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Tunable high-power blue external cavity semiconductor laser

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ABSTRACT

A commercially available high-power GaN-based blue laser diode has been operated in a simple Littrow-type external cavity (EC). Two kinds of EC configurations with the grating lines perpendicular (A configuration) and parallel (B configuration) to the p-n junction are evaluated. Good performance has been demonstrated for the EC laser with B configuration due to the better mode selection effect induced by the narrow feedback wavelength range from the grating. Under an injection current of 1100 mA, the spectral linewidth is narrowed significantly down to ~0.1 nm from ~1 nm (the free-running width), with a good wavelength-locking behavior and a higher than 35 dB-amplified spontaneous emission suppression ratio. Moreover, a tuning bandwidth of 3.6 nm from 443.9 nm to 447.5 nm is realized with output power of 1.24 W and EC coupling efficiency of 80% at the central wavelength. The grating-coupled blue EC laser with narrow spectral linewidth, flexible wavelength tunability, and high output power shows potential applications in atom cooling and trapping, high-resolution spectroscopy, second harmonic generation, and high-capacity holographic data storage.

1. Introduction

Along with the advance in material growth and device process technology, GaN-based edge-emitting semiconductor lasers are under active development. Nowadays, GaN-based violet, blue, and green multi-mode laser diodes (LDs) with the output power greater than 1 W have been commercially available [1]. However, the performance of LDs is limited by the poor mode-selection characteristic of Fabry-perot (FP) laser structure and the flat gain profile of semiconductor material, which result in the broad lasing linewidth and untunable wavelength. If tunable single mode operation can be achieved, such high-power lasers could be very useful for a variety of applications such as atom cooling and trapping [2], high-resolution spectroscopy [3], second harmonic generation [4], and high-capacity holographic data storage [5]. One possibility to shape the laser emission behavior is to change the chip design and append frequency selective components directly during the LD manufacturing process. With this technology, light emission with tunable wavelength, narrow linewidth, and high output power has been commercially achieved for GaAs-based Distributed feedback (DFB) [6] and distributed-Bragg-reflection [7] LDs. However, the fabrication technique of such GaN-based LDs is too complex to be widely commercially available. Nichia corporation reported continuous-wave (CW) operation of first-order AlInGaN 405 nm DFB LD on the free-standing GaN substrate [8]. The single longitudinal mode emission can be maintained up to an output power of 60 mW. However, the wavelength tuning control was not mentioned and the cost of material was very high. As far as we know, Nichia company is the only one who has reported CW operation of GaN-based DFB laser.

Alternatively, optical feedback achieved by adding an external-cavity (EC) element such as diffraction grating, can not only enhance the wavelength tunability, but also reduce the intrinsic linewidth. Correspondingly, much effort has been devoted to developing a grating-coupled EC laser [5,9–16]. Lonsdale et al. have reported a 398 nm-EC laser with a maximum tuning bandwidth of 6.3 nm. However the output power is limited by the low-power LD [10]. Hildebrandt et al. have fabricated an EC laser with an anti-reflection-coated GaN-based LD. A total tuning range of 4 nm and an optical output power of 30 mW were realized [11]. Tanaka et al. has reported an EC laser with a wavelength of 405 nm and an output power of 80 mW for holographic data storage [5]. Recently, Ruhnke et al. demonstrated a 400 mW EC laser at 445 nm based on a commercially available high-power LD [16]. Then they used this home-made EC laser as pump source for single-pass second harmonic generation at 222.5 nm [4]. Our research team has been working on GaN-based EC laser since 2013. The performance of a violet (~405 nm) EC laser with the injection current below and just above the free-running lasing

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threshold has been investigated [14]. Although there have been some reports on GaN-based grating-coupled EC lasers, the research is mainly focused on the low-power ones, while the high-power EC laser needs more studies. Generally, in order to obtain high power output, a gain device with wide stripe width and high tolerable working current is needed. In this situation, optimization of the EC configuration is very important for improving the mode selection effect. Besides, the working current is generally far beyond the free-running lasing threshold, and the competition between the inner FP cavity resonance and EC resonance makes the tuning properties become more complex.

In this paper, we fabricate a high-power grating-coupled EC laser by employing a commercially available high-power GaN-based blue LD. Two kinds of Littrow configurations with the grating lines perpendicular (A configuration) and parallel (B configuration) to the p-n junction are constructed and the properties are investigated in detail. By using B configuration, 1.24 W-output power, 3.6 nm-wavelength tuning range, ~0.1 nm spectral linewidth, and higher than 35 dB-amplified spontaneous emission suppression ratio are realized simultaneously under an injection current of 1100 mA. The improved performance should be more beneficial to its applications.

2. Experiments

Fig. 1 shows the schematic diagram of the constructed two kinds of Littrow EC configurations. For A configuration, the grating lines are perpendicular to the p-n junction of gain device. While for B configuration, the gain device is rotated by 90° and the grating lines are parallel to the p-n junction. Both of the EC lasers consist of four optical components: a gain device, a beam collimator, an external grating, and a plane mirror.

The gain device under investigation is a commercially available high-power GaN-based LD emitting at around 445 nm (Nichia, NDB7875-E). The stripe width is estimated to be ~15 μm according to the observation under a microscope. The output beam has a far-field divergence of 25.5° full width at half maximum (FWHM) perpendicular to the p-n junction (fast axis), and 3.5° parallel to the p-n junction (slow axis). When in use it was mounted on a thermo-electrically cooled and temperature controlled plate with a fixed temperature of 20 ± 0.3 °C. Under continuous-wave injection, the device has a threshold current of 130 mA and a maximum output power of 1.6 W. To operate safely below damage threshold, we limited the operation current to be less than 1100 mA with a maximum free-running power of 1.56 W.

In the EC laser, the radiation emitted on the fast axis of gain device is nearly collimated by using an aspherical lens with a numerical aperture of 0.5 and a focal length of 8 mm (Thorlabs, 352240-A). Then the collimated light beam with the size of 7 mm in this direction hit a 2400 grooves/mm-grating under the Littrow angle, where the first order of diffraction is reflected into itself. By rotating the grating, the EC resonance wavelength can be selected. The light diffracted in the zeroth order is used for out-coupling. The length of the EC laser is about 18 cm. In order to avoid the alteration of the output beam direction during the tuning process, a beam-correction mirror is applied.

For the used two kinds of EC configurations, the grating presents different diffraction efficiency due to its polarization-sensitivity. It is known that the light emitted from the LD is polarized in the plane of p-n junction. For A configuration, the grating shows a much higher first order diffraction efficiency of 36% and a much lower zeroth order diffraction efficiency of 44%, while for B configuration, the diffraction efficiency is only 11.5% in the first order and is 76% in the zeroth order.

3. Results and discussion

Before performing EC tuning experiments, the properties of the free-running gain device are characterized. The normalized emission spectra of the device at four different injection currents are depicted in Fig. 2. Obviously, the lasing peak red-shifts with increasing current. Such behavior can be attributed to the decrease of the band-gap energy induced by the increasing temperature under the higher injection level. Besides, a significant broadening of the lasing spectrum with increasing current can also be observed. The FWHMs are 0.52, 1.01, and 1.08 nm for the injection current of 300, 700, and 1100 mA, respectively. This is related to the broadened gain spectrum induced by the band-filling effect. A high-resolution spectral measurement result shows that the longitudinal-mode interval is 0.025 nm. This results in a FP cavity length of around 1.6 mm.

Then, two kinds of grating-coupled EC lasers are constructed and compared. Fig. 3 shows a comparison of light output power versus injection current (*P-I*) curves among the free-running gain device and the EC lasers tuned at ~445 nm measured from the zeroth order of the grating. For the EC lasers with A and B configurations, the threshold current (I_{th}) is reduced to ~95 mA, compared with that of free-running gain device (130 mA). Besides, the slope efficiency is extracted according to the *P-I* curve above its threshold and it decreases from 1.625 W/A to 0.655 and 1.280 W/A. It is well known that for conventional edge-emitting semiconductor lasers, an increase in the facet reflectivity will reduce the output loss, and thus the I_{th} and slope efficiency. Similarly, as an extension of the FP cavity, the grating-coupled EC laser can also be equivalent to a two-mirror cavity by combining the first-order diffraction of the grating with the reflection of laser end facet [17]. The additional diffraction of the external grating increases the effective reflectance of output end, leading to the reduction in the I_{th} and

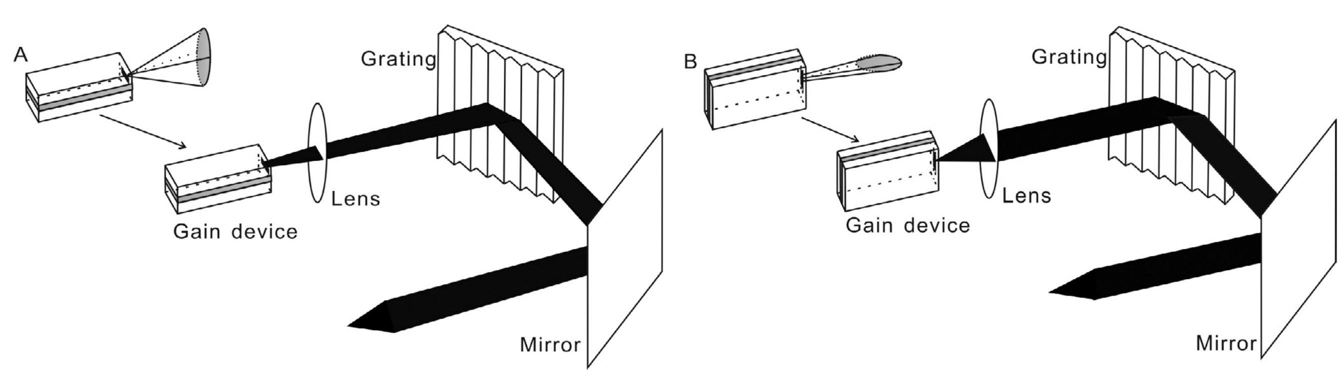

Fig. 1. Schematic diagram of two kinds of EC configurations: (A) grating lines are perpendicular to the p-n junction, (B) grating lines are parallel to the p-n junction.