

Review

Advances and Applications of Narrow-Linewidth Vertical-Cavity Surface-Emitting Lasers

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Abstract

Vertical-cavity surface-emitting lasers (VCSELs) have emerged as essential light sources for atomic-precision measurement, quantum-secure communication, high-speed optical transmission, and laser coherent scanning detection, owing to their low power consumption, high-quality beam characteristics, and ease of two-dimensional integration. However, the fundamental limitation on linewidth narrowing in VCSELs arises from their inherently short resonator, resulting in a natural linewidth on the order of 50–100 MHz. This limitation prevents conventional VCSELs from meeting the stringent requirements of advanced applications, making the ultra-narrow linewidth a key focus in optoelectronics research. This review analyzes representative achievements and application scenarios of narrow-linewidth VCSELs, evaluates the merits and limitations of industrial-grade devices, and envisions future directions in next-generation optoelectronic systems. Distinct from existing reviews, it integrates key single-mode fabrication techniques, quantitative linewidth requirements across applications, silicon photonic integration, and scalable manufacturing trends, establishing a complete mechanism–technology–application–industry analytical framework.

Keywords: vertical-cavity surface-emitting laser (VCSEL); narrow linewidth; optical feedback

1. Introduction

Since its conception by Professor Kenichi Iga at the Tokyo Institute of Technology in 1977 [1–3], the vertical-cavity surface-emitting laser (VCSEL) has undergone nearly five decades of development and emerged as a pivotal light source in the field of optoelectronics. Compared with conventional edge-emitting semiconductor lasers (EELs), VCSELs exhibit distinctive advantages including low threshold current, low power consumption, high beam quality, stable single-longitudinal-mode operation, and ease of two-dimensional integration [4–7]. These superior properties have driven their widespread adoption in optical communications, 3D sensing, optical interconnects, optical computing, and biomedical applications [8–10].

With the continuous advancement of precision measurement technologies, such as chip-scale atomic clocks (CSACs), atomic gyroscopes, and optically pumped magnetometers [11–13], higher performance requirements have been placed on laser sources. Among these, CSACs represent one of the most important application areas for narrow-linewidth VCSELs [14,15]. Atomic clocks utilize the precise frequency of atomic energy level transitions as a time standard, imposing strict performance requirements on



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laser sources: narrow linewidth (typically less than 20 MHz), high-temperature stability ($\geq 80^\circ\text{C}$), stable single-mode output, and high polarization stability [16–19].

Furthermore, narrow-linewidth VCSELs demonstrate broad application prospects in fields, such as quantum key distribution, coherent optical communication, and lidar. In the field of quantum sensing, in which quantum effects are utilized to achieve ultra-high-precision measurements, narrow-linewidth VCSELs serve as light sources that can improve the signal-to-noise ratio and reduce measurement errors [20,21]. In the field of quantum key distribution (QKD), the polarization-encoded BB84 protocol requires high-quality single-photon sources or weakly coherent pulse sources. By designing VCSEL arrays at specific wavelengths and integrating subwavelength gratings to achieve polarization control, a compact solution can be provided for practical QKD systems [22–24]. In differential-phase-shift QKD, the laser linewidth should remain below 0.35% of the asymmetric Mach–Zehnder interferometer free spectral range to keep the quantum bit error rate below 1%; for a 1 GHz interferometer, this corresponds to approximately 3.5 MHz [25]. In coherent optical communications, systems impose strict requirements on the linewidth and phase noise of light sources. Recent digital signal processing can tolerate MHz-class transmitters, and even 3 MHz lasers have been employed in high-order coherent links when phase-noise compensation is available [26]. Narrow-linewidth VCSELs help improve the transmission rate and range of communication systems [27,28]. Similarly, in lidar applications, linewidth directly affects phase noise, range precision, and chirp linearity, making sub-MHz-to-MHz-level sources highly attractive for precision ranging and integrated photonic lidar engines [29–31].

Beyond sensing and communications, VCSELs are also becoming important building blocks for photonic neural networks and reservoir computing. Coherent VCSEL neural networks have demonstrated femtojoule-per-operation efficiency and high compute density in deep-learning hardware [32]. Single-VCSEL reservoir and spiking-neural-network schemes have further shown strong potential for time-series prediction and multitask processing [33–35], while hyper-multiplexed integrated optical tensor processors indicate that wafer-fabricated, micron-scale lasers can support scalable photonic accelerators for artificial intelligence [36]. These developments suggest that future narrow-linewidth VCSELs should be evaluated not only for spectroscopy or atomic devices but also for phase-sensitive neuromorphic and optical-computing platforms.

However, while EELs can achieve linewidth compression down to the kilohertz level and below via external-cavity optical feedback, VCSELs suffer from an intrinsically broader linewidth due to their unique short-cavity architecture. Meanwhile, their symmetric geometric structure and gain distribution increase the difficulty of mode selection and stability regulation. Conventional VCSELs with an inherent short cavity length (typically 1–1.5 optical wavelength) exhibit a linewidth in the range of 50–100 MHz, far exceeding the natural linewidth of atomic systems (e.g., 5 MHz for cesium atoms). This intrinsic limitation poses a grand challenge for linewidth compression and hinders their adoption as reliable light sources in applications with extremely high requirements for spectral purity and stability, such as precision metrology and atomic clock systems [37–42]. Accordingly, effective linewidth compression of VCSELs has become one of the core research topics in this field.

It is important to emphasize that narrow-linewidth operation of VCSELs fundamentally builds upon robust single-mode (SM) VCSEL technology [43–52]. Without effective suppression of higher-order transverse modes, the spectral purity and linewidth stability required for precision applications cannot be achieved.

Laser linewidth is a critical parameter that determines the temporal coherence of laser emission, with its intrinsic value originating from spontaneous emission noise [53,54].

According to the Schawlow–Townes linewidth formula, laser linewidth is closely correlated with the quality factor (Q-factor) of the resonant cavity, which is in turn governed by cavity length, mirror reflectivity, and other structural parameters [55,56]. Therefore, the core principle for laser linewidth compression is to suppress spontaneous emission noise and boost the Q-factor of the resonant cavity either by optimizing the resonator structure or by introducing an external feedback mechanism [57].

Over the advances of narrow-linewidth VCSEL technologies, three primary technical routes have been established: (1) external-cavity optical feedback technology; (2) coupled-cavity structure technology; (3) surface patterning technology. Starting from fundamental principles, this paper systematically emphasizes the physical link between linewidth, single-mode control, phase stabilization, and manufacturability.

2. Fundamental Principles of VCSELs and Linewidth Limitation Mechanisms

2.1. Basic Structure of VCSELs

The resonant cavity of a VCSEL consists of top and bottom distributed Bragg reflectors (DBRs) and an active region, in which light travels back and forth between the two mirrors and obtains optical amplification and gain [58,59]. Typically, the top and bottom DBRs are formed by stacking alternating dielectric layers with different refractive indices, each with a thickness of $1/4$ of the optical wavelength. The constructive interference of interface reflections during light propagation enables ultra-high reflectivity ($>99\%$), making DBRs the most widely used reflectors in modern VCSELs. The active region of a VCSEL is predominantly based on quantum well structures, with a thickness of approximately half the optical wavelength [4].

The structure of a typical electrically pumped VCSEL is illustrated in Figure 1. Generally, the top electrode of a VCSEL adopts a ring-shaped geometry. Current is injected from the top electrode, passes through the top DBR into the active layer and then through the bottom DBR to the negative electrode. After injection from the designed electrode, the current converges through a current confinement region formed by an oxide aperture or ion implantation, stimulating radiation in the active region [60,61]. To improve the energy conversion efficiency of VCSELs, oxide confinement or proton implantation is commonly employed to achieve simultaneous current and optical confinement, enabling the concentration and recombination of carriers in the active region. Typically, to achieve a good milliwatt-level output power from a VCSEL, it is necessary to precisely control the diameter of the oxide aperture. Expanding the aperture diameter will boost the VCSEL's output power, while also ensuring mode stability [62].

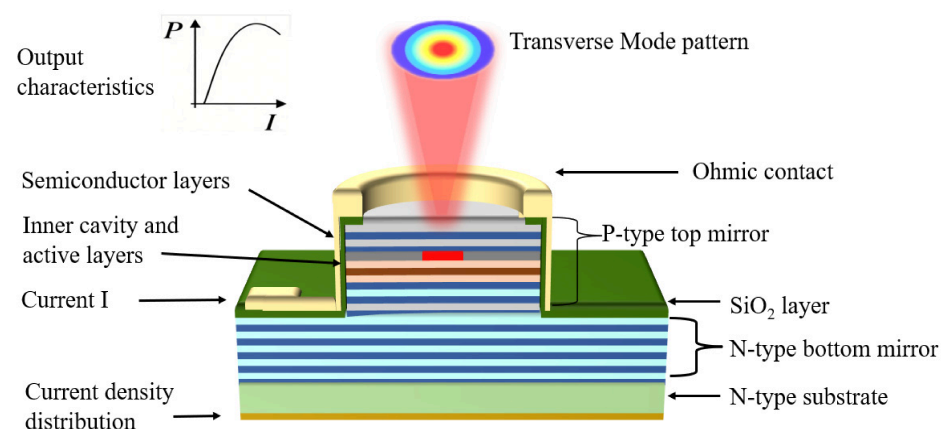


Figure 1. Schematic of a typical VCSEL structure.

2.2. Linewidth Limitation Mechanisms

Laser linewidth essentially reflects the phase noise level of the optical field. The output linewidth of a VCSEL is mainly limited by the following factors: Spontaneous emission noise, which is the intrinsic origin of laser linewidth. In 1958, Schawlow and Townes first derived the laser linewidth formula induced by spontaneous emission, known as the Schawlow–Townes formula [42]. Subsequently in 1982, Henry revised the linewidth formula, with the original and the modified Schawlow–Townes formulas expressed as [41]

$$\Delta\nu_0 = (h\nu/P_0) (n_{sp} \eta_0 \pi) (\Delta\nu_c)^2 \quad (1)$$

$$\Delta\nu = (1 + \alpha^2) \Delta\nu_0 \quad (2)$$

where $h\nu$ is the photon energy; P_0 is the output power; n_{sp} is the population inversion factor; η_0 is the optical output coupling efficiency; and $\Delta\nu_c$ is the cold-cavity linewidth. Equation (1) indicates that spontaneous emission sets the minimum phase-diffusion rate of the laser: a higher output power and a narrower cold cavity reduce the fraction of randomly emitted photons that perturb the coherent field. Equation (2) shows that carrier-induced amplitude fluctuations are converted into phase fluctuations through the linewidth enhancement factor α . A larger α means stronger amplitude–phase coupling and therefore greater phase noise, so semiconductor lasers are usually broader than the ideal Schawlow–Townes limit. Therefore, linewidth narrowing in VCSELs is not only a matter of increasing power but also of reducing amplitude–phase coupling and stabilizing the cavity mode.

2.2.1. Linewidth Enhancement Factor (α -Factor)

Henry defined the linewidth broadening factor as the ratio of the real part to the imaginary part of the change in the complex refractive index of the active region [22], with the expression

$$\alpha = \frac{\Delta n'}{\Delta n''} \quad (3)$$

where $\Delta n'$ is the change in the real part of the complex refractive index, and $\Delta n''$ is the change in the imaginary part. Meanwhile, the gain characteristics of the laser adjust correspondingly with variations in carrier concentration, and the linewidth enhancement factor α describes the proportional relationship between the change in refractive index and the change in gain. For VCSELs operating at room temperature, the α value is typically around 3, which can be measured experimentally by fitting the gain variation (measured via amplified spontaneous emission (ASE) spectroscopy) at different injection currents below the threshold current with the wavelength shift induced by varying injection currents under lasing conditions [63]. Notably, temperature must be strictly controlled during wavelength-shift measurements to eliminate the influence of thermal effects on the results.

By optimizing the structural design and material selection of the active region, such as adopting quantum dot structures, the linewidth enhancement factor can be effectively reduced, thereby achieving linewidth compression. The introduction of tunnel junctions or quantum dot structures has also been demonstrated to facilitate a reduction in the α -factor and further narrowing of the laser linewidth [64].

2.2.2. Laser Output Power

According to the Schawlow–Townes formula, the laser linewidth $\Delta\nu$ is inversely proportional to the output power P_0 near the threshold. When the laser just reaches the threshold, the fundamental mode power increases, and higher-order modes are effectively suppressed as the drive current rises, leading to a narrow trend in linewidth. However, with a further increase in the drive current, higher-order modes gradually emerge, and

the competition between modes intensifies, resulting in linewidth broadening [65]. In oxide-confined VCSELs, the size of the oxide aperture directly determines the ability to control higher-order modes: a small aperture is beneficial for suppressing higher-order modes but limits the output power, while an increased aperture improves the output power but weakens the confinement of higher-order modes, easily triggering multi-mode lasing and linewidth broadening. To describe the influence of higher-order mode lasing on linewidth, the root-mean-square (RMS) linewidth is commonly used to characterize the RMS fluctuation of the instantaneous optical frequency [66]:

$$\Delta\lambda_{RMS} = \sqrt{\left[\sum_{i=1}^n P_i \left(\lambda_i - \frac{\sum_{i=1}^n P_i \lambda_i}{\sum_{i=1}^n P_i} \right)^2 \right] / \sum_{i=1}^n P_i} \quad (4)$$

where P_i and λ_i represent the peak power and corresponding wavelength of the i th mode, respectively. Although the RMS linewidth is mainly used to describe frequency noise, which has a different spectral broadening mechanism from that induced by phase noise, it exhibits a positive correlation with the spectral linewidth. When higher-order modes appear, frequency noise is enhanced; the RMS linewidth increases; and the spectral linewidth broadens accordingly. In VCSELs, although increasing the drive current or oxide aperture helps to boost the output power P_0 , the linewidth does not simply vary inversely with power due to the interference of higher-order modes. The actual performance shows that the linewidth first decreases and then increases with rising P_0 .

Near threshold-to-moderate injection levels, the Schawlow–Townes intrinsic linewidth decreases with increasing photon number as output power rises, leading to overall linewidth narrowing. However, as injection current increases further, pronounced device self-heating causes relative detuning between the gain spectrum peak and cavity resonance wavelength, exacerbating gain–cavity misalignment and reducing differential gain. Concurrently, carrier-induced refractive index fluctuations and the phase–amplitude coupling effect associated with the Henry linewidth enhancement factor are amplified. These processes further induce transverse-mode competition, polarization switching, and even transient mode hopping, resulting in increased frequency noise and subsequent linewidth widening. Therefore, maintaining robust single-mode operation of the laser is a prerequisite for achieving linewidth compression.

2.2.3. Population Inversion Factor

The population inversion factor n_{sp} , also defined as the spontaneous emission factor, is the ratio of the spontaneous emission rate to the stimulated emission rate per laser mode, with the expression

$$n_{sp} = \frac{R_{sp}}{g v_g K} \quad (5)$$

This factor reflects the degree of population inversion. A higher n_{sp} indicates a lower inversion level, meaning that, after electrons are excited to the conduction band via stimulated absorption, they are more inclined to return to the valence band through spontaneous emission. This spontaneous emission process exacerbates the phase instability of the laser and degrades its monochromaticity and coherence. The value of n_{sp} is closely related to the active region structure, and optimizing the quantum well design can effectively reduce the spontaneous emission factor, thereby mitigating the negative impact of spontaneous emission on linewidth.

2.2.4. Cavity Length Limitation

The ultra-short cavity structure of VCSELs leads to a short photon lifetime, which in turn limits improvement in the Q-factor. As can be seen from the formula, the linewidth is

proportional to the square of the cold-cavity linewidth, which is one of the most critical parameters determining the linewidth of VCSELs. The calculation formula for cold-cavity linewidth is

$$\Delta\nu_c = Tc/2n_gL_C \quad (6)$$

where T is the round-trip optical loss (including transmission and coupling loss); n_g is the group velocity index; and L_c is the effective cavity length. Equation (6) shows that the cold-cavity linewidth is inversely proportional to the effective cavity length of the laser. Modifying the effective cavity length of the laser can reduce its cold-cavity linewidth, thereby compressing the emission linewidth. This is also one of the most commonly used methods for VCSEL linewidth narrowing [67].

Meanwhile, the Q-factor reflects the energy storage and loss characteristics of the optical cavity. A high Q-factor means that the optical cavity has excellent energy storage capacity and low loss, thus exhibiting a narrower linewidth. Introducing an additional resonance mechanism into the resonant cavity to achieve a high Q-factor is also the most widely used method for linewidth compression.

3. Key Technologies and Optimization Methods for Narrow-Linewidth VCSELs

Several SM VCSEL technologies have been developed over the past decades. Zn-diffusion apertures enable simultaneous improvement of SM output power and modulation speed by creating a built-in lateral index guide, which suppresses higher-order modes while maintaining low optical loss [43–45]. Buried tunnel junctions (BTJs) provide efficient current confinement and optical mode control in long-wavelength VCSELs, with the regrown tunnel junction aperture offering precise definition of the current injection area and reducing free-carrier absorption losses [46–48]. Surface relief engineering, in which a shallow etched pattern is fabricated on the top surface of the VCSEL, introduces a phase shift that discriminates against higher-order transverse modes by modifying the mirror reflectivity profile [46,49]. Additionally, on-chip external feedback cavities integrated with microlenses have been demonstrated to enhance fundamental transverse-mode oscillation and achieve stable SM operation with side-mode suppression ratios (SMSRs) exceeding 30 dB [50]. These strategies reduce modal density and improve side-mode suppression before additional linewidth-narrowing elements are introduced, and they therefore form an essential technical foundation for narrow-linewidth VCSEL design [51,52].

However, single-mode designs alone generally cannot fundamentally overcome the intrinsic linewidth limit of conventional VCSELs imposed by their ultra-short cavities. As discussed earlier in this work, the natural linewidth of conventional VCSELs typically remains on the order of 50–100 MHz. Therefore, the key advances in narrow-linewidth VCSELs do not merely repeat single-mode selection itself but rather build upon stable single-mode oscillation to further reduce the Schawlow–Townes linewidth and the phase noise associated with the Henry factor correction term, through approaches including external optical feedback, coupled-cavity enhancement, monolithically integrated passive high-Q cavities, and surface high-selectivity mode engineering.

In this sense, single-mode VCSEL technology addresses the question of “which mode oscillates”, while narrow-linewidth VCSEL technology further addresses “whether this mode can oscillate stably with higher spectral purity and lower frequency noise”. These two technologies are not mutually exclusive but rather form a continuous technological lineage with a clear hierarchical relationship.

In laser physics, linewidth is a critical parameter characterizing the monochromaticity of laser emission. Theoretical studies have shown that the intrinsic linewidth of a laser is proportional to the square of the cold-cavity linewidth of the resonant cavity. Since the

cold-cavity linewidth is inversely proportional to the optical length of the resonant cavity, effective compression of the intrinsic linewidth can be achieved by optimizing the resonator design, especially by increasing the cavity length.

However, in practical operating environments, the output linewidth of the VCSEL is also affected by various external disturbances, such as cavity thermal deformation caused by temperature fluctuations, structural perturbation of the resonant cavity induced by mechanical vibration, and refractive index changes caused by acoustic noise. At present, the main technical methods to achieve linewidth compression of VCSELs focus on increasing the resonant cavity length of the VCSEL, external optical feedback, and surface patterning. These routes differ not only in achievable linewidth but also in integration level, fabrication complexity, environmental robustness, and suitability for different application scenarios [Table 1].

Table 1. Development trends of VCSEL linewidth-narrowing technology.

Technology Category	Core Principle	Typical Linewidth Range	Advantages	Limitations	Commercial Maturity
External-cavity optical feedback	Extend photon lifetime, improve the Q factor, and suppress spontaneous emission noise	Strong feedback: KHz level~sub-MHz [49–53]	Large linewidth narrowing, single-mode stability	Bulky system, low integrability, high precision	Low (laboratory-scale systems)
		Weak feedback: 2~40 MHz [54,55]	Low system noise, easy regulation of feedback phase, low sensitivity to environmental disturbances	Strict integration constraints, disturbance-prone	Medium (prototype devices)
Coupled-cavity structure	Increase effective cavity length, suppress mode competition	1 MHz~tens of 30 MHz [56–58]	High monolithic integrability, wide thermal stability	High epitaxial precision demand, complex fabrication	Medium–High (near commercialization)
Surface patterning	Nano-patterned gratings enhance mode selectivity	Minimum 2.46 MHz~10MHz [66–68]	Synergistic linewidth-polarization optimization, high-T stability	Complex design, high nanofabrication cost	Low–Medium (research stage)

3.1. External-Cavity Optical Feedback Technology

External-cavity optical feedback is a classic method for linewidth compression of semiconductor lasers. By adding optical elements such as mirrors outside the laser to form an external-cavity resonant structure, the photon lifetime can be significantly prolonged, and the Q-factor can be improved, thereby compressing the linewidth.

In 1986, Tkach and Chraplyvy at AT&T Bell Laboratories systematically investigated the spectral characteristics of 1.5 μm distributed-feedback (DFB) lasers under different feedback levels. They found that the mode characteristics and linewidth of the device evolve with feedback strength: under weak feedback, appropriate adjustment of the feedback phase achieves excellent linewidth compression and mode hopping suppression; under strong feedback, the linewidth is significantly narrowed, but the noise intensity also increases [68]. This seminal study laid the theoretical foundation for the application of external-cavity feedback technology, enabling device performance optimization such as mode competition suppression and linewidth narrowing by tuning the feedback strength, and it remains widely cited to this day.

Mizunami et al. achieved external-cavity optical feedback by integrating a fiber Bragg grating into a single-mode fiber. Laser light was coupled via a self-focusing lens, narrowing the VCSEL linewidth from 85 pm to 64 pm. Controlling the laser drive current further compressed the linewidth to 52 pm [69]. The structural diagram is shown in Figure 2. Hlaing et al. experimentally studied the spectral characteristics of multi-mode VCSELs under optical feedback. They found that proper adjustment of the feedback mirror's angle and position suppresses higher-order modes and that optical feedback greatly narrows the laser linewidth. Under optimal feedback strength, the linewidth is reduced from over 40 GHz to around 10 GHz [70]. Dowd et al. conducted beat frequency measurements on two external-cavity feedback VCSELs, generating a 190 kHz linewidth millimeter-wave

signal. The original VCSEL linewidth was 65 MHz, reduced by two orders of magnitude to ~100 kHz [71]. Jiang et al. proposed a method to compress the VCSEL linewidth using resonant feedback from an on-chip micro-ring add-drop filter. The high-Q external-cavity system employs an optical circulator and a 3 dB coupler. Experiments achieved a Q-factor of 1.36 million and an instantaneous linewidth of 32.6 kHz with good frequency and spectral stability [72].

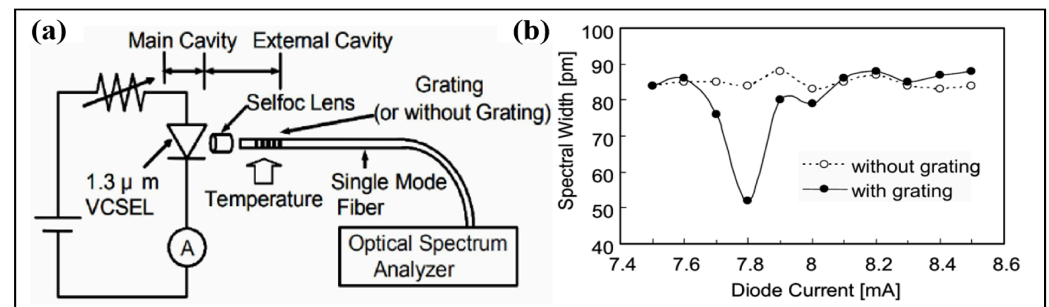


Figure 2. Experimental setup [69]. (a) Structural diagram of optical feedback VCSEL based on fiber Bragg grating. (b) Measured spectral width of the VCSEL output with and without a fiber Bragg grating used for variation of the laser.

External-cavity optical feedback can be divided into strong-feedback and weak-feedback regimes. While the above studies focus on system-level optimization, the device itself remains unchanged. External-cavity feedback technology also has inherent drawbacks: increased system volume, reduced integration, high sensitivity to feedback phase, and susceptibility to environmental disturbances. These limitations have driven researchers to explore more-compact and stable linewidth compression schemes. In recent years, researchers have designed solutions with better integration, smaller volume, and monolithic integration of the device and feedback system.

Because linewidth reduction in external-cavity VCSELs is strongly phase-dependent, practical deployment increasingly relies on active phase stabilization. Representative solutions include piezo/MEMS cavity-length tuning, current tuning, Pound–Drever–Hall or harmonic locking, and digital optoelectronic servo loops that monitor reflection, beat-note, or error signals and continuously correct the feedback phase [73,74]. For highly integrated systems, self-injection locking to high-Q micro-resonators is also attractive because the resonator simultaneously filters frequency noise and provides a passive phase reference [73]. In future compact VCSEL modules, the combination of on-chip photodetection, automatic bias control, and feedback-phase locking will be crucial for maintaining narrow linewidth under temperature and vibration perturbations.

Ouvrard et al. fabricated microcavity and external-cavity VCSELs on half-VCSEL structures: the microcavity adopted a 99% reflectivity $\text{TiO}_2\text{-SiO}_2$ dielectric mirror, and the external cavity integrated a 10 GHz spacing air gap and a 99.5% reflectivity 15 mm curvature concave dielectric mirror, which exhibited narrower linewidth with high SMSRs [75]. Chow et al. fabricated MEMS-tunable, curved thin-film mirrors to form a long optical cavity with VCSELs. This wafer-level external cavity boosts cavity length and Q-factor, yielding 2.1 mA threshold, 2 mW power, ideal single-mode performance (theoretical sub-MHz linewidth) and an experimental 8.5 MHz linewidth [76]. In 2022, Wang’s team (CIOMP, CAS) developed a microlens-integrated external-cavity VCSEL with a non-magnetic package (≤ 0.03 nT, p-p). It delivered 38 MHz linewidth and 36.3 dB SMSR at 90 °C with stable single-mode operation, satisfying atomic magnetometer needs [16].

In 2025, the team led by Professor Baolu Guan at Beijing University of Technology fabricated a novel, coupled VCSEL integrated with a cholesteric liquid crystal (CLC)

film [77]. Cholesteric liquid crystals possess a unique helical molecular structure that can selectively reflect circularly polarized light (Figure 3a,b). This work takes advantage of the weak optical feedback effect of the outer cavity of the CLC, resulting in a significant compression of the linewidth of the VCSEL. When the length of the coupled cavity is less than 150 μm , it can deliver an ultra-narrow linewidth of 2.46 MHz while maintaining a low threshold current and high beam quality (Figure 3c,d). This pioneering work is the first to successfully apply liquid crystal materials to VCSEL linewidth compression, opening up a new technical route.

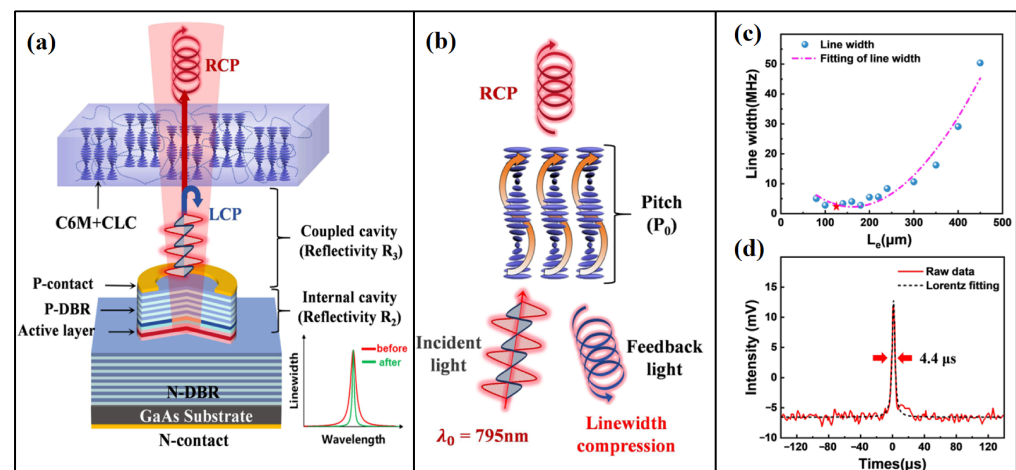


Figure 3. Sample and experimental setup [77]. (a) Schematic diagram of the narrow-linewidth coupled-cavity CLC-VCSEL. (b) Principle of optical feedback in CLC film. (c) Variation of laser linewidth with different L_e under 1 mA operation current; the red asterisk point indicates the smallest data of the linewidth measurement. (d) Linewidth results and the corresponding Lorentzian fitting curve at the asterisk point.

3.2. Coupled-Cavity Structure Technology

Coupled-cavity structures achieve optical field coupling within the cavity by integrating multiple resonant cavities on the same chip, thereby prolonging the photon lifetime and improving the Q-factor. According to different coupling methods, they can be divided into longitudinally coupled cavities and transversely coupled cavities. Longitudinally coupled cavities form a multi-cavity cascaded structure by adding additional cavity layers above and below the active region, while transversely coupled cavities realize coupling through optical field overlap between adjacent devices.

In 2009, Serkland's group at Sandia National Laboratories achieved linewidth narrowing in 850 nm monolithic VCSELs by extending the effective cavity length [78]. The simulated cold-cavity linewidth decreased from 50 MHz to 23 MHz with a spectral reduction of 0.051 nm, while the measured linewidth was halved, as presented in Figure 4. Fan Y. L. et al. from the University of Chinese Academy of Sciences further compressed the output linewidth of the laser to 32 MHz by adding four layers to the bottom DBR to increase the length of the internal resonant cavity [79]. They also tested the device performance at different temperatures, demonstrating that it can operate at 90 °C as required by CSAC systems. In 2024, Wu's group at IMECAS demonstrated a novel 795 nm longitudinally coupled, three-cavity VCSEL comprising one active cavity and two passive cavities [18]. Epitaxially integrated transition layers within the bottom DBR extend the effective cavity length, prolonging photon lifetime and suppressing higher-order transverse modes via enhanced diffraction loss. The device exhibits a linewidth of 7.3 MHz and single-mode output power of 4.6 mW at 25 °C, although precise cavity resonance–gain matching remains essential for stable single-longitudinal-mode operation.

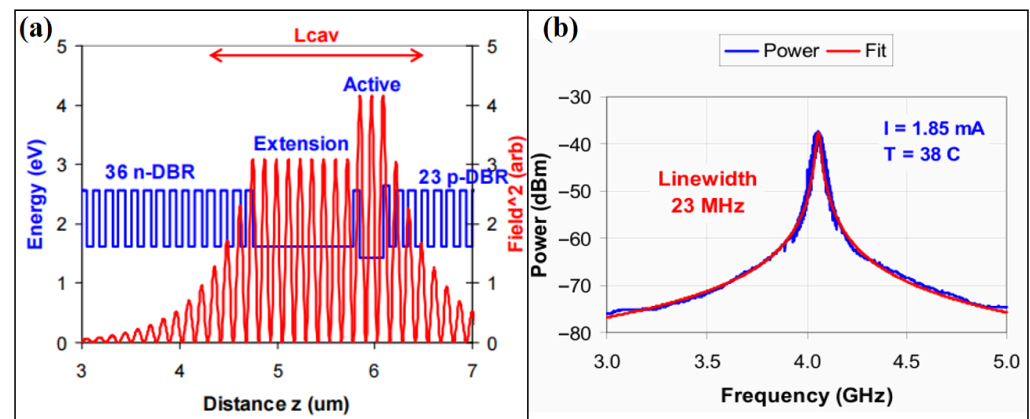


Figure 4. Epitaxial structure and simulated standing wave field distribution, effective cavity length L_c (a) narrow linewidth VCSEL design increases the effective cavity length of n-DBR cycle and (b) corresponding linewidth values [56].

To date, the optimal linewidth narrowing achieved using coupled-cavity configurations has reached 1.11 MHz. In 2026, Wu's group at UESTC demonstrated a monolithically integrated, passive-cavity VCSEL embedded in the bottom DBR, yielding an intrinsic linewidth of 1 MHz. The device exhibits excellent SMSRs, polarization suppression, low beam divergence, and low threshold current, with stable single-mode operation over a broad temperature range. When integrated into a cesium atomic clock, it delivers a frequency stability of $1.89 \times 10^{-12} \tau^{-1/2}$, representing an internationally leading breakthrough in precision metrology and quantum sensing [80].

The common feature of the above schemes is that they increase the effective cavity length, effectively prolonging the photon lifetime and compressing the linewidth. However, they require precise control of the thickness of each cavity layer, and single-longitudinal-mode output of the VCSEL must be achieved by adjusting the cavity length and the matching between the cavity resonance and the gain spectrum.

3.3. Surface Patterning Technology

The principle of achieving narrow-linewidth output through surface patterning mainly involves introducing specific nanoscale patterns, photonic crystals, or Bragg reflector structures on the surface of the gain medium or within the cavity. These structures can precisely control the propagation path and resonance conditions of light. The patterned surface can selectively enhance or suppress specific optical modes, thereby improving mode selectivity, reducing the impact of mode competition, and achieving narrow-linewidth output. In addition, the patterned structure can increase the photon residence time and reduce photon leakage loss, thereby improving the quality factor, which is a physical quantity measuring the quality of the optical cavity.

The formation of traditional high-Q resonant cavities mainly relies on photonic crystals, ring resonant structures, DBRs, and distributed-feedback (DFB) structures. A subwavelength grating (SWG) refers to a diffraction grating with a period smaller than the optical wavelength [81,82]. When a plane wave is incident on the SWG, only the zero-order diffracted wave can propagate, while higher-order diffracted waves become evanescent waves. By rationally designing the grating parameters, the evanescent wave can achieve phase matching with the waveguide mode, resulting in guided-mode resonance (GMR), which realizes high reflectivity and ultra-narrow linewidth at a specific wavelength [83,84]. SWGs exhibit the characteristics of high reflectivity, narrow bandwidth, polarization selectivity, and wavelength tunability [85]. Meanwhile, high-contrast gratings (HCGs), which are made of high-refractive-index materials, are also used to achieve narrow linewidth [86].

At present, significant progress has been made in the research on narrow-linewidth VCSELs based on gratings. Zhou et al. introduced a high-Q resonant cavity employing a high-contrast grating (HCG) capable of broadband reflectivity exceeding 99% [87]. The structure comprises an HCG top mirror, an air gap, an active λ cavity, and a bottom n-DBR, yielding an emission FWHM of ~ 0.07 nm and a Q-factor of approximately 14,000.

Guan's group at Beijing University of Technology systematically explored coupled-cavity VCSELs integrating subwavelength gratings (SWGs) and high-contrast gratings (HCGs) [88–90]. Numerical optimization of grating and cavity parameters enabled an ultra-narrow linewidth of 2.74 MHz, with preferential TE-mode amplification and TM-mode suppression. The device exhibits an outstanding optical polarization suppression ratio (OPSR) exceeding 40 dB and stable linewidth performance up to 80 °C, as illustrated in Figure 5. As a promising pump source for atomic clocks, the VCSEL linewidth plays a pivotal role in determining clock precision and stability.

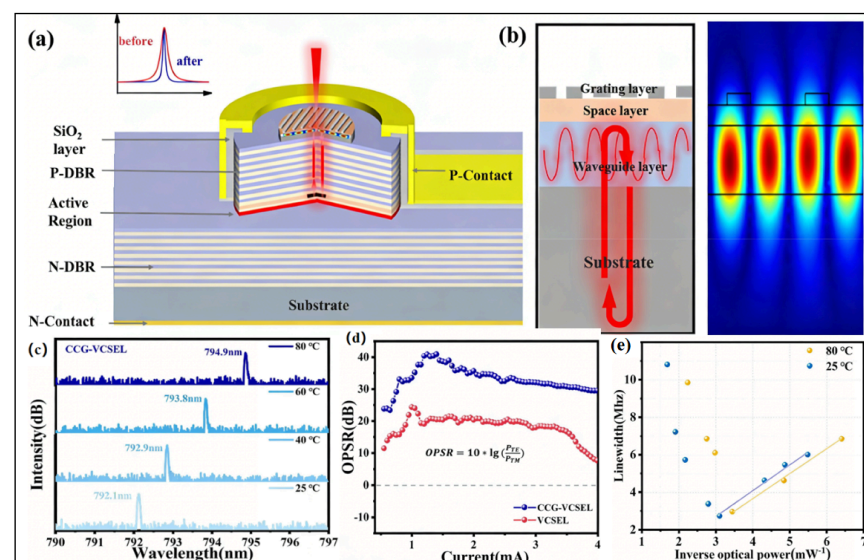


Figure 5. (a) Schematic diagram of the HCG-VCSEL structure. (b) Schematic diagram of the optical coupling of the active region resonant light and the guided-mode resonance grating (GMRG) waveguide layer and the electric field diagram. Spectra of the (c) HCG-VCSEL. (d) OPSR comparison between HCG-VCSEL and VCSEL. (e) Under the test conditions of 25 and 80 °C, respectively, the output linewidth of HCG-VCSEL changes with the inverse optical power [89].

Although surface patterning, particularly HCGs or metasurface architectures, can substantially reduce the VCSEL linewidth via enhanced mode selectivity and reflective phase engineering, industrial translation of such schemes remains constrained by several practical limitations. First, key performance metrics are highly sensitive to nanoscale feature precision, etch depth, sidewall roughness, and wafer-scale uniformity, resulting in relatively narrow process windows. Second, complex nanofabrication increases wafer-level manufacturing costs and may degrade device yield and batch-to-batch consistency. Third, surface structures are vulnerable to thermal stress, packaging-induced strain, and contamination, which can compromise long-term environmental robustness.

Nevertheless, recent advances in deep-UV lithography, nanoimprint lithography, wafer-scale metasurface manufacturing, and co-integration of VCSELs with planar photonics have unlocked strong potential for scalable replication and functional integration of surface-patterned VCSELs. Accordingly, this technology is expected to evolve along two parallel pathways: high-performance precision devices for low-volume applications and standardized wafer-level surface functional integration for scalable production.

3.4. Other Technical Routes

Quantum dots (QDs) possess a discrete energy level structure, which can significantly reduce the linewidth enhancement factor (α -factor), thereby compressing the laser linewidth [91,92]. Newell et al. investigated the subthreshold gain and linewidth enhancement factor α of 1.22 μm InAs quantum dot lasers. Using an improved ASE spectral measurement method, they found that the gain increases super linearly and is flat within a 3 nm range, with an α as low as 0.1 measured at 61 mA (before gain saturation) [93]. Quantum dot VCSELs also exhibit the advantages of excellent temperature stability and low threshold current.

In the fabrication process of VCSELs, an oxide confinement layer is generally used to confine the optical field and transverse current of the VCSEL. VCSELs with a small oxide aperture can suppress the lasing of transverse higher-order modes, reduce the frequency noise caused by mode competition, and narrow the linewidth of the VCSEL to a certain extent. Kao et al. pointed out in their study that, by reducing the output aperture of an 850 nm multi-transverse-mode VCSEL from 11 μm to 3 μm , single-mode VCSEL output can be obtained, with a laser linewidth of 0.03 nm [94].

Metasurfaces and metamaterials are emerging novel optical elements in recent years that enable flexible manipulation of the optical field through subwavelength structures [95–97]. Introducing metasurfaces into VCSEL structures can realize functions such as anomalous reflection, polarization control, and wavefront shaping, providing new possibilities for VCSEL performance optimization. Optimizing and manipulating the beam quality using metasurface structures provides a new possibility for VCSELs to not only optimize the beam quality (such as linewidth compression) but also control the beam angle and phase in the future.

Chang Hasnain's group proposed a single-transverse-mode VCSEL employing a chirped high-contrast metastructure (HCM) top mirror with lateral graded reflectivity [98]. This design efficiently suppresses higher-order modes while simplifying fabrication, enabling stable single-mode operation with SMSR > 40 dB across a wide temperature and current range. The results reveal that superior single-mode operation is accompanied by a modified Gaussian beam waist radius, which offers a promising route toward further linewidth narrowing in VCSELs.

Overall, the three narrow-linewidth VCSEL technology pathways are each optimized for distinct engineering objectives. External optical feedback is best suited for experimental systems requiring rapid prototyping and validation with ultimate narrow-linewidth performance, though its primary limitations lie in long-term stability and packaging complexity. Coupled-cavity/extended-cavity architectures offer a more balanced trade-off among integration density, stability, and linewidth compression capability, making them particularly ideal for applications such as CSACs that demand stringent size, power consumption, and long-term reliability specifications. Surface patterning and mode engineering, by contrast, provide distinct advantages in single-mode selection, polarization control, and wavefront shaping and are exceptionally well-suited for co-design with planar optical components, beam-shaping elements, and on-chip integrated systems.

4. Summary and Prospects

This review systematically dissects the physical mechanisms underlying linewidth broadening in VCSELs and comprehensively assesses state-of-the-art technical routes for narrow-linewidth VCSELs, with a central focus on three core directions: coupled-cavity engineering, optical feedback regulation, and monolithic polarization mode control. Ground-breaking advances typified by CCG-VCSELs, CLC-VCSELs, and passive-cavity embedded VCSELs have fundamentally overcome the linewidth limitations imposed by the intrinsic

ultra-short cavity architecture of conventional VCSELs. These devices deliver ultra-narrow linewidth, exceptional single-mode performance, and stable output power, fully satisfying the stringent requirements of chip-scale atomic clocks and quantum sensing applications while elevating the spectral coherence of monolithic VCSELs to match distributed-feedback semiconductor lasers and retaining their inherent merits of low threshold current, high integration density, and low power consumption.

Despite these remarkable achievements, three core bottlenecks persist: the inherent trade-off between linewidth narrowing and integration density, insufficient environmental robustness under harsh operating conditions, and high-precision fabrication requirements with low yield and high cost that impede large-scale commercialization.

Looking ahead, research will focus on five transformative directions: (i) synergistic innovation of novel material systems and ultra-high-quality-factor (Q-factor) resonant cavity designs and single-mode-first cavity designs combining BTJ, Zn-diffusion, surface-relief, or grating mode filters with linewidth-narrowing structures; (ii) optimized high-performance external-cavity feedback systems, phase-stabilized integrated feedback using micro-rings, MEMS, or on-chip servo control [72–74]; (iii) monolithic integration of fully functional coherent optoelectronic chips; (iv) extreme-environment performance optimization via opto-thermal co-regulation; (v) heterogeneous integration of VCSELs with silicon/silicon-nitride photonics, wafer-level micro-optics, and micro-transfer-printed components for low-cost mass production [31,99–101].

With interdisciplinary innovations across materials science, laser physics, and micro-/nanofabrication, narrow-linewidth VCSELs are poised to break through current performance boundaries and emerge as the core cornerstone of next-generation miniaturized precision optical systems.

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