SCIENCE CHINA
Information Sciences

• REVIEW •

August 2022, Vol. 65 181401:1–181401:18
https://doi.org/10.1007/s11432-021-3454-7

Advances in wide-tuning and narrow-linewidth external-cavity diode lasers

Qiang CUI[1,2], Yuxin LEI[1*], Yongyi CHEN[1*], Cheng QIU[1], Ye WANG[1,3], Dexiao ZHANG[1,4], Lutai FAN[1,2], Yue SONG[1], Peng JIA[1], Lei LIANG[1], Yubing WANG[1], Li QIN[1], Yongqiang NING[1] & Lijun WANG[1*]

[1]*State Key Laboratory of Luminescence and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun* 130033*, China;*
[2]*Daheng College, University of Chinese Academy of Sciences, Beijing* 100049*, China;*
[3]*School of Opto-Electronic Engineering, Changchun University of Science and Technology, Changchun* 130022*, China;*
[4]*Jiguang Semiconductor Technology Co., Ltd., Changchun* 130033*, China*

Received 31 December 2021/Revised 1 March 2022/Accepted 8 March 2022/Published online 24 June 2022

Abstract The external-cavity diode laser is advantageous in terms of low noise, high side-mode suppression ratio, high temperature stability, simple structure, and low cost, which has been the preferred scheme to realize wide-tuning and narrow-linewidth characteristics. Thus, it has been widely used in optical communication, lidar, environmental monitoring, spectral analysis, optical coherence tomography, and other frontier fields. Herein, we introduce the technical scheme and review the development status of wide-tuning and narrow-linewidth external-cavity diode lasers in detail. Primarily, the structure, working principles, and performance characteristics of external-cavity diode lasers are deeply analyzed according to different structures. The structural characteristics, key technologies, optical performance and application fields of state-of-the-art studies in recent years are discussed. Finally, the challenges and potential development prospects of wide-tuning and narrow-linewidth external-cavity diode lasers are analyzed and discussed.

Keywords wide tuning, narrow linewidth, external-cavity diode laser, semiconductor laser, Littrow, Littman

Citation Cui Q, Lei Y X, Chen Y Y, et al. Advances in wide-tuning and narrow-linewidth external-cavity diode lasers. Sci China Inf Sci, 2022, 65(8): 181401, https://doi.org/10.1007/s11432-021-3454-7

1 Introduction

With the rapid development of the Internet era, optical communication technology, an important application field of semiconductor lasers, has placed higher requirements on the spectral tuning range and linewidth characteristics of semiconductor lasers. Optimizing the linewidth characteristic of a light source can increase the transmission length and transmission capacity of an optical communication system. Expanding the spectral tuning range of a light source can reduce the number of required lasers and improve the flexibility of the optical communication network, which is beneficial for realizing the miniaturization and integration of a communication system to reduce cost [1–3]. Additionally, wide-tuning and narrow-linewidth laser sources are widely used in the high-resolution spectral analysis [4], lidar [5, 6], environmental gas detection [7], coherent light detection [8], spatial coherent laser communication [9], biomedicine [10], and atomic clock timing [11].

Semiconductor lasers based on internal-cavity feedback, such as distributed feedback (DFB) and distributed Bragg reflector (DBR) semiconductor lasers, have difficulty eliminating the effect of linewidth broadening caused by the inherent large cavity loss and spontaneous radiation of the gain medium, which considerably restricts linewidth characteristics [12, 13]. Moreover, electric tuning based on the carrier-dispersion effect or thermal tuning based on the thermo-optic effect limits the wavelength-tuning range

* Corresponding author (email: leiyuxin@ciomp.ac.cn, chenyy@ciomp.ac.cn, wanglj@ciomp.ac.cn)

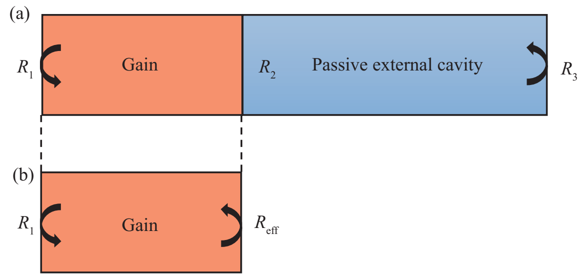

Figure 1 (Color online) (a) ECDL model and (b) equivalent cavity surface model.

of these lasers to a few nanometers [14, 15]. As related applications progress, the linewidth and spectral characteristics of internal feedback semiconductor lasers no longer meet the ever-increasing requirements. An external-cavity diode laser (ECDL) was introduced to achieve a wider wavelength-tuning range and narrower linewidth characteristics of the laser light source [7]. The ECDL is based on a semiconductor gain chip, and external mode-selection components, lens and mirrors are introduced to extend the resonant cavity outside the gain chip. Compared with the internal-cavity feedback semiconductor laser, the ECDL relies on its longer cavity length and more flexible tuning components to obtain a narrower linewidth and a wider wavelength-tuning range. In addition, the ECDL possesses the advantages of a simple structure, high side-mode suppression ratio (SMSR), low noise, and high temperature stability; therefore, it has become a research hotspot in recent years.

This article reviews the research progress on wide-tuning and narrow-linewidth ECDLs. In Section 2, we introduce the characteristics and principles of the ECDL based on different structures. In Section 3, research advances and applications of different ECDL types are discussed. Finally, the development status of the ECDL is summarized, and its challenges and potential development directions are discussed in Section 4.

2 Structures and principles of ECDL

An ECDL typically comprises an active-gain internal-cavity region and a passive-feedback external-cavity region. The active-gain region generally consists of a gain chip that provides spectral gain, and the gain-spectrum range of the gain chip determines the maximum wavelength-tuning range of the ECDL. The external-cavity region typically includes optical feedback elements, such as gratings, filters, and waveguides. The wavelength-tuning and linewidth-narrowing functions are primarily realized through the external cavity. The ECDL structure is equivalent to the model structure shown in Figure 1(a). The reflectivity of both sides of the active-gain cavity is referred to as R_1 and R_2, and the other side of the passive external cavity is referred to as R_3. Moreover, the entire passive external-cavity region is equivalent to a cavity surface $R_{\rm eff}$ in Figure 1(b) [16].

ECDLs can be divided into three categories: discrete-device-type ECDL, which is constructed by the coupling of various discrete modules, waveguide-type ECDL based on external low-loss waveguides, and fiber-type ECDL, which is coupled with external special fiber structures.

2.1 Discrete-device-type ECDL

Discrete-device-type ECDLs can be divided into three structures: Littrow-ECDL, Littman-ECDL, and filter-ECDL, based on the different mode-selection devices and mechanisms in the external resonant cavity.

2.1.1 *Littrow-ECDL*

As shown in Figure 2, the Littrow-ECDL typically comprises a gain chip, coupling lens, and diffraction grating. The grating in the external cavity is the main mode-selection element, which performs the functions of wavelength tuning and linewidth narrowing. The performance of the Littrow-ECDL strongly depends on the grating. Commonly used diffraction gratings include reflection [17–19], transmission [20], and blazed gratings [21].

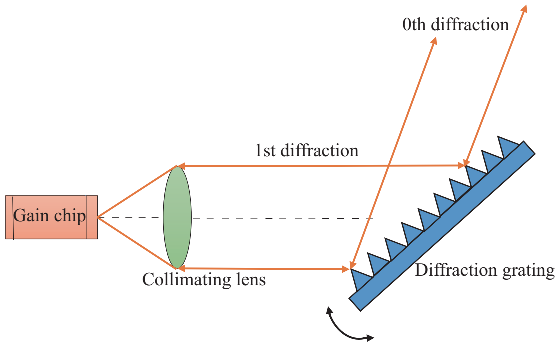

Figure 2 (Color online) Schematic of Littrow-ECDL.

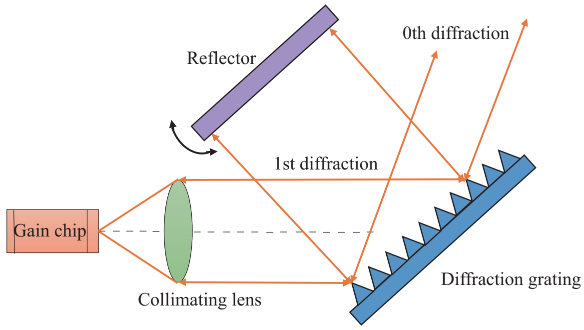

Figure 3 (Color online) Schematic of Littman-ECDL.

First, the light emitted from the gain chip, after being collimated by the lens, diffracts on the grating. The first-order diffraction is then fed back to the active area of the gain chip along the incident optical path. The reflection end face of the gain chip and grating constitute the resonant cavity, and zero-order diffraction is used as the output laser. Using the resonant mode formula (1) of the resonant cavity and the minimum-loss wavelength formula of the grating (2), the wavelength that satisfies the lasing condition can be determined [22]

$$L = q(\lambda_q/2), \tag{1}$$

$$\lambda = 2a\sin\theta, \tag{2}$$

where L is the effective cavity length, q is a positive integer, λ is the wavelength, a is the grating period, and θ is the diffraction angle of the grating. Wavelength tuning is achieved by rotating the grating angle to change the first-order diffraction angle θ. Under ideal conditions, the wavelength-tuning range of the Littrow-ECDL is similar to the gain-spectrum width of the gain chip.

According to the linewidth formula of the grating external-cavity laser [23],

$$\Delta\nu = \frac{\Delta\nu_0}{(1+\alpha^2)\cos^2\varphi}\frac{R_2}{(1-R_2)^2 R_d}\left(\frac{nl}{L}\right)^2, \tag{3}$$

where $\Delta\nu$ is the linewidth of the external-cavity laser, $\Delta\nu_0$ is the linewidth of the gain chip, α is the linewidth expansion factor, cosφ is the phase-matching factor, R_2 is the reflectivity of the rear face of the laser cavity, R_d is the first-order diffraction efficiency of the grating, and l is the length of the laser's internal cavity. Building an external cavity with a grating can significantly increase the effective laser-cavity length. The introduction of the grating increases the reflectivity of the end face of the resonator and reduces the threshold gain. It is beneficial to increase stimulated emission and suppress spontaneous emission to make the laser linewidth narrower.

2.1.2 *Littman-ECDL*

As shown in Figure 3, the Littman-ECDL is typically formed by adding a mirror to the grating side of the Littrow structure. The first-order diffraction is reflected by the mirror and returned to the grating for the second diffraction. Then, the first-order diffraction is fed back to the active region of the gain chip along the incident light path to produce resonance. Unlike the Littrow structure, wavelength tuning is controlled by rotating the mirror instead of the grating.

Figure 4 shows a schematic of the Littman-ECDL mode selection. Figure 4(a) shows the gain-spectrum range of the gain chip. The mirror and grating make the light resonate only in the $\delta\lambda$ wavelength range, where the loss decreases sharply. Figures 4(b) and (c) show the spectrograms of the gain chip and the external-cavity laser, respectively. The longitudinal mode intervals of the gain chip ($\Delta\lambda_d$) and external-cavity laser ($\Delta\lambda_c$) are as follows [24]:

$$\Delta\lambda_d = \frac{\lambda^2}{2n_g l}, \tag{4}$$

$$\Delta\lambda_c = \frac{\lambda^2}{2(L_f + L_d + L_r)}, \tag{5}$$

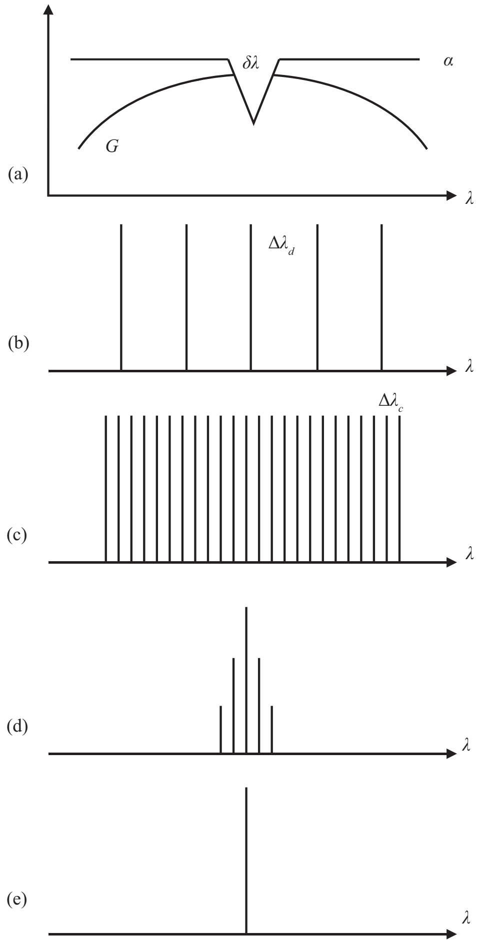

Figure 4 Schematic of Littman-ECDL mode selection. (a) Gain-medium gain curve and loss curve; (b) gain chip spectrogram; (c) external-cavity spectrogram; (d) gain-saturation competition; (e) mode competition results in a single longitudinal mode.

where n_g is the group refractive index, L_f is the distance between the laser exit point and collimator lens, L_d is the distance between the collimator lens and diffraction grating, and L_r is the distance between the diffraction grating and tuning mirror. Since the length of the external cavity is significantly larger than that of the internal cavity, the free spectral range (FSR) of the external cavity is notably smaller than that of the internal cavity, as shown in Figures 4(c) and (b). After the gain-saturation competition and mode competition, shown in Figure 4(d), the peak wavelength in the range of $\delta\lambda$ forms single longitudinal mode lasing, as shown in Figure 4(e). By rotating the mirror, the $\delta\lambda$ range moves to achieve wavelength tuning.

The linewidth of the Littman-ECDL can be expressed as [25]

$$\Delta\nu = \Delta\nu_0 \frac{1}{[1 + \tau/\tau_{\rm in}(1 - \sqrt{R_2/R_{\rm out}})]^2}, \tag{6}$$

where $R_{\rm out} = R_r R_d R_d$ is the reflectivity of the external cavity, and R_r is the reflectivity of the mirror. τ and $\tau_{\rm in}$ are the times that the photons take to travel back and forth between the active region of the gain chip and the external cavity, respectively; these times are related to the lengths of the internal and external laser cavities. Therefore, the linewidth of the Littman-ECDL is closely related to the length of the external cavity, reflectivity of the output end of the gain chip, first-order diffraction efficiency of the grating, and reflectivity of the tuning mirror [26]. In addition, a previous study unveiled that a higher grating resolution results in a narrower linewidth [27].

2.1.3 *Filter-ECDL*

The filter-ECDL typically comprises a gain chip and devices with an optical filtering function in the external resonant cavity. The basic structure is shown in Figure 5.

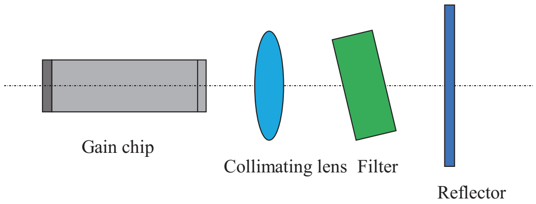

Figure 5 (Color online) Schematic of filter-ECDL.

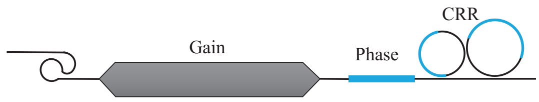

Figure 6 (Color online) Schematic of MRR-ECDL.

Commonly used optical filter components include the Fabry-Perot (FP) cavity etalon [28], acousto-optic tunable filter (AOTF) [29, 30], electro-optic tunable filter [31], birefringent filter (BRF) [32, 33], interference filter (IF) [34, 35], micro-electro-mechanical systems (MEMS) tunable optic filter [36], all-dielectric thin film Fabry-Perot filter (AFPF) [37], guided-mode resonator filter (GMRF) [38], and liquid crystal film [39]. By choosing different optical filters, the wavelength-tuning and linewidth-narrowing laser mechanisms also change accordingly. Therefore, lasers exhibit significant differences in performance. The most significant feature of the filter-ECDL is its extremely high flexibility.

The mode-selection function of the optical filter in the external resonant cavity is an important factor for the single longitudinal mode output of the filter-ECDL. In general, the above-mentioned optical filter components have a mode-selection feature, and each has a mode with the highest transmittance. When the multimode laser emitted by the gain chip passes through the optical filter, only the beam with the highest-transmission-peak wavelength can pass through, thereby achieving longitudinal mode selection. However, some optical filters have a periodic comb spectrum, which does not have a mode-selection function. It must cooperate with other devices or lasers to achieve the highest transmission peak through spectral superposition and mode competition, which results in a single longitudinal mode output. Therefore, the principle of the wavelength tuning of the filter-ECDL is based on changing the position of the highest-transmission-peak wavelength by changing the filter's refractive index, transmission angle, or FSR of the periodic comb spectrum by tuning the cavity length. Meanwhile, combined with the phase-matching region, the linewidth can be further narrowed based on the precise mode selection of the filter and the effective cavity-length increase.

2.2 Waveguide-type ECDL

As shown in Figure 6, a microring resonator (MRR)-type ECDL is typically formed by coupling a semiconductor optical amplifier (SOA) and planar optical waveguide, and the waveguide acts as an external resonator cavity. Planar optical waveguides include a phase-adjustment region and an MRR structure. The MRR is usually a double-microring structure with unequal radii that realizes the mode-selection function through asymmetric coupling. In addition, auxiliary structures, such as the Mach-Zehnder interferometer (MZI) [40], may be added to the optical waveguide to improve laser performance. Currently, the commonly used MRR optical waveguides are Si-based [19, 41–43], SiON-based, and Si_3N_4-based [40, 44].

The mode-selection mechanism of the MRR-ECDL typically superimposes two MRR spectra with different FSRs. As shown in Figures 7(b) and (c), the spectra of two filters with different FSRs are superimposed to align one λ_1 wavelength peak; however, the other peaks are staggered. Eventually, the superimposed spectrum is formed, as shown in Figure 7(d), and the laser realizes a single-mode operation.

Based on this, the MRR is electrically tuned or thermally tuned through the carrier-dispersion effect or thermo-optic effect, and the effective refractive index of the waveguide is changed. According to (7), which describes the resonance of light in the microring, the tuning function of the resonance wavelength can be realized.

$$q\lambda_q = n_{\rm eff} L, \tag{7}$$

where $n_{\rm eff}$ is the effective refractive index of the waveguide. However, owing to material refractive-index limitations, if only one MRR is adjusted, its tuning range is typically only a few nanometers. Therefore, the Vernier effect was introduced to achieve a wider wavelength-tuning range. By adjusting one of the dual MRRs so that its spectrum moves only a short distance, the alignment wavelength of the superposition spectra of the two MRRs can be changed from λ_1 to λ_2, thereby achieving a larger range of peak-wavelength switching. If the dual MRRs are adjusted simultaneously, the spectrum can be kept aligned and moved as a whole to achieve the continuous tuning of the lasing wavelength.

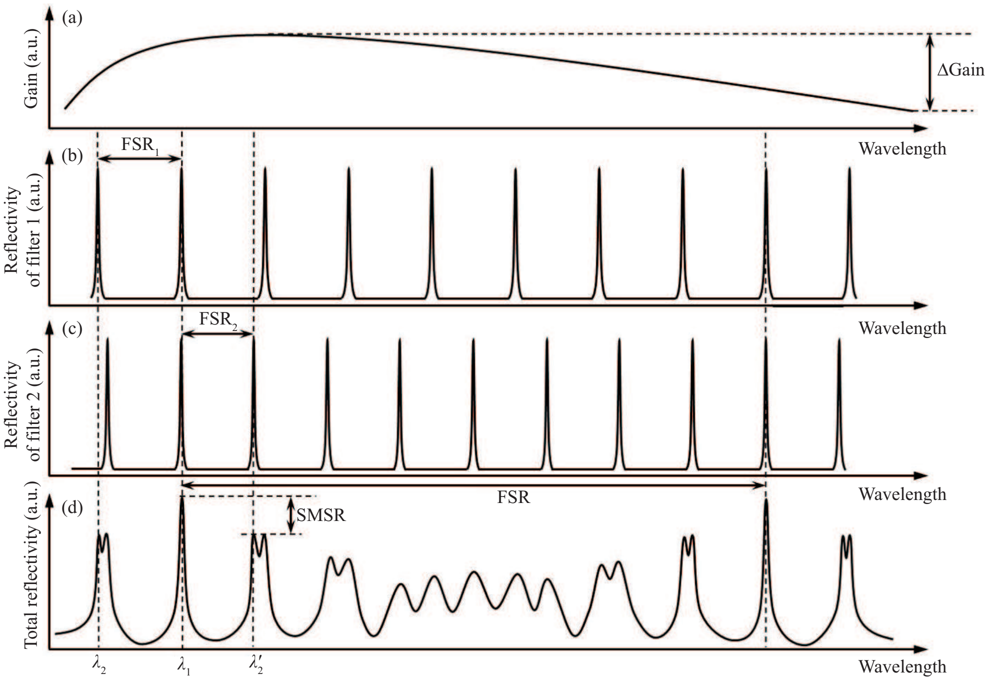

Figure 7 Schematic of MRR-ECDL mode selection based on cursor effect. (a) Gain-medium gain curve; (b) "filter 1" comb spectrum; (c) "filter 2" comb spectrum; (d) superimposed spectra of two filters.

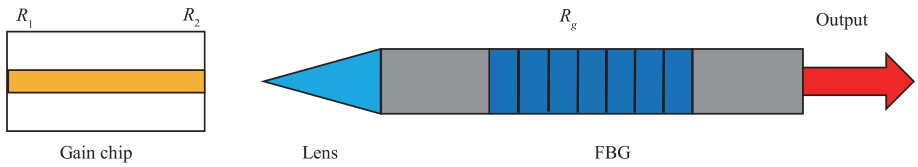

Figure 8 (Color online) Schematic of FBG-ECDL.

The linewidth narrowing of this type of laser is primarily achieved by a low-loss waveguide, high-Q-factor resonator, and an increase in the effective cavity length. It is worth mentioning that the microring waveguide structure can significantly increase the effective cavity length for a small structure size.

2.3 Fiber-type ECDL

A fiber-Bragg-grating (FBG) structure was introduced to the ECDL, owing to the continuous advancement of fiber grating technology. The gain chip is coupled with the FBG in the external resonant cavity through a tapered fiber lens to form an FBG-ECDL. The structure is shown in Figure 8.

By adjusting the temperature of the FBG or the external stress, the Bragg wavelength of the fiber grating can be changed to tune the wavelength of the FBG-ECDL. Moreover, the large group delay at the hypotenuse of the fiber grating can effectively narrow the linewidth of the semiconductor laser; therefore, the FBG-ECDL has an extremely narrow linewidth characteristic and a dynamic single-mode characteristic.

3 Research progress of ECDL

3.1 Discrete-device-type ECDL

3.1.1 *Littrow-ECDL*

The Littrow-ECDL provides the advantages of a wide wavelength-tuning range in the order of 100 nm or even submicron, fine adjustment, simple structure and realization, and high output power. However, the system has a large size owing to the use of mechanical rotating parts in this type of structure. Additionally, it is difficult to install and adjust the optical path. Moreover, the linewidth of this laser type is relatively wide, typically in the order of gigahertz. The grating has a high sensitivity; therefore, the structure is more susceptible to the influence of external light noise. Currently, Tsinghua University in China [45], Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences (CIOMP) [17], the University of Texas, Austin in the USA [46], Peter the Great Saint-Petersburg Polytechnic University in Russia [18], Australian National University [21], the University of Tampere in Finland [19], Brolis Semiconductors UAB in Lithuania [47], Aston University in England [48], among other research institutions [49–53], have conducted in-depth research on this topic.

As early as the 1960s, the Littrow structure was proposed for wavelength selection in multiwavelength lasers [49]. After more than 50 years of development, considerable progress has been made in this field. In 2019, Chen et al. [50] from the National Cheng Kung University of China reported a 445-nm blue InGaN diode laser in a traditional Littrow structure. The laser adjusts the position of the grating via piezoelectric ceramics (PZT) to achieve a single longitudinal mode laser output with a wavelength-tuning range of over 4 nm, maximum output power of 20 mW, and linewidth of 4.7 MHz.

However, the traditional Littrow structure [51–53] directly emits light from the grating; therefore, the output light direction changes with the rotation of the grating. With further improvements in the structure [48, 54–56], this problem is effectively solved when the laser is output from the back end of the gain chip. Currently, most research schemes in this category are based on an improved Littrow structure. In 2019, Wang et al. [17] of CIOMP studied tunable ECDLs based on bimodal-sized quantum dots. The laser adopts an improved Littrow external-cavity structure, which outputs from the rear face of the gain chip. The improved Littrow structure ensures that the laser is emitted by first-order diffraction, which enables an increase in power while keeping the light-emitting direction unchanged. The gain medium uses an InGaAs/GaAs bimodal-sized quantum-dot laser; the collimating lens is an aspheric mirror; the grating line density is 1200 l/mm; and, the total cavity length is 78 mm. By rotating the grating angle, the laser can achieve a wavelength-tuning range of 28.9 nm (970.1–999 nm), linewidth of less than 0.2 nm, and stable laser output power of 120 mW. In 2021, Wang et al. [45] from Tsinghua University developed a Littrow-ECDL based on InAs/InP quantum-dot lasers in the 1.5-μm band with a tuning range of 92 nm and maximum output power of 6.5 mW @ 500 mA. In the same year, Giraud et al. [57] of Alpes Lasers SA in Switzerland used the improved Littrow structure with an interband cascade laser as the gain chip. The laser achieved a wavelength-tuning range of 360 nm (313 cm^{-1}) from 3.22 to 3.58 μm, with a maximum output power of 13 mW.

In 2019, Podoskin et al. [18] of Peter the Great Saint-Petersburg Polytechnic University in Russia studied high-power tunable ECDLs based on InGaAs quantum wells to increase the output power of this type of laser. The laser adds a cylindrical lens to the original Littrow external-cavity structure to correct for divergent radiation. The laser has a continuous output power of 13 W, linewidth of 0.15 nm, wavelength-tuning range of 100 nm (960–1060 nm), and SMSR of 45 dB.

To reduce back reflection and the influence of the internal-cavity mode, the gain chip has gradually been changed from a straight-ridge waveguide to an inclined end-face waveguide [48, 58]. In 2020, Ojanen et al. [19] from the University of Tampere in Finland proposed tunable lasers based on inclined end-face waveguide gain chips. The grating rotates along the external pivot point to reduce the mode jump. The experiment shows that the tuning range of the laser reaches 154 nm (2513–2667 nm), with a 10 mW average maximum output power and a 100 mW peak power.

Subsequent research enabled the linewidth of the Littrow-ECDL to be narrowed to the kilohertz range. In 2020, Kapasi et al. [21] from the Australian National University developed a 2-μm narrow-linewidth tunable laser for gravitational-wave detection. Using a reflective blazed grating, the linewidth is narrowed to 20 kHz within a 10-ms integration time. The output power exceeds 9 mW, increasing up to 15 mW at a high current, and the wavelength-tuning range is 120 nm (center wavelength 1920 nm).

In addition to rotating the grating, the wavelength tuning of the Littrow-ECDL can also be achieved by translating a collimating lens. In 2010, Okamura et al. [59] from the International Christian University in Japan achieved continuous tuning of approximately 8 nm by translating the collimating lens in a Littrow structure. The lasing wavelength is changed by approximately 1 nm by shifting the collimating lens by 1 μm. In addition, the influence of the diffraction grating in the Littrow-ECDL was also studied. In 2016, Chi et al. [53] from the Technical University of Denmark observed that when using holographic diffraction gratings, the laser has higher efficiency and narrower linewidth, whereas when using engraved diffraction gratings, the laser has a wider wavelength-tuning range. In 2017, Ding et al. [60] from Xiamen University in China showed that the narrow feedback-wavelength range of the grating can produce a better mode-selection effect; thus, a PN junction of the gain chip placed parallel to the grating scribed line performs better than that at a vertical position.

Research on the Littrow-ECDL is relatively mature; therefore, in addition to more in-depth studies on the performance improvement of lasers, many reports on its applications have also been published. This laser type can achieve a wide wavelength-tuning range and high spectral resolution [61]; therefore, it is primarily used in gas-spectrum detection [7,62], industrial process control [63], and precision measurement calibration [64, 65].

3.1.2 *Littman-ECDL*

The Littrow- and Littman-structured ECDLs both achieve wavelength selection by changing the tilt angle of the mode-selection device in the external cavity. The difference is that the Littman-structured laser selects the wavelength using grating diffraction twice. Therefore, it exhibits better mode-selection characteristics than the Littrow structure [66]. Its linewidth can easily reach hundreds of kilohertz, and its tuning range can still be maintained over a wider range and even improved. However, the introduction of additional optical components further increases the system complexity. This type of structure still has limitations such as large system size, high level of difficulty in the installation and adjustment of the optical path, susceptibility to external light noise, and higher loss than the Littrow-ECDL. Currently, researchers at Central China Normal University [66], Universidad Carlos III de Madrid in Spain [67], Aston University in England [68], and Sacher Lasertechnik in Germany [69], among other institutions [70–72] have conducted Littman-ECDL research.

The Littman external-cavity structure was first used in dye lasers in the 1970s [73]. In the 1990s, the structure was applied to the ECDL [70]. After more than two decades of development, this type of structure has become one of the classic ECDL types. In 2016, Luo et al. [66] of Central China Normal University reported a 6.9-μm external-cavity quantum cascade laser using a traditional Littman external-cavity structure. The continuous tuning range exceeds 300 cm^{-1}, from 1340 to 1640 cm^{-1}, and the linewidth is less than 0.14 cm^{-1}. The fine-tuning ability of the external-cavity quantum cascade laser is proved by measuring the absorption spectrum of moisture in air.

Reflective diffraction gratings are typically used to achieve a mode-selection function in the external-cavity structure. Moreover, transmissive diffraction gratings can also be used. In 2018, Shirazi et al. [20] from Kyungpook National University in Republic of Korea developed an ECDL for optical coherence tomography (OCT) systems. The laser uses a transmissive diffraction grating as the mode-selection device in the Littman external cavity. After the laser is collimated by the lens, it is incident on the transmission diffraction grating. The diffracted light is then irradiated on the tuning mirror and fed back to the resonant cavity. The transmitted light of the grating is output as the laser. The mirror is rotated to achieve a wavelength tuning of 829.2–881.5 nm with a tuning range of 52 nm.

Similar to the improved Littrow structure, the output face of the Littman-ECDL was changed from the grating to the back end of the chip [71]. This improved design achieved remarkable results in single-mode tuning and output-power enhancement [72]. In 2018, Chichkov et al. [68] from Aston University in England realized a 3.2-μm wavelength-tunable, GaSb-Based, cascaded type-I quantum-well laser. This scheme adopts an improved Littman-Metcalf structure. A grating with a reticle density of 450 l/mm is used as the tuning component of the external cavity, and the gain chip is a cascade-pumped GaSb chip with a narrow-ridge waveguide structure. The experimental results show that the laser provides an 8-mW continuous-wave output power at room temperature, and the wavelength-tuning range exceeds 300 nm (3 μm band) in continuous-wave and pulsed modes.

In 2017, Jiménez et al. [67] conducted related research to realize a miniaturized Littman-ECDL package. The small laser is packaged within a compact space, and it has the characteristics of high output power, narrow linewidth, tunability, and high SMSR, which enables portability and handheld device operation. When the laser power exceeds 50 mW, the SMSR reaches 60 dB, and the linewidth is less than 100 kHz. However, it has only a GHz-level tuning range. Because once the device is assembled, the mirror cannot be tilted. The wavelength can only be slightly tuned over current, which limits the range of it.

In 2019, Hoppe et al. [69] from Sacher Lasertechnik in Germany proposed a new type of Littman external-cavity structure based on a MEMS system to further improve stability, repeatability, tuning range, and speed. In this new structure, the laser beam is first irradiated on the rotatable MEMS mirror and then reflected on the reflective grating. The grating, which acts as a frequency selector, reflects first-order diffraction to the MEMS mirror, and the light is then reflected to the gain chip for oscillation. Finally, the laser emits light from the back of the chip, and its tuning speed reaches the order of kilohertz.

Using the MEMS rotating mirror, the cavity length and angle can be changed simultaneously, and the wavelength can be tuned without mode hopping.

The mode-hop-free tuning of lasers is important in many applications. For example, it can prevent the distortion of interference fringes in frequency-scanning interference [74] and reduce measurement uncertainty [75]. However, the tuning range is still limited without mode hopping in practice owing to mechanical errors, vibrations, gain chip surface reflectivity, temperature, and air conditions. Many theoretical studies have proven that the three spectra of the external-cavity length, grating feedback angle, and internal-cavity length can be synchronously tuned by selecting a suitable position for the mirror pivot point and controlling the laser current [76]. Moreover, the mode-hopping tuning range of the laser can be effectively expanded when combined with mode matching [77]. In addition, in the exploration of the Littman-ECDL structure, roof prisms have sometimes been used as external-cavity reflectors instead of flat mirrors. This is because the roof prism can continue reflecting in one direction regardless of the tilt angle, and it has low-scattering optical quality [78].

Owing to their similar structure and performance characteristics, the application fields of the Littman-ECDL are similar to those of the Littrow external-cavity structure, such as spectroscopy [76, 79], biomedicine [72, 80], precision measurement [20, 81], and environmental monitoring [82].

3.1.3 *Filter-ECDL*

Compared with the two above-mentioned types of semiconductor lasers that use gratings as external-cavity mode-selection devices, the filter-ECDL provides the advantage of higher flexibility in components and structures. It can obtain a wavelength-tuning range of up to 100 nm or a linewidth of less than 100 kHz, according to specific requirements. In addition, there is ample room for the optimization of tuning speed, output power, system size, and compactness. The Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences [37], National Time Service Center, Chinese Academy of Sciences [35], Hong Kong Polytechnic University in China [28], Institute of Electron Technology in Poland [83], Australian Defense Science and Technology Group [29], Axsun Technology in the USA [84], Stel'makh Polyus Research Institute in Russia [30], among other institutions [85–89] have conducted in-depth research on filter-ECDLs.

In 1993, researchers from ThermoTrex [85] in the USA discovered that PZT can be used to fine-tune the length of the external feedback cavity to achieve a fine adjustment of the laser output frequency. Similarly, ECDLs use FP filters as external mode-selecting elements, and they are typically tuned by changing the length of the cavity. In 2010, Kuznetsov et al. [84] of Axsun Technology in the USA introduced a reflective FP cavity tunable laser. A silicon MEMS tunable FP filter is used as an external mode-selection element on one side of the resonant cavity. The filter is composed of two mirrors, one of which is located on a movable silicon film that is driven by static electricity for discrete wavelength tuning. The other side of the resonant cavity comprises a reflector at the output coupling end of the fiber, which can effectively increase the length of the laser cavity. Using this external-cavity structure, the miniaturized integrated package was realized, and the application of the 1060 and 1300 nm lasers was demonstrated in OCT. The tuning range is 140 nm, with a scan rate and output power exceeding 100 kHz and 100 mW, respectively.

In 2011, Zhang et al. [28] from Hong Kong Polytechnic University used the Vernier effect of two etalons to achieve model selection and improve the SMSR. The linewidth of the ECDL is less than 100 kHz; the tuning range reaches 40 nm; the SMSR exceeds 60 dB; and, the fiber-coupling output power is greater than 20 mW.

In addition to the above-mentioned wavelength tuning, achieved by changing the cavity length, an FP cavity filter can also be achieved by rotating the filter. In 2010, Xiao et al. [37] of the Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, used an AFPF combined with a total mirror to prepare a new type of ECDL. When the AFPF rotates around a fulcrum, its peak transmission wavelength has a linear relationship with the cosine value of the incident angle of the laser beam, thereby performing a wavelength-tuning function. The laser can be tuned without mode hopping in the 1550 nm band, and the tuning range is up to 40 nm.

Extensive research has also been conducted on the use of an IF as a mode-selection component. In 2012, Thompson et al. [86] from the University of Melbourne in Australia studied a narrow-linewidth tunable ECDL based on a wide-bandwidth IF external cavity. The laser performs wavelength tuning by rotating the IF. The wavelength-tuning range exceeds 14 nm, and the linewidth is 26 kHz. In 2018, Pan et al. [34] from the Beijing University of Technology in China studied a narrow-linewidth ECDL based on a wide-bandwidth IF. The results produced a laser output with a linewidth of approximately 95 kHz, spectral purity of 2.9 MHz, and long-term frequency stability of 5.59×10^{-12}. In 2020, Zhang et al. [35] from the National Time Service Center of the Chinese Academy of Sciences used a narrow-bandwidth IF to select the spectrum of the ECDL, and a cat-eye reflector provided optical feedback. The laser has a working wavelength of approximately 698.45 nm, current-controlled tuning range of more than 40 GHz, piezoelectric-controlled tuning range of 3 GHz, linewidth of approximately 180 kHz, and output power of 35 mW.

In 2017, Kasai et al. [87] of Tohoku University in Japan used a multilayer dielectric interference filter and a SiO_2 plate with anti-reflection coatings on both sides to form an external-cavity mode-selection component. By rotating the multilayer dielectric interference filter and the SiO_2 plate using a motor, the center wavelength of the filter and the optical path length of the SiO_2 plate can be changed to achieve quasi-continuous wavelength tuning. The laser achieves wavelength-tuning ranges exceeding 40 and 35 nm and linewidths less than 7.7 and 8 kHz in the full L-band and C-band, respectively. The relative intensity noise (RIN) is lower than −130 dB/Hz.

In 2020, Guillemot et al. [38] from iTEOX in France conducted a study based on a GMRF ECDL in the 1506-nm band. The gain medium of this scheme is an FP single-stripe diode that has an anti-reflection coating on one side and laser output on the other. A spherical lens is used to collimate the beam. The GMRF glued on the PZT is used as both the filtering element and resonant end face. By fine-tuning the length of the resonator, the frequency-tuning range is 14 GHz without mode hopping, which is consistent with the expected FSR of the resonator at 20 GHz. The laser linewidth is 366 kHz.

In 2020, Russia's Stel'makh Polyus Research Institute [30] reported a study on an ECDL with two AOTFs used as frequency-selective components. The laser has a tuning range of 60 nm (815–875 nm) with an output power of 3 mW. The linewidth of the steady-state laser-emission spectrum reaches 25 MHz. In scan mode, the maximum tuning rate of the AOTF is 104 $nm \cdot s^{-1}$, and the linewidth is 0.022 nm (8.8 GHz).

In addition to edge-emitting semiconductor lasers, the gain chip of the filter-ECDL can also be a vertical external-cavity surface-emitting laser (VECSEL). The characteristics of this laser indicate that the gain medium generally needs to be pumped by an external light source, and its resonant cavity is primarily an external-cavity structure [88]. In addition, the external-cavity mode-selection components of this type of laser are mostly BRFs and FP etalons. In 2017, Broda et al. [83] from the Institute of Electron Technology in Poland reported the wide-tuning of an optically pumped VECSEL with a dual-mode resonant microcavity. The laser adopts a V-shaped cavity structure. After the VECSEL gain chip is light-pumped, the output light is irradiated on the high-reflecting mirror and then reflected to the BRF in the V-shape. Finally, the laser is output through the output coupling mirror. The wavelength-tuning function is realized by rotating the BRF. Moreover, the laser achieves a wavelength-tuning range of 95 nm with a laser center wavelength of 985 nm and an output power between 5 and 95 mW by controlling the high-reflectivity mirror in the resonant cavity and the temperature of the active area using the pump power and heat extraction.

In 2020, the same group [33] also studied membrane external-cavity surface-emitting lasers (MECSELs) with a wavelength above 1600 nm. The laser is different from a V-shaped structure. The resonant cavity is composed of two dielectric mirrors. The rotating BRF produces a 133-nm wavelength-tuning range, from 1695 to 1828 nm.

In 2021, Priante et al. [90] from University of New Mexico in the USA studied the tunability and linewidth of the MECSEL pumped in the well. By adjusting the BRF, the wavelength-tuning range of this laser is 1124–1195 nm (71 nm), and the linewidth is 1.7 nm. The output power of the MECSEL reaches 28.5 W owing to the 4f multi-pass pumping architecture.

The performance of ultra-narrow-linewidth semiconductor lasers has been considerably optimized based on the utilization of high-Q whispering-gallery-mode resonator (WGMR) lasers [91]. In 2020, OEwaves Inc. in the USA [89] reported a 780-nm self-injection-locked ECDL with a hertz-level instantaneous linewidth. The gain chip emits laser, which is coupled into a WGMR made of mechanically polished crystalline MgF_2 through a prism. The resonant Rayleigh backscattered light from the WGMR is self-injected and locked into the gain chip, which stabilizes the laser. The tuning method applies external stress to the WGMR through a piezoelectric actuator. This method can narrow the linewidth of the laser by 40 dB; the instantaneous linewidth can reach 5 Hz; the RIN can be reduced by 10 dB; the tuning range is 12.8 GHz; and, the output power is 4.6 mW.

There have been related application studies on filter-ECDLs based on an atomic clock, radioisotope detection, and OCT swept-frequency light sources [84]. The National Time Service Center of the Chinese Academy of Sciences developed a compact and highly stable 698 nm filter-type tunable narrow-linewidth ECDL, which is specially used in space strontium Sr optical clocks [35]. The University of Tokyo in Japan used the narrow-bandwidth interference filter ECDL to develop Sr resonance ionization spectroscopy with high isotope selectivity, which can be applied to the background-free analysis of radioactive Sr-90 in marine samples [92].

3.2 Waveguide-type ECDL

MRR-ECDLs have the advantages of low cost, low power consumption, high integration, and small size; their linewidth characteristics are better and can easily reach tens of kilohertz. With the development of the new generation of MRR-ECDLs, the linewidth can even reach hundreds of hertz. The optical waveguide exhibits low loss, good filtering characteristics, and high SMSR. From a single-ring structure to a double-ring structure, the tuning range can be expanded to tens of nanometers using the double-ring Vernier effect. Notably, the wavelength tuning range of a single laser of the new generation of MRR-ECDLs has reached more than 100 nm. However, the coupling loss between the waveguide and the gain chip is still high, which limits any increase in the laser output power. Currently, the University of California, Santa Barbara (UCSB) in the USA [93], NEC Corporation in Japan [41], Institute of Semiconductors, Chinese Academy of Sciences [42], Columbia University in the USA [43], University of Tampere in Finland [19], Dublin City University in Ireland [40,44], among other institutions [94–96] have conducted in-depth research on MRR-ECDLs.

As early as the 1990s, in-depth investigations on the MRR characteristics were conducted [94]. Over the past two decades, semiconductor lasers based on MRR have developed rapidly, and various waveguide materials and structures have been developed. The spectral output of a single MRR is only the comb spectrum; therefore, it is difficult to use as a wavelength-tuning filter. Thus, it is typically mixed and integrated with other components to obtain the tuning function required to achieve the tuning wavelength. In 2011, research on ECDLs based on polymer Bragg reflectors (PBRs) and single MRRs was reported by the Korea Electronics and Telecommunications Research Institute [95]. The resonant cavity of the laser is composed of a PBR, gain chip, and single MRR. Wavelength tuning is controlled by the high thermal-optical effect of the PBR, and discrete tuning is conducted by combining the predetermined mode spacing of the ring resonator as a comb reflector. When the reflection wavelength of the PBR is superimposed on one of the feedback wavelengths of the MRR, single-mode oscillating lances are obtained. The laser has a tuning range of 14.5 nm in the 1550-nm band, tuning step of 0.8 nm, and maximum output power of 0.6 mW. In addition, the single MRR can also have excellent performance in improving other important characteristics of ECDLs. In 2021, UCSB [96] integrated the laser with a single MRR on the ultra-high-Q SiN waveguide. The laser realized a linewidth of 3 Hz by using the external feedback of the MRR.

The increasing maturity and cost reduction of semiconductor-processing technology enable the further improvement of the overall performance of lasers to meet the needs of optical-communication development; thus, double-MRR ECDLs have attracted increasing research attention. In addition to a traditional ring-shaped microring, some studies have adopted a square-shaped microring scheme [97]. In 2009, Chu et al. [41] from the NEC Corporation of Japan first proposed the fabrication of a tunable ECDL using silicon photon technology. This study uses an InP-based SOA as a gain chip that couples with a dual-MRR fabricated on an SOI substrate. The wavelength-tuning function is realized by the thermal-optical response and the Vernier effect of the dual-MRR. Finally, a wavelength-tuning range of 38 nm is achieved in the C or L bands, and the tuning power is 26 mW. Compared with the traditional SiON waveguide, the size of the laser is reduced to 1/25, and the power consumption is reduced to 1/8 [98,99].

In 2018, Guan et al. [43] from Columbia University studied wide-tuning and narrow-linewidth III-V/silicon-based mixed ECDLs for coherent communication. The study uses an InP-based reflective semiconductor optical amplifier (RSOA) as the gain chip and a spot-size converter (SSC) to couple with the external cavity formed by the silicon-based MRR. The wavelength-tuning function of the laser is realized by a wavelength-selective reflector, which is composed of a double-microring Vernier structure and Y-junction. The experimental results show that the center wavelength is 1550 nm; the tuning range exceeds 60 nm; the maximum output power is 11 mW; SMSR reaches 55 dB; and, the linewidth is 37 kHz.

Compared with Si-based waveguides, Si_3N_4 waveguides are advantageous in terms of a large refractive-index difference, large transparency range, small linear-propagation loss, and small nonlinear effects, which are conducive to the improvement of linewidth characteristics. In 2018, Yi et al. [44] from Dublin City University in Ireland studied hybrid InP-TriPleX photonic integrated tunable lasers based on Si_3N_4 MRRs. As the external-cavity Si_3N_4 waveguide platform is composed of two cascaded MRRs with slightly different radii that use the Vernier effect to achieve wavelength tuning. The phase section of the device can realize the fine-tuning of the wavelength, and the power-tuning section can optimize the output power. The phase, MRR, and power-tuning sections are all controlled by temperature. The experimental results show that the laser achieves a tuning range of approximately 50 nm in the 1550-nm band, an output power of 10 dBm, an SMSR over 50 dB, and a linewidth of less than 80 kHz over the entire tuning range. The narrowest linewidth obtained is 35 kHz.

In 2021, the same group [40] studied dual-tunable modules based on InP-Si_3N_4 integration. This study uses an InP-based reflective SOA as the gain chip, which is coupled with the phase section, MZI-tunable coupler, and dual Si_3N_4-based MRRs of the Vernier structure to form an ECDL. The phase section, MZI-tunable coupler, and MRRs can be thermo-optically controlled. Two wavelengths can be provided through the series connection of the dual lasers, each of which can provide a tuning range of 70 nm. Finally, the ECDL achieves a tuning range from 1470 to 1575 nm, which covers the entire C-band and part of the S band over 100 nm, with a RIN of −165 dB/Hz.

In 2018, Radosavljevic et al. [100] from Ghent University in Belgium fabricated a thermally tunable double-MRR Vernier structure on a Ge-on-SOI waveguide platform coupled with a gain chip to enable the MRR-ECDL to operate in the mid-infrared band. The laser realized a wavelength tuning range of 108 nm in the 5-μm band.

In addition to the above-mentioned resonant-cavity structure, which is coupled with the MRR waveguide on one side of the gain chip, dual MRRs were integrated on each side of the gain chip as a resonant cavity through heterogeneous integration [101]. The wavelength tuning is achieved by tuning the waveguide temperature below that of the MRR. The laser has a coarse tuning range of 29 nm, linewidth of 160 kHz, an SMSR of over 40 dB, and output power of 15 mW.

Currently, new integrated coherent tunable lasers provide new ideas for MRR-ECDLs. This new type of waveguide external-cavity structure uses ultralow-loss waveguides to make three or more large-diameter MRRs [102]. Large MRRs avoid the increase in loss caused by the small size of the microring in the double-ring Vernier effect [103–107], and they effectively improve the wavelength-tuning range, linewidth characteristics, and noise characteristics of the laser [108]. This new generation of MRR-ECDLs has a wavelength-tuning range of more than 100 nm, and the linewidth is increased to 100 Hz [93].

In 2021, the Morton Photon Corporation of the United States and UCSB [108] collaborated on a new type of coherent tunable laser. The laser is designed and manufactured based on a complementary metal-oxide-semiconductor (CMOS) silicon photonics platform. Heterogeneous integrated III-V materials are used as the gain region to couple with the external-cavity waveguide, including the phase control region, tunable coupler, and three ultralow-loss MRRs with larger ring sizes than the Si-based waveguide. The resonant cavity is composed of a tunable reflector on the left side of the gain chip and an MRR reflector on the right side. The output end can be a tunable reflector or coupler that can filter out the influence of spontaneous radiation noise. Through the temperature control of the MRR, the laser achieves a wavelength-tuning range of 118 nm, which covers the S, C, and L bands. The Lorentz linewidth is less than 100 Hz; the RIN is less than −155 dBc/Hz; and, the maximum on-chip optical power is 15 mW.

MRR-ECDLs are commonly used in the field of optical communications, such as in microwave generators for microwave communications [109], dense wavelength-division multiplexing (DWDM) systems, the light source of direct current transceivers [40], and coherent optical transmission [43, 44].

In addition to the above-mentioned MRR waveguide structures, related research on the wavelength tuning and linewidth characteristics of other waveguides has also been conducted. In 2010, Kim et al. [110] from Pusan National University in Republic of Korea used a flexible polymer Bragg reflector as an external cavity and directly tuned the Bragg wavelength by applying strain to achieve a range of 80 nm, from 1495 to 1575 nm.

In 2019, Xiang et al. [111] from UCSB formed an ultra-narrow-linewidth fixed-wavelength hybrid laser based on an externally extended Si_3N_4 Bragg grating and a semiconductor gain chip with a laser output power of 24 mW, Lorentz linewidth of 320 Hz, and single wavelength of 1544 nm.

In 2020, Park et al. [112] of Pusan National University in Republic of Korea studied a tunable Bragg-grating filter based on a polymer optical waveguide, which can realize the wavelength-tuning function of ECDLs. The polymer waveguide adopts a two-stage cascaded tilted Bragg grating and an asymmetric Ybranch waveguide structure. The waveguide grating has a greater refractive-index tunability owing to the high thermo-optical effect and strong temperature limitation of the polymer waveguide. The wavelength-tuning range reaches 12 nm in the 1520-nm band; the SMSR exceeds 35 dB; and, the adjacent channel crosstalk is −25 dB.

In 2021, Luo et al. [113] from CIOMP studied a highly linearly polarized narrow-linewidth hybrid semiconductor laser in the C-band. The laser consists of a gain chip and an external-cavity high-birefringence waveguide Bragg grating. According to the experiments, the SMSR of the laser reaches 50.2 dB; the linewidth is 4.15 kHz; and, the maximum output power is 8.07 mW.

3.3 Fiber-type ECDL

The most prominent feature of an FBG-ECDL is its excellent linewidth characteristic, which can easily reach several kilohertz or even below 1 kHz. However, owing to its limited tuning method, the wavelength-tuning range is very small, generally only a few nanometers. In addition, an FBG-ECDL also has the advantages of a simple structure, low noise output, small size, low cost, and good stability. The structure of the ring fiber external cavity was introduced to further improve the FBG-ECDL performance. Currently, the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences (SIOM) [114, 115], KTH Royal Institute of Technology in Sweden [116], and University of Rennes in France [117], among other institutions [118–120], studied this topic.

In the 1980s, there were related reports on fiber-Bragg reflectors used for laser-mode selection and linewidth reduction [118]. After more than 30 years of development, many improvements have been made in this field. The gain medium of the laser was expanded to simultaneously achieve a high FBG-ECDL output power and narrow linewidth. In 2011, Loh et al. [119] of the Massachusetts Institute of Technology reported a packaged ECDL with high power and narrow linewidth at a wavelength of 1550 nm. The laser couples a two-channel curved-channel slab-coupled optical waveguide amplifier (SCOWA) and FBG through a lens fiber. The SCOWA gain medium has the advantages of low optical confinement, a large mode size, low optical loss, and low noise. The Lorentz linewidth of this laser is 1 kHz; the RIN is less than −160 dB/Hz; and, the output power reaches 370 mW.

In 2018, Sun et al. [114] of SIOM reported a low-noise ECDL based on polarization-maintaining fiber gratings. The butterfly-encapsulated laser has a Lorentz linewidth of 4.85 kHz and RIN less than −155 dB/Hz in the 1550-nm band. In 2021, Congar et al. [117] from the University of Rennes studied near-ultraviolet InGaN lasers with narrow linewidths based on an external-cavity FBG. The output power of the laser is 1.3 mW; the SMSR is 44 dB; and, the intrinsic linewidth can reach 16 kHz.

Extensive research was also conducted on the wavelength tunability of FBG-ECDLs. In 2014, Duraev et al. [120] of NOLATECH, Russia reported a single-frequency-tunable ECDL based on a single-mode FBG. Experiments have proved that the wavelength-tuning function can be achieved by changing the injection current, temperature of the active area of the gain chip, and temperature of the fiber grating. In this study, the laser-tuning range is 1.5 nm, with a tuning step less than 0.02 nm, output power of 10 mW, and linewidth of 10 kHz. In 2017, Zhang et al. [115] of SIOM studied the thermal tuning of a narrow-linewidth FBG-ECDL at 1550 nm. The laser has a linewidth of 35 kHz, linear tuning speed of 65 pm/°C (8.125 GHz/°C), and continuous mode-free tuning range of 0.5 nm.

A ring-shaped external cavity with an all-fiber structure, which can effectively extend the cavity length, was adopted to further suppress the phase/frequency noise and narrow the linewidth at high frequencies. In 2016, Wei et al. [121] of SIOM reported a narrow linewidth DFB-ECDL using FBG-FP self-injection locking technology. By injecting the transmitted light from the FBG-FP cavity into the DFB laser through a polarization-maintaining grating, resonant optical feedback is performed. Using this technology, the system can achieve noise suppression of more than 70 dB at a Fourier frequency between 5 Hz and 1 kHz. In addition, the system maintains a white-noise level as low as 40 Hz^2/Hz, Fourier frequency of more than 1 kHz, natural Lorentz linewidth of 125 Hz, and RIN less than −142 dBc/Hz above 2 MHz. Through the DFB temperature and injection current tuning, a quasi-continuous tuning of 0.8 nm is achieved.

In addition, some studies have realized wavelength tuning using the fiber-ring cavity. In 2020, Gao et al. [122] of Yangtze University in China used the temperature of the fiber grating and a DFB laser to conduct wavelength tuning. When the fiber grating works at 40°C and the DFB at 10°C, it outputs dual-wavelength lasers at 1550.32 and 1552.40 nm, with a wavelength interval of 2.08 nm. When the working temperature difference between the DFB and fiber grating is changed from 30°C to 0°C, the wavelength interval can be adjusted from 2.08 to 5.34 nm to achieve wavelength tuning. In the following year, the same group [123] used dual DFB lasers and fiber gratings to develop a three-wavelength laser. The experimental results show that a stable three-wavelength laser output was obtained at 1545.53, 1551.15, and 1553.94 nm. By adjusting temperature, a tunable wavelength interval between 2.79 and 5.60 nm was obtained.

In 2019, Lindberg et al. [116] of the KTH Royal Institute of Technology used a chirp fiber-Bragg grating (CFBG) and SOA to form a laser and used a pulse pair with a variable delay to drive the SOA. Wavelength tuning is achieved using cyclic pulses to target different areas in the CFBG. The laser output has a tuning range of 40 nm in the 1550-nm band, tuning resolution of 3.3 pm, power change of 1.46 dB, and linewidth of less than 30 pm. In 2020, this group [124] used an SOA as the gain medium and modulator, and a CFBG as the reflector at both sides of the resonator to construct a C-shaped cavity. The laser achieved a tuning range of 35 nm in the 1550-nm band. Although the FBG-ECDL wavelength-tuning range increased, the linewidth characteristics were also significantly affected. In addition, the external-cavity structure of the ring fiber typically requires a long length, which significantly affects the device volume.

Currently, the preparation process of FBG-ECDLs is relatively mature. This type of laser can be widely used in distributed optical-fiber sensing [125], coherent spectrum analysis [115], and synthetic-aperture radar [126].

4 Summary and prospects

ECDL can meet the requirements of lidar, optical communication systems, spectral analysis, atomic clock timing, as well as future communication technologies [127] for a wide wavelength-tuning range and narrow linewidth characteristics of laser light sources. We expound on the principle of wide-tuning and narrow-linewidth ECDLs and review recent research progress in this field. The advantage of discrete-device-type ECDLs lies in a wider wavelength-tuning range. Among them, the Littrow structure has a wider tuning range and larger output power than the Littman structure, whereas the Littman structure has a narrower linewidth characteristic. Moreover, there are many types of filter-ECDLs, and their performance is closely related to that of the mode-selection filter. Therefore, they have high flexibility and development potential. However, the discrete-device-type ECDLs have many discrete components; thus, the overall system size is not easy to shrink. Therefore, the discrete-device-type ECDL is suitable for fields that do not require high integration and a small device size but a high wavelength-tuning range and spectral resolution. Examples include gas spectral detection, measurement calibration, biomedical detection, and atomic clock timing. Waveguide-type ECDLs are easy to integrate, small, low cost, and have good linewidth characteristics. They are suitable for coherent optical communication, optical sensing, and other applications. The tuning range and linewidth characteristics of MRR-ECDLs are relatively balanced; hence, they are suitable for the field of photonic integration and have broad application prospects. The fiber-type ECDLs have outstanding linewidth characteristics but a limited tuning range. They are suitable for high-precision time-frequency transmission, fiber-optic sensing, and other fields with low tuning requirements.

In the information age, the rapid development of fields such as coherent optical communication and vehicle-mounted lidar has resulted in higher requirements for a wide wavelength-tuning range and narrow linewidth characteristics for laser light sources. Moreover, the system integration, volume, and reliability must be considered for wide-tuning and narrow-linewidth ECDLs during the development process. Currently, MRR-ECDLs with high integration and a relatively balanced performance have broad application prospects. By optimizing the material and structure of the optical waveguide and improving the coupling efficiency between the optical waveguide and gain chip, the overall performance can be further improved. Future research should include obtaining narrower linewidths more easily for discrete-device-type ECDLs while ensuring the wavelength-tuning range and output power. Moreover, we should explore how both the system size and the difficulty of optical-path coupling and alignment can be reduced. In addition, filter-ECDLs have considerable flexibility; therefore, they have great development potential in terms of performance improvement and device size through the study of new filter components and structures. Currently, there are few studies on the tuning speed of ECDLs; however, the tuning speed will also become an important performance parameter as application requirements increase. It can be further optimized by improving tuning methods, such as by seeking alternative tuning methods in MRR-ECDLs.It is worth noting that stability and reliability are also crucial problems restricting the development of

ECDLs. Methods such as reducing discrete components, replacing UV glue fixation with laser welding and optimizing packaging structures can improve its stability and reliability, and further expand its applications.

Acknowledgements This work was supported by National Science and Technology Major Project of China (Grant Nos. 2018YFB-0504600, 2018YFB0504603), National Natural Science Foundation of China (Grant Nos. 62090051, 62090052, 62090054, 11874353, 61935009, 61934003, 61904179, 61727822, 61805236, 62004194), Science and Technology Development Project of Jilin Province (Grant Nos. 20200401069GX, 20200401062GX, 20200501006GX, 20200501007GX, 20200501008GX), Key R&D Program of Changchun (Grant No. 21ZGG13), Special Scientific Research Project of Academician Innovation Platform in Hainan Province (Grant No. YSPTZX202034), and "Lingyan" Research Program of Zhejiang Province (Grant No. 2022C01108).

References

1 Cheng Q, Bahadori M, Glick M, et al. Recent advances in optical technologies for data centers: a review. Optica, 2018, 5: 1354–1370
2 Olsson S L I, Cho J, Chandrasekhar S, et al. Probabilistically shaped PDM 4096-QAM transmission over up to 200 km of fiber using standard intradyne detection. Opt Express, 2018, 26: 4522
3 Lu B, Wei F, Zhang Z, et al. Research on tunable local laser used in ground-to-satellite coherent laser communication. Chin Opt Lett, 2015, 13: 091402
4 Yang Q F, Shen B, Wang H, et al. Vernier spectrometer using counterpropagating soliton microcombs. Science, 2019, 363: 965–968
5 Poulton C V, Byrd M J, Russo P, et al. Long-range LiDAR and free-space data communication with high-performance optical phased arrays. IEEE J Sel Top Quantum Electron, 2019, 25: 1–8
6 Lang X K, Jia P, Chen Y Y, et al. Advances in narrow linewidth diode lasers. Sci China Inf Sci, 2019, 62: 061401
7 Gasmi K, Al-Jalal A, Al-Basheer W, et al. Blue external-cavity diode laser for NO_2 gas detection. In: Proceedings of Semiconductor Lasers and Laser Dynamics IX, ELECTR NETWORK, 2020. 1135616
8 Zhao Q L, Zhang Z T, Wu B, et al. Noise-sidebands-free and ultra-low-RIN 15 μm single-frequency fiber laser towards coherent optical detection. Photon Res, 2018, 6: 326–331
9 Wu W R, Chen M, Zhang Z, et al. Overview of deep space laser communication. Sci China Inf Sci, 2018, 61: 040301
10 Grafen M, Delbeck S, Busch H, et al. Evaluation and benchmarking of an EC-QCL-based mid-infrared spectrometer for monitoring metabolic blood parameters in critical care units. In: Proceedings of Optical Diagnostics and Sensing XVIII: Toward Point-of-Care Diagnostics, San Francisco, 2018
11 Newman Z L, Maurice V, Drake T, et al. Architecture for the photonic integration of an optical atomic clock. Optica, 2019, 6: 680–685
12 Hjelme D, Mickelson A. On the theory of external cavity operated single-mode semiconductor lasers. IEEE J Quantum Electron, 1987, 23: 1000–1004
13 Kakiuchida H, Ohtsubo J. Characteristics of a semiconductor laser with external feedback. IEEE J Quantum Electron, 1994, 30: 2087–2097
14 Ghafouri-Shiraz H, Lo B S K. Distributed Feedback Laser Diodes: Principles and Physical Modelling. New Jersey: John Wiley & Sons, Inc, 1997
15 Kotaki Y, Ishikawa H. Wavelength tunable DFB and DBR lasers for coherent optical fibre communications. IEE Proc J Optoelectron UK, 1991, 138: 171–177
16 Luo C C, Zhang R Y, Qiu B C, et al. Waveguide external cavity narrow linewidth semiconductor lasers. J Semicond, 2021, 42: 041308
17 Wang Y, Zhou Y L, Wu H, et al. A tunable external cavity laser operating at excited states of bimodal-sized quantum-dot. Jpn J Appl Phys, 2019, 58: 051013
18 Podoskin A, Golovin V, Gavrina P, et al. Ultrabroad tuning range (100 nm) of external-cavity continuous-wave high-power semiconductor lasers based on a single InGaAs quantum well. Appl Opt, 2019, 58: 9089–9093
19 Ojanen S P, Viheriälä J, Cherchi M, et al. GaSb diode lasers tunable around 2.6 μm using silicon photonics resonators or external diffractive gratings. Appl Phys Lett, 2020, 116: 081105
20 Shirazi M F, Kim P, Jeon M, et al. Free space broad-bandwidth tunable laser diode based on Littman configuration for 3D profile measurement. Opt Laser Tech, 2018, 101: 462–467
21 Kapasi D P, Eichholz J, McRae T, et al. Tunable narrow-linewidth laser at 2 μm wavelength for gravitational wave detector research. Opt Express, 2020, 28: 3280–3288
22 de Labachelerie M, Sasada H, Passedat G. Mode-hop suppression of Littrow grating-tuned. Appl Opt, 1994, 33: 3817–3819
23 Long R, Wang H L, Gong Q, et al. Optical feedback of semiconductor external cavity laser (in Chinese). Commun Technol, 2013, 46: 142–144
24 Duarte F J. Tunable Lasers Handbook. San Diego: Academic Press, 1995
25 Zhou P, Wu Y Q, Zhang R Z. Effect of collimating lens misalignment on linewidth of littman-Metcalf grating external cavity laser (in Chinese). Infrared Laser Eng, 2021, doi: 10.3788/IRLA20210168
26 Sun H, Menhart S, Adams A. Calculation of spectral linewidth reduction of external-cavity strong-feedback semiconductor lasers. Appl Opt, 1994, 33: 4771–4775
27 Loh H Q, Lin Y J, Teper I, et al. Influence of grating parameters on the linewidths of external-cavity diode lasers. Appl Opt, 2006, 45: 9191–9197
28 Zhang X M, Wang N, Gao L, et al. Narrow-linewidth external-cavity tunable lasers. In: Proceedings of International Conference on Optical Communications & Networks, Guangzhou, 2011
29 Gambell A, Simakov N, Ganija M, et al. Intra-cavity semiconductor laser tuning using a frequency compensating acousto-optic tunable filter pair. In: Proceedings of AOS Australian Conference on Optical Fibre Technology (ACOFT) and Australian Conference on Optics, Lasers, and Spectroscopy (ACOLS), Melbourne, 2019
30 Magdich L N, Chamorovskiy A Y, Shidlovsky V R, et al. Tunable semiconductor laser with two acousto-optic tunable filters in its external cavity. Quantum Electron, 2020, 50: 136–140
31 Ménager L, Cabaret L, Lorgeré I, et al. Diode laser extended cavity for broad-range fast ramping. Opt Lett, 2000, 25: 1246–1248

32 Alfieri C G E, Waldburger D, Nürnberg J, et al. Mode-locking Instabilities for high-gain semiconductor disk lasers based on active submonolayer quantum dots. Phys Rev Appl, 2018, 10: 044015
33 Broda A, Jezewski B, Sankowska I, et al. SWIR MECSEL emitting above 1600 nm. In: Proceedings of Vertical External Cavity Surface Emitting Lasers (VECSELs) X, 2020. 11263
34 Pan G Z, Guan B L, Xu C, et al. Broad bandwidth interference filter-stabilized external cavity diode laser with narrow linewidth below 100 kHz. Chin Phys B, 2018, 27: 014204
35 Zhang L B, Liu T, Chen L, et al. Development of an interference filter-stabilized external-cavity diode laser for space applications. Photonics, 2020, 7: 12
36 Gu Y, Hu G Q, Wu X P, et al. Wavelength control technology for F-P cavity-based MEMS TOF. Study Opt Commun, 2009, 6: 45–47
37 Xiao X, Yu F Q. A novel wavelength tuning method in external cavity diode laser with all-dielectric thin film fabry-perot filte. In: Proceedings of Photonics & Optoelectronic, Chengdu, 2010
38 Guillemot L, Oksenhendler T, Pelloquin S, et al. Guided-mode resonance filter extended-cavity diode laser. Laser Phys, 2020, 30: 035802
39 Mizutani K, de Merlier J, Sudo S, et al. Liquid crystal mirror-based wavelength-tunable laser module with asynchronous mode cavity. IEEE Photon Technol Lett, 2006, 18: 1299–1301
40 Dass D, Costas M T, Barry L P, et al. 28 GBd PAM-8 transmission over a 100 nm range using an InP-Si_3N_4 based integrated dual tunable laser module. Opt Express, 2021, 29: 16563–16571
41 Chu T, Fujioka N, Ishizaka M. Compact, lower-power-consumption wavelength tunable laser fabricated with silicon photonic-wire waveguide micro-ring resonators. Opt Express, 2009, 17: 14063–14068
42 Zhou Z, Yuan X, Gu M, et al. Design of double-ring resonator for tunable lasers on silicon. In: Proceedings of Optoelectronics and Micro/Nano-Optics, Beijing, 2017
43 Guan H, Novack A, Galfsky T, et al. Widely-tunable, narrow-linewidth III-V/silicon hybrid external-cavity laser for coherent communication. Opt Express, 2018, 26: 7920–7933
44 Lin Y, Fan Y, Boller K J, et al. Characterization of hybrid InP-TriPleX photonic integrated tunable lasers based on silicon nitride (Si_3N_4/SiO_2) microring resonators for optical coherent system. IEEE Photonics J, 2018, 10: 1–8
45 Wang Y, Luo S, Ji H M, et al. Continuous-wave operation of InAs/InP quantum dot tunable external-cavity laser grown by metal-organic chemical vapor deposition. Chin Phys B, 2021, 30: 018106
46 Jiang Y F, Vijayraghavan K, Jung S, et al. External cavity terahertz quantum cascade laser sources based on intra-cavity frequency mixing with 1.2–5.9 THz tuning range. J Opt, 2014, 16: 094002
47 Vizbaras K, Dvinelis E, Šimonyte I, et al. High power continuous-wave GaSb-based superluminescent diodes as gain chips for widely tunable laser spectroscopy in the 1.95–2.45 μm wavelength range. Appl Phys Lett, 2015, 107: 011103
48 Fedorova K A, Gorodetsky A, Rafailov E U. Compact all-quantum-dot-based tunable THz laser source. IEEE J Sel Top Quantum Electron, 2017, 23: 1–5
49 Hard T. Laser wavelength selector and output coupler. IEEE J Quantum Electron, 1969, 5: 321–321
50 Chen M H, Hsiao S C, Shen K T, et al. Single longitudinal mode external cavity blue InGaN diode laser. Opt Laser Tech, 2019, 116: 68–71
51 Shimada Y, Chida Y, Ohtsubo N, et al. A simplified 461-nm laser system using blue laser diodes and a hollow cathode lamp for laser cooling of Sr. Rev Sci Instrum, 2013, 84: 063101
52 Ruhnke N, Müller A, Eppich B, et al. 400 mW external cavity diode laser with narrowband emission at 445 nm. Opt Lett, 2014, 39: 3794–3797
53 Chi M, Jensen O B, Petersen P M. Tuning range and output power optimization of an external-cavity GaN diode laser at 455 nm. Appl Opt, 2016, 55: 2263
54 Tsai T, Wysocki G. External-cavity quantum cascade lasers with fast wavelength scanning. Appl Phys B, 2010, 100: 243–251
55 Chi M J, Jensen O B, Petersen P M. High-power dual-wavelength external-cavity diode laser based on tapered amplifier with tunable terahertz frequency difference. Opt Lett, 2011, 36: 2626–2628
56 Stry S, Zediker M S, Hildebrandt L, et al. Compact tunable diode laser with diffraction-limited 1 Watt for atom cooling and trapping. In: Proceedings of Conference on High-Power Diode Laser Technology and Applications II, San Jose, 2004. 17–25
57 Giraud E, Demolon P, Gresch T, et al. Room-temperature continuous-wave external cavity interband cascade laser tunable from 3.2 to 3.6 μm. Opt Express, 2021, 29: 38291–38297
58 Kruczek T, Fedorova K A, Sokolovskii G S, et al. InAs/AlSb widely tunable external cavity quantum cascade laser around 3.2 μm. Appl Phys Lett, 2013, 102: 011124
59 Okamura H. Shift lens external-cavity diode laser for broad wavelength tuning and switching. Opt Lett, 2010, 35: 1175–1177
60 Ding D, Lv X Q, Chen X Y, et al. Tunable high-power blue external cavity semiconductor laser. Opt Laser Tech, 2017, 94: 1–5
61 He K, Wang J P, Hou Y Q, et al. High-spectral-resolution characterization of broadband high-efficiency reflection gratings. Appl Opt, 2013, 52: 653–658
62 Al-Jalali S, El-Daher M S. Detection of multi absorption lines for CH_4 using broadband laser beam modulation. J Opt, 2018, 47: 22–27
63 Takei Y, Arai K, Yoshida H, et al. Development of an optical pressure measurement system using an external cavity diode laser with a wide tunable frequency range. Measurement, 2020, 151: 107090
64 Masui S, Goda S, Kadoya S, et al. Grating periods measurement of multi-pitched grating using Littrow configuration external cavity diode laser. Appl Phys Express, 2021, 14: 076501
65 Lv Q, Liu Z W, Wang W, et al. Simple and compact grating-based heterodyne interferometer with the Littrow configuration for high-accuracy and long-range measurement of two-dimensional displacement. Appl Opt, 2018, 57: 9455–9463
66 Luo W, Duan C X. A broadband pulsed external-cavity quantum cascade laser operating near 6.9 μm. Chin Phys Lett, 2016, 33: 024207
67 Jiménez A, Milde T, Staacke N, et al. Narrow-line external cavity diode laser micro-packaging in the NIR and MIR spectral range. Appl Phys B, 2017, 123: 207
68 Chichkov N B, Yadav A, Zherebtsov E, et al. Wavelength-tunable, GaSb-based, cascaded type-I quantum-well laser emitting over a range of 300 nm. IEEE Photon Technol Lett, 2018, 30: 1941–1943
69 Hoppe M, Rohling H, Schmidtmann S, et al. New wide tunable external cavity interband cascade laser based on a micro-electro-mechanical system device. In: Proceedings of Conference on MOEMS and Miniaturized Systems XVIII, San Francisco, 2019

70 Fuh C N, Chen H C, Liang C P, et al. A tunable diode laser. In: Proceedings of Instrumentation & Measurement Technology Conference, Hamamatsu, 1994. 1089–1090

71 Stry S, Thelen S, Sacher J, et al. Widely tunable diffraction limited 1000 mW external cavity diode laser in Littman/Metcalf configuration for cavity ring-down spectroscopy. Appl Phys B, 2006, 85: 365–374

72 Wang W B, Major A, Paliwal J. Grating-stabilized external cavity diode lasers for raman spectroscopy — a review. Appl Spectr Rev, 2012, 47: 116–143

73 Littman M G, Metcalf H J. Spectrally narrow pulsed dye laser without beam expander. Appl Opt, 1978, 17: 2224–2227

74 Wu X J, Wei H Y, Zhang H Y, et al. Absolute distance measurement using frequency-sweeping heterodyne interferometer calibrated by an optical frequency comb. Appl Opt, 2013, 52: 2042

75 Cabral A P. Calibration of the Fabry-Pérot free spectral range using a tunable laser in a Michelson interferometer. Opt Eng, 2006, 45: 100501

76 Gong H, Liu Z G, Zhou Y L, et al. Extending the mode-hop-free tuning range of an external-cavity diode laser by synchronous tuning with mode matching. Appl Opt, 2014, 53: 7878–7884

77 Saliba S D, Junker M, Turner L D, et al. Mode stability of external cavity diode lasers. Appl Opt, 2009, 48: 6692

78 Breguet J M, Henein S, Kjelberg I, et al. Tunable extended-cavity diode laser based on a novel flexure-mechanism. Int J Optomechatron, 2013, 7: 181–192

79 Starovoitov V S, Kischkat J F, Semtsiv M P, et al. Intracavity photoacoustic sensing of water vapor with a continuously tunable external-cavity quantum-cascade laser operating near 5.5 μm. Opt Lett, 2016, 41: 4955–4958

80 Lee S W, Song H W, Jung M Y, et al. Wide tuning range wavelength-swept laser with a single SOA at 1020 nm for ultrahigh resolution Fourier-domain optical coherence tomography. Opt Express, 2011, 19: 21227

81 Sheng B, Chen G H, Huang Y S, et al. Measurement of grating groove density using multiple diffraction orders and one standard wavelength. Appl Opt, 2018, 57: 2514–2518

82 Bernacki B E, Phillips M C. Standoff hyperspectral imaging of explosives residues using broadly tunable external cavity quantum cascade laser illumination. In: Proceedings of Conference on Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) Sensing XI, Orlando, 2010

83 Broda A, Wojcik-Jedlinska A, Sankowska I, et al. A 95-nm-wide tunable two-mode vertical external cavity surface-emitting laser. IEEE Photon Technol Lett, 2017, 29: 2215–2218

84 Kuznetsov M, Atia W, Johnson B, et al. Compact ultrafast reflective fabry-perot tunable lasers for OCT imaging applications. In: Proceedings of Conference on Optical Coherence Tomography and Coherence Domain Optical Methods in Biomedicine XIV, San Francisco, 2010

85 Choi K, Menders J, Searcy P, et al. Optical feedback locking of a diode laser using a cesium Faraday filter. Opt Commun, 1993, 96: 240–244

86 Thompson D J, Scholten R E. Narrow linewidth tunable external cavity diode laser using wide bandwidth filter. Rev Sci Instrum, 2012, 83: 023107

87 Kasai K, Nakazawa M, Tomomatsu Y, et al. 15 μm, mode-hop-free full C-band wavelength tunable laser diode with a linewidth of 8 kHz and a RIN of-130 dB/Hz and its extension to the L-band. Opt Express, 2017, 25: 22113–22124

88 Kuznetsov M. VECSEL semiconductor lasers: a path to high-power, quality beam and UV to IR wavelength by design. In: Semiconductor Disk Lasers: Physics and Technology. Weinheim: Wiley, 2010. 16–33

89 Lai Y H, Eliyahu D, Ganji S, et al. 780 nm narrow-linewidth self-injection-locked WGM lasers. In: Proceedings of Conference on Laser Resonators, Microresonators, and Beam Control XXII, San Francisco, 2020

90 Priante D, Zhang M, Albrecht A R, et al. In-well pumping of a membrane external-cavity surface-emitting laser. IEEE J Sel Top Quantum Electron, 2022, 28: 1–7

91 Huang Y Z, Ma X W, Yang Y D, et al. Hybrid-cavity semiconductor lasers with a whispering-gallery cavity for controlling Q factor. Sci China Inf Sci, 2018, 61: 080401

92 Iwata Y, Cheon D, Miyabe M, et al. Development of an interference-filter-type external-cavity diode laser for resonance ionization spectroscopy of strontium. Rev Sci Instrum, 2019, 90: 123002

93 Tran M A, Huang D N, Guo J, et al. Ring-resonator based widely-tunable narrow-linewidth Si/InP integrated lasers. IEEE J Sel Top Quantum Electron, 2020, 26: 1–14

94 Hagness S C, Rafizadeh D, Ho S T, et al. FDTD microcavity simulations: design and experimental realization of waveguide-coupled single-mode ring and whispering-gallery-mode disk resonators. J Lightwave Technol, 1997, 15: 2154–2165

95 Yoon K H, Kwon O K, Kim K S, et al. Ring-resonator-integrated tunable external cavity laser employing EAM and SOA. Opt Express, 2011, 19: 25465–25470

96 Xiang C, Guo J, Jin W, et al. High-performance lasers for fully integrated silicon nitride photonics. Nat Commun, 2021, 12: 6650

97 Kim S H, Byun Y T, Kim D G, et al. Widely tunable coupled-ring reflector laser diode consisting of square ring resonators. J Opt Soc Korea, 2010, 14: 38–41

98 Takeuchi T, Takahashi M, Suzuki K, et al. Wavelength tunable laser with silica-waveguide ring resonators. IEICE Trans Electron, 2009, 92: 198–204

99 Ishizaka M, Yamazaki H. Wavelength tunable laser using silica double ring resonators. Electron Comm Jpn Pt II, 2006, 89: 34–41

100 Radosavljevic S, Beneitez N T, Katumba A, et al. Mid-infrared Vernier racetrack resonator tunable filter implemented on a germanium on SOI waveguide platform. Opt Mater Express, 2018, 8: 824–835

101 Srinivasan S, Davenport M, Komljenovic T, et al. Coupled-ring-resonator-mirror-based heterogeneous III-V silicon tunable laser. IEEE Photon J, 2015, 7: 1–8

102 Deki Y, Hatanaka T, Takahashi M, et al. Wide-wavelength tunable lasers with 100 GHz FSR ring resonators. Electron Lett, 2007, 43: 225–226

103 Segawa T, Matsuo S, Kakitsuka T, et al. Full C-band tuning operation of semiconductor double-ring resonator-coupled laser with low tuning current. IEEE Photon Technol Lett, 2007, 19: 1322–1324

104 Matsuo S, Segawa T. Microring-resonator-based widely tunable lasers. IEEE J Sel Top Quantum Electron, 2009, 15: 545–554

105 Oldenbeuving R M, Klein E J, Offerhaus H L, et al. 25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity. Laser Phys Lett, 2013, 10: 015804

106 Hulme J C, Doylend J K, Bowers J E. Widely tunable Vernier ring laser on hybrid silicon. Opt Express, 2013, 21: 19718

107 Xiang C, Jin W, Guo J, et al. Effects of nonlinear loss in high-Q Si ring resonators for narrow-linewidth III-V/Si heterogeneously integrated tunable lasers. Opt Express, 2020, 28: 19926

108 Morton P A, Xiang C, Khurgin J B, et al. Integrated coherent tunable laser (ICTL) with ultra-wideband wavelength tuning and sub-100 Hz lorentzian linewidth. J Lightwave Technol, 2022, 40: 1802–1809
109 Chao R L, Liang L, Shi J W, et al. Fully integrated photonic millimeter-wave tracking generators on the heterogeneous III-V/Si platform. IEEE Photon Technol Lett, 2018, 30: 919–922
110 Kim K J, Kim J W, Oh M C, et al. Flexible polymer waveguide tunable lasers. Opt Express, 2010, 18: 8392–8399
111 Xiang C, Morton P A, Bowers J E. Ultra-narrow linewidth laser based on a semiconductor gain chip and extended Si_3N_4 Bragg grating. Opt Lett, 2019, 44: 3825–3828
112 Park T H, Kim S M, Oh M C. Polymeric tunable wavelength filter with two-stage cascaded tilted Bragg gratings. Opt Express, 2020, 28: 10145–10152
113 Luo X C, Chen C, Ning Y Q, et al. High linear polarization, narrow linewidth hybrid semiconductor laser with an external birefringence waveguide Bragg grating. Opt Express, 2021, 29: 33109–33120
114 Sun G W, Wei F, Zhang L, et al. Low-noise external cavity semiconductor lasers based on polarization-maintaining fiber bragg gratings. Chin J Laser, 2018, 45: 0601004
115 Zhang L, Wei F, Sun G W, et al. Thermal tunable narrow linewidth external cavity laser with thermal enhanced FBG. IEEE Photon Technol Lett, 2017, 29: 385–388
116 Yang X, Lindberg R, Margulis W, et al. Continuously tunable, narrow-linewidth laser based on a semiconductor optical amplifier and a linearly chirped fiber Bragg grating. Opt Express, 2019, 27: 14213–14220
117 Congar A, Gay M, Perin G, et al. Narrow linewidth near-UV InGaN laser diode based on external cavity fiber Bragg grating. Opt Lett, 2021, 46: 1077–1080
118 Brinkmeyer E, Brennecke W, Zurn M, et al. Fibre Bragg reflector for mode selection and line-narrowing of injection lasers. Electron Lett, 1986, 22: 134–135
119 Loh W, O'Donnell F J, Plant J J, et al. Packaged, high-power, narrow-linewidth slab-coupled optical waveguide external cavity laser (SCOWECL). IEEE Photon Technol Lett, 2011, 23: 974–976
120 Duraev V P, Medvedev S V. Single-frequency tunable semiconductor lasers. Semiconductors, 2014, 48: 120–122
121 Wei F, Yang F, Zhang X, et al. Subkilohertz linewidth reduction of a DFB diode laser using self-injection locking with a fiber Bragg grating Fabry-Perot cavity. Opt Express, 2016, 24: 17406–17415
122 Gao S, Luo M, Jing Z G, et al. A tunable dual-wavelength fiber ring-cavity laser based on a FBG and DFB laser injection. Optik, 2020, 203: 163961
123 Gao S, Jing Z G, Chen H Y. A stable triple-wavelength semiconductor optical amplifier ring-cavity laser with two seed DFB lasers and a fiber Bragg grating. Optik, 2021, 238: 166725
124 Lindberg R, Laurell F, Fröjdh K, et al. C-cavity fiber laser employing a chirped fiber Bragg grating for electrically gated wavelength tuning. Opt Express, 2020, 28: 9208–9215
125 Muller M S, Hoffmann L, Bodendorfer T, et al. Fiber-optic sensor interrogation based on a widely tunable monolithic laser diode. IEEE Trans Instrum Meas, 2010, 59: 696–703
126 Toet P M, Hagen R A J, Hakkesteegt H C, et al. Miniature and low cost fiber bragg grating interrogator for structural monitoring in nano-satellites. In: Proceedings of International Conference on Space Optics, 2014
127 You X H, Wang C X, Huang J, et al. Towards 6G wireless communication networks: vision, enabling technologies, and new paradigm shifts. Sci China Inf Sci, 2021, 64: 110301