

Research on Narrow Linewidth External Cavity Semiconductor Lasers

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Abstract: Narrow linewidth external cavity semiconductor lasers (NLECSLs) have many important applications, such as spectroscopy, metrology, biomedicine, holography, space laser communication, laser lidar and coherent detection, etc. Due to their high coherence, low phase-frequency noise, high monochromaticity and wide wavelength tuning potential, NLECSLs have attracted much attention for their merits. In this paper, three main device structures for achieving NLECSLs are reviewed and compared in detail, such as free space bulk diffraction grating external cavity structure, waveguide external cavity structure and confocal Fabry–Perot cavity structure of NLECSLs. The Littrow structure and Littman structure of NLECSLs are introduced from the free space bulk diffraction grating external cavity structure of NLECSLs. The fiber Bragg grating external cavity structure and silicon based waveguide external cavity structure of NLECSLs are introduced from the waveguide external cavity structure of NLECSLs. The results show that the confocal Fabry–Perot cavity structure of NLECSLs is a potential way to realize a lower than tens Hz narrow linewidth laser output.

Keywords: narrow linewidth; external cavity; FSB DG; FBG; silicon-based waveguide; confocal F-P cavity



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1. Introduction

Semiconductor lasers have been applied in many fields, such as high-resolution spectroscopy and broadband communication network systems. Semiconductor lasers need to have the characteristics of a narrow linewidth, high-frequency modulation and wide tunable range at the same time. In other fields, it is required that lasers have the characteristics of narrower output linewidth, larger coherence length, and narrower spatial coherence [1]. By using the external cavity technology, semiconductor lasers can produce stabilized output with a single longitudinal mode and narrow linewidth, and they can also be tuned in the range of tens of nanometers to hundreds of nanometers [2]. At the same time, some other properties of semiconductor lasers are also improved, including a lower threshold, higher output power and larger side mode suppression ratio (SMSR) [3,4]. These properties meet the requirements of coherent optical communication, coherent detection and other applications of NLECSLs. In 1964, J.W. Crowe et al. [5] first proposed the external cavity theory of the semiconductor laser. In 1975, Heckscher H et al. [6] reported the compact and relatively inexpensive external cavity structure of the laser with the III-V compound semiconductor.

An NLECSL includes a semiconductor laser active section and an external cavity. The active section, which typically contains a III–V semiconductor quantum wells structure, is used to provide the optical gain for the whole cavity, and thereby determines the lasing

wavelength range. The external cavity is used to select the lasing wavelength, while reducing the linewidth. The natural cleaving surface at both ends of the active section chip is the resonant cavity, which is called the internal cavity or the intrinsic cavity [7]. The cavity composed of the external feedback element and the chip cleaving surface is called the external cavity. Through the external cavity, part of the output light is fed back to the active region for multiple gain, thereby narrowing the linewidth and reducing the phase noise and intensity noise of the lasers [8]. There are many kinds of external feedback components, such as free space bulk diffraction grating, fiber Bragg grating (FBG), waveguide and Fabry–Perot (F-P) cavity and the combination of these components. NLECSLs have many advantages, such as good monochromaticity, high stability, long coherence length, and so on. Therefore, NLECSLs are widely used in the fields of photoelectric detection, coherent communication, precision measurement, optical frequency standards, absorption spectrum measurement and the study of the interaction between lights and matters [9]. In this paper, free space bulk diffraction grating (FSBDG) external cavity structure, waveguide external cavity structure and confocal F-P cavity structure, the three main device structures for achieving NLECSLs, are expanded upon. Among them, the confocal F-P cavity can further narrow the linewidth. Lewoczko-Adamczyk W et al. [10] proposed the mode of optical self-locking with the external single-chip confocal F-P cavity; when the output power exceeds 50 mW, the corresponding Lorentz linewidth is only 15.7 Hz, which is the highest level in the world at present.

2. FSBDG Structure of NLECSLs

The FSBDG is one of the most widely used external mirrors. It has good performance, especially in its wide tuning range, high spectral resolution, and flexible and precise tunability. Great progress in the ECSL with FSBDG mirror have been achieved, and the results of research and development in the field are continuously transferred to industrialization. Wavelength selectivity and tunability of FSBDG ECSL can be realized by adjusting the incident angle to the FSBDG plane. Different applications put forward different tuning requirements; some require a large tuning range with hopping allowed, whereas others require fine continuous tuning without hopping. This paper focuses mainly on the latter. The continuous tuning range and precision are dependent on the design of optics and related mechanics. Two configurations are well developed and widely used, including the Littrow structure and Littman structure, which are introduced as follows.

2.1. Littrow Structure of NLECSLs

The Littrow structure of NLECSLs is shown in Figure 1. The output light of the Littrow ECSL is collimated by the lens group to obtain the horizontal parallel light, which is incident to the FSBDG external cavity for optical feedback. After FSBDG splitting, the first-order diffraction is fed back to the active region of the laser, and the light field in the active region interacts with each other, resulting in the gain difference between the longitudinal modes and the gain is larger. The longitudinal mode excitation satisfying the laser excitation condition is excited, and the mode with the small gain is lost. By changing the wavelength of the FSBDG external cavity feedback light, the laser output with different wavelengths can be obtained, so as to realize wavelength tuning [11].

In 2016, Shin D K et al. [12] used the SAF gain chip and FSBDG Littrow structure of ECSL and realized the maximum injection current was 195 mA, the maximum output power was 83 mW, the Lorentz linewidth was 4.2 kHz, and the Gaussian linewidth was 22 kHz.

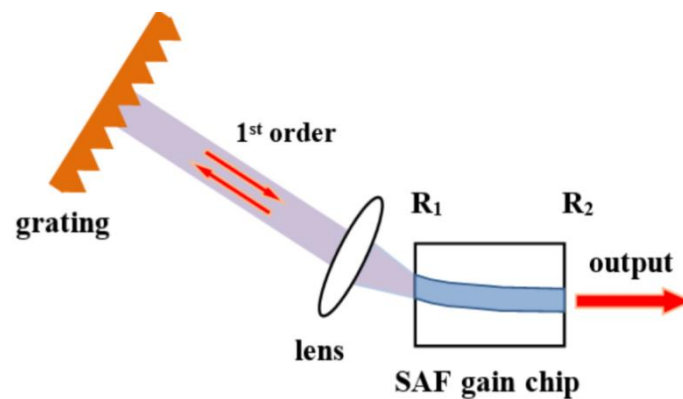


Figure 1. Littrow structure of NLECSLs.

In 2018, Xu B et al. [13] used a commercially available high-power green LD as a gain device and the influence of FSB DG parameters on the performance of external cavity laser was studied. For the Littrow structure of ECSL with the first-order diffraction beam as the feedback and the zero-order diffraction beam as the coupling output, the tuning bandwidth was 11.0 nm and the output power was close to 400 mW.

In 2019, Wang Yan, et al. [14] built an ECSL with Littrow structure using a 1200 groove/mm FSB DG with 91% first-order diffraction efficiency as an external cavity. The maximum SMSR could reach 65 dB and the tunable range could reach 209.9 nm.

In 2021, Lucia Duca et al. [15] reported an ECSL based on an improved Littrow structure, by placing a piezoelectric transducer behind the 780 nm diode laser; the wavelength adjustment by rotating the FSB DG was separated from the fine adjustment of the external cavity. The free spectral range was 3.6 GHz, the SMSR reached 48 dB, and the Lorentz linewidth was 540 kHz. Table 1 shows the performances of the Littrow structure of NLECSLs. Littrows structure of NLECSLs are widely used in many applications, due to its advantages of simple structure and convenient operation. However, the direction of output beam will rotate in tuning. This shortcoming must be overcome for many applications.

Table 1. The performances of Littrow structure of NLECSLs.

Central Wavelength	Tuning Range	SMSR	Line Width	Output Power	Publication Time
1080 nm	100 nm	-	4.2 kHz	83 mW	2016 [12]
525 nm	11.0 nm	-	0.08–0.18 nm	400 mW	2018 [13]
1550 nm	209.9 nm	65 dB	-	48.9 mW	2019 [14]
780 nm	3.6 GHz	48 dB	540 kHz	-	2021 [15]

Note: “-” denotes that the data are not available.

2.2. Littman Structure of NLECSLs

In the Littman structure, as shown in Figure 2, the FSB DG position is fixed; the wavelength of the semiconductor laser can only be changed by adjusting the position of the plane mirror. The laser output beam direction is constant, the linewidth becomes narrow, but the output laser power is less than Littrow structure of ECSL. In the Littman structure, the collimated laser grazes onto the FSB DG, and the incident angle of the beam is large. Compared with Littrow structure, when the laser irradiated the grating, more diffracted lasers are generated, anyone of them laser output linewidth is narrower [16].

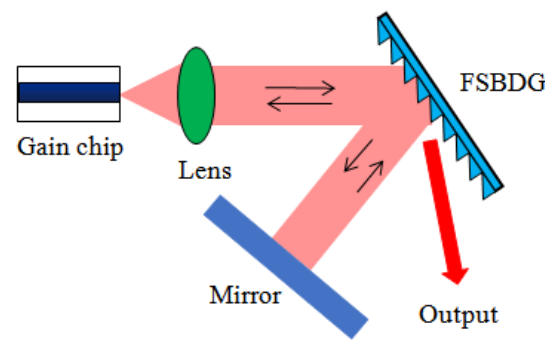


Figure 2. Littman structure of NLECSLs.

In 2018, N. Torcheboeuf et al. [17] reported a 222 nm tuning range, using a compact external cavity GaSb-based diode laser and micro-electro-mechanical system (MEMS) mirror. In the tuning range, the power range was 8–24 mW, the SMSR was 50 dB, and the mode hopping was controllable 18 GHz.

In 2020, Hoppe M et al. [18] optimized the ECSL of 1550 nm bent waveguide based on GaSb with the MEMS with the concept of ECSL cavity, and realized the tuning range of 106 nm, covering the wavelength range from near infrared to MIR.

In 2021, Morten Hoppe et al. [19] used a laser diode with a central wavelength of 2.02 μm . The collimated laser beam passed the MEMS mirror at approximately the 45° angle. It was reflected onto the reflection grating. The arrangement of the optical components was chosen to achieve optimal illumination of the grating. In the gain chip with curved waveguide, both facets are accessible, where the laser beam is coupled out via the rear facet of the laser diode, resulting in a higher efficiency of the resonator, with an SMSR of 2.02 μm and a central wavelength of 53 dB. Table 2 shows the performance of the Littman structure of NLECSLs. The Littman structure of NLECSLs provides an output beam with a stable direction. Tuning of the Littman structure of NLECSLs is realized by the rotating mirror. Since it does not change the incident angle to the grating, the direction of the output beam is stable.

Table 2. The performance of Littman structure of NLECSLs.

Central Wavelength	Tuning Range	SMSR	Line Width	Output Power	Publication Time
2221 nm	222 nm	50 dB	18 GHz	8~24 mW	2018 [17]
1550 nm	106 nm	55 dB	-	30 mW	2020 [18]
2.02 μm	110 nm	53 dB	-	7.1 mW	2021 [19]

Note: “-” denotes that the data are not available.

3. Waveguide Structure of NLECSLs

There are two types of waveguide structure of NLECSLs, including FBG and silicon-based waveguide. When the fiber grating is used as the feedback element of the external cavity laser, the linewidth performance is excellent and the tuning range is wider, but the volume is larger, the refractive index is smaller, the size is larger, and the absorption loss of material is larger [20]. Using the external low loss waveguide as the optical feedback element can effectively reduce the linewidth of the semiconductor laser and obtain low noise spectral characteristics. Due to its small size, low energy consumption, low loss and the ability to integrate with other optical components, NLECSLs based on silicon-based waveguides have become a competitive and attractive candidate laser in many coherent applications [21].

3.1. FBG Structure of NLECSLs

FBG structures of NLECSLs in optical fiber transmission systems have become a research hotspot. The FBG structure of NLECSL has its AR facet facing the FBG, the FBG end coupled directly to the gain chip and the other end of the FBG acts as the end reflector of the external cavity. With AR coating on the gain chip, the lasing wavelength may be selected by choosing the appropriate FBG, as shown in Figure 3.

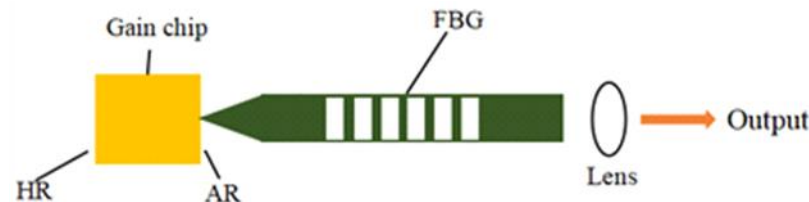


Figure 3. FBG structure of NLECSLs.

In 2011, Loh W et al. [22] reported a 1550 nm InGaAlAs/InP quantum well, high power, low noise encapsulated ECSL demonstration. The laser consisted of a dual-channel curved channel plate coupled with an optical waveguide amplifier and a 2.5 GHz narrow bandwidth FBG passive cavity using a lens fiber. Under the bias current of 4A, ECSL generates 370 mW of fiber-coupled output power, and its Gaussian linewidth and Lorentz linewidth are 35 kHz and 1 kHz, respectively.

In 2016, Lynch S G et al. [23] demonstrated a new integrated platform with FBG. The high thermal conductivity of silicon substrate contributes to the heat dissipation and thermalization of the device. The geometric shape of the device is precisely designed with a small inclined plane, which connects the end of integrated platform to eliminate unnecessary optical feedback, and its layout can minimize the angular coupling loss between waveguides. The laser works in a single mode at 1532.83 nm, with an output power of 9 mW and a linewidth of 14 kHz.

In 2017, Li Zhang et al. [24] combined a semiconductor gain chip and FBG with enhanced thermal sensitivity, and demonstrated a mode-free external cavity laser design. The compact ECSL had a narrow linewidth of 35 kHz, SMSR greater than 50 dB, and the mode-free tuning range was 62.5 GHz.

In 2019, Huang D et al. [25] demonstrated an ultra-low loss silicon based waveguide (0.16 dB/cm) with a linewidth of 1 kHz and an output power of more than 37 mW, and a long FBG fully integrated extended distributed Bragg reflector laser with a narrow bandwidth. The combination of narrow linewidth and high power enables it to be used in coherent communication, radio frequency photonics and optical sensing.

In 2021, Antoine Congar et al. [26] realized a 400 nm FBG InGaN-based laser diode. A narrow band FBG was fabricated under near ultraviolet light. The device has a SMSR of 44 dB and an inherent linewidth of 16 kHz.

In 2022, Suqs et al. [27] reported a laser based on the FBG ECSL module near the wavelength of 1550 nm, using the combination of narrow linewidth technology and frequency stable transfer technology to narrow the laser intrinsic Lorentz linewidth to 15 kHz. Table 3 shows the performances of the FBG structure of NLECSLs. The FBG structure of NLECSL is easily obtain narrow linewidth, high SMSR and high wavelength thermal stability. It is easy to design and screen the gain chip and FBG separately; the performances of FBG structure of NLECSL can be optimized and it is very convenient to be used in fiber systems.

Table 3. Performance of FBG structure of NLECSLs.

Central Wavelength	Tuning Range	Line Width	Output Power	Publication Time
1550 nm	-	1 kHz	370 mW	2011 [22]
1532.83 nm	20 pm	14 kHz	9 mW	2016 [23]
1550.4 nm	62.5 GHz	35 kHz	-	2017 [24]
1565 nm	2.9 GHz	1 kHz	37 mW	2019 [25]
400 nm	-	16 kHz	-	2021 [26]
1572 nm	22 GHz	15 kHz	25 mW	2022 [27]

Note: “-” denotes that the data are not available.

3.2. Silicon-Based Waveguide Structure of NLECSLs

With the maturity of the silicon optical chip design and process platform, the external cavity feedback elements based on silicon, Si_3N_4 and other materials endlessly emerge, and with the help of various microcavity structures, the linewidth of ECSL can be further compressed. It has the characteristics of high reliability and low power consumption of the monolithic integrated structure, as well as the narrow linewidth and wide tuning characteristics of the external cavity structure, and has gradually become a hotspot in the research field of NLECSLs [28]. Vissers E et al. [29] studied the hybrid integrated mode-locked laser diode with silicon nitride expansion cavity in 2021, coupled the silicon nitride external cavity with the InP active chip, and obtained the line width of 31 Hz. In 2018, Guan H et al. [30] studied III-V/Si hybrid external cavity lasers. The Si_3N_4 edge-coupled silicon chip is mixed into the spot size converter in the silicon chip. The maximum output power of the laser is 11 mW, the measured minimum linewidth is 37 kHz (maximum < 80 Hz), and the SMSR is 55 dB.

In 2019, Guo Y et al. [31] demonstrated a III-V/silicon nitride hybrid external cavity laser. The tuning range of ECSL is 45 nm, the SMSR is 60 dB, and the linewidth is about 100 kHz.

In 2020, Kharas D et al. [32] showed a high-power on-chip 1550 nm laser, which was integrated into a silicon nitride waveguide and distributed Bragg reflector grating photonic integrated circuit by a bending channel and a two-way InGaAsP/InP plate coupled with an optical waveguide amplifier. The driving current of the single-mode emission optical power of 312 kW was 2.5 A, and the linewidth of 192 kHz was integrated.

In 2020, Guo Y Y et al. [33] demonstrated hybrid lasers by using InP reflective semiconductor optical amplifier chips coupled with Si_3N_4 tunable reflector chips. The laser wavelength tuning range was 160 nm, and the linewidth was 30 kHz.

In 2020, Sia Jx et al. [34] adopted the hybrid integration of the III-V optical amplifier and extended, low-loss wavelength-tunable silicon cursor cavity, and first reported the III-V/silicon hybrid wavelength-tunable laser in the rich wavelength region of 1647–1690 nm. When the continuous wave operates at room temperature, the output power can reach 31.1 mW, the maximum SMSR is 46.01 dB, and the line width is 0.7 kHz.

In 2021, Guo Y Y et al. [35] reported a widely tunable III-V/ Si_3N_4 hybrid integrated external cavity laser. Under 500 mA injection current, the maximum output power was 34 mW. In the tuning range of 58.5 nm, the SMSR exceeds 70 dB. The laser linewidth is 2.5 kHz. The same structure was used in the optical fiber communication conference and exhibition next year, but its performance was higher than last year, reaching a record of about 170 nm tuning range. The linewidth of the laser decreased slightly less than 2.8 kHz [36].

In 2021, Zhao R L et al. [37] reported a wavelength tunable hybrid integrated external cavity laser for C-band. Two parallel reflective semiconductor optical amplifier gain channels are composed of Y branches in the Si_3N_4 photonic circuit to increase the optical gain. The SMSR is about 67 dB and the pump current is 75 mA. The linewidth of the unpackaged laser is 6.6 kHz, and the on-chip output power is 23.5 mW.

In 2021, McKinzie K A et al. [38] demonstrated the hybrid integration of an InP-based laser and amplifier array PIC and high-quality factor silicon nitride microring resonator. Laser emission based on the gain of the interference combination amplifier array in the external cavity was formed by the feedback from the silicon nitride micro resonator chip; the linewidth was reduced to 3 kHz, and the average output power was 37.9 mW. Table 4 shows the performances of silicon-based waveguide structures of NLECSLs. Silicon-based waveguide structures of NLECSLs have excellent characteristics, such as compact structure, low cost, mass production, integrated packaging, small size, etc., and have a wide tuning range, while achieving a narrow linewidth. At present, the technical difficulty of silicon-based waveguide structures of NLECSL involves how to improve the coupling efficiency and reduce the reflectivity at the coupling. In addition, the heat accumulation and dissipation during the thermo-optic effect tuning process takes a certain amount of time, which affects the high-speed tuning. How to further improve the modulation speed is a big challenge.

Table 4. Performance of silicon-based waveguide structure of NLECSLs.

Central Wavelength	Tuning Range	SMSR	Line Width	Output Power	Publication Time
1565 nm	1560–1570 nm	-	31 Hz	300 mW	2021 [29]
1550 nm	60 nm	55 dB	37 kHz	11 mW	2018 [30]
1540 nm	45 nm	60 dB	100 kHz	0.78 mW	2019 [31]
1550 nm	-	55 dB	192 kHz	312 mW	2020 [32]
1559 nm	160 nm	55 dB	30 kHz	-	2020 [33]
1670 nm	1647–1690 nm	46.01 dB	0.7 kHz	31.1 mW	2020 [34]
1550 nm	58.5 nm	70 dB	2.5 kHz	34 mW	2021 [35]
1546 nm	44 nm	67 dB	6.6 kHz	23.5 mW	2021 [36]
1542 nm	1513–1564 nm	42 dB	3 kHz	37.9 mW	2021 [37]
1550 nm	170 nm	64 dB	2.8 kHz	24.8 mW	2022 [38]

Note: “-” denotes that the data are not available.

4. Confocal F-P Cavity Structure of NLECSLs

To further narrow the linewidth on the basis of the structure of the ECSL, it is necessary to use the mode selection element with a narrow bandwidth. The interference filter or F-P cavity and narrow-band filter are the structures of the external cavity optical feedback technology that are commonly used to narrow the linewidth [39]. Compared with the optical cavities used in the traditional fiber narrow linewidth laser, solid narrow linewidth laser and chip external cavity narrow linewidth laser, the high quality factor F-P cavity has an extremely low thermal effect, nonlinear effect and ultra-high temperature stability [40].

Confocal F-P cavity structures of NLECSLs are designed as a monolithic confocal F-P cavity and the focused laser beam is coupled with the tilted monolithic confocal F-P cavity. The tilt angle of the cavity, with regard to the optical axis of the laser system, prevents the non-resonant feedback from the cavity being re-injected into the emitter; this ensures resonant-only optical feedback in the laser diode, as shown in Figure 4.

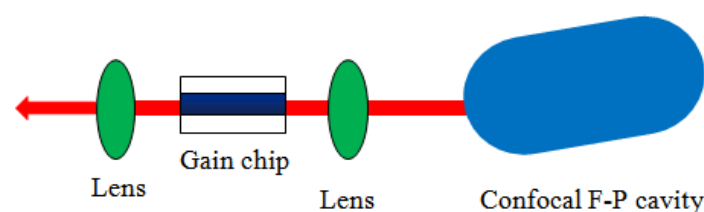


Figure 4. Confocal F-P Cavity structure of NLECSLs.

A 657 nm ECSL system with stable output frequency was proposed in 2011 [41]. Through a narrowband high transmission interference filter, the instantaneous linewidth of the laser emitted by this new diode laser system was 7 kHz and the linewidth was 432 kHz. In the same year, Yang et al. [42] proposed a wide-cavity ECSL with a linewidth of kilohertz using optical feedback from a single folded F-P cavity. The linewidth of the ECSL was successfully reduced to 6.8 kHz.

In 2012, Yang Z et al. [43] proposed a NLECSL with high-precision dual-mirror non-confocal cavity optical feedback. Through Lorentz fitting, the full width half maximum linewidth of the laser was reduced to 100 Hz, and the instantaneous linewidth was reduced to 30 Hz.

In 2014, Luo Z et al. [44] proposed an extended cavity diode laser with MHz linewidth. The optical feedback technology of the folded Fabry–Perot cavity was used to replace the mirror in the traditional ECSL configuration. The effective laser reduced the linewidth and stable frequency, and the linewidth of the laser was reduced from about 20 GHz to 15 MHz.

In 2015, Lewoczko-Adamczyk W et al. [10] proposed a compact, ultra-narrow linewidth semiconductor laser based on a 780 nm distributed feedback diode laser, which was self-locked to an external single-chip confocal F-P cavity mode. When the output power exceeds 50 mW, the Lorentz linewidth corresponding to the resonant optical feedback laser is 15.7 Hz.

In 2015, Pyrlik C et al. [45] proposed a DFB based on 1.5 mm length and 780 nm with a single confocal Fabry–Perot cavity. Both surfaces of DFB are coated with anti-reflection coating. The tilt of the external resonator cavity relative to the optical axis of the laser system is 15° , which can prevent the non-resonant feedback of the cavity from being reinjected into the transmitter. The line width of 31 Hz is obtained in the paper.

In 2017, Christopher H et al. [46] focused the light emission of the DFB semiconductor laser chip into a confocal resonant feedback cavity. Therefore, the resonant feedback is re-injected into the DFB diode laser chip. The light emitted from the other side of the DFB laser chip is collimated through an optical isolator and coupled to the single-mode fiber. The Lorentz linewidth of about 630 Hz is obtained by the self-delayed heterodyne device. The corresponding FWHM level technical linewidth is about 30 kHz.

In 2018, the ultra-narrow bandwidth dual filter was used as the ECSL of the laser longitudinal mode selection element developed by the Institute of Optoelectronics, Shanxi University. For the angle of the rotating narrow band filter, the laser wavelength coarse tuning range was 14 nm. The linewidth of the narrow-band filter ECSL is measured by the fiber delay beat method. The linewidth is about 187 kHz [47].

In 2018, Yu Li et al. [48] developed a new on-chip semiconductor laser by introducing the cursor effect and self-injection locking effect between the F-P diode laser on the silicon chip and the external micro resonator. The narrow linewidth of the laser is 8 kHz, and the wide switching range is 17 nm.

In 2020, Zhang L et al. [49] used a narrow-band interference filter for spectral selection, and used a cat-eye reflector for optical feedback to design an ECSL. The ECSL works near 698.45 nm. The tuning range of the current control is more than 40 GHz, and the tuning range of piezoelectric control is 3 GHz. The ECSL line width measured by heterodyne beat frequency is about 180 kHz.

In 2021, YongXiang Zheng et al. [50] demonstrated a method of laser frequency stabilization in a wide tuning range by installing piezoelectric ceramic actuators into the Fabry–Perot cavity to stabilize the ultraviolet laser. In order to suppress the piezoelectric drift, the piezoelectric actuator adopts a two-layer symmetrical structure to achieve a tuning range of 14.7 GHz. It can be extended to the wavelength from ultraviolet to infrared. The wavelength of ECSL is 369.5 nm and the linewidth is 20 MHz.

In 2021, Jakup Ratkoceri et al. [51] observed the stable locking region of the injection-locked FP laser by using the delay self-zero difference technique and the RF spectrum of the external cavity FP laser. The center wavelength is 1546.244 nm, and the 3 dB Lorentz linewidth is 100 MHz. Table 5 shows the performance of the confocal F-P cavity structure of

NLECSLs. The confocal F-P cavity structure of NLECSLs shows wide band frequency noise suppression characteristics with a narrow linewidth; the confocal cavity length and the cavity mirror's curvature radius must be matched to avoid breaking the mode degeneracy, which means higher requirements for accuracy when using higher finesse cavities.

Table 5. Performance of confocal F-P cavity structure of NLECSLs.

Central Wavelength	Tuning Range	Line Width	Output Power	Publication time
657 nm	0.5 GHz	432 kHz	-	2011 [41]
689 nm	3.97 GHz	6.8 kHz	20 mW	2011 [42]
689 nm	4 MHz	100 Hz	-	2012 [43]
635 nm	5–20 GHz	15 MHz	5 mW	2014 [44]
780 nm	-	15.7 Hz	50 mW	2015 [10]
780 nm	-	31 Hz	38 mW	2015 [45]
1064.49 nm	-	630 Hz	4 mW	2017 [46]
852 nm	1.5 GHz	187 kHz	56 mW	2018 [47]
1555 nm	17 nm	8 kHz	-	2018 [48]
698.45 nm	40 GHz	180 kHz	36 mW	2020 [49]
369.5 nm	14.7 Hz	20 MHz	-	2021 [50]
1547 nm	20 nm	100 MHz	-	2021 [51]

Note: “-” denotes that the data are not available.

5. Conclusions

In this paper, the three main device structures of NLECSLs are expanded upon. By comparing a large number of data, we conclude that the confocal F-P cavity structure of NLECSLs is the best structure to achieve a narrow linewidth, and could obtain the narrowest linewidth, which is more precise and more suitable for applications that require a high accuracy of the linewidth. NLECSLs are developing towards high power and narrower linewidth. Through the continuous development of new optical feedback elements and optical resonator design, the ultra-narrow linewidth laser below 20 Hz has been realized. Combined with its characteristics of small volume, light weight, high conversion efficiency and wide spectral range, it will be widely used in the fields of ultra-high precision lidar, inter satellite communication, coherent optical communication, laser spectroscopy, atomic clock pumping, atmospheric absorption measurement and optical fiber communication. How to realize the wide tuning range, narrow linewidth laser output is a main research direction for the future development of NLECSLs. In addition, a narrow linewidth laser is critical for its application as a pump source for generating an extremely narrow linewidth Brillouin output [52]. Currently, different approaches to narrow linewidth lasers have distinct characteristics. In the future, new technologies will lead to further compression of the laser linewidth, improvement of frequency stability, expansion of wavelength, and increase in power, which will pave the way for human beings to explore the unknown world.

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