Characterization of mode competition phenomena in (Al,In)GaN laser diodes

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ABSTRACT

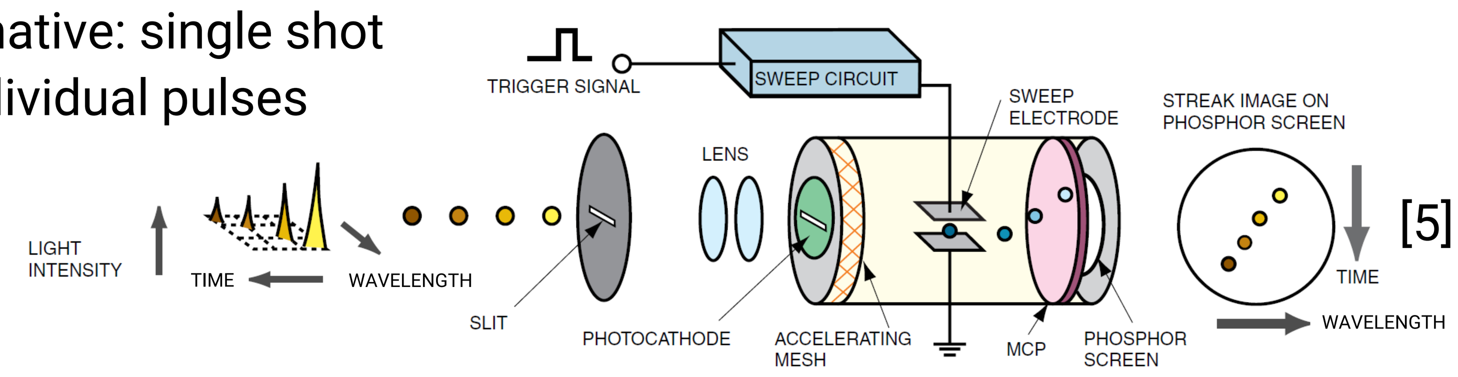
(Al,In)GaN laser diodes have various recent applications, such as laser projection systems in augmented/virtual reality glasses [1], which require a modulation with frequencies ranging from 100 MHz to 1 GHz. On the corresponding nanosecond to microsecond time scale, we investigate the spectral-temporal dynamics of green InGaN laser diodes in high resolution. For interpretation we simulate the longitudinal mode dynamics using a multi-mode rate equation model [2,3]. The observed effects at pulse onset include the turn-on delay and relaxation oscillations as well as a fast red shift. In longer pulses, we investigate mode competition with mode hopping towards longer wavelengths, which repeats cyclically. Single shot measurements show significant variations between single pulses. Consequently, much of the dynamics cannot be observed in usual averaged / time-integrated characterization.

EXPERIMENT

Streak camera setup

Combination with monochromator (600 l/mm or 2400 l/mm grating) [4]
→ High temporal and spectral resolution

- Usual: integration over ≈10^6 pulses → time-averaged investigation
- Alternative: single shot
  → individual pulses



SIMULATION

Rate equation model

Solving for charge carrier numbers $N_{1/2}(t)$ for each QW and photon number $S_p(t)$ for each longitudinal mode [2,3,4]

$$\frac{dN}{dt} = \eta\frac{I}{q_e} - AN - BN^2 - CN^3 - \sum_p v_{gr} S_p g_p$$

$$\frac{dS_p}{dt} = v_{gr}(g_p - g_{th})S_p + \beta B_r N^2$$

+ unequal pumping of multiple QWs [6]
+ shift of central wavelength with N

Using modal gain model

$$g_p = A_p - BS_p - \sum_{p\neq q}(D_{pq} + H_{pq})S_p$$

Parabola $g_p(\lambda) \sim N$

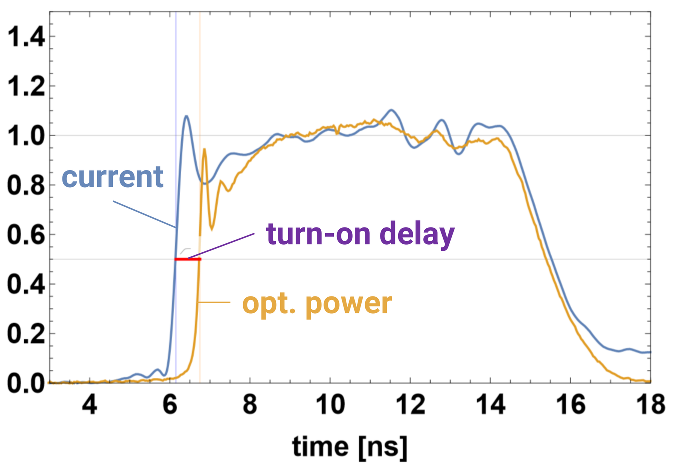
Symmetric / asymmetric mode interaction

Spectral hole burning

INITIAL MODE DYNAMICS

Essential effects on pulse onset

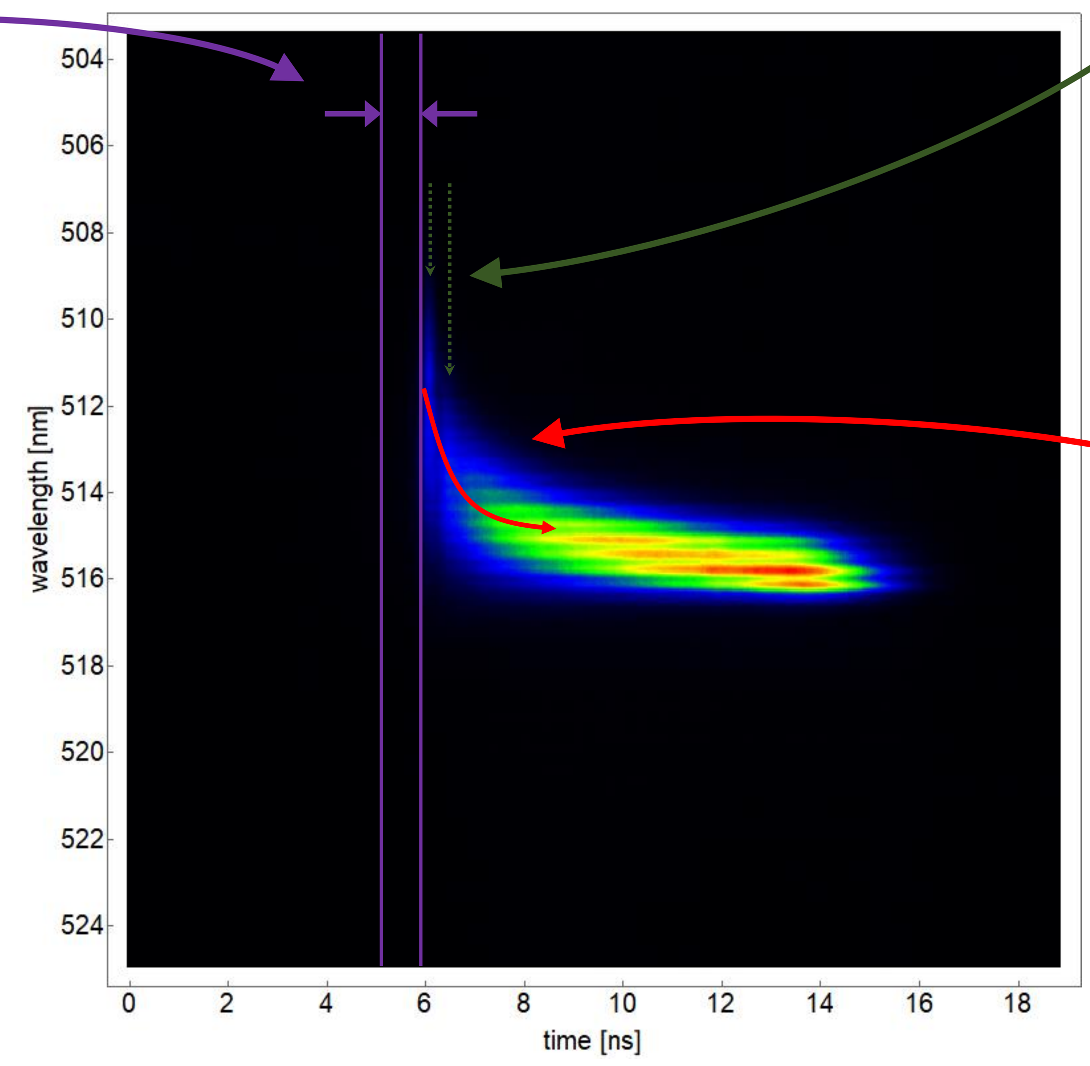
Turn-on delay



Delay between electrical pulse onset and laser emission

- Time for reaching threshold carrier density
- Shortened by high bias or pulse current

Green commercial laser diode measured at $I = 2{,}9\, I_{th}$ using a bias of $0{,}5\, I_{th}$

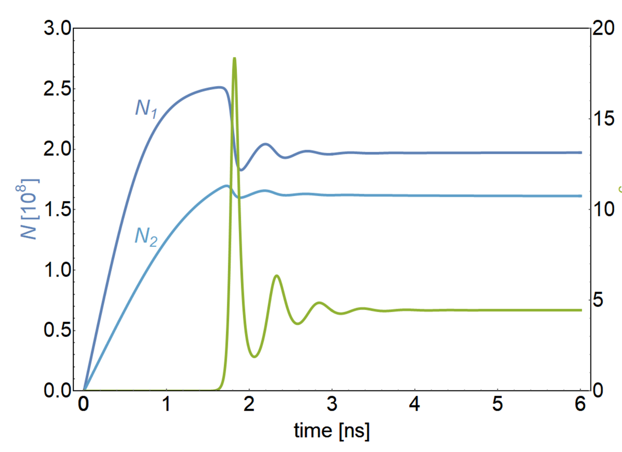


Relaxation oscillations

Few oscillations of coupled overall photon- and carrier density

- Squared frequency is proportional to current

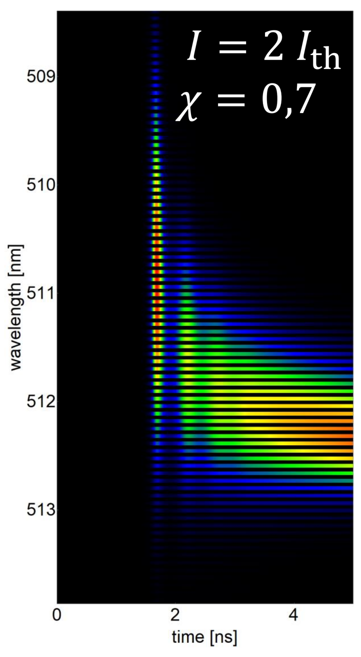
Comparison and analysis with simulations



Fast red shift

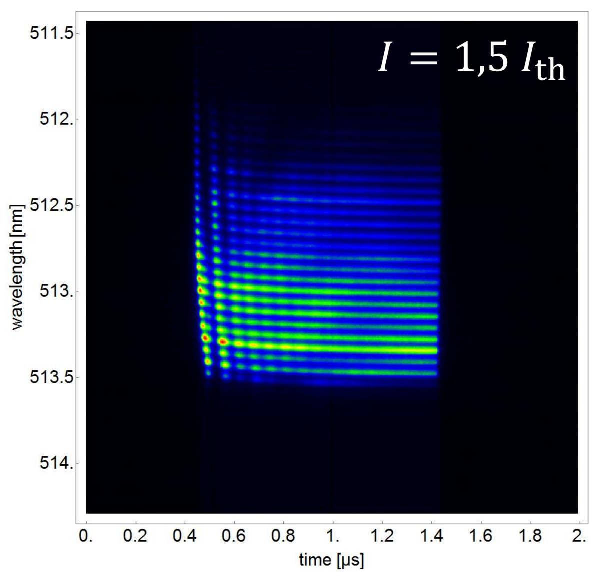
Initial carrier density overshooting
→ screening of Quantum confined Stark effect → shorter wavelength of very first photons, followed by red shift in the next nanoseconds

- Increased effect by unequally pumped QWs



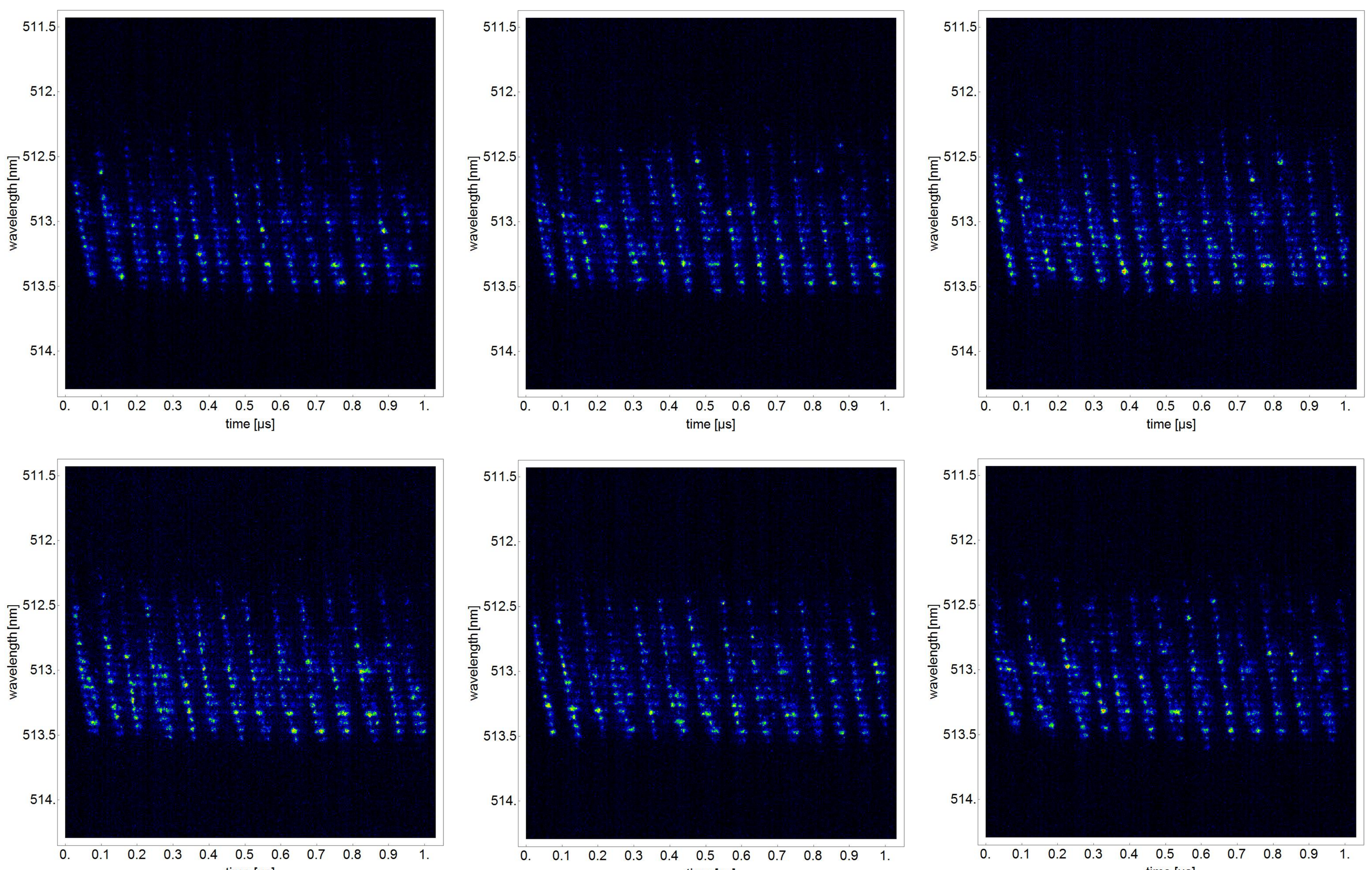
MODE COMPETITION

Integrated measurement



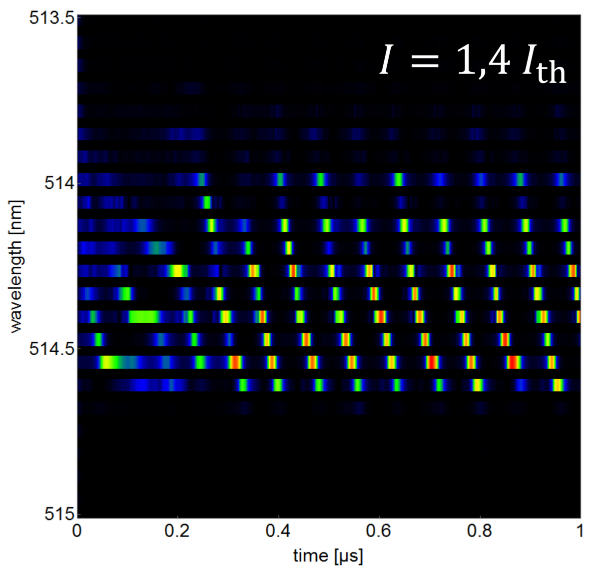
- Nonlinear effects lead to asymmetric gain cross-saturation between neighboring modes [2,3,7] → described with H_{pq} in gain model
- Active modes repeatedly change through the spectrum towards longer wavelength

Single shot measurement

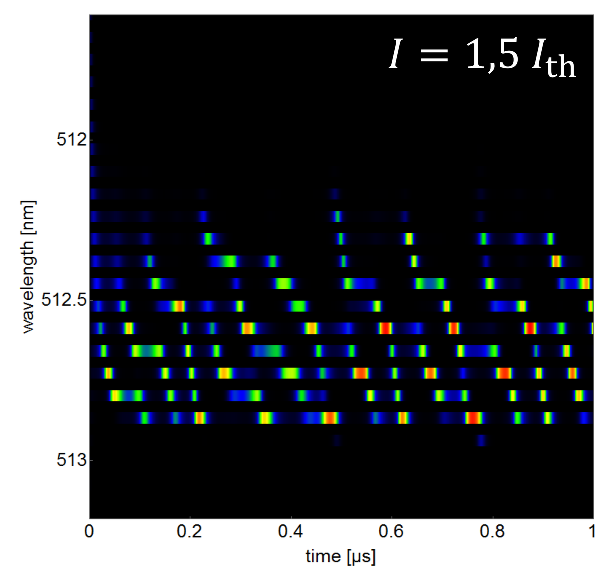


Considerable irregularities in shape and frequency of mode cycles
→ Lead to blurring in integrated measurement after few 100 ns
→ Detailed investigation in single shot mode

Simulation



Microscopical simulation by Eduard Kuhn



Rate equation-based simulation

- Good agreement with the measurements
- Measured irregularities arising due to noise in spontaneous emission → can be included in future simulations

RESULTS

- Fundamental effects in the first nanoseconds of a pulse become important in short pulse operation of laser diodes → significant influence on the spectrum and temporal behavior
- Short pulse behavior and principle of mode competition can be modeled and predicted in different simulations
- Differences between individual single pulses arise from additional effects such as various noise that still need to be considered

REFERENCES

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