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A 1-MHz VCSEL for compact atomic clocks

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Abstract

A 2026 study introduced a transformative design for vertical-cavity surface-emitting lasers (VCSELs), achieving a dramatic narrowing of the intrinsic linewidth to approximately 1 MHz without relying on external optical feedback. This performance is enabled by the monolithic integration of a precisely engineered passive cavity that strategically tailors photon lifetime while suppressing mode competition. The resulting architecture delivers an ultra-compact, scalable, and inherently stable coherent light source, representing a significant advance for chip-scale atomic clocks and quantum sensing technologies.

Keywords: 1-MHz linewidth, VCSEL, Atomic clocks

Next-generation quantum devices such as chip-scale atomic clocks, optical gyroscopes, and magnetometers are reshaping the future of positioning, navigation, and timing (PNT) systems, as well as precision metrology[1,2]. These highly sensitive quantum sensors impose rigorous requirements on their light sources, specifically ultranarrow linewidths, robust single-mode emission, and high levels of system integration. Vertical-cavity surface-emitting lasers (VCSELs) have emerged as promising candidates for these applications because of their ultralow threshold currents, excellent beam quality, and planar architectures that enable cost-effective and wafer-scale manufacturing. VCSELs are fundamentally limited by their short physical cavity lengths, which leads to high round-trip losses and short photon lifetimes within the cavity, resulting in emission linewidths exceeding 100 MHz[3].

Over the past decade, tremendous efforts have been made to narrow the linewidth, but this has often compromised practical applications. For example, conventional strategies typically rely on external components such as microring resonators or bulk optical cavities to reduce the linewidth[4], resulting in bulky and complex systems that are highly sensitive to environmental vibrations[5]. An alternative approach is to extend the VCSEL's internal cavity length, which however, encounters a fundamental limitation known as the FSR (free spectral range) wall (the shrinking of the free spectral range)[6].

A recent study by Tang et al. made a major contribution to overcoming the bottlenecks by completely abandoning the bulky external feedback components[7]. The researchers ingeniously embedded a low-loss "passive cavity" directly into the thick bottom n-type distributed Bragg reflectors (DBRs) of a VCSEL operating at 894.6 nm corresponding to the caesium D1 transition line, which is shown in Fig. 1a. This architecture was designed to extend the optical path within the cavity while avoiding the introduction of nonradiative recombination centres. The underlying microscopic mechanism is further revealed in Fig. 1b, where a precise match between the standing-wave distribution of the electric field distribution and the refractive index is observed. By carefully setting the passive cavity length to 4.5 wavelengths (4.5λ), the antinode of the standing wave is aligned well with the quantum wells to maximise the optical gain. In contrast, the node coincides with the oxide aperture to minimise the

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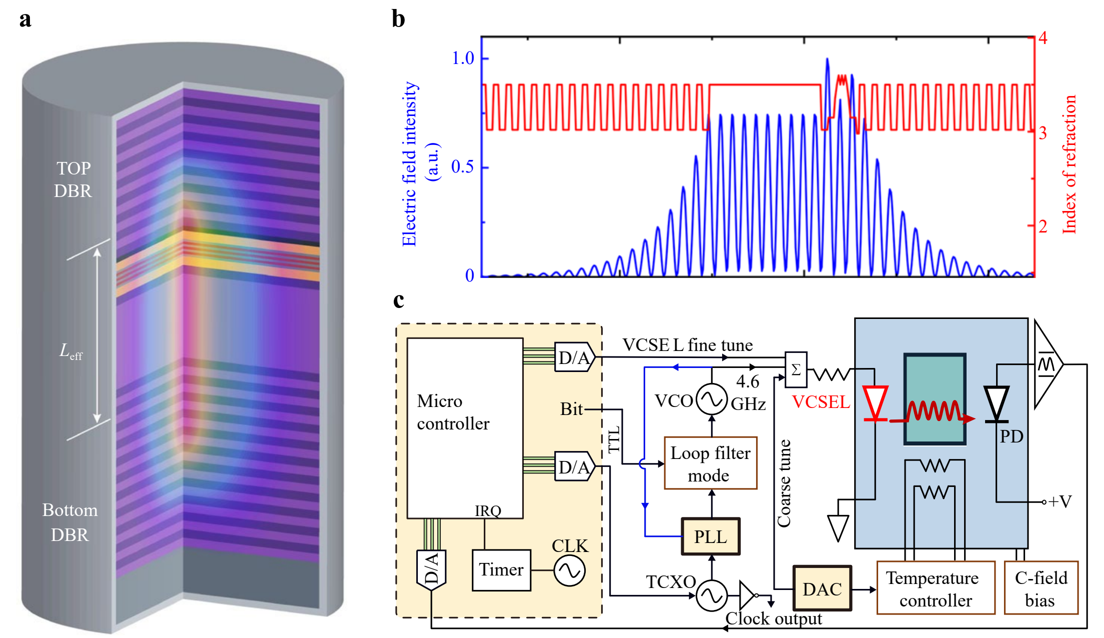

Fig. 1 a 3D structural schematic of the device, illustrating the passive cavity layer embedded in the bottom DBR, the oxide confinement layer, and the quantum well active region. **b** Refractive index profile (red line) and standing wave electric field intensity (blue line) along the longitudinal direction of the device. The presence of the passive cavity redistributes the optical field, extending the effective cavity length and suppressing higher-order modes. **c** Schematic of the caesium vapour-cell CPT atomic clock system testbed based on this VCSEL. Serving as the core light source, the laser directly drives the physics package, achieving a highly stable frequency output. Reproduced and adapted from Ref. 7.

optical loss. More importantly, a cylindrical waveguide structure with transverse optical confinement was achieved in the oxide-confined VCSELs, which significantly reduces the effective refractive index difference (Δn_{eff}) inside and outside the oxide aperture[8]. A small Δn_{eff} is essential for enhancing the diffraction loss of higher-order transverse modes and effectively suppressing their lasing. As a result, this strategy bypasses the multi-mode competition caused by the FSR wall, while simultaneously extending the effective cavity length.

They further constructed a miniature caesium vapour cell coherent population trapping (CPT) atomic clock testbed. In this closed-loop system, the 894.6 nm laser emitted from the VCSEL passes directly through the caesium atomic vapour cell, in which the atomic quantum transition signal is utilised as feedback to lock the microwave frequency. Owing to the low beam-divergence angle (~7°) and ultranarrow linewidth (~1 MHz) realised in the VCSEL without external frequency stabilisation, both the complexity and footprint of the optical system are drastically reduced. Furthermore, the researchers strategically implemented a −12.1 nm "gain-cavity detuning" design, ensuring that the gain peak remains aligned with the cavity mode even at elevated temperatures, e.g., 95 °C, required for atomic clock operation. This compact atomic clock achieves an extremely low Allan deviation of $1.89 \times 10^{-12}\ \tau^{-1/2}$ at the flicker noise floor, with 10,000 s tracking tests showing frequency stability that significantly outperforms state-of-the-art VCSEL-driven atomic clock systems of a similar class[9–13].

From a broader perspective, this study extends beyond setting record-breaking performance metrics. This demonstrates that an advanced monolithic micro-nano optical design, specifically the precise manipulation of the internal standing wave field and refractive index distribution, can push the coherence of semiconductor lasers to new limits without compromising system integration and manufacturability. As the demand for compact and low-power quantum-sensing networks grows rapidly, this passive-cavity-embedded VCSEL architecture, offering both high performance and scalability, is promising for paving the way for next-generation precision timing and quantum metrology technologies from the lab to practical applications.

Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The authors declare no conflicts of interest.

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References

1. Kitching, J. Chip-scale atomic devices. *Applied Physics Reviews* **5**, 031302 (2018).
2. Yu, H. Y. et al. Key technologies in developing chip-scale hot atomic devices for precision quantum metrology. *Micromachines* **15**, 1095 (2024).
3. Camparo, J. C. & Coffer, J. G. Conversion of laser phase noise to amplitude noise in a resonant atomic vapor: the role of laser linewidth. *Physical Review A* **59**, 728-735 (1999).
4. Kondratiev, N. M. et al. Recent advances in laser self-injection locking to high-*Q* microresonators. *Frontiers of Physics* **18**, 21305 (2023).
5. Jiang, L. D. et al. Narrow linewidth VCSEL based on resonant optical feedback from an on-chip microring add-drop filter. *Optics Letters* **46**, 2320-2323 (2021).
6. Serkland, D. K. et al. Narrow linewidth VCSELs for high-resolution spectroscopy. Proceedings of SPIE 7229, Vertical-Cavity Surface-Emitting Lasers XIII. San Francisco, California, United States: SPIE, 2009.
7. Tang, Z. T. et al. 1-MHz linewidth VCSEL enabled by monolithically integrated passive cavity for high-stability chip-scale atomic clocks. *Light: Science & Applications* **15**, 94 (2026).
8. Zhou, Y. L. et al. Large-aperture single-mode 795 nm VCSEL for chip-scale nuclear magnetic resonance gyroscope with an output power of 4.1 mW at 80 °C. *Optics Express* **30**, 8991-8999 (2022).
9. Zhou, H. J. et al. 894.6 nm vertical cavity surface emitting lasers for atomic sensing applications. Proceedings of 2024 IEEE Opto-Electronics and Communications Conference. Melbourne, Australia: IEEE, 2024.
10. Kroemer, E. et al. Characterization of commercially available vertical-cavity surface-emitting lasers tuned on Cs D_1 line at 894.6 nm for miniature atomic clocks. *Applied Optics* **55**, 8839-8847 (2016).
11. Ha, L. C. et al. High-temperature chip-scale atomic clock. *Journal of Physics: Conference Series* **2889**, 012011 (2024).
12. Gruet, F. et al. Metrological characterization of custom-designed 894.6 nm VCSELs for miniature atomic clocks. *Optics Express* **21**, 5781-5792(2013).
13. von Bandel, N. et al. DFB-ridge laser diodes at 894 nm for Cesium atomic clocks. Proceedings of SPIE 9755, Quantum Sensing and Nano Electronics and Photonics XIII. San Francisco, California, United States: SPIE, 2016.