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Advances in narrow linewidth diode lasers

Xingkai LANG[1,2], Peng JIA[1*], Yongyi CHEN[1*], Li QIN[1], Lei LIANG[1], Chao CHEN[1], Yubing WANG[1], Xiaonan SHAN[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*

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Abstract The smart travel era has come and requirement for high precision lidar detection technology is higher and higher. The new solid-state lidars can meet the requirements of intelligent cars in the future, with the advantages of high resolution, strong anti-active jamming ability, small volume, light weight, low cost and so on. The narrow linewidth diode laser is the perfect light source of solid-state lidars. The progress and development of narrow linewidth diode laser technique can greatly improve the application of solid-state lidar. The technology and development status of narrow linewidth diode lasers has been described detailly in the paper. And the design ideas, key fabrication technologies and optical characteristics of various narrow linewidth diode lasers have been analyzed and discussed as well. Finally, the developments of narrow linewidth diode lasers are prospected.

Keywords diode lasers, narrow linewidth, internal cavity optical feedback technology, external cavity optical feedback technology, solid-state lidar

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1 Introduction

1.1 Research background

The human society is ushering in the era of intelligent travel. The development of intelligent vehicles requires a considerable improvement in high-precision detection technology. Thus, developing a high-precision radar technology has become an urgent need.

Traditional high-precision radar technologies such as microwave radar and millimeter-wave radar are not suitable for intelligent vehicles owing to their low detection accuracy, large volume and weight; however, all-solid-state lidar has the advantages of high resolution, strong anti-active jamming ability, small size, and low cost, which meets the requirements for future intelligent vehicles that need high-precision detection technology.

Narrow linewidth laser diodes (NLLDs), with the advantages of small size, light weight, high efficiency, long lifetime, direct current drive, narrow spectral linewidth, and good coherence, are ideal light sources for the generation of high-precision all-solid-state lidars. NLLDs usually integrate frequency selective structures in the resonator or couple with mode selectors outside the laser cavity to control the gain and loss of different wavelengths for compressing their spectral linewidth.

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

1.2 Development of NLLDs

Currently, methods to narrow the linewidth of laser diodes are divided into two categories: internal optical feedback and external cavity optical feedback. With the rapid development of all-solid-state lidar technology, it is necessary to further improve the scanning rate, detection range, and imaging clarity for these methods. Further improvements are required in the spectral characteristics of semiconductor lasers, such as reducing the linewidth of lasers, suppressing low phase noise, and low relative intensity noise. The linewidth characteristics of NLLDs can improve the transmission distance and image sharpness of the beam. Some approaches to reduce the linewidth of semiconductor lasers have already been suggested, and they include increasing the output power, reducing the linewidth enhancement factor, and reducing the inherent linewidth of lasers.

At present, representative research institutions and companies in the field of NLLDs are the Ferdinand Braun Institute, Leibniz Institute of High Frequency Technology of Germany (FBH), DILAS Company of Germany, Bell Laboratory of the United States, Princeton University, III-V Laboratory of France, Northeast University of Japan, Dublin University of Ireland, among others. In the technology of internal optical feedback, various research institutes have successfully reduced the linewidth of semiconductor lasers to 10 kHz by using a new epitaxial chip structure and new grating fabrication technology. In 2016, a high-quality quantum dot distributed feedback (DFB) semiconductor laser [1] was proposed by Kassel University in Germany, which successfully reduced the laser linewidth to 10 kHz. Subsequently, a side-coupled surface grating DFB laser was fabricated by nanoimprint technology at Tampere University, Finland; the laser power was 28.9 mW and the linewidth was less than 10 kHz [2]. In the field of external cavity feedback technology, the German FBH Institute proposed using a DFB laser chip and integrating it with the confocal Fabry Pérot cavity to form a resonant feedback resonator; for this laser, the output power was 50 mW and the Lorentz line width was only 15.7 Hz which is the highest recorded level in the world [3].

Domestic research on NLLDs is slower than that compared to foreign research institutions. The main research institutions are Peking University, Zhejiang University, Chinese Academy of Sciences Institute of Semiconductors (SEMI), Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP), Shanghai Institute of Optics and Fine Mechanics (SIOM), etc. In the field of intracavity optical feedback technology, domestic research institutes have successfully reduced the linewidth of semiconductor lasers to a few kilohertz. SEMI reported a narrow linewidth laser module based on monolithic integrated asymmetric phase-shifted DFB lasers [4]; the excitation wavelength was 1550 nm; the laser power was 26 mW; and the narrowest laser linewidth was 35 kHz. In the field of external cavity optical feedback technology, the Chinese Academy of Metrology successfully reduced the laser linewidth of external cavity semiconductor lasers to 100 Hz and the instantaneous Lorentz linewidth to 30 Hz using the Littman structure of high-precision double mirror nonconfocal cavity [5].

Our research team in CIOMP designed and fabricated a wide-band high-order grating distributed Bragg reflection (DBR) laser. The DBR laser achieved a 3 dB spectral linewidth less than 0.04 nm ($\sim$13.13 GHz) and a stable single longitudinal mode laser output of 213 mW with a side-mode suppression ratio (SMSR) of 42 dB [6]. Then, a shallow etching high-order grating distributed feedback semiconductor laser structure based on a gain coupling mechanism is proposed [7]. Such a high-order grating DFB semiconductor laser can achieve a single-side 144 mW high-power single longitudinal mode laser output with a 3 dB linewidth of 0.04 nm ($\sim$12.62 GHz), and SMSR of 29 dB.

1.3 Chapter introduction of the paper

Section 2 introduces the research progress of NLLDs based on internal optical feedback, including DFB semiconductor lasers, DBR semiconductor lasers, and coupled-cavity semiconductor lasers. Section 3 introduces the research progress of NLLDs based on external cavity optical feedback, including volume holographic grating (VHG), volume Bragg grating (VBG), Fabry Pérot cavity planar waveguide, fiber grating, and other external cavity semiconductor lasers. Finally, Section 4 concludes the paper.

2 Narrow linewidth technique of intracavity optical feedback

NLLDs based on internal optical feedback technology usually adopt integrated Bragg gratings or special waveguide structures. Integrated Bragg gratings can be divided into DBR and DFB semiconductor lasers according to their distribution positions.

Therefore, high-power NLLDs with a compact structure are the focus of research studies globally, and they play an important role in improving the ability of space exploration and space communication. Among them, DFB and DBR semiconductor lasers are important means to realize NLLDs.

2.1 Distributed feedback semiconductor laser

DFB lasers [8] usually distribute the Bragg grating structure throughout the resonator, which plays the role of mode selection and the gain of optical feedback. Figure 1 shows the structure of a DFB laser; this laser has the advantages of superior spectral characteristics and high-speed modulation, and therefore, it is widely used in high-precision detection, optical communication, and in other fields. Research on DFB lasers began in the 1970s; in 1971, the Bell experiment [9] led to the concept of DFB lasers. The next year, they analyzed the working principle and characteristics of DFB lasers using the coupled mode theory of an electromagnetic field [10]. In 1973, Nakamurain designed the first DFB laser by optically pumping the surface of GaAs-based gratings [11]. With the progress of semiconductor epitaxy technology, researchers around the world have been developing new grating technology and developing a variety of new DFB lasers. According to the different types of grating construction, DFB lasers can be divided into two types: secondary epitaxial DFB (RG-DFB) semiconductor lasers with grating attached to the active region, and surface grating DFB (SG-DFB) semiconductor lasers where the grating is etched directly on the surface or side wall of the P-plane optical waveguide of epitaxy chip.

2.1.1 *Secondary epitaxial DFB semiconductor laser*

RG-DFB lasers usually use a secondary epitaxial technique: the metal organic chemical vapor deposition (MOCVD) process is completed after the growth of the N-type or P-type waveguide layer is completed; the growth process is halted and the growth chip is removed using photolithography and etching. The method constructs a set of low refractive index grating structures on its N-type or P-type waveguide layer, and then, it places the chip into the epitaxial device to continue the growth process. Secondary epitaxial grating is distributed near the active region, which is beneficial to the high-efficiency coupling between the grating and the optical mode field, and it can effectively reduce scattering loss, improve coupling efficiency, and achieve frequency selection and line-width compression.

High-power NLLDs are required for near-infrared (760nm to 890 nm) applications such as in atomic optical pumping, atomic clocks, de Broglie interferometers (gyro, gravimeters, gradiometers, accelerometers) and all solid-state lasers. In 2006, FBH developed a wide-band DFB laser with room temperature operation using metal organic vapor phase epitaxy (MOVPE) technology, using holographic lithography. A second-order Bragg grating was fabricated using a wet etching technique to achieve a single longitudinal mode laser output with a lasing wavelength of 808 nm, a laser power of 3 W, and a spectral line width of 0.6 nm ($\sim$275.7 GHz) [12]. From 2012 to 2014, FBH used a secondary epitaxial technique and reported a ridge-wavelength RG-DFB laser in the 780 nm band. By optimizing the cavity length and grating coupling coefficient, the wavelength was 780 nm and the line width was 35 kHz for a 279 mW laser output [13, 14].

In order to meet the 894 nm and 852 nm semiconductor laser sources required for the D1 and D2 line pumping of helium atoms, the French III-V laboratory proposed a large cavity structure DFB laser using the secondary epitaxial technique [15,16]. The laser wavelength was 852 nm, the laser power was 110 mW at an operating current of 50 mA, SMSR $>$ 50 dB, and the Lorentz line width was only 200 kHz; these values meet the Cs atomic D2 line pumping requirements. In 2016, the laboratory and the University of Newcastle, Switzerland proposed a RG-DFB laser, using MOVPE secondary epitaxy to construct a 50-nm-thick InGaAsP grating (period of 273.5 nm) in the P-cladding layer. A rib-waveguide DFB laser with a cavity length of 1.5 mm and a width of 4 μm has a laser wavelength of 894.4 nm at 66.4°C, a laser linewidth of 797 kHz, a laser power of 40 mW at 160 mA, and an SMSR > 50 dB [17]. These values meet the D1 line pumping requirements of Cs atoms in the atomic clock equipment.

Coherent optical communications and fiber optic communications require narrow linewidths, and therefore, high-efficiency semiconductor lasers in the 1064 and 1550 nm bands are required for these applications. In 2010, FBH used a secondary epitaxial technique to construct a second-order grating structure with a coupling coefficient of 2 cm^{-1}, and they developed a 1064-nm-band RG-DFB laser to achieve a laser power of 150 mW while the minimum intrinsic linewidth was 22 kHz [18]. Subsequently, the France III-V laboratory developed a 1500-nm-band DFB semiconductor laser with an asymmetric cladding epitaxial structure and dilute waveguide technology, and they achieved a laser power of 180 mW at 25°C, and 9.7 nm tuning through temperature regulation. This laser has a SMSR > 55 dB, relative intensity noise (RIN) < 160 dB/Hz, and linewidth < 300 kHz [19].

2.1.2 *Surface grating DFB semiconductor laser*

With the advancement of semiconductor epitaxial growth technology and etching technology [20], and in particular the inductively coupled plasma etching technology, researchers are paying more attention to the research of SG-DFB semiconductor lasers based on plasma deep etching technology. The SG-DFB laser can be divided into a large-area grating DFB (BA-DFB) laser and a laterally coupled DFB (LC-DFB) laser according to different grating construction regions, which are respectively on the surface of the epitaxial chip P-plane waveguide. A deep etched ($\geqslant 1$ μm) surface grating is constructed on the sidewall of the waveguide to ensure sufficient coupling of the optical mode field and the grating in the waveguide. The high-order mode is suppressed by the scattering effect, and the single-mode oscillation in the waveguide helps achieve the selected frequency and reduce the laser linewidth; this is carried out to effectively avoid the chip structure defects that may be introduced by the secondary epitaxial technology, improve the reliability and yield of the chip, simplify the preparation process of the DFB laser, and realize high-reliability narrow linewidth laser output. The difficulty in the development of the two lasers is the design and fabrication of the grating structure. The influence of structural parameters such as the grating period, width, and depth on the laser performance should be fully considered, and the combination of high-precision etching technology is required to obtain an ideal laser device.

Tampere University of Technology in Finland reported an LC-DFB laser based on UV nanoimprint technology [21], and developed an 894-nm wavelength LC-DFB laser to achieve a power of 9 mW and a linewidth of 878 kHz for 180 mA. The side mode suppressed the laser output to 35 dB, and the device performance was close to that of the RG-DFB laser. It was an ideal low-cost DFB laser technology solution, which made LC-DFB easier to integrate into large-scale optoelectronic devices. In 2018, Virtanen et al. [2] from the University of Tampere in Finland proposed a narrow-linewidth DFB laser using a nanoimprinting technique to fabricate a third-order lateral surface grating combined with a ridge waveguide structure, achieving a wavelength of 780 nm and a laser power of 28.9 mW at 300 mA, a narrow linewidth output with SMSR > 40 dB, and a line width < 10 kHz; this technology is suitable for manufacturing low-cost miniaturized atomic clock pump modules.

The 1550 nm high-power, narrow-linewidth single-mode DFB semiconductor laser has great potential in applications such as laser radar and space communication. In order to simplify the development of the 1550 nm band DFB laser, Hou et al. [22] of the University of Glasgow in the UK reported a new type of laterally coupled DFB laser in 2012, using technology that combined DFB-LD, curved WG, and tilt-flared WG. They developed a narrow linewidth, laterally coupled, integrated tapered semiconductor amplifier DFB laser with a wavelength of 1550 nm, power of 210 mW, linewidth of only 64 kHz, and SMSR > 45 dB. In 2015, the team at SEMI reported an NLLD module [4] based on a monolithically integrated asymmetric phase-shifted DFB laser, achieving a maximum output power of 26 mW at 200 mA and the narrowest laser linewidth of 35 kHz. At 150 mA, the RIN is less than 165 dB/Hz during the frequency increase from 0.1 to 20 GHz. This laser module can be widely used in optical sensing and coherent optical communication.

From 2013 to 2014, the University of Ottawain Canada [23–25] used step lithography to fabricate a third-order grating structure along the sidewalls of the ridge waveguide to develop lateral coupling of various N-segments. The DFB laser obtained a single mode with a center wavelength of 1560 nm, a SMSR > 52 dB, a wavelength tuning range of $\geqslant 3$ nm, an output power of $\geqslant 6$ mW, and a narrow linewidth of less than 170 kHz at 25°C laser output.

In order to further reduce the spectral linewidth of the laterally coupled DFB semiconductor laser, other researchers proposed a technical solution based on a quantum dot laser chip-based DFB laser. In 2016, Bjelica et al. [1] from the University of Kassel in Germany proposed a high-quality quantum dot laser growth technology, combining it with the traditional DFB grating coupled resonator structure to develop a QD-DFB laser with a laser linewidth of only 10 kHz and an output power of 12 mW. In 2018, the University of Paris-Sacre in France [26] reported a new InAs/InP quantum dot DFB semiconductor laser with low inversion factor and low linewidth enhancement factor for low temperature sensitivity. This laser had a narrow linewidth (160 kHz); its double-sided coating anti-reflection film design improves laser power by 4 mW and inhibits the space hole burning phenomenon.

In order to obtain laser output characteristics for a single longitudinal mode and improve the beam quality, Wang et al. [27] from CIOMP reported a 940-nm-wide-band DFB semiconductor laser with a second-order metal grating structure to achieve a laser power of 400 mW in 2012. The linewidth was 0.09 nm (∼30.5 GHz) and the far field divergence angle was 2.7°C. In 2013, SEMI [28] reported a 1.82-μm band InGaAs/InGaAsP multi-quantum structure DFB laser with a SMSR of 49.53 dB.

The 1060 nm narrow-linewidth semiconductor laser can be employed in laser display applications; it can be used as the pump source for generating the second harmonic. In 2014, SEMI [29, 30] reported a new-wavelength waveguide structure of the 1060 nm band with a cavity length of 1 mm. The DFB laser has an output power of 150 mW and a side-mode suppression ratio of up to 50 dB at an injection current of 350 mA.

Currently, DFB semiconductor lasers mainly study two types of structures: RG-DFB lasers and SG-DFB lasers. The common feature of the two structures is that they distribute the Bragg grating structure in the whole resonator, which plays the role of optical feedback mode selection and gain. Secondary RG-DFB lasers usually employ secondary epitaxy technology. When the growth of the N-type or P-type waveguide layers is completed, a group of low refractive index gratings are constructed on the N-type or P-type waveguide layers by lithography and etching, and then, the chip is placed in the epitaxy equipment to continue the growth process. The secondary epitaxy grating is distributed near the active region, which is beneficial to the efficient coupling between the grating and the optical mode field. It can effectively reduce scattering loss, improve coupling efficiency, and achieve frequency selection and line-width compression. However, the secondary epitaxy technology may introduce defects in the chip structure and improve the reliability and product rate of the chip. SG-DFB lasers etch gratings directly on the surface or side walls of P-plane optical waveguides of epitaxy chips; this ensures that the optical mode field in the waveguide is fully coupled with grating feedback. The scattering effect is used to suppress high-order modes and realize single-mode oscillation in waveguides. The difficulty of SG-DFB development is the design of the grating structure. The effect of grating parameters on laser performance should be considered in the fabrication.

2.2 Distributed bragg reflection (DBR) semiconductor laser

The resonant cavity of a DBR laser (the schematic is as Figure 2) is usually composed of a reflective grating structure and a gain region, which is similar to a Fabry Pérot (FP) cavity, and a passive Bragg grating is constructed at one or both ends of the gain region. The grating replaces one end or both end face mirrors of the FP laser, and the grating structure only functions as a mirror. Since the grating structure has a strong reflection effect on the optical mode satisfying the Bragg condition, the coupling coefficient of the grating region can be adopted. In order to achieve a single longitudinal mode and narrow line width operation of the DBR laser, the maximum reflectance and reflection spectrum width need to be optimized.

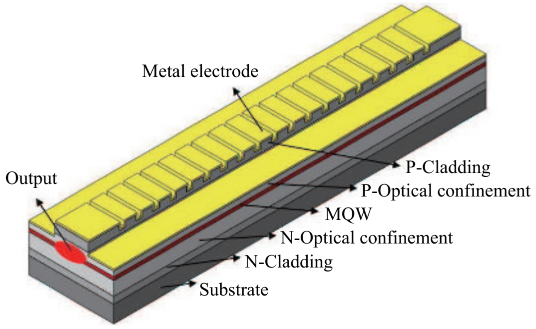

Figure 1 (Color online) Schematic of DFB structure.

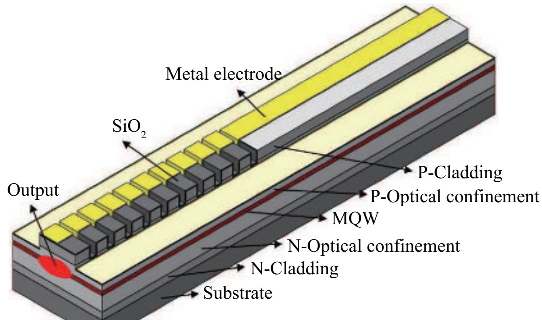

Figure 2 (Color online) Schematic of DBR laser.

In applications such as free-space coherent optical communication, a narrow linewidth semiconductor laser source in the 1064 nm band is required. In 2010, FBH [31] used a 6th-order surface Bragg grating to develop a 1064-nm-band DBR semiconductor laser with a width of 4 μm, and a cavity length of 4 mm, achieving a line width of 180 kHz with an output power of 180 mW. The inherent linewidth is 2 kHz, the threshold current is 65 mA@25°C, and the slope efficiency is 0.41 W/A@25°C.

In order to meet the demand of high-performance fiber laser for narrow linewidth semiconductor laser pumping source in the 975 nm band, Coleman et al. [32] of the University of Illinois developed a 974.8 nm DBR laser with a cavity length of 1.5 mm by etching gratings on the surface of wide strip waveguides (40 μm). The high-power output of 500 mW, 350 kHz laser linewidth, and SMSR $>$ 40 dB is achieved. Subsequently, FBH [33] fabricated an 80-order surface grating DBR laser by ordinary ultraviolet lithography and reactive plasma etching. The high-power output of the 6 W laser power is achieved at the 970 nm band. The electro-optic conversion rate is more than 50%, the optical parametric product is less than 1.8 mm mrad, and the laser linewidth is only 0.41 nm (∼130.7 GHz), which is very suitable for pumping fiber lasers.

Narrow linewidth red laser (∼620–650 nm band) is an important light source for laser spectroscopy, coherent measurement, and holographic technology. To meet this demand, FBH [34] proposed a narrow linewidth DBR laser in the 633 nm band. The total length of the laser resonator is 2 mm; the ridge gain region is 1.5 mm; the grating region is 0.5 mm; the laser power is 10 mW at 150 mA; and the spectral linewidth is less than 1 MHz. The laser exhibited continuous operation for 1700 h at an output power of 14 mW. Subsequently, Paschke et al. [35] reported a RG-DBR laser; they introduced gratings into the laser structure through step lithography and reactive ion etching, and a DBR laser with a wavelength of 626.5 nm was developed. The output power of the laser was over 50 mW 0°C, the laser linewidth was less than 1 MHz for 150 mA, and the SMSR was over 20 dB. This technology can replace the traditional all-solid-state laser as the quantum information experimental light. The source by reducing the size of light source module can effectively enhance the miniaturization of quantum information system.

The 550–620 nm band yellow laser is widely used in the field of atmospheric measurement and biomedicine. Currently, the scheme of all-solid-state lasers pumped by LD in 1180 nm band is used to generate yellow light. To meet this demand, the Tampere University of Technology of Finland [36] proposes a wide-tuning DBR laser, which uses a three-step surface trapezoidal grating combined with a ridge waveguide structure design to avoid secondary epitaxy growth. Meanwhile, it improves the SMSR of the device and achieves high-performance excitation with a laser linewidth less than 250 kHz, power $>$ 500 mW, SMRR $>$ 50 dB, and continuous operation for 2000 h without degradation.

Currently available narrow-linewidth DBR semiconductor lasers use the surface Bragg grating structure as a reflector to achieve frequency selection. By reasonably designing grating structure parameters, ideal grating reflectivity, reflectivity half-width, and the phase change of light waves in grating can be obtained to achieve narrow-linewidth output of DBR semiconductor lasers. Compared with traditional multiepitaxy DBR lasers, the surface DBR laser avoids the problem of low coupling efficiency between waveguides in different locations, reduces the complexity of fabrication process, and improves the application value of DBR lasers.

2.3 Coupled cavity semiconductor laser

In the 1980s, researchers at Bell Laboratory in the United States proposed a coupled-cavity laser, which uses one or more deep grooves to couple two or more resonant cavities to achieve single-mode laser output. First, two FP cavity lasers with very close cavity surfaces were welded to the same heat sink. At this time, the chip gap is equivalent to a deep etching groove. Through the coupling effect of the groove, single-mode laser output can be realized, and the linewidth can reach 500 kHz [37]. After that, researchers from Branna Electronics Company, Dublin University, Glasgow University, Zhejiang University, and other institutions further improved the structure. Coupled cavity lasers based on single etching groove and periodic etching groove were developed respectively, and an ideal narrow linewidth laser output was obtained.

In 2011, Ireland Brana Optoelectronics Co. Ltd. and Newshatt University of Switzerland [38] proposed a separated mode semiconductor laser. By etching several deep grooves on the ridge waveguide, the refractive index perturbation was introduced, and then, an FP mode was enhanced. By losing other modes, the single longitudinal mode laser output was obtained. The laser wavelength was 780 nm, and the spectral linewidth was only 2 MHz. On this basis, Ireland Brana Optoelectronics Company and Dublin City University [39] jointly developed separated mode semiconductor lasers that with a wide operating temperature range. The laser line width is less than 250 kHz, the SMRR is $\sim$40 dB, and the output power is about 4 mW. In 2018, the company [40] also reported a monolithic integrated single-mode red laser diode; for the diode, the laser wavelength is 689 nm, the laser power is 10 mW, the SMRR is 40 dB, the spectral line width is 2 MHz, and the mode-hopping-free output is guaranteed in the range of 0–50.

In 2014, Abdullaev et al. [41] of the University of Dublin in Ireland reported a curved waveguide slot-DBR single-mode laser with Lorentz linewidth of 720 kHz for 160 mA and SMSRs of 50 dB stable single-mode output. In 2017, Yang et al. [42] of Tindel National Institute of Ireland proposed a new type of multi-mode interference waveguide (MMI) laser. By coupling 1$\times$2 MMI with teardrop reflective waveguide, the single-mode excitation in 1562.5 nm band was realized with a radius of 150 μm in the ring waveguide. The line width was 75 KHz for 25°C, and the SMSRs was 30 dB.

In order to meet the demand of low cost 1550 nm band semiconductor laser chips in the field of optical communication, a coupled-cavity semiconductor laser based on Lot grating structure is proposed by Santa Fe University in Dublin. The single longitudinal mode lasers with SMRR of more than 50 dB are realized in 1569 nm band [43]. Professor He et al. [44–46] of Zhejiang University has developed a variety of narrow linewidth coupled-cavity semiconductor lasers with a linewidth of only 80 kHz and a SMRR of 38 dB, using deep etching slot-FP cavity technology.

3 External cavity optical feedback narrow linewidth technology

Narrow linewidth semiconductor lasers based on external cavity optical feedback technology (ECL) usually use external optical elements to feedback and select the output light of semiconductor laser chips, increase the effective length of the resonator, improve the Q value of the quality factor of the resonator, and reduce the linewidth of the laser; moreover, it is easier to achieve low-phase noise and high temperature stability by using passive optical elements for frequency selection and optical feedback. ECL is an ideal light source for space coherent communication, coherent detection, high precision sensing, and other applications.

External cavity feedback semiconductor lasers (ECLs) can effectively avoid the light wave diffraction and scattering loss of internal cavity integrated grating; however, they require high stability of external optical frequency selector coupling optical path and working environment. External optical frequency selector, as the core device of ECL includes: (1) VHG fabricated by laser holography in special photosensitive glass; diffraction grating elements such as VBG; (2) waveguide feedback elements such as low

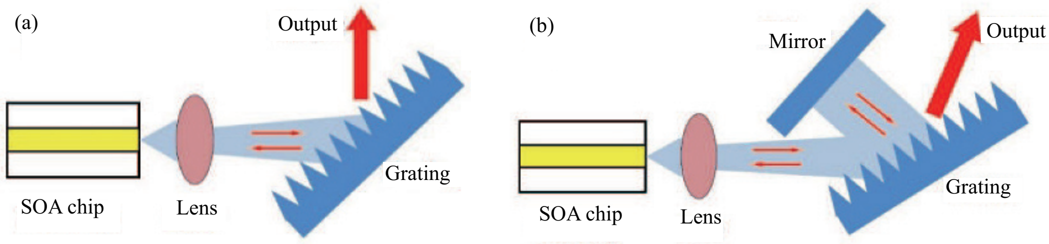

Figure 3 (Color online) Two principal designs of the external cavity tunable systems with bulk diffraction gratings. (a) Littrow configuration; (b) Littman (grazing-incidence) configuration.

loss FP waveguide, coated mirror, and FBG waveguide fabricated by femtosecond laser technology.

3.1 External cavity grating feedback semiconductor laser

The ECL with diffraction grating as feedback element usually adopts a Littrow or Littman structure. The resonators of these two structures are usually composed of semiconductor laser chip, optical lens or mirror, blazed grating, or holographic grating and other optical elements [47]. The structure sketch is shown in Figure 3. Littrow structure ECL is usually composed of a semiconductor chip, an optical lens, and a diffraction grating. By changing the angle of the grating theta, a certain wavelength light wave can be fed back to semiconductor laser chip, which can greatly improve the diffraction loss of other wavelength light wave, and then change the overall length of the resonator to achieve wavelength-stable narrow linewidth laser output. The Littman structure ECL is usually composed of the semiconductor chip, optical lens, diffraction grating, and reflectors. The reflector acts as the tuner; the grating is fixed. By changing the angle of the reflector, the incident light is returned along the incident light path. After the second diffraction of the grating, the SMSR is greatly increased and the laser linewidth is further narrowed; however, its structure is more complex than that of Littrow structure ECL. In addition, the complex structure of Littman results in a large power loss, and it is not easy to achieve high power output.

Because Littrow structure external cavity semiconductor laser can obtain relatively high output power while obtaining narrow linewidth output, it has attracted wide attention of researchers. Many scientific research institutes, such as Hanover University of Germany, University of Jena [48], Suleiman Demirel University of Turkey, and Australian National University, have carried out research reports on Littrow structure external cavity semiconductor laser. In 2016, Shin et al. [49] from the Australian National University proposed that Littrow-ECL consist of a gain chip with one-sided tilt output light and a blazed grating (1200 lines/mm) to achieve an output power of 300 mW at 600 mA, wide tuning in the range of 100 nm near the 1080 nm band, a Lorentz line width of 4.2 kHz at 22.5 ms, and an excellent wavelength stability (40 kHz for 11 h). In the same year, the side-of-fringe stabilization technology was adopted by Suleiman Demirel University in Turkey [50] to achieve active frequency stabilization of ECL. Its wavelength tuning range was 60 nm (1000–1060 nm), and its line width was narrowed from 160 KHz to 400 Hz. Subsequently, Suleiman Demirel University [51] implemented a dual-longitudinal-mode lasing ECL using a gain chip with ultralow surface reflectance (0.005%) and a dual Littrow structure to obtain a wavelength tuning range of 120 nm (covering 1470–1590 nm). This dual-wavelength light source is suitable for optical sensing, terahertz source, imaging, dual-wavelength interferometer, optical switch, wavelength division multiplexing, and so on.

Domestic institutions such as Peking University, Xiamen University, Huazhong University of Science and Technology and SIOM [52] have also carried out in-depth research on the Littrow structure external cavity semiconducting lasers. In 2007, Chen et al. [53] of Peking University constructed a Littrow-ECL using commercial semiconductor lasers. The linewidth of the Littrow-ECL was less than 1 MHz at the 780 nm band, and the tuning range was more than 3 GHz continuously. At the same time, the stability of the Littrow-ECL was improved to a 10–12 magnitude. In 2017, Che et al. [54] from Xiamen University reported a Littrow structure ECL, which was constructed by parallel grating lines and GaN-based gain chip node planes. The laser linewidth was reduced from 1 to 0.1 nm (151 GHz), the amplified spontaneous emission suppression ratio was 35 dB, the output power was 1.24 W, the tunable bandwidth was 3.6 nm (443.9–447.5 nm), and the external cavity coupling efficiency of the central wavelength was 80%; a high-power blue laser. In the same year, Zuo's team [55] from Huazhong University of Science and Technology reported a blue-light Littrow-ECL with narrow linewidth and narrower linewidth; the maximum laser power was 500 mW; the laser linewidth was 50 PM (∼75.7 GHz); the tunable range was 2 nm; and the side-mode rejection ratio was more than 20 dB.

In order to further narrow the laser linewidth, the Littman structure external cavity semiconductor lasers were studied by the SIOM, Chinese Academy of Sciences, and Chinese Academy of Metrology. In 2009, Cai's team [56] of SIOM, Chinese Academy of Sciences, studied the polarization characteristics of a Littman-Metcalf external cavity semiconductor laser. The polarization characteristics of ECL were characterized by rotating a semiconductor laser chip (LD) to change the angle between the transverse electric field direction of the LD beam and the grating light. The team found that when the direction of the LD transverse electric field is parallel to the grating slot, the ECL output laser beam is linearly polarized with a linear polarization of 100; when the direction of the LD transverse electric field is angled with the grating slot, the ECL output laser beam is left elliptically polarized. At the same time, the polarization equation of ECL output beam is proposed, which not only provides theoretical support for the study of ECL with high polarization performance, but also helps to develop ECL lasers with circular or elliptical polarization output. In 2012, Zhao et al. [5] of the Chinese Academy of Metrology reported a new type of 100-Hz narrow-linewidth external cavity semiconductor laser. The laser linewidth of ECL was reduced to 100 Hz, the instantaneous Lorentz linewidth was reduced to 30 Hz, and the laser phase noise was significantly suppressed to 50 dB by using the Littman structure of high-precision double mirror non-confocal cavity.

In addition to Littrow and Littman external cavity lasers, there are external cavity lasers that directly use volume gratings (VHG and VBG) as optical feedback elements. In 2009, Hieta et al. [57] of Helsinki University of Technology in Finland reported that a long-cavity long external-cavity semiconductor laser based on VHG. The total cavity length of LC-ECL was 68 mm and the length of the cavity increased to 15 mm, which greatly improved its quality factor Q. Combining with the frequency selection of VHG, the 635-nm band Gauss line width was 900 kHz, and the side-mode rejection ratio reached 35 dB [57]. From 2013 to 2017, FBH and Humboldt University [58, 59] carried out considerable research on 780 and 1064 nm volume holographic Bragg grating (VHBG) external cavity lasers. The ECDL-MOPA laser module was developed; the output power was 575 mW at 1.5 A, the lasing wavelength was 1064.49 nm, the spectral line width was FWHM of ∼30 kHz, and the side-mode rejection ratio was more than 45 dB.

3.2 External cavity waveguide feedback semiconductor laser

The narrow linewidth laser based on external cavity waveguide feedback technology increases the length of the laser resonator by coupling the external low loss waveguide or fiber Bragg grating waveguide, improves the Q value of the laser resonator, achieves the purpose of reducing laser linewidth, and achieves good performance in achieving narrow linewidth laser output. The structure sketch is shown in Figure 4. Using an external low loss waveguide as the optical feedback element can effectively reduce the linewidth of semiconductor lasers and obtain low noise spectral characteristics. A planar waveguide external cavity laser (PW-ECL) has been developed by the University of Maryland and Redfin Integrated Optics Company [60]. It can significantly reduce the frequency noise and intensity noise of ECL, and obtain a narrow linewidth (∼2 kHz) of 1542 nm band with a laser power of 10 mW. In the same period, the Chinese Academy of Metrology [61] also reported that an integrated Fabry Pérot cavity (MFC) was used to replace the traditional external cavity reflector to achieve ECL spectral linewidth of only 6.8 kHz.

With the development of silicon-based photonics, researchers have started to pay attention to the external cavity semiconductor laser technology using silicon-based low-loss waveguide as the feedback element. In 2015, the University of California, Santa Barbara [62], proposed a wide tuning, narrow linewidth monolithic integrated external cavity semiconductor laser. The low loss silicon-based waveguide with a cavity length of 4 cm was used as the optical feedback element. By controlling the optical feedback

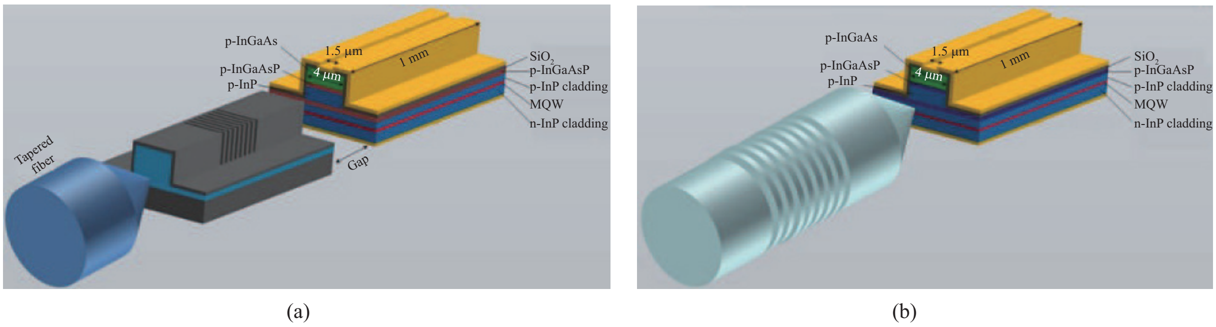

Figure 4 (Color online) Two principal designs of the waveguide external cavity laser diodes. (a) Low loss waveguide structure; (b) fiber grating waveguide structure.

of the external cavity elements, the wide tuning range of 54 nm was achieved in the O-band, and the linewidth of the laser was significantly reduced, both within the tuning range of less than 10 cm. For 0 kHz, the minimum line width can reach 50 kHz. In 2017, Cornell University and Columbia University [63] jointly reported an external-cavity laser based on low-loss silicon-based ring waveguide structure. Using the narrow-band reflection characteristics of high Q-value microresonator and using the ring waveguide to avoid the optical mode feedback, the laser wavelength is 1550 nm, the laser linewidth is 13 kHz, and the output power is 1.7 mW.

In order to obtain a lower noise external cavity laser, Princeton University, FBH, Tohuku University and other research institutes use external cavity crystals as optical feedback elements to achieve low noise output. In 2010, Princeton University [64] used ZnSe wedge crystal as a semi-reflector to provide optical feedback to achieve single longitudinal mode laser output (power up to 40 mW) with a linewidth of 480 kHz. Subsequently, FBH [3] proposed to use DFB laser chip and integrated confocal Fabry Pérot cavity to form a resonant feedback resonator. The output power is 50 mW and the Lorentz linewidth is only 15.7 Hz. At the same time, the ultra-low noise (white noise level $\sim$5 Hz^2/Hz) output is obtained. Its noise level is 5 and 3 orders of magnitude lower than that of conventional DFB lasers and external cavity lasers, respectively. From 2015 to 2018, Aoyama team [65, 66] of Tohuku University proposed a coherent optical negative feedback method to reduce the linewidth of single-mode semiconductor lasers. The linewidth of the laser was optimized from 13.5 MHz to 3 kHz by using external cavity negative feedback lenses. The energy density of frequency modulation (FM) noise was reduced by 35 dB, and the relative intensity noise was lower than 140 dB/Hz. This system can be maintained and a narrow linewidth stable output can be ensured for over an hour.

In recent years, many domestic research institutes, such as SIOM [67,68], SEMI [69,70], have gradually carried out research on optical fiber waveguide external cavity semiconductor lasers, using fiber grating waveguide feedback technology to narrow the laser linewidth of semiconductor lasers to 10 kHz. Among them, Yang et al. [67] of SIOM reported a 1550-nm band self-injection locking ECL based on Bragg grating Fabry Pérot cavity fiber waveguide structure, which realized sub-kilohertz inherent linewidth (Lorentz linewidth 125 Hz) and relative intensity noise $<$ 142 dBc/Hz. SEMI [69] reported a square of double-cycle self-injection compression linewidth based on fiber waveguide. A broadly tunable DBR laser has been successfully developed. The spectrum tuning range is 13 nm (covering 18 channels), the SMRR is more than 38 dB, and the linewidth is less than 10 kHz, reaching the international leading level.

At present, the external cavity feedback structure semiconductor lasers study Littrow type or Littman type diffraction grating feedback external cavity semiconductor lasers and external cavity waveguide feedback semiconductor lasers based on low loss waveguide and fiber grating waveguide structure. Both external cavity feedback lasers use external optical feedback elements to select the laser frequency and compress the linewidth; the linewidth level can reach kilohertz. The advantage of external cavity grating feedback semiconductor lasers is that wavelength tuning can be achieved by adjusting the grating position. At the same time, because of the high efficiency of optical coupling, it is easier to achieve high power output and has a broader application prospect.

4 Summary and prospect

Semiconductor lasers are developing rapidly towards achieving high power and narrow linewidths. In the technology of the inner cavity feedback, narrow linewidth laser output is obtained by optimizing the epitaxy structure of laser chip and waveguide structure, respectively. In the technology of outer cavity feedback, ultra-narrow linewidth laser under 100 Hz is realized by continuously developing new optical feedback elements and optical resonator design. Considering its small size, light weight, high conversion efficiency, and wide spectrum range, it will be widely used in ultrahigh precision lidar, inter-satellite communication, coherent optical communication, laser spectroscopy, atomic clock pumping, atmospheric absorption measurement, and optical fiber communication.

At present, in the research field of narrow linewidth semiconductor lasers in China, owing to alate start, technological limitations, and high-end technology blockade abroad, there are still some gaps. It is necessary to further improve the power and spectral characteristics of semiconductor lasers; solve the secondary high-quality epitaxy growth technology and surface grating high aspect ratio etching technology; overcome high-precision grating and other optical feedback element manufacturing key technology. It is necessary to integrate the domestic superior units that have ability to research on NLLDs to carry out joint research and development, develop breakthrough key technologies, and realize the independent research and development of high power and narrow linewidth semiconductor lasers.

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