Bragg Grating External Cavity Semiconductor Lasers

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External cavity semiconductor lasers (ECSLs) usually refer to the gain chip based on the introduction of external optical components (such as waveguides, gratings, prisms, etc.) to provide optical feedback. By designing the type, position and structure of external optical components, the optical properties of SLs (such as center wavelength, linewidth, tuning range, side-mode suppression ratio (SMSR), etc.) can be changed. Bragg grating external cavity semiconductor laser (BG-ECSL) is a device with a specific optical element (Bragg grating) in the external cavity. BG-ECSLs have excellent performances, such as narrow linewidth, tunability and high SMSR. They are widely used in WDM systems, coherent optical communication, gas detection, Lidar, atomic physics and other fields.

tunable narrow linewidth Bragg grating BG-ECSL

1. Principle of Bragg Grating External Cavity Semiconductor Lasers (BG-ECSLs)

Grating, also known as diffraction grating, is an optical element composed of a large number (tens of thousands) of equally wide and equally spaced slits, which can make the amplitude or phase of the incident light, or both, produce periodic spatial modulation.

Bragg gratings (period less than 1 μm, also known as reflection gratings) are transparent devices with a periodically varying refractive index. Their structure is shown in **Figure 1**. The reflectance is large in the wavelength region (bandwidth) near a particular wavelength, which satisfies the Bragg condition:

$$m\lambda_B = 2n_{eff}\Lambda\cos\theta \quad (1)$$

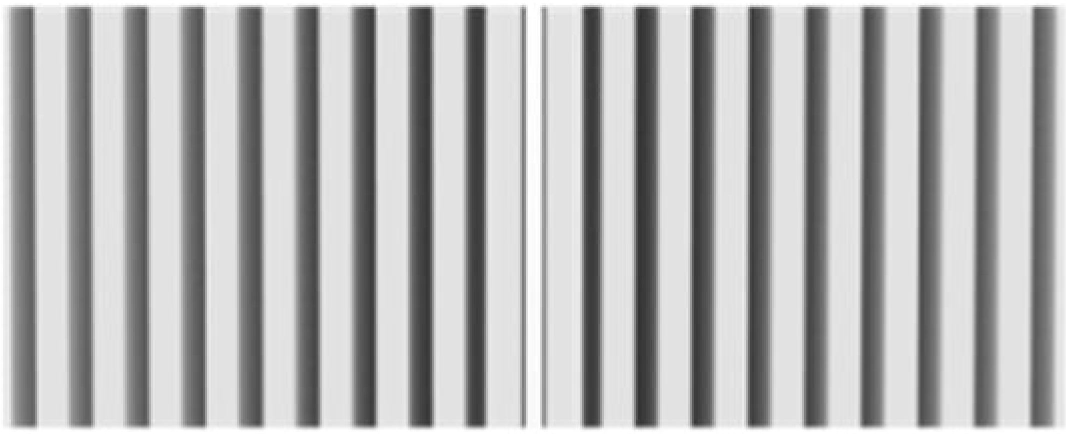

Figure 1. Structure of Bragg grating.

In Formula (1), m is the diffraction order, λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the medium, Λ is the grating period and θ is the propagation angle in the medium relative to normal incidence.

If the above conditions are met, the difference between the wave number of the grating and the wave number of the incident and reflected waves is matched. Other wavelengths of light are hardly affected by the Bragg grating but still produce some sidelobes in the reflection spectrum. Similarly, there is almost no reflection of the beam at other angles of incidence. When the grating is long enough, even a very weak refractive index modulation can achieve almost total reflection of the beam near Bragg wavelength. The principle is shown in **Figure 2**.

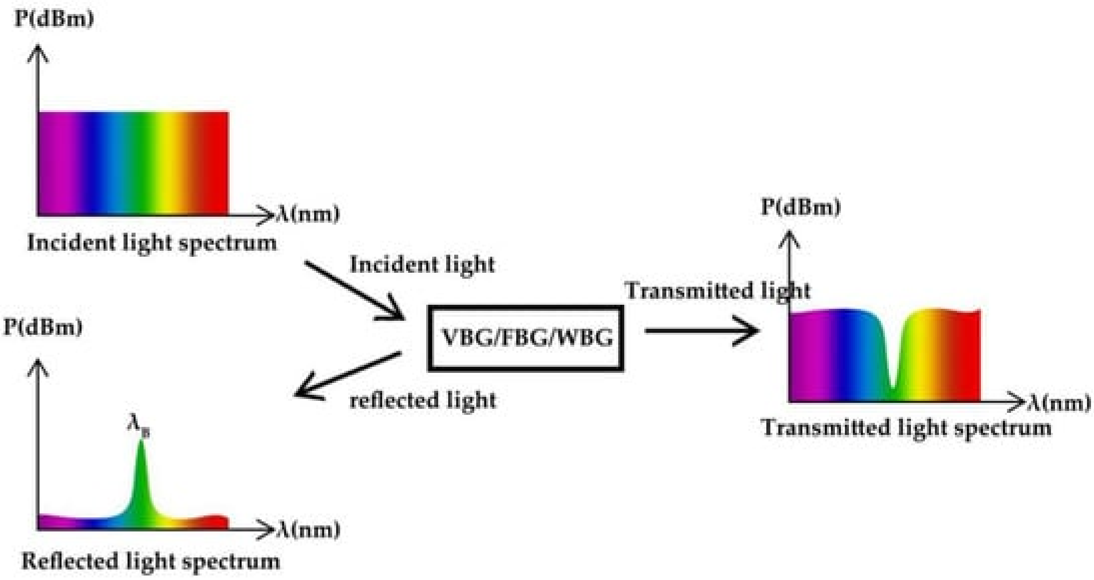

Figure 2. Bragg grating reflection principle.

The linewidth (Δν) of BG-ECSLs (linewidth is usually used to quantitatively characterize the spectral purity of its temporal coherence) can be expressed as follows:

$$\Delta v = (1 + \alpha^2) \frac{{\upsilon_g}^2 \mathrm{h} \nu \mathrm{g} n_{sp} \alpha_m}{8\pi P_0} \quad (2)$$

In Equation (2), α is the specific linewidth increase factor of the semiconductor laser, υ_g is the group velocity, h is the Planck constant, ν is the frequency, g is the gain factor, n_{sp} is the spontaneous emission factor (reflecting incomplete particle number inversion), α_m is the output loss of the cavity and P_0 is the output power.

Where α can be expressed as:

$$\alpha = \frac{\mathrm{d}\overrightarrow{\mathrm{n}} / \mathrm{dN}}{\mathrm{dg} / \mathrm{dN}} \quad (3)$$

vector n and g represent the real and imaginary parts of the complex refractive index of the active medium, respectively, and dg/dN is the differential gain. Due to the different materials, it is generally between 2 and 5, and from Equation (2), it can be seen that the output power of the laser is inversely proportional to the linewidth.

The SMSR of BG-ECSLs (SMSR is usually a replay index used to characterize its single-longitudinal modeling) can be expressed as:

$$SMSR = 10 \lg \frac{P_1}{P_2} \quad (4)$$

where P_1 is the optical power of longitudinal mode, and P_2 is the maximum optical power of edge mode. The larger the SMSR of the laser, the better its single-mode characteristics, and the more stable the single-mode output of the laser. When the edge mode rejection ratio is greater than 20 dB—that is, the optical power of the main longitudinal mode is more than 100 times of the maximum optical power of the edge mode—the laser in this working state can be considered as a single longitudinal mode laser.

2. Research Progress of BG-ECSLs

The structures of BG-ECSLs can be mainly divided into the VBG structure, FBG structure and WBG structure. This research mainly discusses the research progress of VBG structure, FBG structure and WBG structure of BG-ECSLs. BG-ECSLs have a long history. Since the 1970s, in order to make Bragg grating in fiber and other materials, people have carried out a lot of research on the effect of UV radiation damage in silica, germanium-doped silicon glass and other materials. Nowadays, there are many kinds of Bragg grating, and the application fields are also very wide. Due to the unique characteristics and potential application prospects of Bragg grating, since the first batch of BG-ECSLs came out, a large number of companies have studied and continuously optimized the performance of BG-ECSLs. At present, Coherent, OptiGrate, DILAS and so on are well-known in the world. Among them, the United States, Germany, France, Sweden, Canada, Japan and other countries have certain technical advantages in the development of BG-ECSLs. In China, there are also a large number of companies and research institutions developing relevant cutting-edge technologies, such as Wuhan National Laboratory of Optoelectronics, Shanghai Institute of Optics and Precision Instruments, Chinese Academy of Sciences, Beijing Institute of Semiconductors, Chinese Academy of Sciences, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, etc. BG-ECSLs can be widely used in optical communication, biotechnology, environmental detection, material processing and other fields and has potential application prospects in high-precision detection, quantum communication system and other fields.

3. Applications

BG-ECSLs can be widely used in optical communication, gas detection, coherent light detection, synthetic aperture Lidar, spectral gas sensing and other fields and has potential application prospects in underwater optical communication, spaceborne carbon dioxide detection Lidar, biomedical imaging system, high-speed long-distance quantum communication system, etc. [1][2][3]. In this research, the principle of BG-ECSLs is described, and the research achievements and latest progress in this field in the past ten years are reviewed. As shown in **Table 1**, the linewidth of VBG-ECSLs is in the range of kHz-THz (generally in the order of kHz-GHz), the SMSR is in the range of 16~57 dB and the tuning range is in the order of GHz (most of them are tens of picometers). The narrowest linewidth can be as low as 2 kHz while having SMSR up to 57 dB, but the continuous tunable range is small, only 0.063 nm. The maximum tuning range is 1.9 nm. The linewidth of FBG-ECSLs is in the range of kHz~GHz and that of SMSR is in the range of 25~82 dB. The tuning range is in the order of GHz and THz (from tens of picometers to tens of nanometers, and the tuning range is better than that of VBG-ECSLs). The narrowest linewidth can be as low as 125 Hz while having a continuous tunable range of 0.8nm. The maximum SMSR is 82 dB with a narrow linewidth of 16 kHz. The maximum continuous tuning range is 48 nm. The linewidth of WBG-ECSLs is in the range of KHz~GHz, and that of SMSR is in the range of 15~82 dB. The tuning range is in the order of GHz and THz (from hundreds of picometers to tens of nanometers, the tuning range is better than FBG-ECSLs). The narrowest linewidth can be as low as 320 Hz, and the SMSR can be greater than 55 dB. The maximum SMSR is greater than 60 dB, and the linewidth is less than 17 kHz, which can be continuously tuned to 20.2 GHz. The maximum tuning range is 81.8 nm. From the characteristics of commercial BG-ECSLs products, it is not difficult to find that VBG-ECSLs can obtain relatively large output power, while FBG-ECSLs and WBG-ECSLs can obtain a relatively wide tuning range, and the tuning range of WBG-ECSLs is larger, because commercial products are highly targeted (most of them are aimed at a certain module in a certain application or even a certain band). In order to meet the parameter requirements of their application field, most companies do not pursue performances with a low parameter impact on the field. For the application of DWDM, the company pursues parameters such as tuning range, linewidth, output power, SMSR, etc. when conducting research on commercial products, but some parameters cannot obtain the optimal values at the same time. For example, according to Formula (2), if the linewidth is narrower, the output power will be lower. Therefore, in the design of products, it is necessary to meet the requirements of the primary parameters (tuning range), combined with the existing technology, comprehensive consideration of production costs, product stability and other factors to adopt the optimal choice.

Table 1. Comparison of different kinds of BG-ECSLs.

Type	VBG	FBG	WBG
Main Materials	Photo-Thermo-Refractive, Polymer	Glass, Crystal, Plastomer	Si, SiO_2, Si_3N_4, $LiNbO_3$, Polymer
Linewidth Range	2 kHz~1.5 THz	125 Hz~312 GHz	320 Hz~85.3 GHz
Min linewidth	2 kHz	125 Hz	320 Hz
SMSR Range	16 dB~57 dB	15 dB~82 dB	15 dB~60 dB
Max SMSR	57 dB	82 dB	60 dB
Tuning Range	0.011 nm~2 nm	0.1 nm~85 nm	0.16 nm~100 nm
Max Tuning Range	2 nm	85 nm	100 nm
Output Power	10 mW~106.4 W	0.05 mW~670 mW	0.5 mW~312 mW
Maximum Output Power	106.4 W	670 mW	312 mW

The advantages of VBG-ECSLs are the simple structure of the outer cavity and the lack of moving parts, thus providing maximum mechanical stability and reliability. and the center wavelength of the outer cavity structure can be adjusted by tilting the angle of the VBG or changing the cavity length. It plays an important role in biomedicine, optical data storage, synthetic aperture Lidar, quantum optical sensors and other fields. FBG-ECSLs can compress the linewidth of narrow lasers more efficiently, even to the sub-kHz magnitude. It has the advantages of simple and compact structures, narrow linewidths, good stability and a certain tuning ability, and the production cost is low, so the manufacturing process is more mature. However, due to the small refractive index, the large size and large material absorption loss of FBG material itself, it is not conducive to improving the output power of ECSL. Therefore, FBG-ECSLS is suitable for a narrow linewidth, but the tuning range and power requirements are not high. It can be widely used in optical fiber sensing, spectral gas sensing, optical coherence tomography and other fields and has potential application prospects in underwater optical communication, microwave photonics, spaceborne carbon dioxide detection Lidar, ground–starlight Doppler ranging and so on. WBG-ECSLs can not only narrow the linewidth but also maintain good SMSR and tuning capability. Compared with VBG-ECSLs and FBG-ECSLs, WBG-ECSLs have excellent comprehensive performances, which not only have narrow linewidth characteristics but can also maintain a relatively large tuning range and SMSR. Moreover, due to the particularity (good thermal stability) of waveguide materials (Si, SiO_2 and Si_3N_4), WBG-ECSLs has a smaller central wavelength offset with the temperature. The work performance is more stable. Moreover, waveguide has the advantages of a simple structure, small size, low noise and low manufacturing cost, which can be combined with CMOS technology for large-scale production. Through the selection of gain media, materials, integrated devices, new external cavity structure design and optimization of Bragg waveguide structure, so as to improve the coupling efficiency and reduce the waveguide loss, so as to achieve a narrower linewidth, wider tuning range, higher SMSR, lower noise, low-cost and small-volume performance WBG-ECSLs. In general, with the continuous maturation of silicon chip designs and process platforms, the types of external cavity feedback components based on SiO_2, Si_3N_4 and other materials have become more diverse. By introducing the WBG structure, the linewidth of WBG-ECSLs can be compressed, and the coherence of the output can be improved. In addition, the wavelength tuning range of WBG-ECSLs can also be significantly increased. WBG-ECSLs can be widely used in gas detection, coherent optical communication, wavelength division multiplexing system and other fields and have potential applications in multicomponent detection, multi-atom cooling, high-precision spectral detection, biomedical imaging system, high-speed long-distance quantum communication system and so on.

At present, due to the late start and technical blockade, the research on BG-ECSLs still has a certain gap with the international top level. Therefore, the key technologies (epitaxial growth, etching, etc. [4]) should be continuously broken through in the future research, and the device structure should be optimized [5]. The internal cavity (gain chip) optimizes the chip structure. The external cavity (Bragg grating and other optical feedback components [6][7][8]) adjust the structure of the existing optical components and design the optical feedback components with a better performance. In general, WBG-ECSLs are a potential approach for laser output with integration, small size, narrow linewidth, wide tuning range, stable spectral output and high side-mode rejection ratio. Using WBG as an optical feedback element is still the mainstream direction of BG-ECSLs.

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