

## Demonstration of an InGaN/GaN-based optically pumped multiquantum well distributed feedback laser using holographically defined third-order gratings

Daniel Hofstetter,<sup>a)</sup> Robert L. Thornton, Michael Kneissl, David P. Bour, and Clarence Dunnrowicz  
*Xerox Palo Alto Research Center, 3333 Coyote Hill Road, Palo Alto, California 94304*

We demonstrate an optically pumped InGaN/GaN-based multiquantum well distributed feedback laser in the blue spectral region. The third-order grating providing feedback was defined holographically and dry etched into the upper waveguiding layer by chemically assisted ion-beam etching. When aligning the stripe-shaped pump beam either parallel or perpendicular to the grating grooves, we found a considerably lower pumping threshold, higher slope efficiency, a slightly longer emission wavelength, and a much narrower linewidth for the geometry with the pump beam orthogonal to the grating lines. A nearly constant emission wavelength of 400.85 nm and a linewidth of 0.7 Å were observed under various pump intensities. To the best of our knowledge, this is the narrowest linewidth ever reported for an optically pumped device in this material system.

The fabrication of an electrically pumped laser in the blue spectral region has attracted a lot of attention in the past couple of years. Both pulsed and continuous-wave operation of InGaN/GaN-based devices have been demonstrated at room temperature.<sup>1,2</sup> One of the main concerns in nitride lasers is the fabrication of high-quality mirrors. Up to now, most research groups use sapphire substrates for GaN growth; however, the misorientation between the sapphire and the GaN cleavage planes does not readily permit cleaving of the facets. Polishing of the laser mirrors also does not entirely satisfy because it is a very time-consuming process. Although dry-etched mirrors with high reflective coatings seem to work well in this material system, there is still a certain demand to improve the cavity properties of nitride lasers as far as mirror loss and especially mode selection are concerned. One of the possible solutions of this problem is the implementation of distributed feedback (DFB), which eliminates the need for excellent cavity mirrors. A relatively straight forward way to explore this idea is the fabrication of an optically pumped device. According to this, Hofmann *et al.*<sup>3</sup> reported an optically pumped DFB laser in the InGaN/GaN material system. However, their device was a simple double heterostructure, employed a second-order diffraction grating for surface emission, and the grating was generated using e-beam direct writing. In this letter, we demonstrate the fabrication of a nitride-based multiquantum well (MQW) DFB laser with a holographically defined third-order grating, which results in edge emission. When compared to the Fabry–Perot-type emission observed from the same material, a reduced threshold pump intensity, a higher slope efficiency, and a much narrower linewidth were seen.

The fabrication of these devices relied on growing a 4 μm thick GaN layer on C-face sapphire. On top of this layer, we grew a 500 nm thick Al<sub>0.08</sub>Ga<sub>0.92</sub>N lower cladding layer,

a 100 nm thick GaN lower waveguiding layer, a 40 nm thick active region with five In<sub>0.15</sub>Ga<sub>0.85</sub>N quantum wells (QWs) and GaN barriers, and a 180 nm thick GaN upper waveguiding layer. The third-order grating with a period of 240 nm was then defined by a holographic exposure using two-beam interference with a 325 nm UV HeCd laser (LICONIX model 3210N, 10 mW). The transfer into the semiconductor was achieved by dry etching in a chemically assisted ion-beam etching (CAIBE) system.<sup>4,5</sup> The grating depth was 45 nm; for an asymmetric trapezoid-shaped grating at a GaN/air interface, this results in a calculated coupling coefficient of 250 cm<sup>-1</sup>. Because of the grating having also a certain amount of surface roughness and a nonideal tooth shape, we estimated the coupling coefficient to be somewhat reduced, on the order of 200 cm<sup>-1</sup>. An atomic force microscope (AFM) surface scan of the grating is shown in Fig. 1(a). A root-mean-squared (rms) surface roughness of around 5 nm was observed on the bottom of the etched areas; this is comparable to the rms roughness of CAIBE etched flat surfaces.

Optical pumping was carried out using a pulsed 337 nm N<sub>2</sub> laser ( $r_{\text{pulse}} = 10$  Hz,  $P_{\text{peak}} = 250$  kW,  $W_{\text{pulse}} = 75$  μJ) whose light was focused to a 100 μm wide and approximately 4 mm long stripe; this defined a gain-guided lasing region on the sample. In order to be able to measure the InGaN/GaN laser output intensity at different pump levels, we attenuated the pump beam by inserting a variable number of 1 mm thick glass slides between the lenses and the sample. The output of the InGaN/GaN laser was collected by a 30× microscope objective, focused onto a quartz fiber and fed into either a high- or low-resolution grating spectrometer. The high-resolution spectrometer (SPEX,  $\Lambda = 1800$  lines/mm,  $d_{\text{focus}} = 1.26$  m,  $\Delta\lambda_{\text{resolution}} = 0.3$  Å) allowed the measurement of the laser spectrum and the determination of the linewidth. The output intensity as a function of the pump intensity was measured by an ORIEL low-resolution spectrometer with 0.1 m focal distance, 1 nm resolution, and a grating with 1200 lines/mm. Both spectrometers had array

<sup>a)</sup>Electronic mail: hofstetter@parc.xerox.com

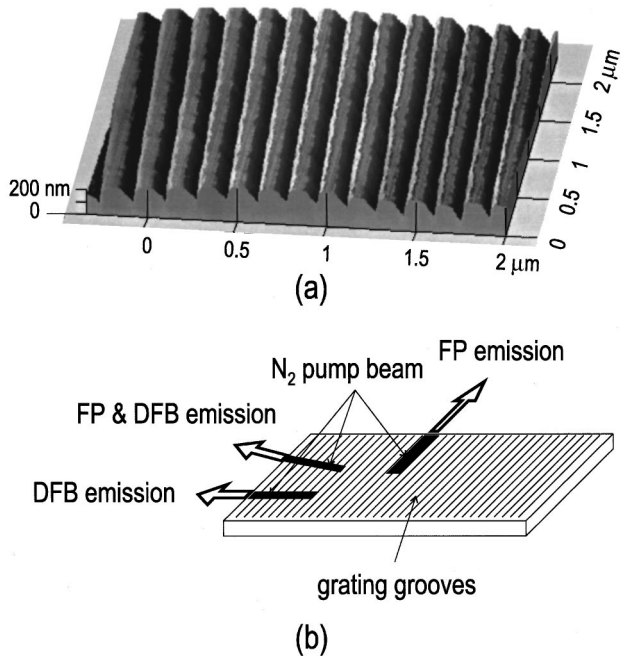


FIG. 1. (a) AFM surface scan showing the CAIBE etched third-order grating in the upper waveguiding layer. (b) Schematic drawing of the sample with different orientations of the stripe-shaped pump beam.

photodetectors with 1024 elements at their output slits; intensity versus wavelength data could thus be acquired by collecting light for up to 30 s in order to get a good signal-to-noise ratio.

The piece on which we performed these experiments was approximately  $10 \times 10 \text{ mm}^2$  in size, and all four facets were fabricated by scribing from the back and subsequent cleaving. Although this method resulted in a poor Fabry–Perot (FP) cavity, and in addition, the  $\text{N}_2$  laser beam was pumping 30%–40% of the cavity length only, FP-type laser emission could be observed as well as DFB laser emission. The orientation of the grating lines relative to the pump beam determined which emission would become the dominant one. A schematic drawing of the sample with the grating and the pump beam in both orientations is shown in Fig. 1(b).

Typical emission spectra of both FP- and DFB-type lasing are shown in Fig. 2. It is evident that the emission of the FP laser peaks at 398 nm with a typical linewidth of around  $25 \text{ \AA}$ , whereas the DFB laser exhibits a peak wavelength of 400.85 nm and a much narrower linewidth of  $0.7 \text{ \AA}$ . As will be discussed below, we observed far-field patterns typical for optically pumped lasing for both the FP and DFB emission. There was also a characteristic threshold behavior in the output versus pump intensity curve in both cases. This gives us confidence that the feature at 398 nm is, in fact, a lasing peak and not only amplified stimulated emission. While the linewidth of the FP laser agrees well with values from the literature,<sup>6–8</sup> the DFB value is the smallest linewidth ever reported for an optically pumped InGaN/GaN laser to the best of our knowledge. Since the resolution of the spectrometer is  $0.3 \text{ \AA}$ , we are not entirely convinced that the device oscillates in a single longitudinal and lateral mode. However, it could also be possible that other mechanisms like thermal chirping during the individual pumping pulse, unequal inten-

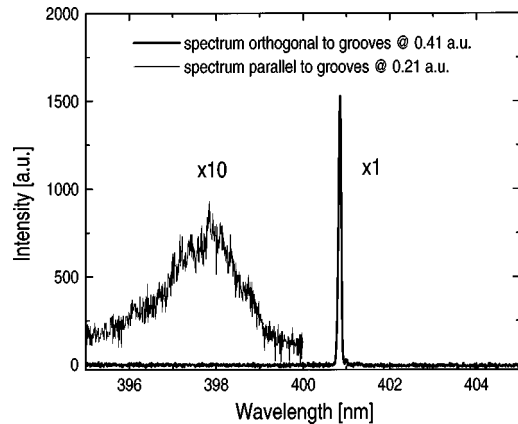


FIG. 2. Emission spectrum of an optically pumped DFB laser at  $2 \times 10^{11}$ . The broader peak at 398 nm belongs to the FP-type emission. Please note that the FP spectrum has been cut at 400 nm for better visibility of the DFB peak.

sity among the pulses, or even the absence of a well-defined cavity are responsible for the broadening.

The emission wavelength and the grating order allowed us to calculate the effective refractive index of the lasing mode; the value obtained when performing this calculation is 2.505. The small emission peak at the long-wavelength shoulder of the main peak is suppressed by almost 20 dB; its wavelength is 401.03 nm. The gap between this small peak and the main emission could account for the stop band of the Bragg reflector, corresponding to a coupling coefficient of around  $180 \text{ cm}^{-1}$ , which is in good agreement with the calculated value of  $200 \text{ cm}^{-1}$ . From light-emitting diodes fabricated from the same material, we estimated the gain to peak at 398 nm with a full width at half maximum of 12 nm; indicating that both FP and DFB lasing wavelengths are well within the gain peak of the material.

A comparison of the peak intensities between the FP and the DFB emission shows a factor of 20 higher peak intensity at only half the pump intensity for the DFB laser. This is due to the long unpumped, and therefore, lossy section of the FP laser. Measurements of the pump versus output intensity characteristics were carried out at room temperature. As shown in Fig. 3, we observed an intensity threshold of around 0.1 a.u. for the DFB and 0.2 for the FP laser. From the transmission of our glass slides and the BK7 glass lenses, we estimated that the threshold intensity for the DFB laser (0.1 a.u.) corresponds to roughly  $1 \text{ MW/cm}^2$ . The slope efficiency of the DFB laser was approximately 40 times larger than the slope of the FP laser. Presumably, the fabrication of a short, full-length pumped cavity would give a fairer comparison between the slope efficiencies of the two laser types. Although linewidth and emission wavelength are likely to have suffered somewhat from the absence of a high-quality FP laser cavity, we do not believe that effects like band filling or heating had a significant yet measurable impact on them. Optical pumping experiments on short bars fabricated from similar material showed comparable wavelength and linewidth data to the FP emission described here.<sup>9</sup>

In order to illustrate the presence of two distinctive emission wavelengths corresponding to the two lasing mechanisms, we pumped the material in a way such that the pump beam was at an angle of  $70^\circ$  to the grating lines (see

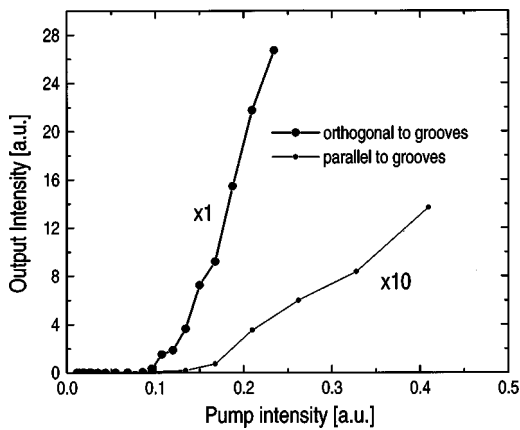


FIG. 3. Pump versus output intensity curves of optically pumped DFB and FP lasers fabricated on the same piece of material. The slope of the DFB laser is 40 times steeper than the slope of the FP laser.

Fig. 2, flagged as “FP & DFB emission”). This geometry allowed the device to oscillate in both FP- and DFB-type lasing mode simultaneously. The spectra were measured with the low-resolution spectrometer and are shown in Fig. 4. Here, it becomes obvious that the spontaneous emission peak of the material, which was measured at the lowest pump level, is much broader than the two lasing peaks, namely, on the order of 15 nm. At higher pump intensities, the FP emission starts first, and finally, the DFB emission overwhelms the FP peak. When going to a larger angle than  $25^\circ$ , the narrow DFB peak becomes weaker until it finally disappears. This fact is consistent with the observation that the backward DFB emission was pointing into a direction

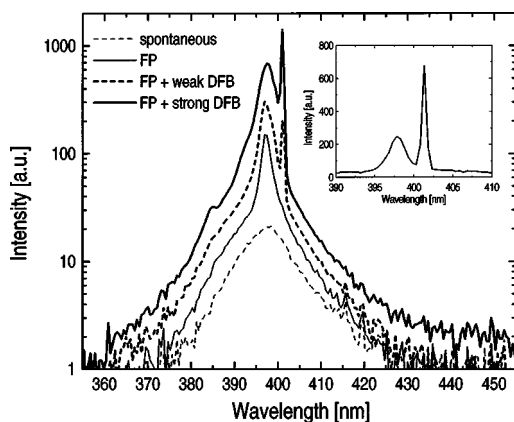


FIG. 4. Low-resolution spectra of the device when tilting the pump beam to about  $70^\circ$  to the grating grooves. For higher pump intensities, DFB and FP peaks are visible at the same time. The inset shows the relevant part of the spectrum at an expanded x-axis scale.

exactly perpendicular to the grating grooves, independent from the orientation of the pump beam.

As mentioned above, we quantitatively characterized the far-field patterns of both the FP and the DFB emission. Due to the absence of an AlGaIn upper cladding layer, the result of these measurements was similar to what we reported earlier<sup>9</sup> on optically pumped InGaIn/GaN lasers. In the vertical direction, the far field revealed two main emission lobes at angles of around  $\pm 34.5^\circ$  to the horizontal and a number of weaker intensity maxima in between. In the backward direction, we observed a strong emission lobe at  $34.5^\circ$  to the horizontal direction as well.

In conclusion, we have demonstrated an optically pumped InGaIn/GaN-based MQW DFB laser. The threshold intensity was somewhat reduced when compared to FP-type lasers, and was on the order of  $1 \text{ MW/cm}^2$ . The emission of the DFB laser was at a wavelength of 400.85 nm and was as narrow as  $0.7 \text{ \AA}$  compared to 398 nm and  $25 \text{ \AA}$  for the FP emission. The linewidth of the DFB emission is the smallest ever reported for an optically pumped laser in this wavelength range. The primary emission peak did not change its position on the wavelength scale over a range of pump intensities, which indicates strong coupling to the grating resonance peak.

The authors would like to thank Fred Endicott and Greg Anderson for help in setting up the experiment, Gary Evans from Southern Methodist University, Dallas (TX), for valuable discussions, and Noble M. Johnson and Ross Bringans for helpful support. The authors give special thanks to LICONIX, Inc. in Santa Clara, CA, for providing the appropriate HeCd laser for holography. This work was supported by the Defense Advanced Research Projects Agency (DARPA Contract No. MDA 972-96-3-0014), and the Swiss National Science Foundation.

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