Narrow-line InGaN/GaN green laser diode with high-order distributed-feedback surface grating

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We demonstrate narrow-line green laser emission at 513.85 nm with a linewidth of 31 pm and side-mode suppression ratio of 36.9 dB, operating under continuous-wave injection at room temperature. A high-order (40th) distributed-feedback surface grating fabricated on multimode InGaN-based green laser diodes via a focused ion beam produces resolution-limited, single-mode lasing with an optical power of 14 mW, lasing threshold of 7.27 kA cm−2, and maximum slope efficiency of 0.32 W A−1. Our realization of narrow-line green laser diodes opens a pathway toward efficient optical communications, sensing, and atomic clocks. © 2019 The Japan Society of Applied Physics

The advent of InGaN laser diode (LD) technology at green wavelengths has been made possible by continuous effort on improving issues related to crystal quality arising from high index (In) composition.1–5) Broad-area multimode LDs emitting at 525 nm and 1 W of optical power are now commercially available,6) and applications such as solid-state lighting7) and laser projectors8) are driving the need for these green emitters. Other specialized applications including sensing,9) atomic clocks,10) and underwater optical communications11) require not just a conventional green laser but a narrow-line or single-wavelength green source. Currently, these are scarce and based on external and/or out-sized optical components. A solution to this problem is the monolithic integration of distributed-feedback (DFB) gratings on LDs.11) This has been demonstrated on mature infrared12) and red LD emitters,13) as well as on InGaN-based blue and violet LDs.14–18) However, a green-emitting InGaN DFB LD remains to be demonstrated.

Different types of DFB gratings have been achieved including buried,19–21) surface,22–25) and ridge sidewall gratings.26–29) The surface and sidewall gratings are the most suitable for green LDs since buried gratings require overgrowth,30) which tends to compromise the material quality, particularly critical for InGaN-based green laser structures.3) Related to fabrication, low-order gratings (first, second, etc.) require elaborate holographic or electron beam lithography.21,13) On the other hand, high-order gratings (20th, 30th, etc.) benefit from reduced fabrication complexity while being able to directly quantify the effect of the DFB grating on the device. Our approach demonstrates the feasibility of achieving narrow-line emission using DFB gratings on InGaN-based green lasers.

The design of the DFB gratings follows the Bragg condition22) given by

\[ \frac{m \lambda}{2n_{\text{eff}}} = \Lambda, \]  

where \( m \) is the order of the grating, \( \lambda \) is the wavelength in vacuum, \( n_{\text{eff}} \) is the effective refractive index, and \( \Lambda \) is the grating period. \( \Lambda = 4.12 \mu m \) was initially calculated for an emission wavelength of 515 nm assuming an \( n_{\text{eff}} \) of 2.5. The pattern was designed and exposed (Fig. 1) to a green LD (Oslam PLP520) with an FIB (FEI Helios NanoLab 650) at 16 keV and 3.3 nA for \( \sim \)16 min. The green LD consisted of a Fabry–Perot (FP) ridge-waveguide with a ridge width of \( \sim 4 \mu m \) and cavity length of \( \sim 905 \mu m \) [Fig. 2(a)]. In a first experiment, three consecutive sections of 22 groove pairs (i.e., periods of alternating refractive index) were fabricated on device A. These sections were named “+1 DFB”, “+2 DFB”, and “+3 DFB”, referring to the fact that they were fabricated on the same device and each section was consecutively introduced along the same ridge waveguide, thus forming a longer DFB section. The location of these grating sections is shown in Figs. 2(a) and 2(b), as red, green, and blue periodic bar schematics. Device A was characterized before and after fabrication of each grating section. An optical micrograph of the fabricated device depicting the three grating sections is shown in Fig. 2(b). During optimization of the fabrication process we achieved a test device depicting this type of DFB grating along the full cavity length. Figure 3 illustrates the diffractive effect of this DFB grating.

Electro-optical characterization was conducted in continuous-wave (CW) current injection with a Keithley 2520 system and a silicon photodetector in an integrating sphere (Labsphere). The operating temperature was stabilized using a thermoelectric cooler (TEC) and a TEC controller (Thorlabs ITC 4005). High-resolution (10 pm) spectral measurements were conducted with an optical spectrum analyzer (Yokogawa AQ6370B). The spectrum of the LD taken at 300 mA (8.29 kA cm−2) and 20 °C is plotted in Fig. 4(a), illustrating the evolution of the lasing emission after fabrication of each of the three consecutive DFB sections. The DFB effect can be evaluated by the reduction of resonant modes, which can be seen directly from the spectra and quantified by the side-mode suppression ratio (SMSR). We obtained SSMR values of 0.2 dB, 0.34 dB, 1.45 dB, and 2.23 dB, respectively, for the FP-LD, +1 DFB, +2 DFB, and +3 DFB. A peak shift was observed due to mismatch between the Bragg resonant wavelength and the FP main resonance from the cavity.

The grating reduced the output power from 141 mW (FP-LD at 300 mA, CW) down to 49.6 mW (+3 DFB at 300 mA, CW)
Given the initial characteristics of the FP-LD, it is expected to have a power reduction due to mode selection and annihilation. A similar optical power reduction has been observed previously, and it can be related to increased scattering and a strong coupling coefficient. In return, the DFB grating provided stability to the lasing emission. This can be seen in Fig. 4(b) where a kink is initially observed on the FP-LD light output curve. The kink is further suppressed in the same device after the DFB gratings are fabricated. Additionally, from the current–voltage (IV) characteristics [Fig. 4(b)], we determined a series resistance ($r_s$) of $\sim 3.25 \Omega$ at 300 mA. The value of $r_s$ did not change significantly ($\pm 0.25 \Omega$) before and after fabrication of the DFB gratings, i.e., the creation of the grating using this method did not degrade the electrical performance of the LD.

From the spectral emission of the device with three DFB gratings ($+3$ DFB in Fig. 4(a)), we selected the dominant peak (515.674 nm) to calculate experimentally the effective refractive index ($n_{eff}$) using (1). We obtained $n_{eff} = 2.5033$. Furthermore, using the mode spacing of the lasing modes ($\Delta \lambda \sim 0.053$ nm) and the relations given by $^{35}$

![Fig. 1. (Color online) Scanning electron micrograph of the DFB grating as etched with the FIB on the surface of an InGaN-based green laser diode.](image1)

![Fig. 2. (Color online) DFB laser diode (LD). (a) Scanning electron micrograph of the green LD. (b) Optical microscope image of the back-facet section of the LD with the fabricated DFB grating. The red, green, and blue periodic lines are overlaid to represent the DFB grating sections, i.e., $+1$ DFB, $+2$ DFB, and $+3$ DFB.](image2)

![Fig. 3. (Color online) Optical microscope image of a green LD depicting a DFB grating all along the cavity length, illustrating the diffraction of white light by the grating. The insets (1, 2, 3, 4, 5) are images taken at different viewing angles.](image3)

![Fig. 4. (Color online) Electro-optical characteristics of the DFB-LD (device A). (a) Spectral evolution after each consecutive DFB grating segment (i.e., $+1$ DFB, $+2$ DFB, $+3$ DFB). (b) Light-output–current–voltage ($L–I–V$) characteristics after each DFB grating segment.](image4)
where $\Delta \lambda$ is the lasing mode spacing, $n_{\text{eff,g}}$ is the effective group index, and $L$ is the cavity length, we estimated $n_{\text{eff,g}} = 2.772$ and a dispersion ($\lambda / d\lambda$) of $\sim 5.21 \times 10^{-4}$ nm$^{-1}$.

The measured $n_{\text{eff}} = 2.5033$ allowed us to design a DFB grating with improved accuracy and wavelength matching the FP-LD modes.

A DFB grating with period $\Lambda = 4.114 \mu m$ was calculated and fabricated with an FIB on device $B$. As seen in Fig. 5(a), the resulting device showed narrow-line emission at 513.85 nm with an SMSR of 36.9 dB at 300 mA (8.29 kA cm$^{-2}$) of CW and 20 °C. The SMSR is the highest value reported for any InGaN-based DFB LD to date.

The measured $n_{\text{eff}} = 2.5033$ allowed us to design a DFB grating with improved accuracy and wavelength matching the FP-LD modes.

Using Eqs. (1)–(3), we obtained $n_{\text{eff}} = 2.4981$, $n_{\text{eff,g}} = 2.7524$, and a dispersion of $\sim 4.95 \times 10^{-4}$ nm$^{-1}$. From the refractive index data of the earlier device $A$, we would have expected $n_{\text{eff}} = 2.5043$ for $\lambda = 513.85$ nm. The difference between the expected and the measured value is 0.0062 (0.25%). This difference is likely due to the unresolved dispersion ($\lambda / d\lambda$), as well as the variability in the fabrication process and devices.

The influence of operating temperature on the emission of the DFB-LD is shown in Fig. 7, where we can observe narrow-line emission and a tuning coefficient of 0.0128 nm K$^{-1}$ from 12.5 °C to 40 °C. The nominal temperature is obtained from the
Fig. 7. (Color online) Temperature dependence on the emission of the DFB-LD (device B) with a tuning coefficient of 0.0128 nm K\(^{-1}\) (see the inset for details).

At 25 °C we observed narrow-line emission with SMSR >2.43 dB and a FWHM of 75.8 pm, given by two dominant lasing modes. The devices under test featured a high-reflective mirror in the rear facet. This characteristic provides a random phase shift \((\varphi)\) to the DFB laser.\(^{37}\) As such, we designed our grating to have \(\varphi = \pi/2\), so that the traveling wave of the grating would be reflected constructively. However, it is difficult to determine with precision the position of the effective reflection, added to the variability in the fabrication process. These facts potentially could be the reason for the additional lasing modes found under varying working conditions such as changes in temperature.

In conclusion, we demonstrated 14 mW narrow-line emission with a FWHM of 31 pm and SMSR of 36.9 dB at green wavelengths (~514 nm) by integrating a 40th-order DFB surface grating onto an InGaN-based LD by maskless etching with an FIB. A reduction in the FWHM from 544 pm down to 31 pm was demonstrated and the device characteristics were discussed. Our work paves the way for future development of single-wavelength green LDs with the realization of the DFB structure. This could enable immediate implementation of narrow-line green LDs on various applications, such as atom cooling, spectroscopy, and optical communications.

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