and precision measurements. Narrow-linewidth lasers are critical for resolving spectral features and probing delicate quantum phenomena. However, despite the myriad applications, existing laser systems predominantly exist in the form of bulky benchtop setups, limiting their deployment outside of research laboratories. The development of chip-scale lasers capable of offering both wide tunability and narrow linewidths represents a significant advancement toward miniaturizing and democratizing these technologies.

Our chip-scale laser platform leverages micrometer-scale silicon nitride resonators, which exhibit high quality factors (Q), and hybrid integration of commercial FP laser diodes. This integration enables us to achieve wide tunability and narrow-linewidth lasing across the visible spectrum. By designing a broadband and low-loss optical-feedback scheme based on ring resonators, we ensure mode-hop-free operation and high side-mode suppression ratios (SMSR).

In contrast to previous approaches reliant on Vernier filters, which often require complex and bulky setups, our method simplifies the laser architecture while maintaining high performance. Fewer phase shifters reduce noise and thermal crosstalk, leading to improved stability and efficiency. The compactness of our design, coupled with its robustness, makes it well-suited for integration into chip-scale devices for various applications in quantum optics, optical clocks, and atomic physics.

The ability to achieve tunable and narrow-linewidth lasing from near-UV to near-IR wavelengths on a chip-scale platform opens up exciting possibilities for advancing research and technology. For instance, in quantum information processing, where precise control of quantum states is crucial, our chip-scale lasers can enable the implementation of quantum gates and quantum algorithms with unprecedented efficiency and precision.

Furthermore, in the field of quantum sensing and metrology, where high-precision measurements are essential for detecting and characterizing small signals, our chip-scale lasers can serve as robust and reliable light sources. Their narrow linewidths and wide tunability make them ideal for applications such as magnetometry, gravimetry, and precision spectroscopy, enabling advancements in fundamental science and practical technologies alike.

Moreover, the compactness and versatility of chip-scale lasers can revolutionize fields such as biomedical imaging and sensing, where precise and non-invasive optical techniques are essential. By integrating our lasers into portable and miniaturized devices, researchers and clinicians can perform high-resolution imaging, spectroscopy, and diagnostics in a variety of settings, including clinical and field environments.

Additionally, the scalability of our chip-scale laser platform opens up possibilities for multiplexed and parallelized operations in quantum information processing and other applications. By integrating multiple laser sources on a single chip, researchers can increase throughput and efficiency, paving the way for scalable quantum computing and communication systems.

Overall, the development of chip-scale lasers with wide tunability and narrow linewidths represents a significant step forward in advancing both fundamental research and practical applications in various fields. As these technologies continue to mature and become more accessible, they have the potential to revolutionize industries ranging from telecommunications and sensing to healthcare and beyond.

We implement a novel approach to collapse the longitudinal modes of the edge-coupled FP laser diodes, effectively transforming them into single-frequency lines through independent phase control of the bus waveguide and ring resonator (Fig. 2a). By utilizing the ring phase shifter to modulate the wavelength of the reflected light and the bus phase shifter to manipulate its phase, we can finely adjust the laser output. When the resonator is detuned from the modes of the FP laser, the ring becomes decoupled from the system (Fig. 2b, top), allowing the FP diode to emit multiple longitudinal modes simultaneously (Fig. 2b, bottom).

However, upon aligning the ring resonance to a mode of the FP laser, a portion of its optical power is reflected back to the diode (Fig. 2c, top). By further manipulating the phase of this reflected light using the bus phase shifter to ensure constructive interference with the light inside the FP laser, a phenomenon known as self-injection locking occurs. This process converts the output of the chip into a single-frequency laser with a remarkably narrow linewidth (Fig. 2c, bottom). While self-injection locking has traditionally been employed in free-space external-cavity diode lasers, its adaptation to integrated photonics in the infrared spectral range has enabled the development of ultranarrow-linewidth, tunable lasers, and fully integrated frequency comb generation.

Our chip-scale lasers offer both coarse and fine wavelength tuning capabilities. Coarse tuning is achieved by aligning the ring resonance to different longitudinal modes of the FP laser, effectively altering the output wavelength. Fine tuning, on the other hand, is accomplished through frequency pulling, a process wherein we adjust the ring resonance while the laser is locked, thereby changing the frequency of the optical feedback and consequently the lasing wavelength. Throughout this frequency-pulling process, we maintain the bus phase shifter constant. Alternatively, we can also achieve frequency pulling by modulating the FP laser current while keeping the ring resonance fixed.

This innovative approach to wavelength control offers unparalleled versatility and precision in chip-scale laser technology. By harnessing the power of integrated photonics and leveraging the unique properties of silicon nitride resonators, we have created a platform that enables researchers and engineers to manipulate light with unprecedented control and accuracy. As a result, our chip-scale lasers hold tremendous potential for a wide range of applications in quantum optics, optical clocks, atomic and molecular physics, and beyond. With further refinement and optimization, these lasers may become indispensable tools in advancing our understanding of the quantum world and driving technological innovation in various industries.

We demonstrate tunable lasing in the near-UV (404 nm), deep-blue (450 nm), blue (488 nm), green (520 nm), red (660 nm) and near-IR (785 nm) wavelength ranges, with coarse tuning up to 12.5 nm and mode-hop-free fine tuning up to 33.9 GHz (Fig. 3). In addition, we achieve fibre-coupled powers of up to 10 mW and typical SMSRs above 35 dB (Supplementary Section 2.6) with stable mode-hop-free opera- tion up to 5.7 h, limited only by the coupling-stage drift (Supplementary Section 2.8). To characterize our chip-scale lasers, we collect the chip output using edge-coupled cleaved fibres (Fig. 2a and Supplementary Section 1.3). We observe a reduction in the threshold current of the chip-scale lasers compared with the free-running FP laser diodes, which is a characteristic signature of self-injection locking39–42 (Sup- plementary Section 2.3). We measure the coarse-tuning ranges from

1.6 nm to 12.5 nm (Fig. 3a) limited by the gain bandwidth of the FP laser

diodes, and the mode-hop-free fine-tuning ranges from 1.6 GHz to 33.9 GHz (Fig. 3b) (Supplementary Section 2.7). We summarize the tuning ranges, fibre-coupled powers and SMSRs of all the chip-scale lasers in Table 1. We obtain the coarse-tuning ranges by overlapping the chip's output spectra acquired using an optical spectrum ana- lyser for different self-injection locked wavelengths. We measure the mode-hop-free fine-tuning ranges by changing the power applied to the ring microheater while monitoring the lasing wavelength with a wavemeter (Supplementary Section 2.7) after self-injection lock- ing of the lasers. For our chip-scale lasers, the wide tunability of many nanometres, the large mode-hop-free tuning ranges of up to tens of gigahertz and the fibre-coupled output power levels of several mil- liwatts are paralleled only by state-of-the-art benchtop laser systems (Supplementary Section 4).

We show fine-tuning speeds of up to 7 GHz μs–1 via modulation of the ring microheater (Fig. 4a) and up to 267 GHz μs–1 via modulation of the FP laser current (Fig. 4b), the latter being limited only by our experimental setup. We characterize the microheater-based frequency tuning speeds by scanning a fixed FP interferometer and we measure a 3 dB modulation bandwidth of around 32 kHz across the whole visible spectrum (Supplementary Section 2.9.1). The fast and long-range tuning (up to tens of gigahertz) that is enabled by our microheaters makes our lasers ideal for applications such as in swept-wavelength spectroscopy43 and frequency-modulated continuous-wave LIDAR (light detection and ranging)36,37,44. We characterize the FP laser-current modulation by beating the chip-scale laser output to a commercial laser and we apply modulation frequencies of up to 20 MHz (Supplementary Section 2.9.2), limited only by our experimental setup. The ultrafast and short-range tuning (up to several gigahertz) that is enabled by the current modulation is crucial for laser frequency stabilization and linewidth narrowing via negative electronic feedback38,45,46. Our tuning speeds are faster than the specifications of state-of-the-art commer- cial laser systems (≤0.02 GHz μs–1 for piezo tuning; Supplementary Section 4.2) and of integrated or partially integrated visible lasers (≤4.1 × 10−7 GHz μs−1; Supplementary Section 4.1).

We measure the linewidths of the chip-scale lasers and obtain intrinsic linewidths ranging from <8 kHz to <26 kHz from deep-blue to near-IR regions and an effective linewidth of <3.3 MHz for the near-UV region, which are all upper bounds limited by our instruments (Table 1). We determine the linewidths from deep-blue to near-IR wavelengths.

| Centre wavelength (nm) | Coarse-tuning range (nm) | Mode-hop-free fine-tuning range (GHz) | Fine-tuning rate (GHz μs$^{-1}$) | Fine-tuning 3dB modulation bandwidth | Measured intrinsic linewidth (kHz) | Measured effective linewidth (kHz) | Estimated intrinsic linewidth (kHz) | SMSR (dB) | Fibre-coupled output power (mW) | Estimated on-chip power (mW)[a] | Approximate footprint (FP laser diode+photonic chip) (mm$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 785 | 12.5 | 33.9 | 7.1 (microheater) 267 (laser current)[b] | 34 kHz (microheater) >20 MHz (laser current)[b] | <9[b] | <359[b] | <1.1 | ≥37 | 10.00 | 11.24 | 0.6×2 |
| 660 | 4.9 | 33.0 | 3.4 (microheater) | 31 kHz (microheater) | <10[b] | <427[b] | <1.4 | ≥35 | 4.42 | 7.13 | 0.6×2 |
| 520 | 6.0 | 8.2 | N/A | 32 kHz (microheater) | <26[b] | <373[b] | <0.4 | ≥37 | 9.89 | 10.75 | 0.6×2 |
| 488 | 5.6 | 3.7 | N/A | 31 kHz (microheater) | <8[b] | <505[b] | <1.4 | ≥37 | 1.75 | 8.33 | 0.6×2 |
| 455 | 4.5 | 2.0 | N/A | 32 kHz (microheater) | <9[b] | <374[b] | <6.9 | ≥37 | 1.74 | 5.61 | 0.6×2 |
| 404 | 1.6 | 1.6 | N/A | N/A | N/A | <3,300[b] | <1,500 | ≥21 | 0.02 | 0.13 | 0.6×2 |

We conduct linewidth measurements by analyzing the heterodyne beat note between our chip-scale lasers and commercial narrow-linewidth laser systems using a spectrum analyzer (Supplementary Section 2.10). To characterize the linewidth, we fit the beat notes with a Voigt profile, allowing us to extract both the Lorentzian contribution, corresponding to the white noise defining the intrinsic linewidth, and the Gaussian contribution, representing the flicker and technical noises broadening the effective linewidth. Additionally, we determine the effective 3 dB linewidths of the lasers based on the total Voigt linewidths (Supplementary Section 2.12).

To cover a broad spectral range, we adjust the temperature of the FP lasers to shift the center wavelengths of our chip-scale lasers, enabling overlap with the tuning ranges of the commercial lasers (Supplementary Sections 2.10 and 3). Given that the commercial laser systems exhibit intrinsic linewidths of several kilohertz and effective linewidths of hundreds of kilohertz (Supplementary Section 3), our analysis indicates that the beat notes are constrained by their linewidths. Specifically, for the near-IR chip-scale laser, we directly measure its frequency noise using a linewidth analyzer, suggesting an intrinsic linewidth ranging from 314 Hz to 1.26 kHz (Supplementary Section 2.11).

For the near-UV laser, we determine its effective linewidth to be less than 3.3 MHz by scanning it with an FP interferometer, which offers a resolution limited to 2.5 MHz (Supplementary Section 2.10). Through theoretical estimation, we project the intrinsic linewidths of the chip-scale lasers to be less than 7 kHz across the deep-blue to near-IR regions and less than 1.5 MHz for near-UV wavelengths (Table 1 and Supplementary Section 2.13). These estimates further corroborate the experimental findings presented in Fig. 5, suggesting that our instruments likely impose the limitations observed.

The linewidths we demonstrate are comparable to those of state-of-the-art narrow-linewidth and tunable visible lasers (Supplementary Section 4), typically found in bulky benchtop systems. However, our chip-scale lasers offer the advantage of compactness and portability, potentially revolutionizing various fields by enabling high-precision optical measurements and applications in a compact form factor.

## II. Discussions

Our chip-scale visible lasers demonstrate exceptional performance across key specifications, including tuning range, tuning speed, linewidth, power, and side-mode suppression ratio (SMSR), previously achievable only with bulky benchtop laser systems. Remarkably, our platform eliminates the need for free-space optical components, boasting a compact micrometre-scale footprint while robustly covering nearly an octave of the electromagnetic spectrum. This compactness, combined with broadband operation, facilitates scalability, allowing integration of multiple lasers emitting at different wavelengths onto a single chip. For applications requiring a single-fiber output, diverse colors can be merged into a regular or photonic crystal single-mode fiber using an on-chip wavelength multiplexer. Such a compact and highly coherent multi-color laser engine holds significant promise for a wide array of applications, including quantum optics, atomic clocks, biophotonics, augmented reality/virtual reality, spectroscopy, and visible-light communications.

Through independent control of on-chip microheaters, laser current, and laser temperature, we achieve precise and gap-free tuning across wide spectral ranges of several nanometers within the visible spectrum. By aligning the ring resonance and FP longitudinal modes at desired wavelengths, our platform enables versatile tuning capabilities. Moreover, we extend coarse-tuning ranges by several nanometers towards longer and shorter wavelengths by adjusting the temperature of the FP lasers, as evidenced by linewidth measurements in the deep-blue and red regions (Fig. 5 and Supplementary Section 2.10). By driving microheaters and laser current in a feed-forward fashion, we can broaden frequency-pulling ranges, further enhancing tuning flexibility.

The performance of our lasers, particularly frequency-pulling ranges and output powers, is primarily constrained by coupling losses between FP lasers and the photonic chip, dictating self-injection locking strength through reflected light levels. Optimization of couplings can potentially refine laser specifications, especially in the near-UV spectral range where coupling losses are currently higher (Supplementary Sections 1.3 and 2.13). In addition to our tapering strategy, compact and low-loss resonators with single-mode operation may be achievable through adiabatic coupling schemes to rings with constant multi-mode cross-sections, as explored in infrared wavelengths. The robustness of self-injection locking can facilitate scaling to higher on-chip power levels using commercial high-power (>1 W) visible-light laser diodes, enabling fully integrated high-power sources for nonlinear optics, optical cooling, and trapping.

The availability of the wafer-scale Si3N4 platform in photonic foundries enables cost-effective mass production and large-scale deployment. These distinctive attributes of our chip-scale platform challenge the existing paradigm where high-performance visible lasers rely on discrete benchtop components, thus heralding the advent of fully integrated visible-light systems for applications spanning life sciences, atomic research, and vision sciences.

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