Slight, T. J., Yadav, A., Odedina, O., Meredith, W., Docherty, K. E., Rafailov, E. and Kelly, A. E. (2017) InGaN/GaN laser diodes with high order notched gratings. *IEEE Photonics Technology Letters*, (doi:10.1109/LPT.2017.2759903)

InGaN/GaN Laser Diodes with High Order Notched Gratings

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***Abstract*—We report on InGaN/GaN distributed feedback laser diodes with high order gratings emitting at a single wavelength around 428 nm. The 39th order notched gratings have the advantage of a simplified fabrication route with no need for overgrowth. The laser ridge and grating were formed by electron beam lithography followed by ICP etching. The as-cleaved lasers emitted in the pulsed regime with a peak single-mode output power of 15 mW. Optimization of the grating design should lead to higher power single wavelength operation.**

***Index Terms*— Semiconductor lasers, Distributed feedback laser diodes, InGaN, GaN, Sidewall grating, Slotted laser, Notched grating. Lateral grating.**

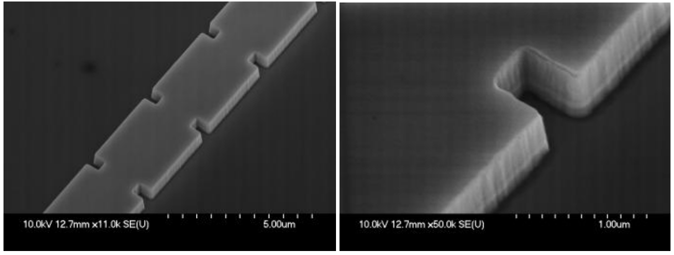
I. INTRODUCTION

LASER Diodes based on Gallium Nitride (GaN) have found a wide range of applications ranging from atomic spectroscopy [1] to optical communications [2]. To fully exploit many of these application areas there is a requirement for a GaN laser diode with high spectral purity and wavelength selectivity. For example in atomic clocks, where a narrow line width blue laser source can be used to target the atomic cooling transition [3][4], and in fluorescence spectroscopy for medical diagnostics where one can accurately target the emission wavelength [5].

Previously, GaN DFB lasers have been realised by one of two approaches, buried [6][7], or surface gratings [8]. Buried gratings require complex overgrowth steps which have the potential to introduce epi-defects. Surface gratings designs, all though simpler to fabricate, can compromise the quality of the p-type contact due to dry etch damage and are also prone to increased optical losses in the electrically un-pumped grating regions. Using shallow etched lateral grating designs, some of these issues are resolved [9], however deeply etched lateral gratings, [10], benefit from a much simpler fabrication route and have the potential for larger coupling coefficients. The authors have previously reported third order sidewall gratings in the InGaN/GaN material system [11][12], with single wavelength emission. In this paper we go on to investigate lasers with higher order gratings, which have the advantage of less stringent fabrication tolerances due to the larger grating dimensions. Additionally, these devices have the potential for narrower linewidths than conventional DFB laser diodes [13] and so could be particularly suited to supplications such as atomic cooling.

II. DESIGN

Our chip designs are based on 39th order gratings and are conceptually similar to devices described in [14]. Conventionally for this type of device the grating consists of slots etched into the top of the laser waveguide ridge. However this approach is not suited to GaN laser diodes where the p-type GaN contact layer should remain continuous along the ridge to minimise resistance and avoid optical losses in the p-type GaN. In our design the index perturbations are introduced as regularly spaced notches in the ridge sidewall thus maintaining the continuity of the contact.



(a) (b)

Fig. 1. SEM micrograph of the as etched grating (a), and at higher magnification (b).

With high order gratings of this type the coupling coefficient κ is significantly less ($\kappa\sim2\ \mathrm{cm}^{-1}$) than can be achieved with 3rd order gratings ($\kappa\sim22\ \mathrm{cm}^{-1}$) [12]. In fact, the dominant sources of optical feedback are the cleaved facets. The effect of the grating is to introduce a wavelength selective optical loss for Fabry-Pérot (FP) modes shifted from the Bragg

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This work was supported by the European Union FP7 project Edocald (project number 605254). Additional support was received through the UK SU2P pilot programme.

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wavelength. Depending on the reflection bandwidth of the grating, lasing can be in a single or narrow band of FP modes.

The grating bandwidth is a function of the reflectivity of the individual notch pair. The lower the reflectivity the narrower the bandwidth but the larger the number of pairs required to maintain the required total reflectivity. For a GaN laser the effective modal index is low (~2.4) so the FP modes are closely spaced at ~0.05 nm and the grating bandwidth should be of a similar value to achieve single wavelength operation. We used the TMM (transmission matrix method) along with effective modal indices found using a 2D mode solver to calculate the grating bandwidth. This technique is approximate [15] but gives us an estimate of the required grating length. Our design used 125 notch pairs along the ridge which we estimate to have a bandwidth 0.08 nm.

III. FABRICATION

The lasers were fabricated from commercially available GaN epi-material described in [12]. Ridges with and without 39th order gratings were defined using electron beam lithography (EBL). Inductively coupled plasma (ICP) etching was then used to form the 520 nm deep grating and ridge, leaving a 160 nm thick residual layer between the foot of the ridge and the quantum wells. Process conditions were optimized to give the vertical and smooth etch profile required for good grating performance. Fig 1 shows electron micrographs of an etched high order grating. Electrical contacting was achieved using Pd/Au on the p-GaN cap. The processed wafer was then lapped to 100 μm thickness and subsequently cleaved into die of 1000 μm cavity length. Full details of the fabrication process can be found in [11].

IV. RESULTS & DISCUSSION

The as cleaved, uncoated lasers were characterized under pulsed drive conditions, 30 μs pulse width and 140 Hz repetition rate for L-I-V measurements and 200 ns, 5 kHz for spectral measurements.

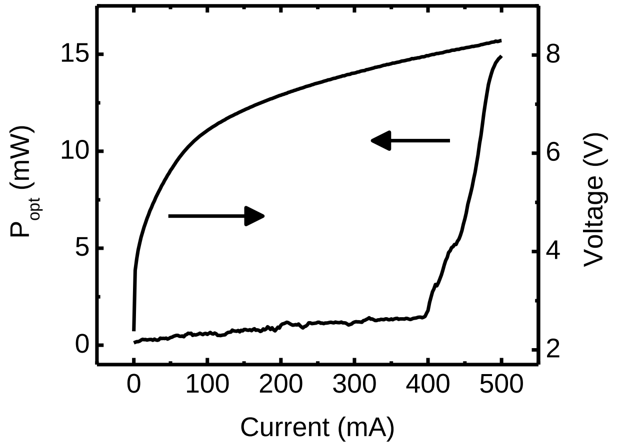

Fig. 2. Optical power and voltage as a function of pulsed drive current for device A.

We used an Ocean Optics spectrometer with 0.1 nm resolution and for higher resolution measurements a Horiba iHR550 with spectral resolution of 0.025 nm. Note that there was a difference in measured wavelength of around 0.5 nm between the two spectrometers.

A range of devices (A to D) with different grating pitches and emission wavelengths were tested (table 1). All devices had a ridge width of 2.5 µm (1.5 µm at the notches). Fig 2 shows the voltage and optical power as a function of drive current for device A. Peak power is 15 mW measured at a drive current of 500 mA. Notched lasers and Fabry-Perot lasers processed from the same wafer both demonstrated similarly high threshold currents which was thought to be due to the quality of the epi material. The slope efficiency of the FP lasers was higher (0.48 mA/ mW) than the notched lasers (0.13 mA/ mW) which was attributed to scattering losses from the grating.

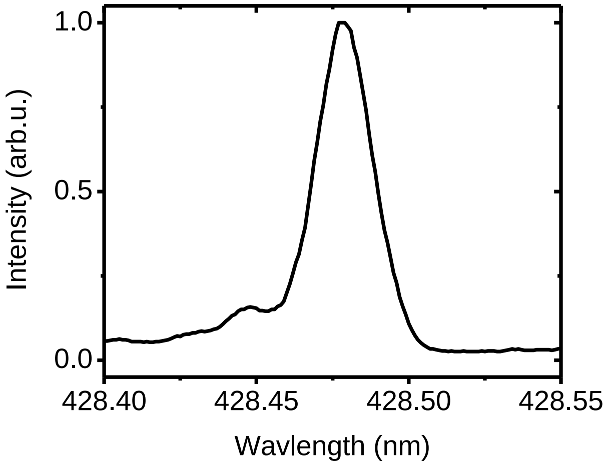

Fig.3. Emission spectrum of device A at drive current of 500 mA.

From fig 3 we can see that the device is lasing in a single FP mode up to drive currents of 500 mA before becoming multimode at higher drive currents (fig 4). This is due to FP modes shifted from the Bragg wavelength reaching threshold as wavelength dependent losses [14] are overcome. Introducing more slot pairs with weaker index contrast would decrease the bandwidth of the grating and potentially improve single mode performance at higher drive currents.

TABLE I
WAVELENGTH, GRATING PITCH & EFFECTIVE INDEX FOR DEVICES A TO D

Device	Nominal Grating Pitch (nm)	Measured Emission wavelength (nm)	Grating order	Effective Index
A	3458	428.01	40	2.475
B	3486	430.61	40	2.471
C	3403	431.04	39	2.470
D	3430	433.69	39	2.466

From table 1 we can see that grating pitches of 3458 nm and 3486 nm gave emission at 428.0 nm and 430.6 nm, around 10 nm shorter than would have been expected given the modal index.

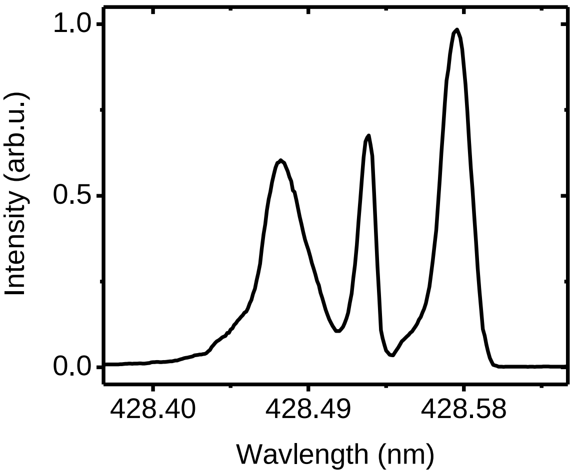

Fig.4. Emission spectrum of device A at drive current of 600 mA.

The explanation for this is that the grating has an FSR (free spectral range) of ~10 nm and lasing is in the next lowest allowed wavelength to the Bragg wavelength. In fact in this case the grating is operating in the 40th order rather than the 39th.

$$n_{eff,g} = n_{eff} - \lambda \frac{dn}{d\lambda} \quad (1)$$

$$\Delta\lambda = \frac{\lambda^2}{n_{eff,g} L_{cav}} \quad (2)$$

From the measured dependence of effective index (n_{eff}) on wavelength (λ), and using (1) we calculate an effective group index ($n_{eff,g}$) of 3.5. Using (2), where L_{cav} is the laser cavity length, we calculate an FSR of 0.052 nm which agrees well with the mode spacing of 0.051 nm observed in fig 4.

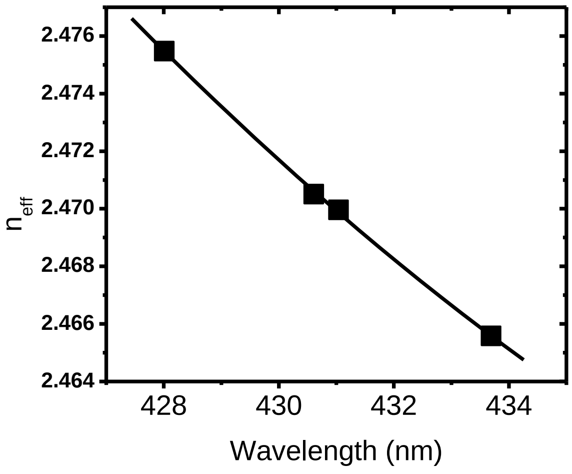

Fig.5. Effective index versus wavelength for chips A to D. Fitted with polynomial function $n_{eff} = 11.04061 - 0.03804x + 4.21327 * 10^{-5}x^2$

For many applications, the ability to thermally tune the output wavelength is key as it allows alignment and tuning across spectral features. By varying the temperature of the heat-sink between 10 °C and 25 °C we were able to temperature tune the single mode emission wavelength of the notched lasers over a range of 0.2 nm (a temperature tuning coefficient of 0.012 nm/K).

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