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Advances in narrow linewidth and wide tuning range external-cavity wavelength-swept lasers

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An external-cavity wavelength-swept laser, characterized by its exceptional temporal coherence and extensive tuning range, serves as a crucial light source for cutting-edge fields such as fiber sensing, lidar, and spectroscopy. The burgeoning growth of optical communication technology has escalated the demand for lasers with narrow linewidth and broad tuning range, thereby catalyzing the swift advancement of external-cavity wavelength-swept diode lasers and their diverse applications. This article comprehensively presents the configurations and operating principles of these lasers, and provides an in-depth review of their development status, specifically focusing on those with narrow linewidth and wide tuning range. The aim is to offer a valuable reference for researchers involved in the development and application of wavelength-swept lasers.

KEYWORDS

narrow linewidth, wide tuning range, external-cavity, wavelength-swept laser, Littman-Metcalf, Littrow

Introduction

Narrow-linewidth lasers with extensive spectral tunable ranges are indispensable for a variety of applications, including quantum optics, molecular physics, gas detection, and space detection [1–4]. However, achieving a balance between narrow linewidth and tunable wavelength continues to pose a significant challenge in the field of laser technology. Currently, prevalent strategies for attaining laser output with these characteristics encompass the use of spectral selection devices (viz. gratings, prisms, etc.) and nonlinear optical frequency conversion (viz. Raman scattering, optical parametric oscillator/amplifier, etc.) [3–8]. Semiconductor-based wavelength-swept lasers, such as external-cavity tunable lasers (ECTLs), distributed Bragg reflector lasers (DBRs), and distributed feedback lasers (DFBs), are renowned for their highly controllable emission properties. These lasers have become indispensable in a multitude of applications, including distributed optical fiber sensing [9–11], atomic and molecular laser spectroscopy [12, 13], reconfigurable optical add/drop multiplexing systems [14], trace gas analysis [15], laser lidar [16], space strontium optical clocks [17, 18], and laser cooling [19]. The swift progression and application of these lasers have led to heightened requirements for linewidth and tunable range. Compared to semiconductor-based wavelength-swept lasers operating with internal-cavity

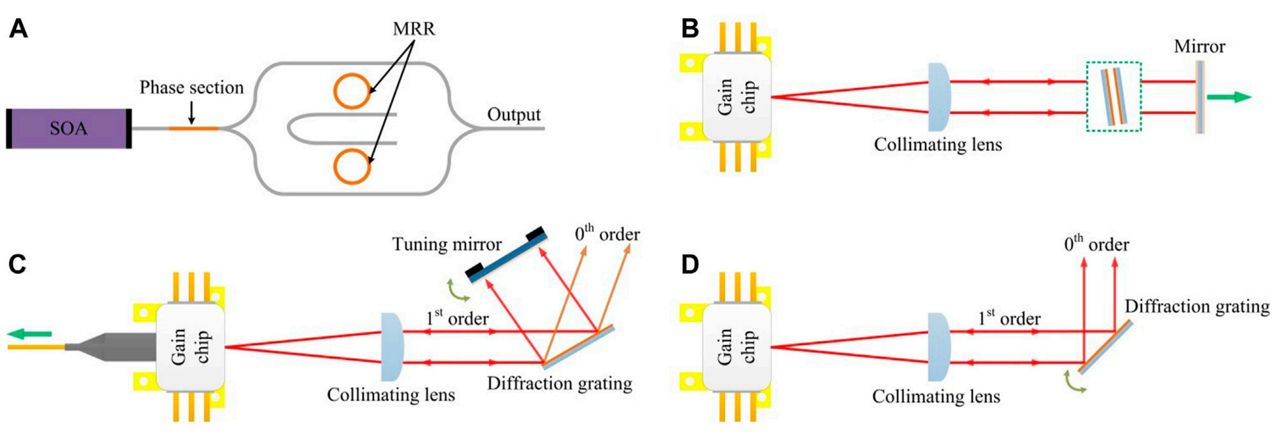

FIGURE 1
(A) Schematic drawing of the MRR-based external-cavity configuration, **(B)** configuration of the filter-type external-cavity tunable laser, **(C)** the Littman-Metcalf cavity configuration, and **(D)** the Littrow cavity configuration.

feedback, ECTLs boast prestigious characteristics such as narrower linewidth, wider tuning range without mode-hopping, higher signal-to-source spontaneous emission ratio, and lower cost, making them one of the most versatile measuring tools. Consequently, research into narrow linewidth and wide tuning range ECTLs has emerged as a hot topic in recent years [20–22]. Over the past few decades, synchronous tuning with mode matching and mode selection has matured, leading to constant updates in the configurations of external-cavity wavelength-swept lasers [23, 24].

This article reviews typical external-cavity configurations of wavelength-swept lasers, summarizing the characteristics, operating theories, and development status of each ECTL. Finally, it provides a summary and an outlook for the future development of narrow linewidth and wide tuning range external-cavity wavelength-swept lasers.

Configurations and operating principles of the wavelength-swept laser

In the realm of optical communication networks and other fields, there exist at least four distinct configurations of the wavelength-swept laser. One such configuration involves the use of a microring resonator (MRR) external-cavity, which can adjust its resonance wavelength through the thermo-optic effect (i.e., thermal control) or the carrier-dispersion effect (i.e., electrical control). Typically, an MRR-based external-cavity configuration comprises a semiconductor optical amplifier (SOA), a phase-adjustment region, and a double-microring optical waveguide structure with unequal radii, which can be based on silicon (Si), silicon oxynitride (SiON), or silicon nitride (Si_3N_4) [25–27]. Figure 1A highlights a schematic drawing of the MRR-based external-cavity configuration. The main mode-selection element in the external-cavity is the superimposed spectrum of two MRR spectra with different free spectral ranges (FSRs), which facilitates wavelength tuning and linewidth narrowing. The Vernier spectrum FSR_{Vernier} shaped by the double-microring resonators can be described as follows [28]:

$$FSR_{\text{Vernier}} = \frac{FSR_1 \times FSR_2}{|FSR_1 - FSR_2|} \tag{1}$$

where FSR_{m} is FSR of the mth ring. When the double-microring optical waveguide undergoes synchronous tuning, the output spectra maintain alignment and shift collectively as described in Eq. 1, thereby achieving a continuous wavelength-tunable output.

The subsequent configuration involves filter-based tunable external-cavity semiconductor lasers that incorporate an optical filter component within the external lasing cavity. Typical filter components encompass the Fabry-Perot interferometer (FPI) [29], nematic liquid crystal [30], birefringence filter [31], acousto-optic tunable filter (AOTF) [32], interference filter (IF) [33], electro-optic tunable filter [34], among others. A general structure diagram is depicted in Figure 1B. The principle of outputting different lasing wavelengths is predicated on the shift in the position of the maximum transmission peak wavelength. This can be achieved by altering the external angle of incidence, the external medium refractive index, or the FSR of the periodic comb spectrum. Concurrently, through the precise mode selection of the chosen optical filter component and a flexible increase in effective cavity length, the spectral linewidth can be further narrowed.

As depicted in Figure 1C, another configuration is the Littman-Metcalf cavity. The primary components of the Littman-Metcalf cavity encompass the gain chip, the collimating lens, the diffraction grating, and the tuning mirror. The diffraction grating, which includes transmission [35], reflection [36], and blazed gratings [37, 38], functions as the principal mode selection element, facilitating wavelength tuning and spectral linewidth narrowing. Light emanating from the gain chip impinges on the diffraction grating, which spatially segregates the spectral components of the gain chip output. The mode-selective effect of the diffraction grating can be expressed by a function associated with its equivalent reflectance R_G. The output of the Littman-Metcalf configuration is the coupled effect of the diffraction grating, external-cavity, and internal-cavity. Consequently, the output mode structure, E_{MS}, can be described as follows [39]:

$$E_{MS} = T_G G_{IC} G_{EC} (R_G) E_0 \quad (2)$$

where T_G, G_{IC}, G_{EC}, E_0 denotes the equivalent transmittance of the diffraction grating, the gain of the internal-cavity, the gain of the external-cavity, the initial energy, respectively. By rotating the tuning mirror, the wavelength is tuned. The linewidth of the Littman-Metcalf cavity is given by the formula [40]:

$$\Delta\upsilon = \Delta\upsilon_0 \left[1 + \tau/\tau_{in}\left(1 - \sqrt{R_2/R_{out}}\right)\right]^{-2} \quad (3)$$

where $\Delta\upsilon_0$ is the intrinsic linewidth of the gain chip, τ_{in} and τ are the times that the photons take to travel back and forth between the external-cavity and the active region of the gain chip, respectively, R_2 is the reflectivity of the output end face of the gain chip, and R_{out} is the reflectivity of the external-cavity. Obviously, the linewidth is closely related to the parameters described in Eq. 3.

The final configuration is the Littrow cavity shown in Figure 1D. In this geometry, the tuning mirror is removed compared to the Littman-Metcalf cavity. The lasing wavelength is tuned by rotating the diffraction grating and thereby changing the wavelength of the optical feedback. The output wavelength that satisfies the resonant condition is determined by Eqs 4, 5, respectively [41]:

$$L = q\left(\lambda_q/2\right) \quad (4)$$

$$\lambda = 2d\sin\theta \quad (5)$$

where L denotes the effective cavity length, q denotes a positive integer, λ denotes the lasing wavelength, d represents the diffraction grating period, and θ represents the diffraction angle of the mode selection element. The linewidth of the Littrow cavity can be express as [42] (namely Eq. 6):

$$\Delta\upsilon = \frac{\Delta\upsilon_0}{(1+\alpha^2)\cos^2\phi} \frac{R_2}{(1-R_2)^2 R_d} \left(\frac{nl}{L}\right)^2 \quad (6)$$

where α, $\cos\phi$, R_d, l is the linewidth expansion factor, the phase-matching factor, the 1st-order diffraction efficiency of the mode selection element, the length of the gain chip's internal-cavity, respectively. Using the diffraction grating to construct an external-cavity can significantly increase the lasing cavity length, thus making the output linewidth narrower.

Research progress of waveguide-type ECTL

Owing to the combination of the availability of complementary metal oxide semiconductor (CMOS) fabrication technology and high index contrast. Thus, the silicon photonics (SiPh) dual MRRs ECTLs with a wide tuning range and narrow linewidth have attracted increasing research attention. In 2009, the first ECTL fabricated with SiPh wire waveguides on a silicon-on-insulator (SOI) substrate was demonstrated by Chu et al. [25], achieving a maximum tuning span of 38 nm in the 1,530 nm–1,565 nm (namely, C-band) or 1,565 nm–1,610 nm (namely, L-band) and a side-mode suppression ratio (SMSR) more than 30 dB along the whole tuning range. Using a similar hybrid silicon platform, in 2013, Hulme et al. designed and fabricated dual intra-cavity ring resonators ECTL [43]. The laser has a thermal tuning range of more than 40 nm, the SMSR greater than 35 dB, and the minimum on-chip output power of 0.45 mW. Meanwhile, they measured the linewidth based on the delayed self-heterodyne method [44], and the linewidth value was calculated to be 338 kHz. In 2018, Guan et al. conducted a study on the III-V/silicon hybrid ECTL based on a SOI platform [26]. The corresponding experimental results showed that the ECDL can be tuned from 1,515 nm to 1,575 nm with a SMSR in excess of 46 dB, the linewidth was as narrow as 37 kHz, and the maximal relative intensity noise (RIN) was better than −135 dB/Hz. However, due to the large linear-propagation loss and large thermo-optic coefficient of the Si material, it is difficult to further improve linewidth characteristics. Compared with Si-based material, the Si_3N_4-based materials are advantageous in terms of low linear-propagation loss and small thermo-optic coefficient, which are conductive to narrowing the linewidth. Later that same year, Yi et al. reported a hybrid photonic integrated ECTL based on Si_3N_4 MRRs [27]. Experiments have proved that the fine-tuning of the lasing wavelength can be realized by changing the temperature of the phase section. In this study, the tuning range of the ECTL was approximately 50 nm, with a SMSR exceeding 50 dB, and the narrowest linewidth measured was 35 kHz. In 2021, a novel InP-Si_3N_4 dual laser module was demonstrated by Dass et al. [45], each of which was fabricated using hybrid coupling of an InP-based SOA and a low loss Si_3N_4 feedback circuit. This work presented an ECTL which can be tuned over 100 nm while maintaining the SMSR greater than 50 dB with a RIN of about −160 dB/Hz. In 2023, Chen et al. reported a hybrid integrated Si_3N_4 ECTL with full C-band wavelength tenability and narrow-linwidth output [46]. In this study, the InP gain chip was coupled with the Si_3N_4 dual micro-ring, then integrated with the AlGaInAs quantum well rib waveguide SOA through the dual-collimating lens coupling. A wavelength tuning range of 55 nm was obtained, the SMSR over 50 dB was measured, and the linewidth was narrower than 8 kHz.

Research progress of filter-type ECTL

Compared with the above mentioned ECTLs that use dual MRRs as mode-selection component, the filter-type-ECTL provides the advantage of higher flexibility in optical filters. In 1993, Choi et al. verified that piezoelectric ceramics (PZT) can fine-tune the effective length of the external-cavity to obtain the tuning of the lasing wavelength [47]. Similarly, the filter-type-ECTLs are tuned by changing the effective length of the external-cavity or rotating the filter. In 2011, Zhang et al. reported their work on ECTL, which utilized two etalons in the external-cavity to realize narrow-linewidth and wide tuning output [48]. A tuning range of about 40 nm with the linewidth less than 100 kHz was measured. In 2012, Thompson et al. carried out a study on wide-bandwidth filter-type-ECTL [49]. The linewidth of the ECTL was around 26 kHz, and the tuning range exceeded 14 nm. In 2017, Kasai et al. demonstrated a long external-cavity structure with a tunable optical filter [33]. The coarse and fine wavelength-tuning can be obtained by simultaneously changing the peak transmittance wavelength of the multi-layered dielectric interference filter and the length of the AR-coated SiO_2 plate. The lasing wavelength was successfully tuned over 40 nm without mode hopping in the full C or L-bands, and the linewidth of less than 8 kHz and 7.7 kHz were measured, respectively. In 2020, Zhang et al. used a bandwidth of 0.48 nm IF with a peak transmittance of up to 96% to adjust the lasing

TABLE 1 Comparison of external-cavity wavelength-swept lasers.

Type	Advantages	Disadvantages	Linewidth	Tuning range	Ref	Years
MRRs-ECTL	(1) Easy to integrate	The coupling loss is high	338 kHz	≥40 nm	[43]	2013
			37 kHz	60 nm	[26]	2018
	(2) The linewidth and tuning range characteristics are relatively balanced		35 kHz	~50 nm	[27]	2019
			8 kHz	55 nm	[46]	2023
Filter-ECTL	It has high flexibility in components and configurations	Its performance is closely related to the filter	100 kHz	~40 nm	[48]	2011
			≤8 kHz	40 nm	[33]	2017
			180 kHz	40 GHz	[17]	2020
			0.022 nm	64 nm	[32]	2020
Littman-Metcalf-ECTL	(1) Narrow linewidth	(1) Large system size	≤0.06 nm	9.88 nm	[51]	2003
	(2) Large tuning range	(2) It is susceptible to external light noise	200 kHz	80 GHz	[52]	2012
	(3) High SMSR	(3) It is difficult to install and adjust the optical path	50 kHz	40 nm	[53]	2013
			98.27 kHz	100 nm	[38]	2023
Littrow-ECTL	(1) Wide wavelength-tuning range	(1) The linewidth is relatively wide	2.5 MHz	10 nm	[59]	2007
	(2) Large output power	(2) It is difficult to install and adjust the optical path	2.9 kHz	135 nm	[60]	2016

wavelength [17]. It had a coarse wavelength tuning range over 40 GHz by current-controlled method, a fine tuning range over 3 GHz by PZT-controlled method, and the output linewidth was about 180 kHz. In the same year, Magdich et al. reported an ECTL with a linear external resonator and two AOTFs [32]. This study indicated that this optical scheme can significantly compress the output spectral linewidth in both sweep and stationary modes. A minimum linewidth of 0.022 nm can be achieved when the tuning rate of the AOTF reaches 104 nm/s, with a maximum tuning range of 64 nm.

Research progress of Littman-Metcalf-type ECTL

The Littman-Metcalf-type ECTL provides the advantageous of a wider tuning range, and a narrower linewidth in the order of hundreds of kilohertz. Unfortunately, the introduction of additional optical components reduces the flexibility of the external-cavity structure. In 1978, Littman et al. designed the Littman external-cavity structure for the first time and used it in dye lasers [50]. After decades of development, this configuration has been widely used in ECTL, and has become a mainstream structure. In 2003, Jin et al. reported a narrow-band ECTL using a classical Littman-Metcalf structure [51]. The continuously tuning in wavelength region of 797.38 nm ~ 807.26 nm was obtained, and the linewidth is smaller than 0.06 nm. In 2012, Zhang et al. presented a compact ECTL based on a simple single-axis-MEMS mirror to boost tuning speed and compress linewidth [52]. A wide tuning range about 40 nm with a narrow linewidth of less than 50 kHz was obtained, and its tuning speed can reach the order of kilohertz. In 2013, Wei et al. adopted a star-flexure hinge as the tuning mechanism to construct the ECDL [53]. Its external-cavity structure parameters were calculated and optimized according to Eq. 2, showing tuning range over 80 GHz without mode-hopping, and the linewidth of 200 kHz. In 2017, Jiménez et al. proposed a micro-packing ECTL which overcome the drawbacks of traditional ECTL [54]. The experimental results showed that the laser provided a below 100 kHz output linewidth, and the SMSR can reach 60 dB. However, the lasing wavelength can only be slightly changed by current-controlled, which limited the tuning range of GHz-level. In 2018, Shirazi et al. adopted a transmissive mode selection element to develop an ECTL [35]. The output laser beam derived from the transmitted light of the diffraction grating. A tuning range of 52 nm was realized. In 2021, the ECTL was modeled to study the longitudinal allowance error for mode-hopping free tuning by our group [55]. The influence of the distance from pivot point to motion axis of PZT motor and the diffracting point of the diffraction grating, the installation angle of the diffraction grating, and the grating groove density were analyzed, respectively. The results showed that mode-hopping can be effectively avoided with careful choosing the parameters above. Based on the above theoretical analysis results, in 2023, our group reported a narrow linewidth ECTL without mode-hopping and experimentally studied its tuning characteristics [38]. The ECDL achieved a continuous wavelength tuning range of 100 nm from 1,480 nm to 1,580 nm with no mode-hopping, with a SMSR of more than 65.54 dB, and with a linewidth of less than 98.27 kHz. Besides, mode compensation [56] and/or roof prisms [57] have been used to improve the performance of the ECTL.

Research progress of Littrow-type ECTL

Compared with the Littman-Metcalf-type ECTL, the difference is that the Littrow cavity selects the resonant frequency only once using the mode selection component. Therefore, the linewidth of this type is relatively wide, the output power is relatively high, and the ability to resist the influence of external noise is relatively strong. In 1969, Hard designed the first Littrow configuration for lasing frequency selection [58]. After nearly 55 years of development, impressive results have been achieved. In 2007, Guan et al. reported an ECTL based on Littrow configuration [59]. By changing the angle of the mode selection component, wavelength of the ECTL can be tuned from 775 nm to 785 nm with the output linewidth of less than 2.5 MHz. In 2016, A single-mode frequency-stabilized by frequency locking method ECTL was proposed by Bayrakli, which was locked to a FPI with a FSR of 1.5 GHz [60]. By rotating the diffraction grating, the ECTL can obtain a coarse wavelength-tuning of 135 nm, linewidth of less than 2.9 kHz. However, the main disadvantage of the Littrow-type ECTL is that the output beam steers as the mode selection component is rotated. In 2018, Guo et al. designed a new and enhanced configuration for mirror-grating Littrow-type ECTL, which had the characteristics of the large mode-hop-free tuning range and the direction of the output beam was basically unchanged [61]. The experiment showed that the continuous tuning range of the ECTL reached 4.34 nm operating at 805 nm, with a 0.033 mm lateral displacement. In 2019, Wang et al. constructed the improved ECTLs to investigate the relationship between the grating features and the SMSR, which outputted from the rear face of the commercial gain chip keeping the direction unchanged [62]. The ECTL can achieve a tunable range of 209.9 nm, SMSR of more than 65 dB, and output power of 48.9 mW. In 2021, Giraud et al. adopted the AR-coated interband cascade laser as the gain chip to develop the improved Littrow-type ECTL [63]. A continuous tuning range of 360 nm from 3,220 nm to 3,580 nm with a maximum output power of 13 mW was obtained at 293 K. In addition, in order to reduce the influence of the internal-cavity mode, some scholars began to use ridge waveguide gain chip instead of straight waveguide [64–66]. Meanwhile, by translating the collimating lens, the tuning of the Littrow-type ECTL can also be realized [67].

Conclusion and outlook

In conclusion, owing to their exceptional output characteristics, such as narrow linewidth and wide tuning range, ECTLs can cater to the needs of numerous applications. However, to adapt to diverse application scenarios, it is crucial to analyze and summarize the typical configurations of ECTLs, as shown in Table 1. Currently, the MRR-ECTL, with its balanced output characteristics and high integration, is witnessing rapid development and finds the most extensive application among ECTLs. The Littman-Metcalf-type ECTL is also frequently employed as a primary structural design due to its superior spectral resolution. Concurrently, it is essential to explore strategies to mitigate the challenges associated with coupling difficulty, alignment, and overall system size. A noteworthy point is the long-term stability, which will inevitably influence the development trajectory of ECTLs. Furthermore, the task of calibrating parameters for narrow linewidth wavelength tunable lasers presents a substantial challenge in the current progression of laser technology [68–71]. This has been one of the key catalysts in the swift advancement of laser linewidth, noise, and stability measurement technologies over recent decades.

Author contributions

LS: Writing–review and editing, Writing–original draft, Funding acquisition. JW: Writing–review and editing, Conceptualization. LH: Writing–review and editing, Supervision, Investigation, Funding acquisition. AZ: Writing–review and editing, Supervision, Investigation. ZZ: Writing–review and editing, Investigation. SQ: Writing–review and editing, Supervision, Investigation. YW: Writing–review and editing, Investigation. ZL: Writing–review and editing, Resources, Investigation, Funding acquisition. JJ: Writing–review and editing, Supervision, Investigation. SZ: Writing–review and editing, Supervision, JL: Writing–review and editing, Supervision, Funding acquisition. JH: Writing–review and editing, Investigation. HJ: Writing–review and editing, Supervision, Investigation.

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Conflict of interest

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