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Tuning Properties of External Cavity Violet Semiconductor Laser *

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A tunable grating-coupled external cavity (EC) laser is realized by employing a GaN-based laser diode as the gain device. A tuning range of 4.47 nm from 403.82 to 408.29 nm is achieved. Detailed investigations reveal that the injection current strongly influences the performance of the EC laser. Below the free-running lasing threshold, EC laser works stably. While above the free-running lasing threshold, a Fabry–Pérot (F-P) resonance peak in the emission spectrum and a smooth kink in the output power-injection current characteristic curve are observed, suggesting the competition between the inner F-P cavity resonance and EC resonance. Furthermore, the tuning range is found to be asymmetric and occurs predominantly on the longer wavelength side. This is interpreted in terms of the asymmetric gain distribution of GaN-based quantum well material.

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Since the first demonstration of a room-temperature continuous-wave GaN-based violet laser diode (LD) by Nakamura *et al.*,[1] GaN-based LDs have found many applications including optical data storage, laser printer, and laser display. However, as a result of two-facet Fabry–Pérot (F-P) laser structure, untunable lasing wavelength and multi-longitudinal mode emission characteristics restrict the application of these LDs in many cases such as high-resolution spectroscopy, gas analysis, and optical telecommunication. Although the implementation of grating or Bragg reflection structures in LD chips (distributed feedback and distributed-Bragg-reflection LDs) are effective to obtain tunable and single mode emission,[2,3] now it is still commercially unavailable in GaN-based LDs. Alternatively, operation of LDs in an external cavity (EC) provides a feasible approach.

A tunable EC laser is composed of a gain device, beam collimator, and external mode-selection element. Among the basic components, the external mode-selection element is crucial for the external light feedback, and thus has an important impact on the performance of an EC laser including the tuning bandwidth, lasing linewidth, and output power. Various mode-selection elements can be used in EC laser such as diffraction grating,[4] fiber Bragg grating,[5] bandpass interference filter,[6] and electro-optical filter.[7] Among them, the diffraction grating is the most commonly used filter in the EC laser, due to the wide wavelength tunability and the narrow-band light feedback. So far, grating-coupled EC laser has been demonstrated by using commercially available violet and blue GaN-based LDs.[8−14] Lonsdale *et al.* have reported the maximum tuning bandwidth of 6.3 nm at around 398 nm in a Littrow cavity.[9] Hildebrandt *et al.* have investigated the performance characteristics of an anti-reflection (AR)-coated GaN-based LD during operation in a Littrow EC laser.[10] However the tuning properties of GaN-based EC laser have not been studied in detail, which is crucial for further improvement of the device performance.

In this Letter, a Littrow EC configuration is constructed by using commercially available violet GaN-based LD. Firstly the property of a free-running LD is characterized. Then the optical performance of grating-coupled EC laser is investigated. Particularly, the operation mechanism and tuning bandwidth with different injection currents are discussed in detail.

A Littrow configuration is constructed for the EC laser, as schematically shown in Fig. 1. An edge-emitting GaN-based LD (model SLD3232VF, Sony Corporation) emitting at around 405 nm is used as the gain device in this study. An 1800-grooves/mm grating with about 49% diffraction efficiency in its first order is employed, which serves as the frequency selective element and the output coupler of the extended cavity. The output from the LD is collimated by using an AR-coated aspheric lens with a numerical aperture of 0.5, and then hits the grating under the Littrow angle. The light diffracted in the first order is reflected back into the LD, whereas the light diffracted in the zeroth order is coupled out and can be used

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for the measurements. Coarse wavelength tuning is achieved by changing the incidence angle of the grating. In order to avoid the alteration of the output beam direction during the tuning process, a beam-correction mirror is applied. In brief, this Littrow configuration can provide great amounts of feedback due to the small losses incurred from the single dispersive element. Moreover the simple cavity structure with low cost makes the alignment of optical elements robust. In our experiments the LD is operated at room temperature without any temperature control. The emission spectra are detected by using a spectrometer (SpectraPro-2300i, ACTON research Corp.) with a resolution of 0.1 nm.

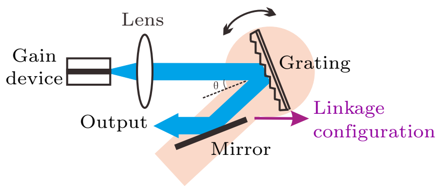

Fig. 1. A schematic diagram of EC laser with a Littrow configuration.

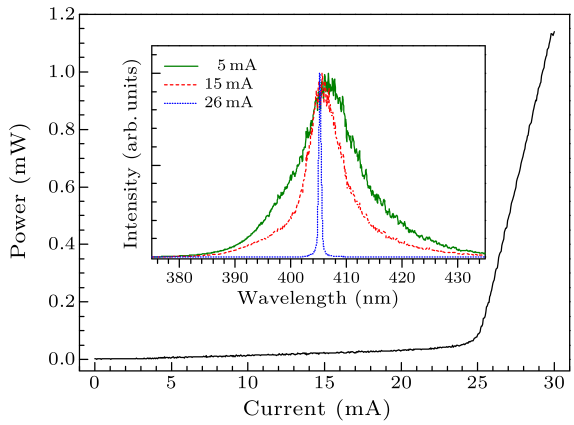

Fig. 2. Light output power as a function of injection current of the free-running GaN-based LD. The inset shows normalized emission spectra at various injection currents.

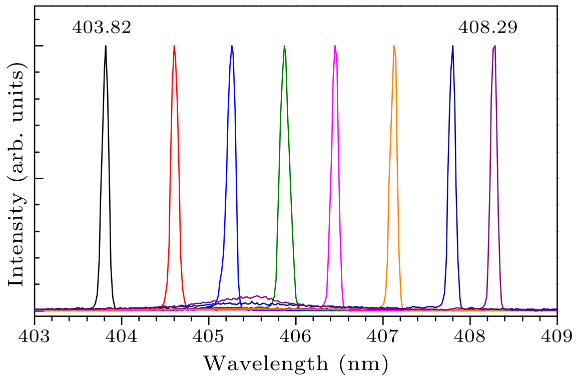

Fig. 3. Lasing spectra of grating-coupled EC laser.

Before performing EC tuning experiments, the property of the free-running GaN-based LD is characterized. Figure 2 shows the light output power as a function of injection current (P–I). A threshold current of 25.1 mA is obtained. The inset of Fig. 2 illustrates the normalized emission spectra of the LD at various injection currents. Spontaneous emission located at 406.7 nm is observed at a current of 5 mA with the full width at half maximum (FWHM) of 11.4 nm. With the injection level increasing, a progressive spectral narrowing is noticed due to the amplification of spontaneous emission. At a current of 26 mA, stimulated emission occurs at a wavelength of 405.24 nm with an FWHM of 0.54 nm.

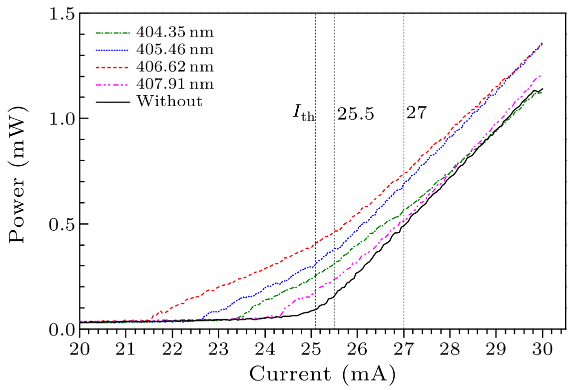

Fig. 4. Comparison of P–I curves for different lasing wavelengths.

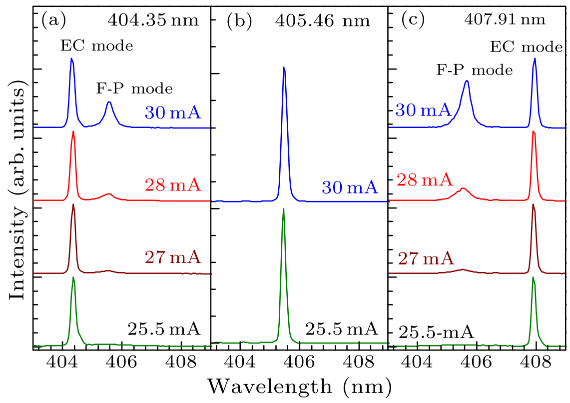

Fig. 5. Emission spectra of the EC laser for three different feedback angles with the lasing wavelength shorter than (a), close to (b), and longer than (c) the F-P resonance wavelength.

The EC tuning performance is examined at 25.5 mA. It is worth noting that the injection current is fixed just above the free-running lasing threshold in order to avoid the inner F-P cavity resonance. A total tuning range of 4.47 nm from 403.82 to 408.29 nm at room temperature is achieved by rotating the grating. Figure 3 shows the lasing spectra of the grating-coupled EC laser with linear scale. The emission spectra exhibit amplified spontaneous emission suppression in excess of 20 dB in the central part of the tuning range. In addition, the resulting optical spectra show an FWHM around 0.1 nm, limited only by the instrumental resolution of the spectrometer.

Figure 4 shows the P–I curves for different EC lasing wavelengths. The characteristic curve without feedback is also drawn for comparison and for quick estimation of feedback level. According to the P–I curves, the working condition of EC laser can globally be divided into three domains by the threshold current $I'_{\rm th}$ of EC laser and threshold current $I_{\rm th}$ of free-running LD:

(1) $I < I'_{\rm th}$: The light output is dominated by spontaneous emission and the output power rises slowly with the increasing injection current.

(2) $I'_{\rm th} < I < I_{\rm th}$: It is known that lasing threshold is reached when the optical gain of the laser medium is exactly balanced by the sum of all the losses experienced by light in one round trip of the laser's optical cavity. Here the system behaves as a complex cavity laser due to the introduction of external grating which makes the loss reduced at the diffracted wavelength. Therefore the threshold current $I'_{\rm th}$ of EC laser is reduced in comparison with that of free-running LD. Correspondingly, $I'_{\rm th}$ depends strongly on the optical gain, inner optical loss in the LD, and the feedback which is related to the diffraction efficiency of the grating. Hence the wavelength around the center of the gain spectra shows the lowest threshold owing to the nearly constant inner optical loss and the constant grating feedback in the whole tuning bandwidth. Notably in Fig. 4, the threshold current at 406.62 nm exhibits the smallest value of 21.5 mA. For the short- and long-wavelength edge, lasing will occur at higher current as long as the gain can compensate for all the losses. Moreover in this region $I'_{\rm th} < I < I_{\rm th}$, because of the insufficient condition for F-P resonance lasing, the EC laser can work stably and only EC lasing mode is present whatever the lasing wavelength is.

(3) $I > I_{\rm th}$: When the injection current is increased beyond $I_{\rm th}$, the EC feedback term is no longer prerequisite for laser operation, thus the competition and interplay between the EC resonance and F-P resonance are expected. Figure 5 shows the emission spectra of the EC laser for three different lasing wavelengths. It is clear that at the center of the gain peak (405.46 nm), only one lasing mode exists. While at the short- and long-wavelength edge (404.35 and 407.91 nm), F-P resonance at 405.6 nm appears and dominates the spectra gradually when the injection current is above 27 mA. Note that in the EC working mode the F-P resonance appears at a higher current compared with the free-running situation. This is mainly due to the gain reduction induced by the carrier consumption in the process of EC lasing. Meanwhile, a smooth kink is observed in the P–I characteristic curves slightly above the $I_{\rm th}$ of free-running LD which stems from the transition between two lasing modes. The origin of the abrupt increase in output power above $I_{\rm th}$ can be explained in terms of the emission direction effect of an LD. As described in Ref. [10], the decreasing reflectivity of the output facet causes an increase of the power at the end of the cavity. Because of the additional diffraction of the external grating, the effective reflectivity of the EC side of the LD is increased in comparison with the solitary cavity facet. Therefore the contribution of F-P resonance above $I_{\rm th}$ induces the reduction of effective reflectivity of the EC side, leading to the abrupt increase of the output power.

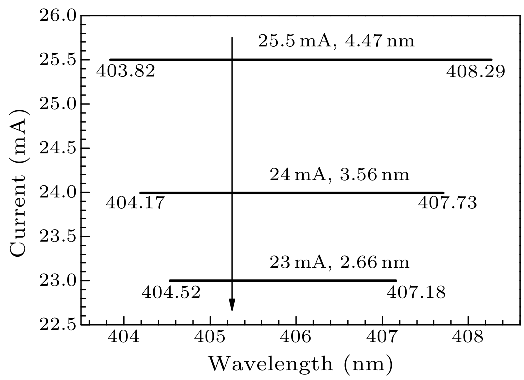

Fig. 6. Tuning range of the EC laser at different injection currents. The arrow indicates the lasing wavelength of the free-running LD.

We also investigate the tuning range for different injection currents. The obtained results, as shown in Fig. 6, show that the tuning range is enhanced for a higher pump level as expected from a state-filling point of view. However, the tuning bandwidth is asymmetric with respect to the free-running lasing wavelength. Since the tuning range reflects the gain distribution of the LD,[15] it is inferred that the gain curve of GaN-based quantum well material is asymmetric with a very abrupt decrease in the short wavelength side.[16] This is also consistent with the asymmetric spontaneous emission spectra of the LD in Fig. 2. In addition, gain saturation is not observed on the long wavelength side due to the high density of states induced by the large effective mass of electrons and holes in GaN-based quantum well material. By designing an optimized structure of the active region such as the multiple asymmetric quantum well layers,[17] an even wider tuning bandwidth is expected.

In summary, the optical performance of grating-coupled EC laser with GaN-based LD is investigated. A tuning bandwidth of 4.47 nm is achieved, covering the wavelength from 403.82 to 408.29 nm. The lasing property of EC laser with different injection currents is discussed. Below the threshold current of free-running LD, the EC laser works stably and EC resonance mode dominates the emission. However, with the increasing injection current, the competition between the EC resonance and F-P resonance is demonstrated. In this case, an F-P resonance peak in the emission spectra and a smooth kink in the P–I characteristic curves are observed simultaneously. In addition, the investigation of tuning range for different injection currents indicates the tuning superiority towards longer wavelength for GaN-based EC laser.

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