# Sub-kHz free-running-linewidth monolithic VECSEL

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**Abstract:** We report the development of a monolithic-cavity GaInP/AlGaInP-based VECSEL at 689 nm with sub-kHz free-running linewidth. A locked Allan deviation of $4\times10^{-13}$ at 1s averaging time is observed, suitable for quantum technology and metrology applications. © 2023 The Author(s)

## 1. Introduction

High performance, compact lasers have direct impact on the efficiency and accuracy of the so-called quantum technologies (QT), particularly those based on cold atoms, such as optical clocks [1]. Depending on the atomic species of interest, different wavelengths and optical powers are required with high stability and linewidths reaching the mHz-level for clock transitions. External cavity diode lasers (ECDLs) are commonly used in QT systems but with limited short wavelength coverage and output power. Furthermore, the Schawlow-Townes-Henry (STH) [2], or fundamental, linewidth limit of ECDLs is calculated to be at the 10s of kHz-level, with environmental, technical, and electronic instabilities causing further linewidth broadening or even coherence collapse. Often, external modules are employed in ECDLs for noise reduction and linewidth-narrowing, but with detrimental impact on bulkiness, complexity, and costs, thus affecting integration with QT systems. Alternatively, monolithic-cavity lasers, such as non-planar ring oscillators (NPROs) [3], are more robust against external noise whilst also providing a compact and rugged package; however, available wavelengths are very limited, and magnetic fields and intensity stabilization are required to avoid spatial hole burning and relaxation oscillations [4]. In this context, vertical-external-cavity surface-emitting-lasers (VECSELs) – also known as semiconductor disk lasers (SDLs) - are being developed as an attractive alternative given their high brightness with no spatial hole burning, extended wavelength coverage and relaxation oscillation-free, low-noise performance thanks to class-A carrier dynamics [5]. In addition, VECSELs typically have a STH limit at the mHz-level, thus providing an ideal platform for the achievement of ultra-narrow linewidths if they can be sufficiently isolated from environmental noise. We have previously demonstrated low noise operation with sub-kHz linewidth of an actively-stabilised air-spaced cavity GaInP/AlGaInP-based VECSEL at 689 nm [6, 7], the wavelength required for laser-cooling neutral strontium atoms, with output power exceeding 100 mW. Recently, to significantly reduce the impact of environmental noise, we have also introduced the concept of a monolithic cavity class A VECSEL, a wavelength customisable, high stability laser platform, with the laser resonator (oscillating in this case at 672 nm) using total internal reflection inside a right-angle prism cavity spacer [8]; however, frequency-locking was not implemented. Here, we report the development of a diode-pumped, monolithic cavity VECSEL at 689 nm for the first time, with a *free-running* linewidth of 940 Hz, reduced to 440 Hz when frequency-locked to a reference. Low relative intensity and frequency noise were observed with an Allan deviation of $3\times10^{-12}$ (400 ms) and $4\times10^{-13}$ (1s) while free-running and locked, respectively, suitable for high performance applications, such as QT and metrology.

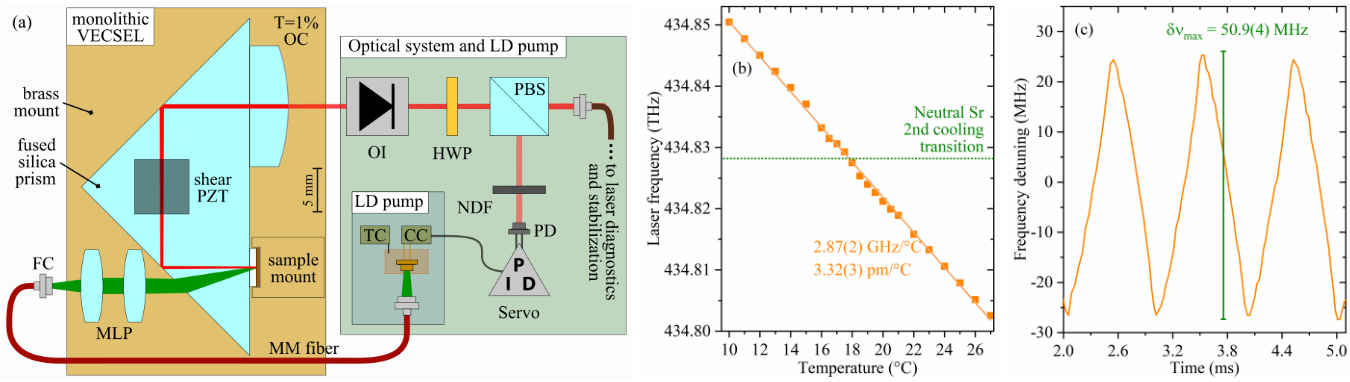


**Fig. 1** (a) Monolithic cavity VECSEL schematic with laser cavity components to scale. (b) Frequency tuning via mount temperature. (c) Fine frequency tuning via shear PZT. FC: fiber coupler; MLP: matched lens pair; OC: output coupler; OI: optical isolator; HWP: half-wave plate; PBS: polarizing beam splitter; NDF: neutral density filter; PD: photodiode; MM fiber: multimode fiber; LD: laser diode; CC: current controller; TC: temperature controller.

## 2. Monolithic cavity VECSEL

A GaInP/AlGaInP-based VECSEL gain structure, similar to the one reported in [6], was used to build the monolithic laser cavity, designed for emission at 689 nm when optically-pumped at around 532 nm. The total internal reflection laser resonator was designed to be inside a high tolerance, 25 mm fused silica right-angle prism (common off-the-shelf component). Both the gain structure and a 1% planar-convex output coupler were capillary-bonded to the hypotenuse of the prism (see Fig. 1a), which was then placed in a brass mount temperature-stabilized at 16 °C. A shear piezo electric transducer (PZT) was mounted on the top of the right-angle prism for wavelength tuning and frequency stabilization purposes. An intensity-stabilized, green diode laser [7] is used as a pump, delivered to the gain structure by a multimode fiber with a maximum power of 1050 mW through one of the lateral faces of the prism. Single frequency emission with a pump-power-limited maximum output power of 39 mW at 689.45

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nm is achieved, with a threshold of 630(20) mW and a conversion efficiency of 8.4(1)%. The emission wavelength is electronically tunable over 80 pm, without mode hopping, via the temperature controller, at a rate of 2.87(2) GHz/°C, or 3.32(3) pm/°C (see Fig. 1b), and via the shear PZT in a span of 50.9 MHz (see Fig. 1c).

## 3. Noise performance

The noise performance was analysed while free-running and when locked to a moderately-high finesse, air-spaced reference cavity (finesse = 1k, free spectral range = 300 MHz) via the Pound-Drever-Hall technique (bandwidth = 500 Hz), with the error signal sent to the shear PZT. The relative intensity noise, or RIN (see Fig. 2a) is measured to be <-102 dB/Hz and <-110 dB/Hz when free-running and locked, respectively, for frequencies in between 100 mHz and 15 MHz. The low frequency intensity noise is significantly reduced when the laser is locked but sharp peaks can still be observed between 10 Hz and 7 kHz, related to mechanical, electronic and pump-injected noise, indicating that further improvements in the stabilization can be performed.

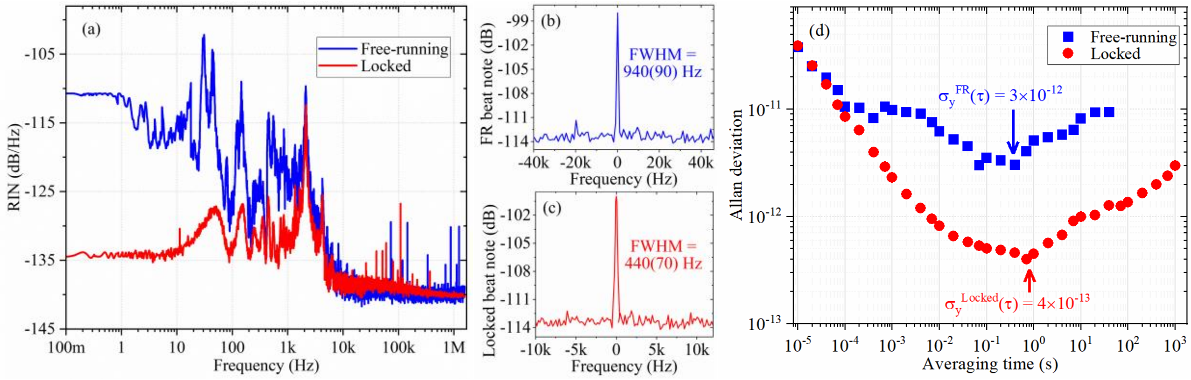


**Fig. 2** (a) Monolithic cavity VECSEL relative intensity noise. (b) Free running and (c) locked heterodyne beat note measurement of the monolithic cavity VECSEL against a second air-spaced-cavity locked VECSEL with estimated linewidth of 200 Hz. (d) Allan deviation measurement.

The linewidth was measured via a heterodyne beat note against a second VECSEL at 689 nm with an estimated linewidth of 200 Hz [6]. The two lasers, separated by a frequency difference of 300 MHz, were combined on a 50:50 splitting ratio non-polarizing beamsplitter into a polarization-maintaining fiber, with the resulting radio-frequency (RF) signal being measured simultaneously by a fast photodetector (bandwidth 1 GHz) and an oscilloscope. Fig. 2b and Fig. 2c present beat note peaks with a full-width at half-maximum of 940(90) Hz and 440(70) Hz, respectively, demonstrating a more robust noise and linewidth performance when compared with air-spaced VECSEL systems. In addition, Allan deviation from the beat note measurement recorded for different ranges of averaging times was calculated. While free-running, the frequency stability of the monolithic cavity VECSEL is measured to be of $3\times10^{-12}$ for an averaging time of 400 ms, staying $<10^{-11}$ for longer times up to 40 s. The locked stability is measured to be $4\times10^{-13}$ for an averaging time of 1s.

## 4. Conclusion

We have demonstrated sub-kHz linewidth operation of a free-running VECSEL for the first time, using a monolithic cavity integrated with a diode-pumped GaInP/AlGaInP gain structure for emission at 689 nm. The laser resonator was designed to use total internal reflection to operate inside an off-the-shelf right-angle prism, with frequency-locking of the solid resonator implemented via a shear PZT. The RIN is measured to be <-102 dB/Hz and <-110 dB/Hz when free-running and locked, respectively. The linewidth and stability of the monolithic cavity VECSEL were measured by performing a heterodyne beat note with an independent narrow-linewidth VECSEL. This confirmed the sub-kHz free-running linewidth with a frequency stability of $3\times10^{-12}$ (400 ms), which is reduced to 440 Hz with a stability of $4\times10^{-13}$ (1 s) when actively stabilized. Although presenting high-performance, further improvements can be made to reduce the intensity and frequency noise to target even lower linewidths towards the VECSEL fundamental linewidth. This can be achieved with further miniaturization of the monolithic cavity geometry and design, and by improving the pump intensity stabilization and VECSEL frequency stabilization. Nevertheless, the monolithic cavity VECSEL architecture provides a robust laser platform with customisable wavelength and ultra-low noise, sub-kHz free-running linewidth operation, ideal for high precision applications, such as quantum technologies and metrology.

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