

# Extended tuning and single-mode operation of an anti-reflection-coated InGaN violet laser diode in a Littrow cavity

D J Lonsdale, A P Willis and T A King

Laser Photonics Group, Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK

Received 1 August 2001, in final form 18 December 2001, accepted for publication 11 January 2002

Published 28 February 2002

Online at [stacks.iop.org/MST/13/488](http://stacks.iop.org/MST/13/488)

## Abstract

An InGaN laser diode operating at 398 nm and with output facet coated with a multi-layer anti-reflection coating has been operated within Littrow external cavities. A maximum manual tuning range of 6.3 nm has been achieved and a continuous tuning range of 0.8 GHz with a single piezo control. Stable single-longitudinal-mode operation has been obtained with a linewidth less than 11 MHz. The effects on total tuning range due to the orientation of the diode output facet within the Littrow cavity are discussed.

**Keywords:** laser characteristics, InGaN laser diode, Littrow external cavities, anti-reflection coating

## 1. Introduction

Operation of a laser diode in a carefully designed extended cavity enables access to large tuning ranges and narrow linewidth operation to be obtained. Numerous extended cavities have been characterized [1–4], each of which has particular strengths and weaknesses. Tightest control over mode selection is typically obtained from extended cavities that employ either multiple passes across a dispersive element (e.g. Littman) or numerous dispersive elements (e.g. extended Littman–Metcalf [2]), as shown by a comparison of basic geometries in [5]. Similarly, it is possible to arrange simpler cavities, such as the Littrow, that can provide greater amounts of feedback due to the smaller losses incurred from the single dispersive element. Moreover, robustness with ease of alignment can be attained at low cost in such simple cavities.

As the ability of a diode laser to lase is dependent on the Fresnel reflections from the facets, strong competition from the internal cavity modes with external cavity feedback is seen in uncoated extended cavity laser systems. If the extended cavity feedback is relatively weak in comparison to the facet reflections, the laser mode may be perturbed enough to produce a very wide bandwidth (many nm) source which has no discernible modes, known otherwise as the coherence collapse

regime. Similarly, other weak feedback effects are characterized and provide effects such as line broadening or line narrowing [6]. However, if the feedback is strong in relation to the facet reflections, the cavity mode is pulled along the gain curve to the point where another longitudinal mode sees higher gain and a mode hop occurs. In some cases a single longitudinal mode is pulled in this way; in others, power shifts between many simultaneous longitudinal modes (see, for example, [7]).

The extent of scanning (continuous tuning without mode hops) obtainable from a particular grating/cavity is critically dependent on the mode number ( $2 \times$  cavity length/wavelength) being preserved. This requires a simultaneous change of feedback and cavity length, and can be achieved for the extended cavity by appropriate selection of a point around which the grating is rotated [8].

Extension to both the scanning range and tuning range can be achieved simultaneously in extended cavity geometries by the addition of an anti-reflection (AR) coating to the output facet. Competition with external cavity feedback is then reduced, and the diode is placed into the strong feedback regime where the lasing mode is controlled solely by the feedback over a large portion of the gain curve.

Applications for the InGaN range of laser diodes have been continually evolving since their initial demonstration

in November 1996 [9], due to both novel engineering and research application, and from the increased understanding of physical mechanisms within the gain medium giving increases in quality, reliability and available wavelength range. InGaN substrates are currently available to provide line-centres between 390 and 440 nm, offer powers of up to 30 mW and options of single or multiple transverse mode and samples are now available with guaranteed lifetimes of 10 000 h [10]. The InGaN substrate has a relatively stable temperature-tuning coefficient of  $0.04 \text{ nm}^\circ\text{C}^{-1}$ , and recent work has shown external cavity tuning ranges of 2.7 nm around line centre, and 5 MHz linewidth [11] for the 5 mW versions.

Until recently, the violet region of the spectrum has only been accessible by coherent sources with such methods as non-linear conversion, the 413 nm line of the Kr laser and various liquid dye lasers (e.g. coumarins). Current semiconductor technologies still cannot compete with the larger powers attainable from these sources, even though the latest InGaN product from Nichia Chemical Industries is rated at 30 mW [10]. However, the potential of the violet-blue laser diodes for use in applications is arguably larger due to their compact size, reduced power supply requirements and the foreseeable drop in unit cost.

Previous studies have been performed with the InGaN laser diode showing the effectiveness in various spectroscopic applications. Using an external cavity diode laser and a free running system, atomic spectroscopy measurements were made of the Doppler broadening of transitions and opto-galvanic spectroscopic measurements of ionization in the potassium atom [12]. Other methods of spectroscopy, such as frequency modulation (FM) and two-tone FM spectroscopy, have been applied to potassium [13] and sum-frequency generation has been used for 254 nm absorption spectroscopy of mercury [14]. Application of these and similar techniques to other atomic absorptions within the InGaN gain bandwidth is now possible.

InGaN has also found a use in confocal microscopy [15] as the short wavelength is effective in exciting fluorescence from various fluorescent probes used in biology and medicine [16]. Similarly, a trial cancer diagnostic system relies on fluorescence detection of photo-excited protoporphyrin IX derived from an exogenous source of 5-ALA. InGaN may be a possible alternative to the mercury lamp as an exciting source and has the potential to increase overall sensitivity.

An investigation has been carried out in this study into the tuning characterization of an InGaN laser diode in external cavities in order to provide assessment of its application potential. This paper describes the operation of the InGaN laser diode in Littrow type external cavities. It shows the enhancement in tuning range obtainable due to the application of an anti-reflection coating, providing common characteristic data for the Littrow cavity set-up. The effects of two possible Littrow geometries on the total obtainable tuning range are discussed.

## 2. Laser cavity tuning characterization

The laser diode under investigation in this study was an InGaN multi-quantum-well (MQW)/GaN/AlGaIn separate-confinement heterostructure device with a stripe width of

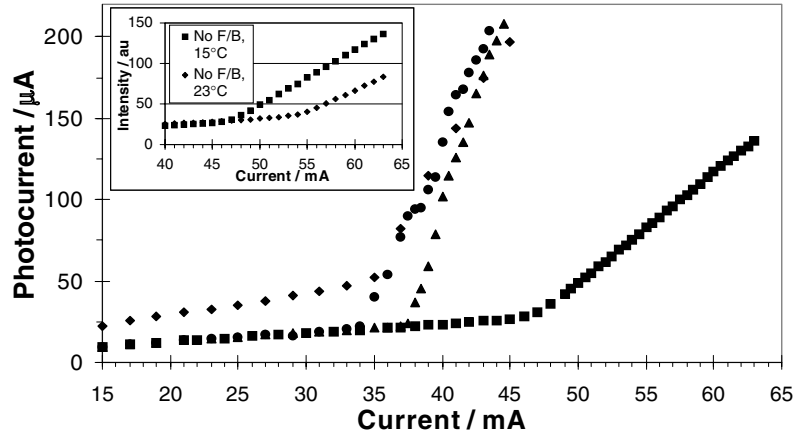
2  $\mu\text{m}$  and MQW depth of 63 nm [17]. The device operated near  $\text{TEM}_{00}$  output and had a nominal output power of 5 mW (Nichia Chemical Industries, model NLHV500A) with a pre-coating threshold of 35 mA. The diode was powered by a constant current source, and was mounted on a thermoelectrically cooled and temperature controlled plate. A multi-layer AR coating was applied to the front facet of the laser diode and a residual reflectivity  $R \leq 8 \times 10^{-5}$  was measured at 398.5 nm (Sacher Lasertechnik, GmbH) at the time of coating [18].

The output from the laser diode was collimated using an AR coated aspheric lens (Opto-Sigma 023-5550 A55) providing a 2 mm focal length and a numerical aperture of 0.5. The reflectivity was less than 1% for each face. Characterization of a Littrow cavity was performed with a pair of gratings having 1800 and 2400 lines  $\text{mm}^{-1}$  (Edmund Scientific [19]), chosen to provide a range of efficiencies to the first order, so that comparisons between feedback, tuning range and cavity parameters could be made. The gratings were placed in a Littrow geometry that was slightly misaligned so that a measurement of the feedback to the first order could be made. The 1800 lines  $\text{mm}^{-1}$  grating (H43222) provided a maximum feedback efficiency to the first order of 76 and 46% for incident polarizations of 's' and 'p', respectively. Similarly, the 2400 lines  $\text{mm}^{-1}$  grating (H43776) provided feedback efficiencies of 13 and 52% for 's' and 'p' polarizations, respectively. These gratings were mounted on a piezoelectric kinematic mirror mount (Thor Labs KC1-PZ/M) for which control was provided by a 150 V supply.

An intrinsic photodiode positioned at the rear facet of the laser diode was used to monitor the laser intensity. From figure 1, it can be seen that the predominant effect of applying the AR coating is to increase laser threshold. Also noticeable below threshold is the reduced measured spontaneous emission due to the predominance of photons exiting the gain region through the AR coated facet (reducing the proportion being measured).

Without feedback the diode can still be made to lase, as shown in the inset of figure 1, due to the temperature dependence of both the refractive index and the gain medium line centre which provide a residual reflectivity higher than that measured at the time of coating. Also shown in figure 1 is the threshold reduction obtained from a highly reflecting plane laser mirror ( $R > 99.5$  from 350–450 nm). The threshold is reduced to 34 mA and gives an overall electrical to optical slope efficiency of 2.6%, which equates to a differential quantum efficiency ( $\Delta\text{QE}$ , photons per electron [20]) of  $8.4 \times 10^{-3}$ . In comparison, feedback from the grating that produced the largest tuning range shows a slightly higher threshold of 37.5 mA and a higher slope efficiency of 3.1% ( $\Delta\text{QE} = 1 \times 10^{-2}$ ). The relative values of both thresholds and slope efficiencies (with feedback) are predicted from laser cavity theory where the gain and losses are equal at threshold.

The emission from the laser diode was polarized preferentially along the stripe of the gain medium with a ratio of 100:1 or greater. As mentioned previously, selecting the polarization of the light incident on the grating provided different efficiencies to the first order feedback. With this in mind we compared Littrow cavity tuning ranges as a function of different cavity geometries and currents. Initial work with a



**Figure 1.** Comparison of laser diode intensity with drive current at 15 °C, before AR coating (◆) and after AR coating (■). Also shown is the threshold reduction for a highly reflecting laser mirror (●) and the 1800 lines mm<sup>-1</sup> grating with 76% feedback to the first order (▲). The inset shows the effect of increasing the operating temperature on the threshold and the output power, replottting the ‘after AR coating’ trace (taken at 15 °C) for comparison.

different uncoated InGaN laser diode had shown a maximum total tuning range of 2.6 nm using the 1800 lines mm<sup>-1</sup> grating with incident polarization orientated in the ‘s’ plane. A 1 nm tuning range was achieved similarly with the 2400 lines mm<sup>-1</sup> grating. In both cases, tuning ranges were dependent on current and in the 1800 lines mm<sup>-1</sup> case the tuning range was limited at higher currents by coherence collapse. No tuning was seen in either case for feedback with light incident on the gratings in the ‘p’ plane.

Figure 2 shows the total tuning range obtainable with the AR coated laser diode for light incident in the ‘s’ plane and with the 1800 lines mm<sup>-1</sup> grating. The tuning range shown was recorded by a single-pass grating tuned spectrum analyser, coupled to a Tektronix TDS 220 oscilloscope and PC. The linewidth shown in figure 2 is not representative of the laser linewidth, but is limited by the slit width of the spectrometer.

The output spectrum was monitored on a pulsed laser spectrum analyser (Burleigh Model 3500) which provided free spectral ranges (FSRs) of 10 and 250 GHz. Initial characterization showed multiple longitudinal modes supported in the external cavity with a typical total linewidth of between 2 and 3 GHz. Whether these were simultaneously supported or were switching was determined by two methods. Coupling the Littrow cavity output to a fibre coupled high speed detector (Newport D-30) and using a radio-frequency spectrum analyser to show any high frequencies beating showed no frequency components, as would be expected for simultaneously supported multiple longitudinal modes, although detection efficiency was low at 400 nm. To corroborate this result, a low finesse 25 GHz static etalon with a linewidth approximately equal to the longitudinal mode spacing was placed between the cavity output and a high speed photodiode detector (Newport 818-BB-20). The etalon transmitted either one or two modes at a time, and these could be seen switching at between 70 and 100 Hz, indicating possible vibrational problems as no high frequency components were observed. Consequently, single-longitudinal-mode operation was achieved with the use of a pneumatic optical table. A 300 MHz FSR spectrum analyser was able to measure a minimum resolution of 11 MHz, and

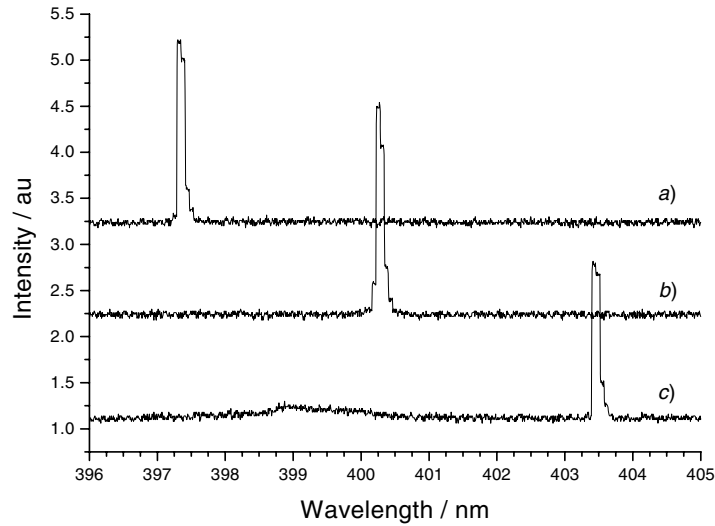
is thought to be the instrument limit at 400 nm, not a true representation of the actual laser linewidth, which is believed to be somewhat narrower.

Central to trace c of figure 2, a broad increase in intensity can be seen around line-centre (399 nm) which is not related to the laser mode. Tuning towards this feature reduced its size as the power was pulled into the laser mode. Tuning away from this feature at line centre allowed it to become more prominent, and tuning past the extremes shown in figure 2 caused the supported mode to abruptly drop away, leaving the prominent central feature which was current- and temperature-dependent. As there are no competing lasing modes in the AR coated substrate, the obtainable tuning range should be directly linked with the gain bandwidth of the material which is related to compositional fluctuations of indium in the gain region [9]. Under this assumption, the gain bandwidth of this sample that is intrinsically accessible to tuning is therefore around 6.3 nm and is relevant to the discussion of feedback for tuning. This result provides further confirmation of the general belief that an AR coating will increase the overall tuning range of a laser diode by a factor of 2 or 3, as indicated by [18].

Also notable is the slightly extended tuning range from line centre achievable towards the blue rather than the ultraviolet. This is explained by the skewed complex susceptibility obtained in semiconductors (see, for example, p 592 of [21]), where the gain fall-off is more pronounced at higher frequencies than it is at lower frequencies. Selection of a substrate tunable to coincide with an absorption maximum should therefore account for this tuning dependence which appears somewhat exaggerated here.

As the results depicted in figure 2 were taken at 17 °C, an increase in tuning range may be obtainable by running at higher temperature, thereby reducing the facet reflectivity further; the diode characteristics without an external cavity at 15 and 23 °C are shown in the inset of figure 1. This was not achievable in our set-up as temperature fluctuations tended to cause alignment fluctuations between diode housing and external cavity components at higher temperatures.

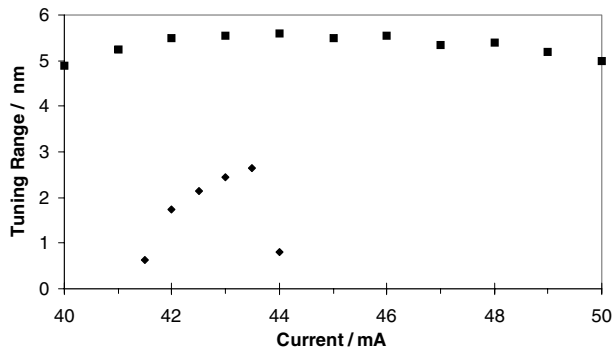
Figure 3 shows the dependence of the total tuning range on current (and indirectly on inversion density) and compares



**Figure 2.** Total tuning range obtainable with 1800 lines  $\text{mm}^{-1}$  grating orientated to provide feedback dispersed across the depth of the MQWs ('s' geometry), showing the short-wavelength (a), mid-wavelength (b) and long-wavelength positions. Diode temperature was maintained at 17 °C.

**Table 1.** Tuning ranges obtained for the gratings and cavities discussed.

Grating: Polarization incident on grating	1800 lines $\text{mm}^{-1}$		2400 lines $\text{mm}^{-1}$	
	Feedback into first order (%)	Max. tuning range (nm)	Feedback into first order (%)	Max. tuning range (nm)
's'	$76 \pm 7$	6.3	$13 \pm 0.5$	4.65
'p'	$46 \pm 2$	4.75	$52 \pm 3$	4.8



**Figure 3.** Tuning range attainable as a function of current for AR coated substrate (■) and an uncoated substrate (◆) shown for comparison.

the coated substrate with results obtained previously from an uncoated substrate. In both systems, the tuning ranges increase with current. However, at higher currents the AR coated laser diode does not fall into the coherence collapse regime as the non-coated diode is seen to do at 44 mA. Rather, the tuning range plateaux at higher currents and has a slight roll-off that coincides with the increase in intensity of the central feature in figure 2(c). Again, increasing the temperature should minimize any residual reflectivity, reducing the feature at line centre, and allow the total tuning range to be attainable at higher operating powers.

With the laser diode's emission polarized along the stripe of the substrate, polarized light incident on the grating in the 's' geometry allowed dispersed light to fall across the depth

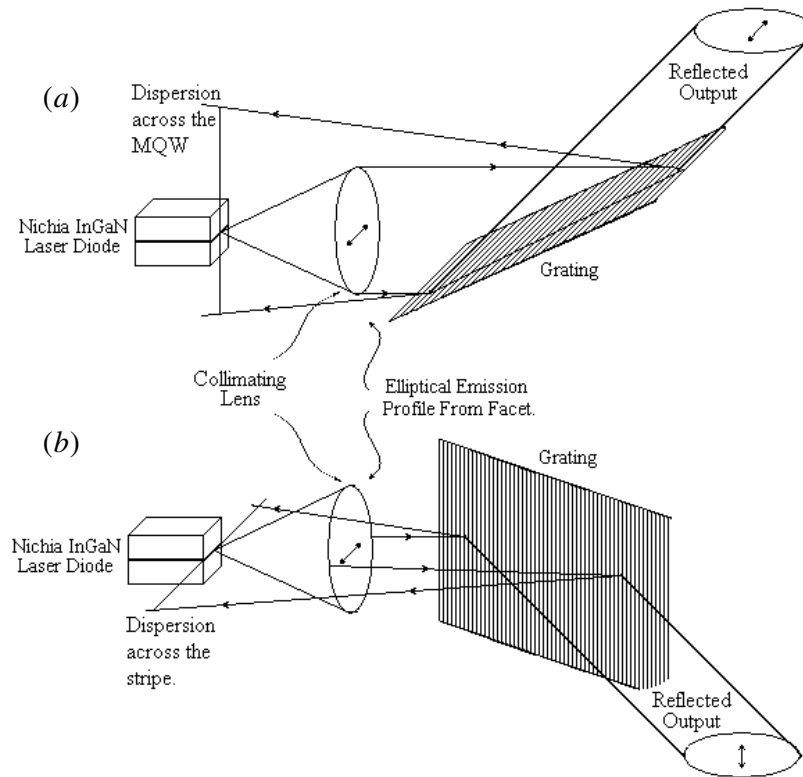
of the quantum wells. Similarly, polarized light incident onto the grating in the 'p' geometry allowed dispersed light to fall across the stripe of the substrate, as shown in figure 4. The total tuning ranges obtained in both 's' and 'p' geometries are shown in table 1.

### 3. Discussion

The platform upon which the laser diode, TEC cooling and extended cavity was mounted became the limiting factor in LD characterization. Due to thermal problems, the system would be allowed to achieve thermal equilibrium before measurements were taken. For scanning purposes, the cavity length limited the single piezo tuning range to approximately half the extended cavity FSR of 1.5 GHz. As the cavity length was invariable, the mode number could not be preserved as the grating was tuned. Considerable enhancements to the scanning range (nm) are to be expected for a correctly rotated-translated grating operating with an AR coated laser diode with  $R < 1.5 \times 10^{-4}$  [8, 22].

As expected, the largest tuning range achieved was with the grating that provided the largest feedback to the first order of the Littrow configuration. However, this is not the only consideration for obtaining the higher extended tuning ranges, as can be seen by comparison of the 2400 lines  $\text{mm}^{-1}$  's' cavity with the other three. Comparatively, the tuning range achieved per % feedback is the highest in this configuration.

Comparative analysis of the tuning range dependence on cavity parameters indicates that predominantly the dispersion of the grating, the power available to couple back into the



**Figure 4.** Representation of the two geometries that provide dispersed feedback into the gain region. Polarization is shown to be parallel to the stripe and disperses across the MQW structure in (a), referred to here as ‘s’ geometry, and disperses across the stripe in (b), referred to here as ‘p’ geometry.

gain region to provide stimulated emission and the fraction of the gain curve dispersed across the dimensions of the gain region combine to produce an overall achievable tuning range. Due to the effect of the grating angular dispersion ( $d\lambda/d\theta = (a/m) \cos \theta$ , where  $a$  is the period of the grating,  $m$  is the order of feedback and  $\theta$  is the angle for feedback into the facet, the 2400 lines  $\text{mm}^{-1}$  grating has a factor of 1.42 more angular dispersion at 400 nm in the Littrow configuration than the 1800 lines  $\text{mm}^{-1}$  grating in the same cavity. This effectively increases the ratio of feedback power available to couple into the gain region from 76:13 to 76:9 for both gratings in the ‘s’ geometry, further increasing the relative tuning achieved per % feedback for the 2400 lines  $\text{mm}^{-1}$  grating. This remarkable independence of feedback power is also seen in the ‘p’ geometry with a total available power ratio of 46:36 fed back across the gain region. Using the gain region dimensions of 2  $\mu\text{m}$  stripe width by 63 nm MQW depth [17], a cavity length of 10 cm, the dispersion of the gratings and the magnifying effect of the collimating lens, the wavelength dispersed across the gain region dimensions in both ‘s’ and ‘p’ geometries due to feedback can be calculated. Here, dispersion across the stripe width of the diode (‘p’ geometry) was calculated to be 0.52 nm for the 1800 lines  $\text{mm}^{-1}$  grating and 0.37 nm for the 2400 lines  $\text{mm}^{-1}$  grating. Similarly, the same calculation for a MQW depth of 63 nm produced a  $\Delta\lambda$  of 0.016 nm (30.8 GHz) for the 1800 lines  $\text{mm}^{-1}$  grating and 0.011 nm (21.7 GHz) for the 2400 lines  $\text{mm}^{-1}$  grating.

The notably high tuning range achieved per % feedback seen with the 2400 lines  $\text{mm}^{-1}$  ‘s’ geometry in comparison to

both ‘p’ geometries is believed to be due to the difference in bandwidth dispersed across the gain region, where it is assumed that the large wavelength range dispersed across the stripe of the gain medium (‘p’ geometry) provides competition to the lasing mode when tuning toward the edge of the gain curve. Consequently, there is a curtailing of the tuning range due to the competition seen in the ‘p’ geometry. Conversely, the small bandwidth dispersed across the MQW dimensions of the ‘s’ geometry allows a much higher tuning range per % feedback (even with small quantities of feedback), as there is comparatively little competition to the lasing mode.

It is interesting to note that the 2.6 and 1 nm ( $\sim 76$  and 9% feedback coupling into the gain region, respectively) tuning ranges achieved without an AR coating and with ‘s’ feedback provide similar accessible tuning ranges for grossly differing feedback powers. No tuning is seen in the ‘p’ geometry as the grating is taking the role of a relatively broadband (i.e. 0.52 nm) feedback. Thus it does not select any particular mode, but shares the feedback between many chip modes when aligned to feedback on line centre, and does not inhibit lasing at line centre when aligned to feedback wavelengths off line centre.

The origin of the competition which limits the tuning range in the ‘p’ geometry is suggested by the apparent homogeneous operation (i.e. single longitudinal mode and switching between individual modes) of an inherently inhomogeneous source. Generally, the lineshape function of a semiconductor laser is a complex function of transition energy and point of operation [20], and is more a combination of homogeneous and inhomogeneous operation rather than either alone. This

would imply that the device is dominated by homogeneous broadening across the tuning range, which then yields to the inhomogeneous nature of the source towards the edges of the gain curve. By analogy to an atomic system, where the homogeneous and inhomogeneous states are clearly defined, the saturation intensities for both homogeneous and inhomogeneous broadening can be described as shown in equations (1) and (2):

$$I_{Sat}^{HOM} \propto \frac{4\pi n^2 h\nu}{(\tau/t_{spon})\lambda^2 g(\nu)} \quad (1)$$

$$I_{Sat}^{INH} \propto \frac{2\pi^2 n^2 h\nu \Delta\nu}{(\tau/t_{spon})\lambda^2}. \quad (2)$$

Here,  $n$  is the refractive index,  $h$  is Planck's constant,  $\nu$  is the frequency,  $\tau$  is the inversion lifetime,  $t_{spon}$  is the spontaneous lifetime,  $\lambda$  is the wavelength,  $\Delta\nu$  is a homogeneous packet of indistinguishable emitters within the inhomogeneous system, and  $g(\nu)$  is the normalized lineshape function which is analogous to the lineshape of a single indium emission centre within a quantum well. It can be seen that the saturation intensity for a homogeneously broadened source is inversely proportional to the lineshape function  $g(\nu)$ , so that saturation becomes increasingly difficult off line centre. Conversely, the inhomogeneous system is not dependent on  $g(\nu)$ , and will stay approximately constant across the tuning range and enable mode competition towards the edges of the gain curve. Moreover, a homogeneous system is known to saturate faster than an inhomogeneous system [21], and will therefore provide the dominant lasing mechanism for moderate power levels around line centre. Supplying further power to the gain region would eventually allow multi-mode operation, as the inhomogeneous system becomes more saturated, which is indeed what is seen at the highest power levels.

Finally, the largest tuning range seen has the smallest tuning per % feedback and is most likely due to a maximum part of the gain curve being accessed, which has previously been linked to the compositional fluctuations of indium in the gain region. Consequently, more feedback is used than is necessary to achieve the maximum tuning range reported here. As the choice of grating and feedback to the first order of a Littrow geometry has repercussions on the output power of an extended cavity, a correct choice of grating can maximize tuning range and optimize tuned output power.

## Acknowledgments

The authors would like to thank the EPSRC for the financial support that has been received and also Bridgewater Ltd, who have provided the violet laser diodes required to carry out this work.

## References

- [1] Kazharsky O, Pakhomov S, Grachev A, Mironov Y, Goncharov I and Matveev A 1997 Broad continuous frequency tuning of a diode laser with an external cavity *Opt. Commun.* **137** 77–82
- [2] Wandt D, Laschek M, Tunnerman A and Welling H 1997 Continuously tunable external-cavity diode laser with a double grating arrangement *Opt. Lett.* **22** 390
- [3] Shaozheng Jin, Yongqing Li and Min Xiao 1996 Single-mode diode laser with a large frequency-scanning range based on weak feedback *Appl. Opt.* **35** 1436
- [4] Binks D J, Ko D, Gloster L and King T A 1998 Laser mode selection in multiarm grazing-incidence cavities *J. Opt. Soc. Am. B* **15** 2395
- [5] Day T, Brownell M and I-Fan Wu 2001 Widely tunable external cavity diode lasers webpage [www.newfocus.com/online\\_catalog/literature/widely.pdf](http://www.newfocus.com/online_catalog/literature/widely.pdf)
- [6] Tkach R W and Chraplyvy A R 1986 Regimes of feedback effects in 1.5- $\mu\text{m}$  distributed feedback lasers *J. Lightwave Technol.* **4** 1655
- [7] Wallace I, Yu D, Harrison R and Gavrielides A 2000 Experimental observations of multi-mode dynamics in an external cavity semiconductor laser *J. Opt. B: Quantum Semiclass. Opt.* **2** 447
- [8] Nilse L, Davies H J and Adams C S 1999 Synchronous tuning of extended cavity diode lasers: the case for an optimum pivot point *Appl. Opt.* **38** 548
- [9] Nakamura S, Pearton S and Fasol G 2000 *The Blue Laser Diode The Complete Story* 2nd edn (Berlin: Springer)
- [10] <http://www.nichia.co.jp/index-e.htm>
- [11] Conroy R S, Hewett J J, Lancaster G P T, Sibbett W, Allen J W and Dholakia K 2000 Characterisation of an extended cavity violet diode laser *Opt. Commun.* **175** 185
- [12] Gustafsson U, Alnis J and Svanberg S 2000 Atomic spectroscopy with violet laser diodes *Am. J. Phys.* **68** 660
- [13] Gustafsson U, Somesfalean G, Alnis J and Svanberg S 2000 Frequency-modulation spectroscopy with blue diode lasers *Appl. Opt.* **39** 3774
- [14] Alnis J, Gustafsson U, Somesfalean G and Svanberg S 2000 Sum-frequency generation with a blue diode laser for mercury spectroscopy at 254 nm *Appl. Phys. Lett.* **76** 1234
- [15] Girkin J M, Ferguson A I, Wokosin D L and Gurney A M 2000 Confocal microscopy using an InGaN violet laser diode at 406 nm *Opt. Express* **7** 336
- [16] Haugland R P 1992 *Molecular Probes; Handbook of Fluorescent Probes and Research Chemicals* 5th edn (Eugene, OR: Molecular Probes Inc.)
- [17] Nakamura S, Senoh M, Nagahama S, Matsushita T, Kiyoku H, Sugimoto Y, Kozaki T, Umemoto H, Sano M and Mukai T 1999 Violet InGaN/GaN/AlGaIn-based laser diodes operable at 50 °C with a fundamental transverse mode *Japan. J. Appl. Phys.* **38** L226
- [18] <http://www.sacher.de>
- [19] <http://www.edsci.com>
- [20] Coldren L A and Corzine S W 1995 *Diode Lasers and Photonic Integrated Circuits* (New York: Wiley)
- [21] Amnon Y 1989 *Quantum Electronics* 3rd edn (New York: Wiley)
- [22] Olsson N A, Oberg M G, Tzeng L D and Cella T 1988 Ultra-low reflectivity 1.5  $\mu\text{m}$  semiconductor laser preamplifiers *Electron. Lett.* **24** 569–70