Longitudinal mode seeding in modulated InGaN laser diodes

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The modulation of InGaN laser diodes is important for applications such as laser projection in cinemas as well as in virtual and augmented reality applications. Here, a modulation frequency in the 100 MHz to 1 GHz range is necessary. On this timescale, pixel crosstalk is a major issue that affects the intensity and spectral properties. We investigate the spectral and temporal dynamics of InGaN laser diodes driven with different pulse patterns. We identify longitudinal mode seeding as a mechanism between interacting pulses which are spaced by several nanoseconds; photons, remaining in the cavity after the trailing edge of the electric pulse, "seed" consequent pulses and promoting their own longitudinal mode. This leads to a changed spectral–temporal mode pattern of the consequent pulse. The long cavity ring-down time of these photons is a consequence of relatively low losses. Further investigations were performed by streak camera measurements of differently biased laser diodes. For a bias below, but close to, the threshold, the optical gain nearly compensates internal and mirror losses. Additional simulations are performed to confirm the experimental results. © 2019 The Japan Society of Applied Physics

1. Introduction

Green laser diodes offer many possibilities for applications such as optical communication and laser projection systems. 1–3 In order to achieve fast data transmission or to scan across all pixels of images with state-of-the-art resolution and an adequate frame rate, fast laser diode modulation is required. 4–7 This corresponds to short-pulse operation with pulse lengths of about 10–100 ns, where various dynamic effects occur which have to be considered. 8–15

In contrast to earlier work on the spectral dynamics of GaN laser diodes, 16–21 the use of a streak camera system allows us to measure the spectral–temporal dynamics of many longitudinal modes simultaneously. For comparison we simulate the longitudinal mode dynamics using a multimode rate equation system. This model is based on the work in Refs. 22–25 and has been further developed in Ref. 26. We adapt the model to our investigated laser diodes and expand it to include, for example, unequally pumped multiple quantum wells. 27

For the parameters used in the model we rely on previous studies of green laser diode stationary and dynamic characteristics. Recombination coefficients, in particular the Auger coefficient, and the injection efficiency for laser diodes have been determined from turn-on delay, relaxation oscillations and optical gain. 28 Optical gain spectra, which are important for inhomogeneous broadening and curvature of the gain at gain maximum and for differential gain have been determined by Hakki–Paoli gain spectroscopy. 29–31 We experimentally investigate the well-known effects in short pulses, such as turn-on delay, 32 relaxation oscillations, 32,33 the fast initial redshift and mode competition. 29 All these effects are reproduced by the simulations, in good agreement with experiment.

In this work we will focus on multiple pulses with variable spacing and pulse length, where interaction of successive pulses occurs due to the remaining photons in the cavity. The pulses influence each other in terms of turn-on delay, wavelength and intensity, which is relevant for applications. Also single-shot measurements are conducted which suggest that, even at the beginning of a pulse, only one mode is active at once, but the main active mode differs from pulse to pulse, seeded by photons that are initially present in each mode.

2. Setup

We characterize a commercial green laser diode using a streak camera setup. To achieve a sufficient spectral resolution to observe the longitudinal mode dynamics, we use a monochromator with a 2400 lines mm–1 grating in front of the streak camera. The laser diode is driven by a combination of a pulse generator and a source meter connected via a bias tee. To measure the current during the pulsed operation, we use an 11 GHz sampling oscilloscope. The pulse pattern used consists of three 10-ns-long pulses with a current of 72 mA which corresponds to 1.5 times the threshold current (Ith) of the diode. The pattern has a repetition rate of 10 kHz to avoid self-heating effects. We vary the spacing between the pulses from 0 to 3.5 ns and the bias current from 0.5 to 0.95 Ith as shown in Fig. 1. The measurements are performed using analog integration, photon counting and single-shot measurements and are validated by simulations.

3. Experimental results

3.1. Analog integration measurements

Measurements are performed to determine the combination of bias current and pulse spacing for which interaction between the pulses occurs. These measurements are done in the analog integrating mode, where the image is generated by integrating over several thousand shots. Examples of streak camera images for two measurements with a similar pulse spacing are shown in Figs. 2(a) and 2(b) for the case of a low and a high bias current (0.5 Ith and 0.95 Ith, respectively) with a pulse spacing of 2 ns. For the low bias case the pulses are independent, meaning that the spectral/temporal shape and intensity is similar for all three pulses. However, for high bias we observe a strong interaction between the pulses. This effect is easily observed in the trace of single longitudinal modes plotted in Figs. 2(c) and 2(d). While the
overall intensity remains nearly identical in both cases, the intensity of the single modes clearly differs when the bias current is high.

To get an overview of the influence of pulse spacing and bias current on the interaction of the pulses, a rough plot is shown in Fig. 3. It is shown that while for biases of $0.9 \, I_{th}$ and less the longest interaction distance reaches $1$–$1.5$ ns, for biases over $0.9 \, I_{th}$ the interaction is still observable for pulse spacings longer than $3$ ns. This long interaction time leads us to the understanding that, rather than carrier dynamics, this interaction is caused by photons that remain in the cavity. This would also explain the strong dependence of the bias current, because the bias influences both the gain and the transparency of the waveguide and therefore has a strong effect on photon lifetime.

Fig. 1. (Color Online) Schematic plot of the pulse pattern driving the laser diode. The pulse length and pulse height are kept constant at $10$ ns and $72$ mA, respectively. The pulse spacing is varied from $0$ to $3.5$ ns and the bias current from $0.5$ to $0.95 \, I_{th}$. The pattern is repeated with $10$ kHz.

Fig. 2. (Color Online) (a), (b) Streak camera measurements of a green laser diode pulsed with $10$ ns pulses with a pulse spacing of $2$ ns, a pulse height of $1.5 \, I_{th}$ and a bias current of (a) $0.5 \, I_{th}$ and (b) $0.95 \, I_{th}$, with analog integration. The trace of the driving current is plotted in white. (c), (d) Intensity traces for the whole spectrum and single longitudinal modes extracted from (a) and (b).
3.2. Photon counting measurements
To examine if there are photons that remain for long enough in the cavity to affect the next pulse, photon counting measurements were performed. In this mode, the intensity is reduced via neutral density filters to the point where the detection of single photons is possible. The noise of the CMOS camera is suppressed in photon counting mode, and therefore the dynamic range is enhanced in comparison with analog integration which allows observation of the photon density between pulses. One example of such a measurement is shown in Fig. 4, where we use the same parameters as in Fig. 2(b). To better observe the photon density between pulses, intensity is plotted on a logarithmic scale. This allows observation of the relatively slow decay of intensity between the pulses. For the parameters shown a sufficient number of photons are still in longitudinal modes, promoting these modes at the beginning of the next pulse. This leads to a carry-over from the mode pattern at the end of one pulse to the beginning of the consequent pulse.

3.3. Single-shot measurements
Because both the analog integration and the photon counting show a combination of thousands of shots, additional single-shot measurements were performed. Here, it is possible to detect a single pulse event and therefore verify if a dominant longitudinal mode is passed on to the next pulse. In Fig. 5, samples of these measurements for a high bias current of 0.95 $I_{th}$ are shown. In the measurements shown two different pulse spacings are used, about 4.5 ns between the first two pulses and about 10 ns between the second and third pulses. Mode seeding can be observed for the shorter pulse spacing, while for the longer pulse spacing no seeding effect is detectable.
4. Simulations

Our approach for simulating laser diode mode dynamics is based on a rate equation model that has been described in the literature.\textsuperscript{32} It describes the charge carrier number \( N \) in the quantum wells and the number of photons \( S \) in the cavity by their time derivative including injection, recombination, emission, absorption and photon outcoupling processes. This simple model is expanded to allow us to describe the photon number in the \( p \)th longitudinal mode \( S_p \) as well as the carrier numbers in two separate quantum wells \( N_1 \) and \( N_2 \). In our model, we assume unequal pumping of the two quantum wells,\textsuperscript{27} which influences the onset dynamics in terms of turn-on delay and fast redshift.

The multimode rate equation system consists of two equations for \( dN_1/dt \) and \( dN_2/dt \) and \( p \) equations describing the photon rates \( dS_p/dt \) and can be written as:\textsuperscript{26}

\[
\frac{dN_1}{dt} = \eta_{inj} \frac{I}{q_e} - R(N_1) - \sum_p v_{gr} g_{p,1} S_p
\]

\[
\frac{dN_2}{dt} = \eta_{inj} (1 - \chi) \frac{I}{q_e} - R(N_2) - \sum_p v_{gr} g_{p,2} S_p
\]

\[
\frac{dS_p}{dt} = \sum_p v_{gr} (g_{p,1} + g_{p,2} - g_{th}) S_p + \beta_{rad} \cdot (N_1^2 + N_2^2).
\]

Carrier recombination occurs as nonradiative Shockley–Read–Hall (SRH) recombination (~\( N \)), radiative spontaneous recombination (~\( N^2 \)) and Auger processes (~\( N^3 \)). Thus the total spontaneous recombination rate can be expressed as:

\[
R(N) = A_{SRH} N + B_{rad} N^2 + C N^3.
\]

The stimulated emission in each longitudinal mode is described by the modal gain \( g_p \), for which we employ a gain model introduced in Ref. 22 and also used in Ref. 26. It includes a fundamental term to express the curvature of the gain spectrum and the proportionality to \( N \), as well as a self-saturation part to account for spectral hole burning and symmetric and asymmetric mode interaction terms, which can describe mode competition.

For simulating mode dynamics in short subsequent pulses, the electrical signal is modeled with parameters according to Section 2 with steady transitions and realistic current rise and fall times of \( \tau = 0.2 \) ns, which correspond to the measurements. For accurate modeling of the mode-seeding effects, the simulation must be performed according to the situation in single pulses, where only a few modes are active in one short pulse as our single-shot measurements show. To include this behavior in the simulations, we add a few photons at a very low rate into two to three randomly chosen modes to support them at pulse onset, where small differences in photon number have a strong effect on light output in the same mode. The photon number variations are changed in each subsequent pulse, which corresponds to independent pulses. Figure 6 shows an example sequence of the simulations. Here three 10-ns-long pulses are spaced by 2 ns and are plotted for three different bias currents. For low bias currents the additional introduced photons at the beginning of the marked longitudinal modes mainly define the shape of each individual pulse. However at higher bias currents, interaction of the pulses is observed. In this situation the seeding of individual longitudinal modes by the remaining photons of the corresponding mode of the preceding pulse is stronger than seeding by the random photons in each pulse. This behavior is in good agreement with the effects shown in the measurements.

5. Conclusion

We show that pulse interaction can occur in InGaN laser diodes in pulsed operation. The consequent pulse will be
influenced if the bias current is large enough to keep the waveguide transparent. Interaction was shown for pulse spacings even above 3 ns. This is caused by the remaining photons in the cavity due to the gain and low absorption in the quantum well. This leads to seeding of the most prominent modes to the consequent pulse, which causes a transition of the mode pattern from the end of one pulse to the beginning of the next. To achieve independent pulse sequences, a trade-off has to be between mode seeding and turn-on delay.

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