Published in Photonics Technology Letters (IEEE) 17, issue 9, 1782-1784, 2005
which should be used for any reference to this work

Observation of Temperature-Independent Longitudinal-Mode Patterns in Violet-Blue InGaN-Based Laser Diodes

Christoph Eichler, Sven-Silvius Schad, Ferdinand Scholz, Daniel Hofstetter, Stephan Miller, Andreas Weimar, Alfred Lell, and Volker Härle

***Abstract*—We present measurements on an aperiodic device-specific longitudinal-mode pattern in InGaN laser diodes. The characteristic shape of this pattern occurs only if the laser is driven slightly above threshold; in addition, it tunes with temperature at exactly the same rate as the cavity modes. By careful selection of the collection optics and averaging ten rapid scans over 15 min in a high-resolution Fourier transform spectrometer, we could exclude possible explanations like beating of mode families, self-pulsation, or external reflections. A naive simulation of the longitudinal modes profiting from their individual "gain profile" along the cavity suggests that we see the signature of quantum-well thickness fluctuations.**

***Index Terms*—Emission spectrum, InGaN laser diodes, irregular spectral envelope.**

I. INTRODUCTION

OPTOELECTRONIC devices based on InGaN have seen a decade of rapid progress and are now ready for applications in large-area displays, lighting, and high-resolution optical storage systems [1]. Nevertheless, many of the fundamental properties of the nitride material system are not well known and a further understanding is required for future progress in light-emitting diode efficiency or laser reliability [2]. Especially material- and growth-related problems and their influence on device performance are not yet understood very well [3]–[5]. The emission spectra of laser diodes offer a particularly simple yet very rich pool of information, which has not been taken advantage of fully. Nevertheless, different methods like, for instance, Hakki–Paoli gain measurements, or Fourier transforms have been successfully applied and interpreted [6], [7].

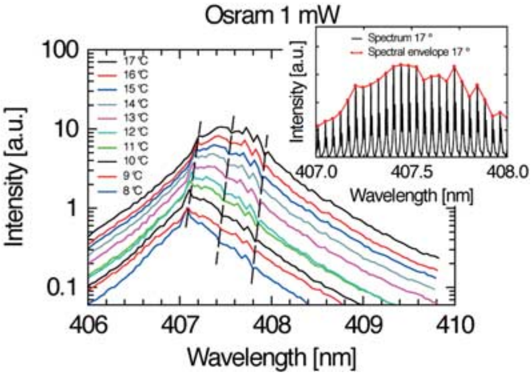

Fig. 1. Spectral envelopes of the Osram laser diode as a function of device temperature and at a constant power level of 1 mW. The spectra were first normalized to one and then displaced vertically for clarity. The inset shows part of a high resolution spectrum along with its spectral envelope. The cavity length was 600 μm and the facet reflectivities 98% and 70%.

II. EXPERIMENT

Here, we present spectral measurements on two different InGaN diode lasers as a function of current and temperature. While the first of these devices was a commercial diode from Nichia, Inc, the second laser came from Osram Opto Semiconductors. The Nichia device was grown on sapphire, whereas the Osram laser was fabricated on a SiC substrate. The exact device structure of the Osram laser is described elsewhere [8]. Emission spectra were acquired using antireflection-coated collimation optics and subsequent coupling of the collimated beam into a Fourier transform spectrometer (NEXUS 870). In order to exclude short time scale spectral fluctuations, we averaged each spectrum ten times, resulting in a measurement time of roughly 15 min per spectrum. During the measurements, the lasers were driven continuously at a constant power/current level just above threshold. An internal Si photodiode of the spectrometer and the highest possible resolution of 0.1 cm^{-1} were used for the experiments. Due to the short wavelength, a typical emission spectrum of such a laser consists of roughly 200 Fabry–Pérot modes. In order to highlight the important information, we will, therefore, show the spectral envelopes of these spectra only. A spectral envelope is the envelope function of the Fabry–Pérot mode spectrum. In the inset of Fig. 1, we present a small section (roughly 20 Fabry–Pérot modes) of a longitudinal mode spectrum along with its spectral envelope. Fig. 2 (top and bottom) shows several envelope functions of both the Nichia and the Osram laser as a function of injection current. Especially for the Osram device, we observe that the envelopes are very smooth for low injection currents, and become increasingly structured when approaching lasing threshold. Far from threshold, the laser shows also a pronounced band-filling. This band-filling and the concomitant wavelength shift stop

C. Eichler, S. Miller, A. Weimar, A. Lell, and V. Härle are with Osram Opto Semiconductors, Regensburg 93049, Germany.

S.-S. Schad and F. Scholz are with the University of Ulm, Ulm 89069, Germany.

D. Hofstetter is with the University of Neuchatel, Neuchatel CH-2000, Switzerland.

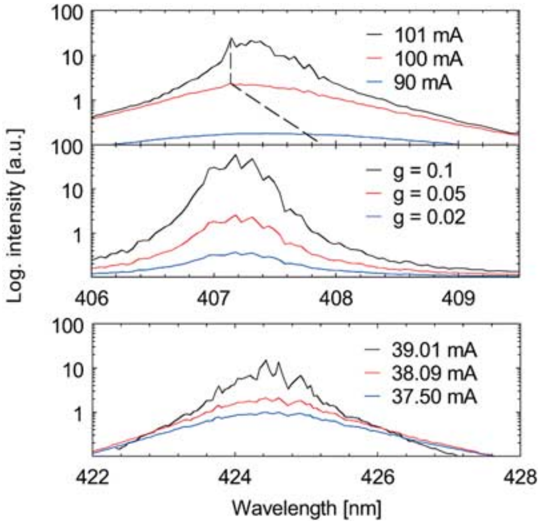

Fig. 2. Top: spectral envelopes as a function of current for the Osram device at 13 °C. The dashed line marks the wavelength shift due to band-filling. Center: simulated spectral envelopes for three different peak gain values according to the formula below. Bottom: current dependent spectral envelopes for the Nichia laser at 15 °C.

as the laser approaches threshold. As a last observation, we mention a second longitudinal mode family which is visible in the inset of Fig. 1.

III. RESULTS

The crucial observation of Figs. 1 and 2 is certainly the aperiodic structure in the spectral envelope. As mentioned above, this pattern occurs at threshold only. One could imagine different possible explanations for this effect. For instance, the intensity distribution between the two lateral modes can change over time. This could lead to a kind of noisy emission spectrum. However, our measurements are averages over 15 min and, therefore, such short time scale changes are not very likely to show up in the spectrum. The same argument can also be used against the idea of a self-pulsating laser. In addition, Nakamura has shown that an InGaN laser diode undergoing self-pulsation suffers from substantial broadening of the single Fabry–Pérot modes [9]. Neither this nor the required high injection levels were present in our experiments. As a further possibility, back reflections from the collection optics could lead to instabilities of the spectrum. Since we used antireflection-coated optical components, we do not believe that this explanation holds any longer. As a next idea, one could imagine a gain modulation due to insufficient lower confinement of the lasing mode and subsequent coupling with a substrate mode [8]. Since this would result in a periodic modulation with roughly 1-nm period of the spectral envelope, this effect again lacks experimental evidence. Finally, defects in the cavity or along the ridge waveguide might cause the observed irregular modulation. Based on the above, we have made further experiments with the ultimate goal to clarify the true origin of the structure in the spectral envelope. For this purpose, we investigated the spectral envelopes as a function of temperature under a constant power/current level. Results for both the Osram and the Nichia device are presented in Figs. 1 and 3, respectively. It becomes obvious that the spectral envelopes shift with temperature, but overall, they do NOT change their fine structure for a range of 10 K. A close inspection of the temperature tuning of the Fabry–Pérot mode comb and several characteristic features in the envelope (dashed lines in Figs. 1 and 3) shows that the tuning rates are identical ($d\lambda_k/dT = 0.015$ nm/K). They correspond to the temperature-induced refractive index change. The considerably faster temperature tuning of the gain curve ($d\lambda_g/dT = 0.04$ nm/K) [10] leads to a slight distortion of the envelopes at higher temperatures. Based on the common tuning rates of the refractive index, the modes, and the features in the spectral envelope, we conclude that the material of the laser itself must be responsible for this modulation. Since the thermal cavity length change is proportional to and roughly 10% of the refractive index change, the influence of the former is indistinguishable from the latter. Given the observation that the structure occurs only close to threshold, we further understand that a gain-related phenomenon must be at the origin of this modulation. Taking into account finally the fact that each InGaN laser (not regarding the type of substrate it was grown on!) shows its specific aperiodic modulation, and that other types of lasers do not show this effect (see, for instance, the quantum cascade laser in [6]), we believe that either the nature of the InGaN quantum wells or the ridge waveguide leads to this structured spectral envelope.

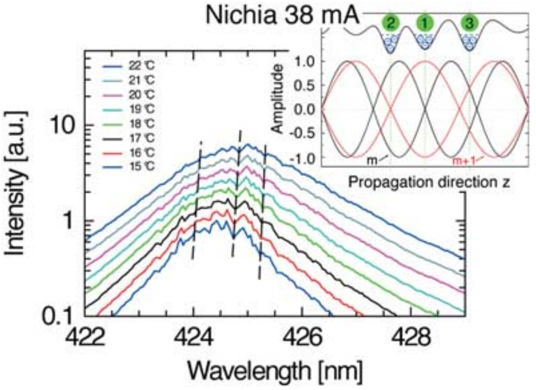

Fig. 3. Spectral envelopes of the Nichia laser diode as a function of device temperature and at a constant current level of 38 mA. The spectra were first normalized to one and then displaced vertically for clarity. The inset shows schematically how the gain modulation influences different cavity modes in a different way.

It is known that the nitride semiconductors have very heavy electron effective masses. In addition, they exhibit huge internal polarization fields which lead to a pronounced quantum confined Stark effect. In order to guarantee sufficient confinement for the carriers and a large spatial overlap between electrons and holes, the quantum wells are usually very thin, on the order of 2–3 nm. It is clear that even a one or two monolayer thickness fluctuation, as typically observed in metal–organic vapor phase epitaxy growth, leads to a severe potential depth modulation of the wells. Measured along the cavity, such fluctuations occur at length scales of typically 10–30 nm, and their “depth” can imply a substantial spatial modulation of the gain along the laser stripe.

IV. SIMULATION

Based on what we said in Section III, the reason for the modulation can be explained as follows: At the deeper parts of the well, carriers get localized, thus resulting in a modulation of carrier density across the well. For low currents, carriers in all parts of the well will contribute to spontaneous emission and nonradiative recombination, but at currents close to lasing threshold, the carrier density in the deep parts of the well gets sufficiently high to produce gain. Different longitudinal modes benefit differently from each single "gain center," as depicted very schematically in the inset of Fig. 3. For instance, at position "1" within the resonator, mode m has a node and, thus, does not see any amplification. But mode $m + 1$ has a maximum at position "1," so it benefits fully of the amplification at this point, and so on. Added up along the ridge, each mode will see its very own amount of amplification, depending on how the gain fluctuations are distributed. From a pure gain point of view, the situation is similar to a vertical-cavity surface-emitting laser: Although the overlap factor of the quantum wells is small, their presence in a maximum of the standing wave is essential for efficient lasing [11]. Given the fact that the two investigated laser diodes were grown on quite different substrates (Nichia: ELOG on sapphire; Osram: SiC), the similarity of their longitudinal mode behavior is an additional argument in favor of a laser cavity-inherent property. In order to make the gain modulation hypothesis more convincing, we tried to simulate the behavior of these lasers in a very naive qualitative way. We assume a certain number of relevant gain centers $m = 100$ and round-trips $n = 1$ in the cavity. Each center sits at a random position $0 < x_i < L$ with a typical cavity length $L = 600\ \mu\text{m}$, and offers an amount of excess gain $g(\lambda_k)$, which is wavelength-dependent and randomly weighted with a factor $0 < w_i < 1$. The interaction of the radiation field with these gain centers happens in a purely geometrical way: The interaction is proportional to the field amplitude of mode number k (wavelength λ_k) at the position of the center. Multiplication of these weighted interactions according to the formula

$$I_k = I_0 \cdot \left[n \prod_{i=0}^{m=1} \left(\frac{g \cdot \Delta\lambda^2 \cdot w_i}{\Delta\lambda^2 + 4(\lambda_k - \lambda_0)^2} \left| \sin\left\{ \frac{2\pi x_i}{\lambda_k} \right\} \right| + 1 \right) \right]^2$$

gives a characteristic relative intensity for each mode. By changing the peak gain g of the Lorentz-shaped gain curve (spectral width $\Delta\lambda = 1$ nm, center wavelength λ_0), i.e., cranking up the injection current, one can increase both peak intensity and modulation depth of the spectrum. This is shown in Fig. 2 (center). It is evident that our model requires quite a small number of relevant gain centers to correctly reproduce the observed modulation. However, we have to keep in mind that a rigorous treatment of the problem involves a dynamical solution of the rate equations. Based on the observations presented above and the crude numerical model used, we believe that we see strong evidence for a gain fluctuation along the laser cavity, most likely caused by quantum-well thickness fluctuations. Compositional fluctuations cannot be excluded; their smaller length scale would just imply a higher number of "weaker" gain centers. Similarly, light absorption or scattering at defects within the ridge could lead to a selective weakening of longitudinal modes and, thus, to a modulation. But given the fact that the defect densities of the two devices with and without ELOG differ by several orders of magnitude, we do not think that defects are responsible for the observed modulation.

V. CONCLUSION

We have presented high resolution spectral measurements on two continuously driven InGaN-based laser diodes. By doing such measurements as a function of temperature, we found a device-specific pattern in the spectral envelopes which tuned with temperature at an identical rate as the Fabry–Pérot modes of the laser. Since the observed modulation occurs only around threshold, we believe in having found the signature of a cavity-inherent and gain-related phenomenon. A simple numerical model based on randomly distributed gain centers along the cavity can qualitatively describe our observations, and thus, supports the idea of a quantum-well thickness or compositional fluctuation.

REFERENCES

[1] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Matsushita, and T. Mukai, "Blue InGaN-based laser diodes with an emission wavelength of 450 nm," *Appl. Phys. Lett.*, vol. 76, no. 1, pp. 22–24, 2000.

[2] C. Eichler, D. Hofstetter, W. Chow, S. Miller, A. Weimar, A. Lell, and V. Härle,, "Microsecond time scale lateral-mode dynamics in a narrow stripe InGaN laser," *Appl. Phys. Lett.*, vol. 84, no. 14, pp. 2473–2475, 2004.

[3] O. Ambacher, J. Majewski, C. Miskys, A. Link, M. Hermann, M. Eickhoff, M. Stutzmann, F. Bernardini, V. Fiorentini, V. Tilak, B. Schaff, and L. Eastman, "Pyroelectric properties of Al(In)GaN/GaN hetero- and quantum well structures," *J. Phys.: Condens. Matter*, vol. 14, pp. 3399–3434, 2002.

[4] C. Humphreys, T. Smeeton, J. Barnard, and M. Kappers, "Is in clustering necessary for bright light emission from GaN-based devices?," presented at the Int. Workshop Nitride Semiconductors (IWN 2004), Pittsburgh, PA, Jul. 2004, Paper B4.8.

[5] J. Narayan, H. Wang, J. Ye, S. Hon, K. Fox, J. Chen, H. Choi, and J. Fan, "Effect of thickness variation in high-efficiency InGaN/GaN light-emitting diodes," *Appl. Phys. Lett.*, vol. 81, no. 5, pp. 841–843, 2002.

[6] D. Hofstetter and J. Faist, "Measurement of semiconductor laser gain and dispersion curves utilizing fourier transforms of the emission spectra," *IEEE Photon. Technol. Lett.*, vol. 11, no. 11, pp. 1372–1374, Nov. 1999.

[7] K. Gan and J. Bowers, "Measurement of gain, group index, group velocity dispersion, and linewidth enhancement factor of an InGaN multiple quantum-well laser diode," *IEEE Photon. Technol. Lett.*, vol. 16, no. 5, pp. 1256–1258, May 2004.

[8] U. Schwarz, E. Sturm, W. Wegscheider, V. Kümmler, A. Lell, and V. Härle, "Excitonic signature in gain and carrier induced change of refractive index spectra of (In,Al)GaN quantum well lasers," *Appl. Phys. Lett.*, vol. 85, no. 9, pp. 1475–1477, 2004.

[9] S. Nakamura, "InGaN multiquantum-well-structure laser diodes with GaN-AlGaN modulation-doped strained-layer superlattices," *IEEE J. Sel. Topics Quantum Electron.*, vol. 4, no. 3, pp. 483–489, May/Jun. 1998.

[10] C. Eichler, S. Schad, M. Seyboth, F. Habel, M. Scherer, S. Miller, A. Weimar, A. Lell, and V. Härle, "Time resolved study of GaN-based laser diode characteristics under pulsed operation," *Phys. Stat. Sol.*, vol. 0, no. 7, pp. 2283–2286, 2003.

[11] M. Y. A. Raja, S. R. J. Brueck, M. Osinski, C. F. Schaus, J. G. McInerney, T. M. Brennan, and B. E. Hammons, "Surface-emitting, multiple quantum well GaAs/AlGaAs laser with wavelength-resonant periodic gain medium," *Appl. Phys. Lett.*, vol. 53, no. 18, pp. 1678–1680, 1988.