Spatio-Temporal Dynamics in the Near Field of a 980nm Ridge Waveguide Pump Laser Diode

M.O. Ziegler (1), E. Miltényi (1), M. Münkel (3), J. Greif (1), G. Jennemann (3), I. Fischer (3), H. Asonen (2), and W. Elsäßer (3)

(1)Department of Physics and Material Science Center,
Philipps-University, Renthof 5, D-35032 Marburg (Germany)

(2)Department of Physics, Tampere University of Technology,
Korkeakoulunkatu 1, FIN-33101 Tampere (Finland)

(3)Institute of Applied Physics, Technical University Darmstadt,
Schlossgartenstr. 7, D-64289 Darmstadt (Germany)

ABSTRACT

The dynamic behavior of the light output from aluminum-free 980nm ridge waveguide GaInAs/GaInAsP/GaInP pump lasers is studied in the high power regime on a picosecond time scale. Three types of the temporal evolution of the turn-on emission dynamics measured by a single-shot streak-camera can be distinguished in the near field, according to the injection current.

First, at moderate pumping, the laser emission evolves through a regime of relaxation oscillations, which can be modelled by rate equations incorporating nonlinear gain. Second, at a higher current, high frequency switching between the left and right part of the active region (ridge width is approx. 5µm) is observed. The frequency of the switching increases proportional to the excitation current amplitude and is in the order of 10GHz. The third regime shows highly complex spatio-temporal dynamics with the coexistence of low and high frequency spatial switching and temporal pulsations. Finally, consequences of the results for applications will be discussed.

Keywords: Semiconductor laser, High power laser, Spatio-temporal dynamics, Near field

1. INTRODUCTION

High output power semiconductor lasers, especially aluminum-free ridge waveguide (RW) semiconductor lasers have attracted great interest during the recent years.[1-4] These lasers, emitting in a single transverse mode, promise considerable applications for the pumping of solid-state lasers and rear-earth-doped fibre amplifiers. Therefore, the aluminum-free material system InGaAs grown on GaAs substrates, is of special interest because it has a number of superior properties compared to the AlGaAs system, e.g. no surface oxidation and fewer crystal defects. This promises a greater protection to catastrophic optical damage (COD) and therefore better reliability, which is necessary for public networks and especially in submarine transmission cables. One crucial point is the importance of the waveguide design, not only for higher output power, but also for attaining efficient fiber coupling.

We propose near field measurements on a picosecond time scale as one new experimental tool to understand the dynamical behavior of high power semiconductor lasers.[5,6] For the measurements on such fast time scales a single-shot streak-camera is used for characterizing the turn-on emission dynamics.
In this paper we present experimental results of the current dependence of time resolved near field measurements of aluminum-free RW-lasers with ridge widths of approx. 5µm. In the following section we shall briefly describe the laser structure and our experimental set-up. In section 3 we shall discuss the observed spatio-temporal dynamics for different pumping levels, perform an eigenmode analysis and finally suggest conclusions on the impact for potential applications.

2. LASER STRUCTURE AND EXPERIMENTAL SET-UP

Turn-on emission dynamics of the near field of a high output power pump laser (aluminum-free RW-laser) emitting at 980nm are investigated. The laser diode consists of a GaInAs quantum well region surrounded by quarternary GaInAsP waveguides and GaInP cladding layers. The length of the laser is 1.6mm and the lateral width of the ridge is approx. 5µm. A more detailed description of the laser structure, the growth system and procedures can be found elsewhere.[1,3] A high-reflectivity rear facet coating (reflectivity of approx. 95%) and an antireflection front facet coating (residual reflectivity of approx. 0.05%) yields in a threshold current of about I_{th}=60mA.
The experimental set-up is shown schematically in Fig. 1. A microscope objective projects a magnified image of the near field intensity distribution of the AR-coated laser facet onto the input slit of a Hamamatsu streak-camera C1587 with a single-sweep unit M1952. This set-up allows to measure spatio-temporal single-shot traces with a time resolution of about 10ps, depending on the length of the selected time window. The high-voltage pulse generator supplies the RW-laser via a power divider with short electrical pulses and produces a trigger signal for the streak-camera. Furthermore, it is synchronized with a second generator, which triggers the gate of the streak-camera. The laser is driven with pulses of 25ns (rise time is approx. 2.5ns) and a repetition frequency of 1kHz. This corresponds to an average electrical power of about 5dBm for the applied pulses, which ensures that junction heating can be avoided. The electronic delay-line allows to choose the temporal position of the spatio-temporal near field traces with respect to the trigger pulse of the streak-camera. The traces can be read out by a CCD-camera and digitally stored by a computer.

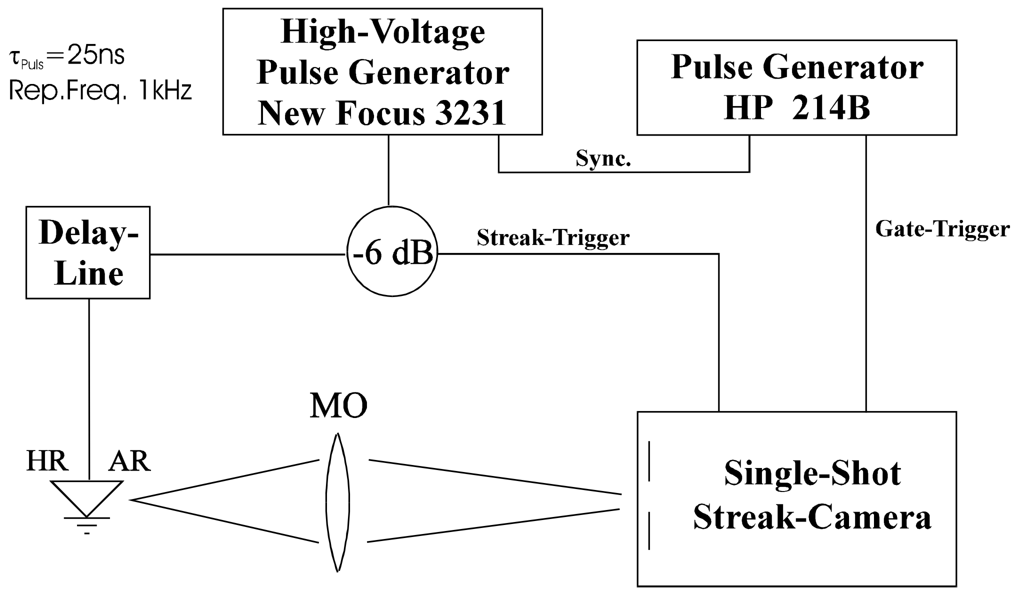


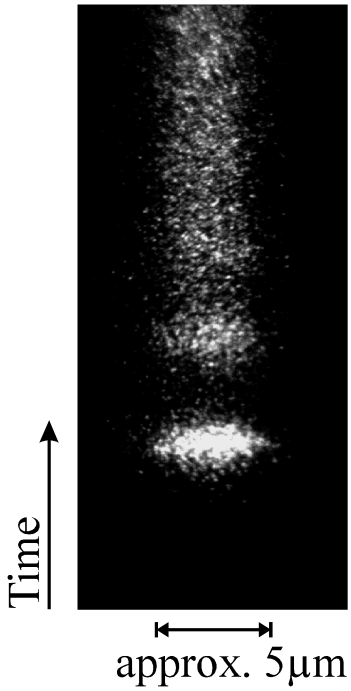
Figure 1: Experimental set-up for near field measurements of a RW-laser

3. EXPERIMENTAL AND THEORETICAL INVESTIGATIONS

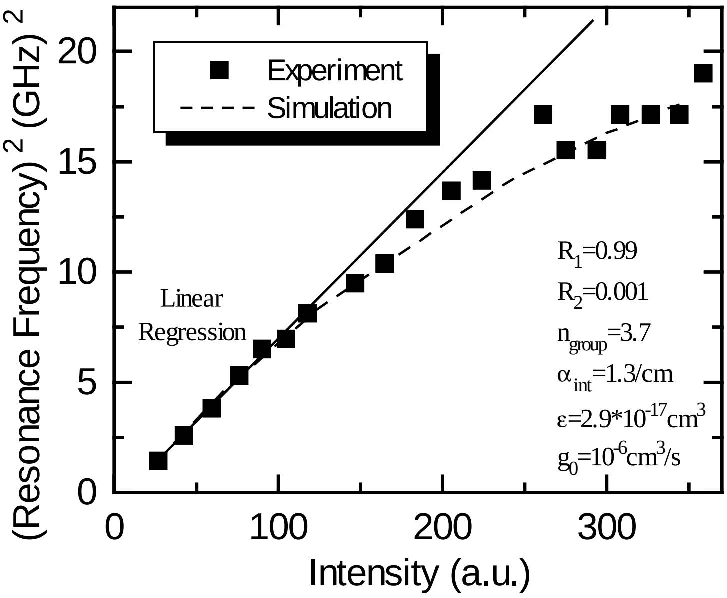
In the following we show that according to the current three regimes of spatio-temporal dynamics can be distinguished.

a) Temporal dynamics for moderate pumping level (I=100 - 400mA)

For moderate pumping levels of about 100mA up to 400mA the laser shows the well known relaxation oscillations. These relaxation oscillations are the dynamic response of the laser on the injected current pulse. A typical single-shot streak-camera image for an applied current of I=170mA is depicted in Fig. 2a. It shows the laterally resolved light intensity emitted from the output facet of the laser. The intensity is encoded in black and white where white corresponds to high intensity values and dark to low intensities. The spatial width of the emission is approx. 5µm, in accordance with the width of the laser structure. The length of the time window is about 3.5ns.



(a)



(b)

Figure 2: a) Spatio-temporal near field of the emitted light intensity. The length of the time window is 3.5ns. b) Square of the resonance frequency as a function of the intensity. The dashed line shows the numerically stimulated results. The straight line is a linear regression to the first six experimental points and indicates the deviation of the quadratic dependence of the resonance frequency on the intensity.

In order to model the experimentally observed relaxation oscillations, we performed rate equation calculations for the photon and carrier density which may be expressed as:[7]

$$\frac{dN}{dt} = \frac{I}{edLw} - \frac{g_0(N - N_t)S}{(1+\varepsilon S)} - \frac{N}{\tau_s}$$

$$\frac{dS}{dt} = \frac{\Gamma g_0(N - N_t)S}{(1+\varepsilon S)} - \frac{S}{\tau_{ph}} + \frac{\beta \Gamma N}{\tau_s}$$

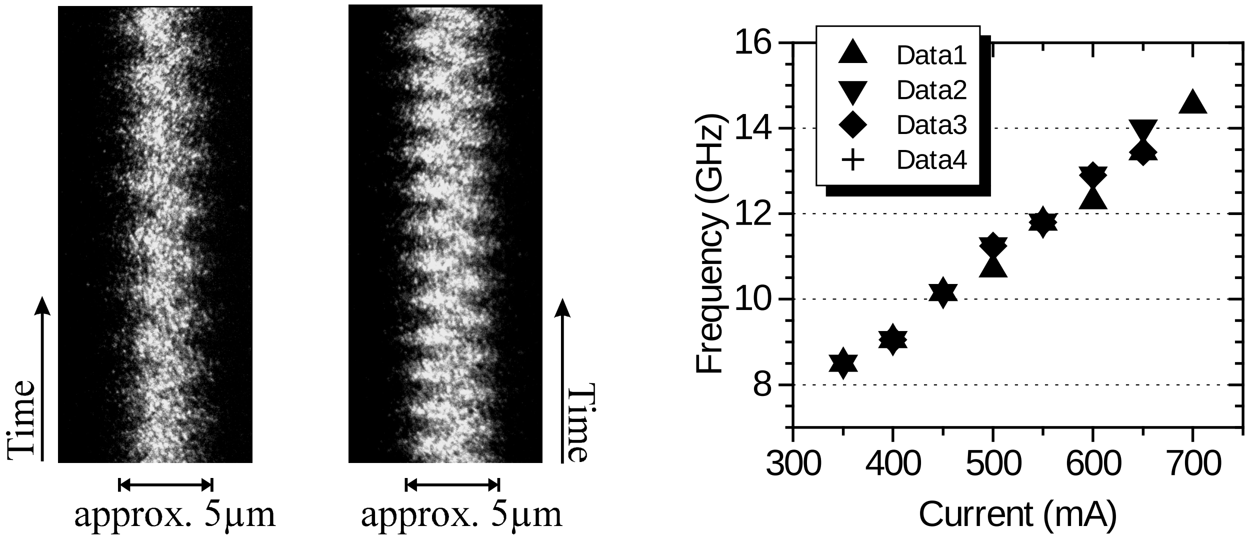
where S, N are the photon and carrier densities in the active region, I is the injected current, dLw is the volume of the active region, g_0 is the differential gain coefficient, N_t is the transparency density, ε is the nonlinear gain coefficient, Γ is the optical confinement factor, and τ_s and τ_{ph} are the carrier and the photon lifetimes, respectively. In this model it is assumed that the laser operates in a single spatial mode. Fig. 2b shows good correspondence between the experimental results and the results of the rate equation simulations. This justifies the use of nonlinear gain formulation for moderate pumping levels in the rate equations for this first regime of temporal dynamics. Nevertheless, we have to state that for the description of thus spatio-temporal dynamics at higher pumping levels, these simple rate equations are not sufficient, as will be discussed in the following.

b) Regular spatio-temporal dynamics for medium power level (I=400 - 700mA)

At higher pumping level of about 400mA up to 750mA, we observe a high frequency switching between the left and right part of the active region. Typical streak-camera images for an injection current of I=350mA and I=550mA are shown in Fig. 3a and 3b. The oscillation period increases proportionally to the excitation current amplitude and is in the order of 10GHz, as shown in Fig. 3c.

This switching between the left and right part of the active region occurs also for longer current pulses and long delay times of about 60ns after the first relaxation oscillation. Additionally, even when applying cw current we have measured a spatio-temporal behavior, which is qualitatively similar as for pulsed current.

First theoretical investigations with laterally dependent rate equations seem to confirm our assumption that this behavior is a result of the interplay of self-focusing, diffraction and spatial hole-burning, which all depend on spatial carrier diffusion as the relevant physical mechanism.[8,9]



(a) (b) (c)

Figure 3: Spatio-temporal near field of the emitted light intensity at a current of a) I=350mA and b) I=550mA. The length of the time windows is 1ns with a delay to the first relaxation oscillation of 7ns. c) Dependence of the oscillation frequency on the applied current.

In order to characterize the underlying dynamics of the spatio-temporal pattern in the output intensity of the RW-laser we performed an eigenmode analysis.[10,11] The resulting N eigenvectors $P_\alpha(x)$ are used for an expansion of the fundamental intensity data field. The intensity field can be reconstructed by adding the temporally averaged intensity field $\langle I \rangle_t$ to the deviation δI of the intensity field at the laser facet with

$$\delta I(x,t) = \sum_\alpha a_\alpha(t) \cdot P_\alpha(x)$$

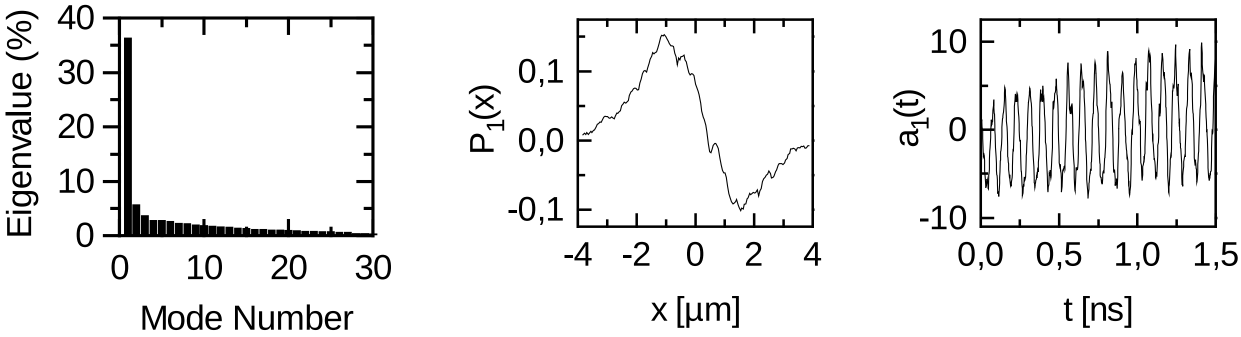
where $a_\alpha(t)$ is the expansion coefficient.

The eigenvalues λ_α of the intensity covariance matrix $C_{k,l}$

$$C_{k,l} = \frac{1}{T}\int_0^T \frac{\delta I(x_k,t)\cdot \delta I(x_l,t)\cdot dt}{\sqrt{\langle I(x_k,t)\rangle_t}\cdot\sqrt{\langle I(x_l,t)\rangle_t}}, \qquad k,l = 1,2,\ldots,N$$

determine the probability of the appearance of the corresponding eigenvektors P_α in the intensity field.

We used the eigenmode analysis on the streak-camera image for an injection current of I=550mA (Fig. 3b). The calculated eigenmode spectrum, which shows that only one eigenmode is dominant, is depicted in Fig. 4a. The intensity field of the first eigenmode and the time dependence of its expansion coefficient is plotted in Fig. 4b and 4c. As expected from the streak-camera image the determining first eigenmode is asymmetric and has an almost periodic time evolution.



(a) (b) (c)

Figure 4: Eigenmode analysis of the spatio-temporal output signal of the RW-laser for I=550mA. a) Eigenvalues of the first 30 eigenmodes. b) First eigenmode of the intensity field. c) Expansion coefficient of the first eigenmode.

The temporal evolution of the calculated intensity field of the first eigenmode is depicted in Fig. 5a. From a comparison between the original streak-camera image in Fig. 5b and the calculated field in Fig. 5a it turns out that the dynamics of the first eigenmode is the dominant contribution. From this dominant asymmetric eigenmode we conclude that in our case e.g. the fiber coupling for pumping a rear-earth-doped fibre amplifier is worse than for a gaussian eigenmode.

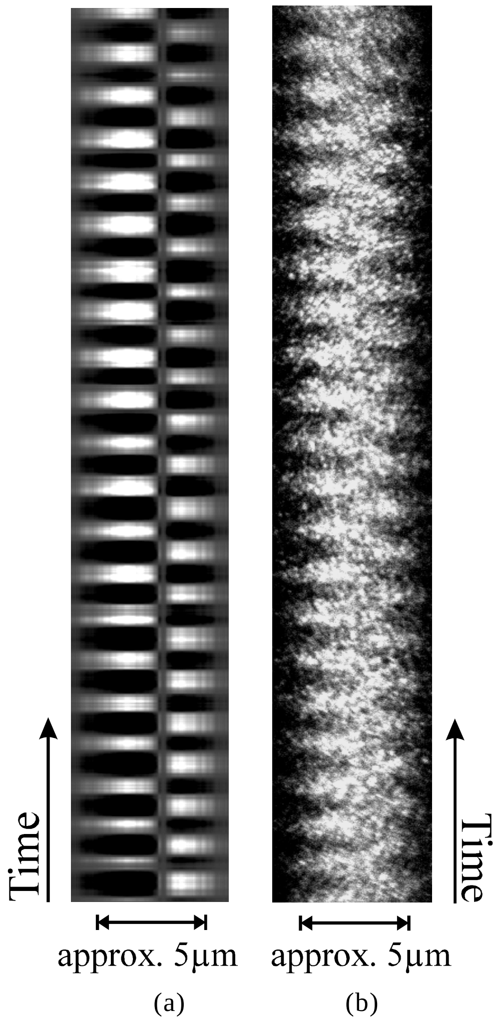
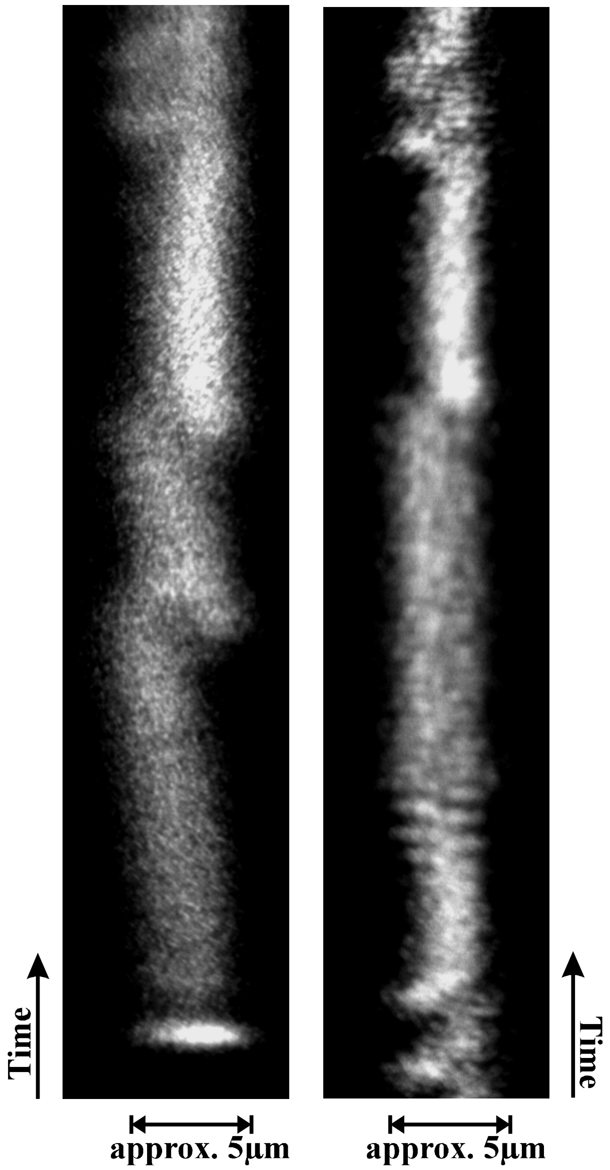


Figure 5: Comparison of a) the calculated intensity field of the first eigenmode and b) the original spatio-temporal output signal of the RW-laser for I=550mA. The length of the time windows is 1.75ns.

c) Irregular spatio-temporal dynamics for high power level (I=700 - 1500mA)

At higher current, we observe highly complex spatio-temporal dynamics as depicted in Fig. 6 for I=1000mA.
As shown in Fig. 6a, after the occurence of the first relaxation oscillation the light starts to migrate to one side of the waveguide with time constants of about 0.5ns to 2ns depending on the current. First theoretical investigations with laterally dependent rate equations result in a qualitatively similar behavior. As soon as one intensity spot reaches an edge, the emission jumps to the opposite side. This behavior is dominating all single-shot pictures. For time windows of about 5ns after the first relaxation oscillations, we observe the coexistence of low and high frequency spatial switching and temporal pulsations (Fig. 6b), whose time series seem to exhibit chaotic deterministic fingerprints. In order to understand this irregular spatio-temporal behavior, further theoretical investigations are necessary.
Polarization dependent measurements ensured that the observed complex spatio-temporal dynamics are not a result of polarization switching as reported e.g. in Ref. 12 for RW-lasers. More than 95% of the emitted light is TE polarized.



(a) (b)

Figure 6: Streak-camera images of the near field of the emitted light intensity for an applied current of I=1000mA a) First relaxation oscillation and b) about 5ns after the first relaxation oscillation. The length of the time windows is 5ns.

4. CONCLUSION

We have presented investigations of the dynamic behavior of the light output from aluminum-free 980nm ridge waveguide GaInAs/GaInAsP/GaInP pump lasers in the high power regime on a picosecond time scale. We showed that three types of the temporal evolution of the turn-on emission dynamics can be distinguished in the near field, according to the injection current.

First, at moderate pumping, the laser evolves through a temporal dynamic regime of relaxation oscillations, which can be modelled by rate equations incorporating nonlinear gain. Second, at a higher current, high frequency switching between the left and right part of the active region (ridge width is approx. 5µm) is observed. The frequency of the switching increases proportional to the excitation current amplitude and is in the order of 10GHz. In order to characterize these regular spatio-temporal dynamics we performed an eigenmode analysis and found a

dominant spatially asymmetric eigenmode. The third regime shows irregular complex spatio-temporal dynamics with the coexistence of low and high frequency spatial switching **and** temporal pulsations.
Our results are not only relevant for the understanding of the physical phenomena of these laser devices, but also important for device optimization for applications, e.g. for pumping of rear-earth-doped fibre amplifiers.

5. ACKNOWLEDGEMENT

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REFERENCES

[1] H. Asonen, A. Ovtchinnikov, G. Zhang, J.N. Näppi, P. Savolainen, and M. Pessa, "Aluminum-free 980-nm GaInAs/GaInAsP/GaInP pump lasers", *IEEE J. Quantum Electron.* **30**, pp. 415-423, 1994.
[2] M. Ohkubo, T. Ijichi, A. Iketani, and T. Kikuta, "980-nm Aluminum-free InGaAs/InGaAsP/InGaP GRIN-SCH SL-QW lasers", *IEEE J. Quantum Electron.* **30**, pp. 408-414, 1994.
[3] M. Toivonen, M. Jalonen, A. Salokatve, J.N. Näppi, P. Savolainen, M. Pessa, and H. Asonen, "All solid source molecular beam epitaxy growth of strained layer InGaAs/GaInAsP/GaInP quantum well lasers (λ=980nm)", *Appl. Phys. Lett.* **67**, pp. 2332-2334, 1995.
[4] P. Savolainen, M. Toivonen, H. Asonen, M. Pessa, and R. Murison, "High-performance 980-nm strained-layer GaInAs-GaInAsP-GaInP quantum-well lasers grown by all solid-source molecular-beam epitaxy", *IEEE Photon. Technol. Lett.* **8**, pp. 986-988, 1996.
[5] I. Fischer, O. Hess, W. Elsäßer, and E. Göbel, "Complex spatio-temporal dynamics in the near field of a broad-area semiconductor laser", *Europhys. Lett.* **35**, pp. 579-584, 1996.
[6] R.K. DeFrees, D.J. Bossert, N. Yu, K. Harnett, and R.A. Elliot, "Spectral and picosecond temporal properties of flared guide Y-coupled phase-locked laser arrays", *Appl. Phys. Lett.* **53**, pp. 2380-2382, 1988.
[7] P. Vasil'ev, *Ultrafast Diode Lasers: Fundamentals and Applications*, Boston: Artech House Publishers, 1995.
[8] M. Münkel, O.Hess, Unpublished.
[9] M. Münkel, F. Kaiser, and O. Hess, "Spatio-temporal dynamics of multi-stripe semiconductor lasers with delayed optical feedback", *Physics Letters A* **222**, pp. 67-75, 1996.
[10] O. Hess, *Spatio-temporal dynamics of semiconductor lasers*, Ph.D. dissertation, Technical University Berlin, Berlin, 1993.
[11] I. Fischer, *Nichtlineare Dynamik und komplexes raum-zeitliches Verhalten von Halbleiterlasern*, Ph.D. dissertation, Philipps-University of Marburg, Marburg, 1995.
[12] A. Klehr, R. Müller, M. Voss, and A. Bärwolf, "Gigahertz switching behavior of polarization-bistable InGaAsP/InP lasers under high-frequency current modulation", *Appl. Phys. Lett.* **64**, pp. 830-832, 1994.