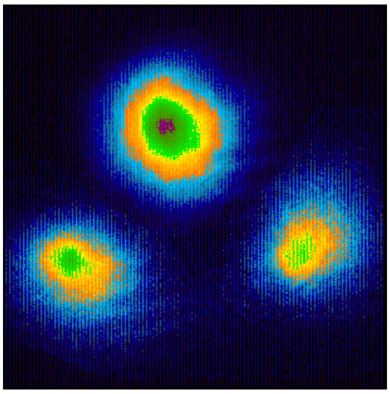
Instabilities of Spatially Coupled $Nd:YVO_4$ Microchip Lasers



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Phase-synchronized lasers

Situation

- Closely spaced lasers in a one- or two-dimensional arrangement
- Weak lateral coupling through overlap of electrical fields

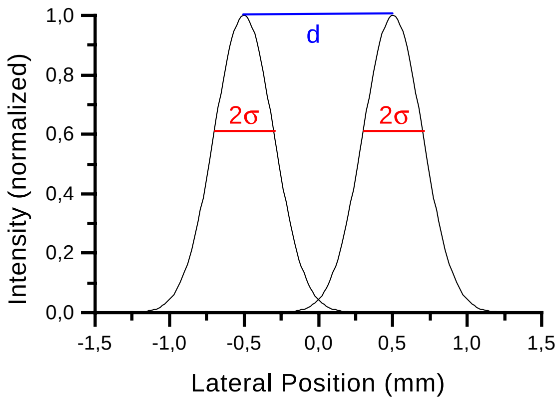
Possible systems

- Semiconductor lasers
  - Stripe arrays
  - VCSEL arrays
- Solid state lasers
  - Nd:YAG lasers
  - Nd:YVO_4 (microchip) lasers

Items of interest

- Conditions for phase locking
- Types of phase locking
- Dynamics of phase locking

Two laterally coupled lasers



Coupled-mode equations for 2 coupled lasers

$$\frac{dE_1}{dT} = \frac{1}{\tau_c}\left[\left(G_1 - \alpha_1\right) E_1 - \kappa E_2\right] + i\omega_1 E_1$$

$$\frac{dG_1}{dT} = \frac{1}{\tau_f}\left(p_1 - G_1 - G_1 \left|E_1\right|^2\right)$$

$$\frac{dE_2}{dT} = \frac{1}{\tau_c}\left[\left(G_2 - \alpha_2\right) E_2 - \kappa E_1\right] + i\omega_2 E_2$$

$$\frac{dG_2}{dT} = \frac{1}{\tau_f}\left(p_2 - G_2 - G_2 \left|E_2\right|^2\right)$$

E_k complex electrical field amplitude
G_k gain
a_k resonator loss
p_k pump coefficient
τ_c resonator round-trip time
τ_f fluorescence time

Control Parameters:

ω_k frequency detuning
$\kappa \equiv -e^{-d^2/2\sigma^2}$ coupling strength

Theoretical Predictions

- Stationary solutions with constant optical phase difference $\Phi = 0, \pi, \ldots$
- $\Phi = 0$ is unstable at finite detuning
- $\Phi = \pi$ is stable
- *an amplitude instability – with synchronized optical phase – should occur for intermediate coupling strengths and detunings*

Numerical Results

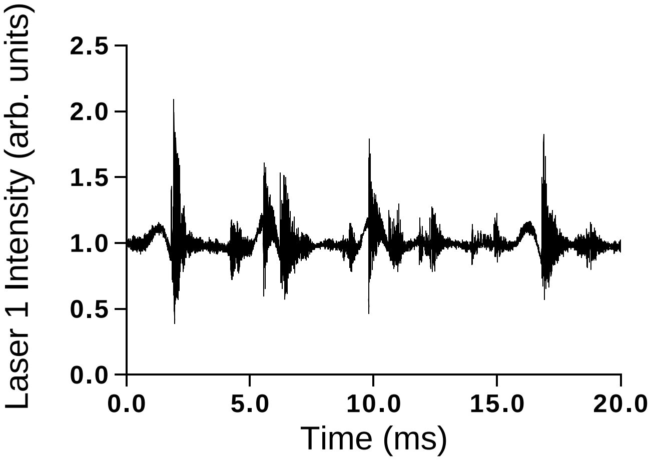
Maximum pulsation amplitude as a function of:
Detuning $\Delta\omega$ / Laser spacing d

K.S. Thornburg, Jr., M. Mller, R. Roy, T.W. Carr, R.-D. Li, and T. Erneux, Phys. Rev. E 55, 3865 (1997)

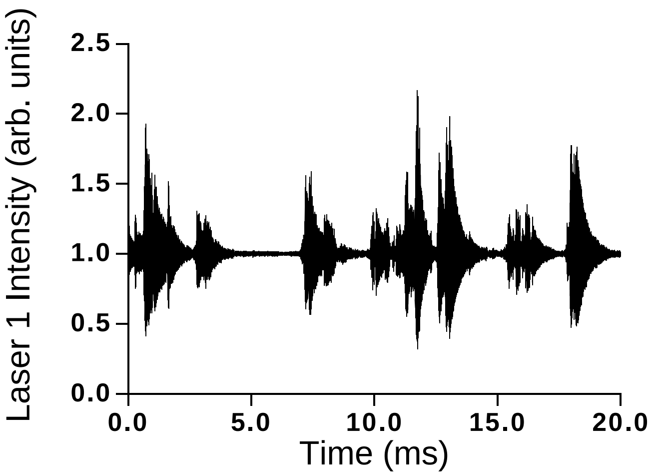
Previous Results

Ar$^+$-laser pumped Nd:YAG rod

- The instability does appear in the vicinity of the stationary phase synchronization regime
- There is good agreement with the predicted parameter regime
- Only short bursts of oscillations can be observed:

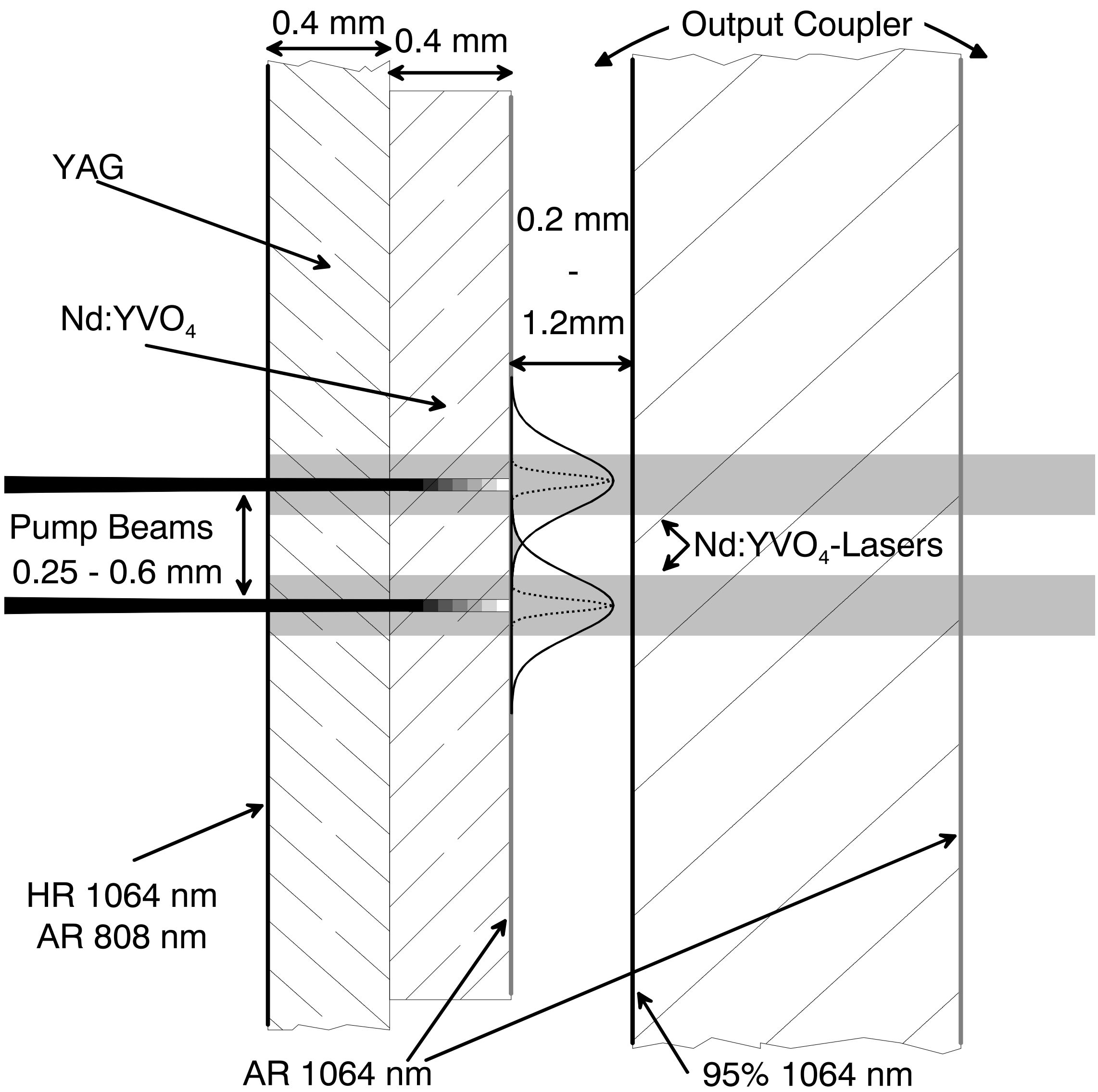


- The bursting behavior is caused by strong detuning fluctuations – as shown by comparison to simulations including such fluctuations:



K.S. Thornburg, Jr., M. MIler, R. Roy, T.W. Carr, R.-D. Li, and T. Erneux, Phys. Rev. E 55, 3865 (1997)

$Nd:YVO_4$ Microchip Resonator



- high absorption and gain

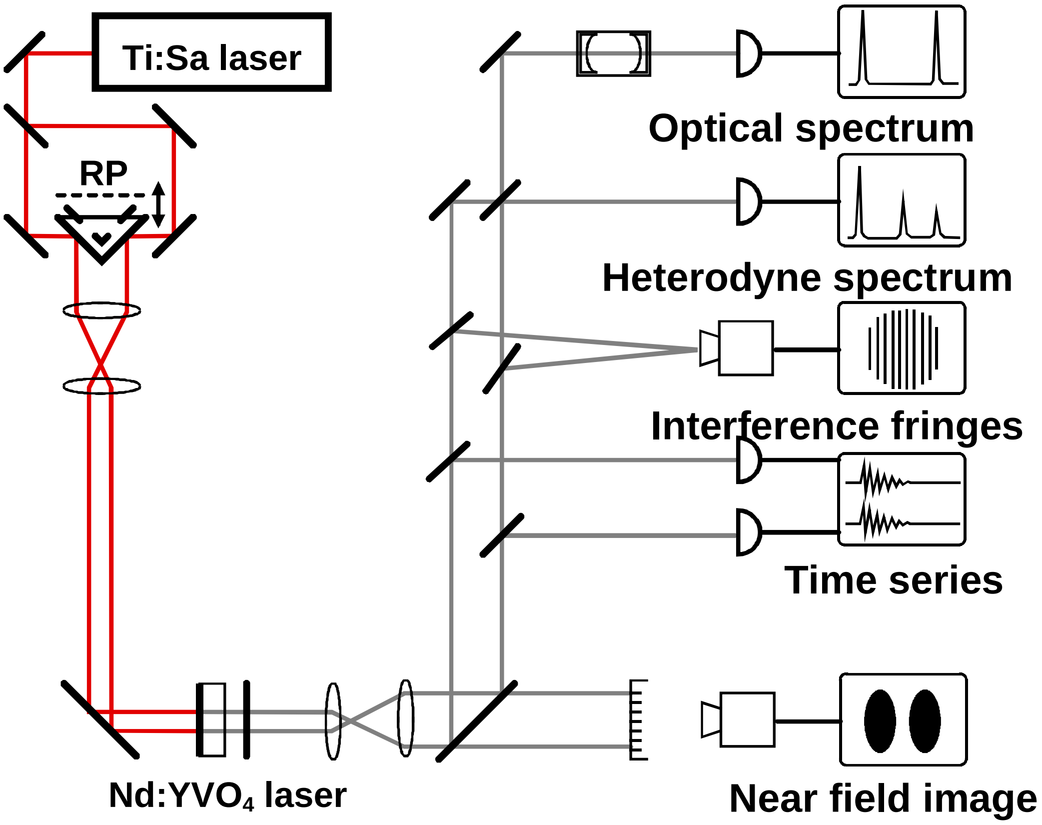
  → thin $Nd:YVO_4$ slice (0.4 mm)

  - → very short, compact resonator
  - → single-mode laser operation
  - → short round-trip time τ_c
- polarisation-selective lasing material

  → well-defined polarisation of both lasers
- up-conversion effects with Ti:Sa pump

  → reduced upper lasing level lifetime τ_f

Nd:YVO_4 Experiment



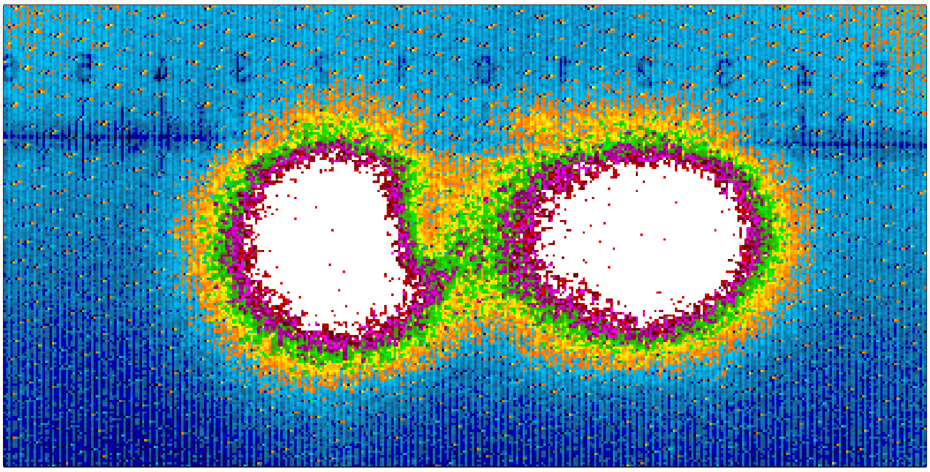
Adjustment of control parameters:

- spacing: translation of reflecting prism RP
- detuning: tilt of output coupler

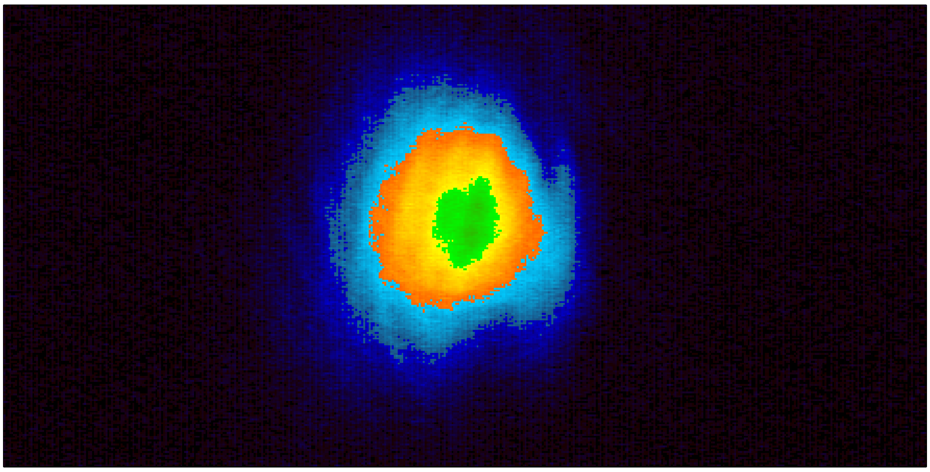
Simultaneous measurement of

- Ti:Sa Pump beam power
- Ti:Sa Pump beam spacing
- Nd:YVO_4 optical spectrum → single mode operation?
- Nd:YVO_4 heterodyne spectrum → detuning
- Nd:YVO_4 fringes → degree of phase synchronization
- Nd:YVO_4 time series → instability?
- Nd:YVO_4 near field image → beam spacing
- Nd:YVO_4 far field image → type of phase correlation

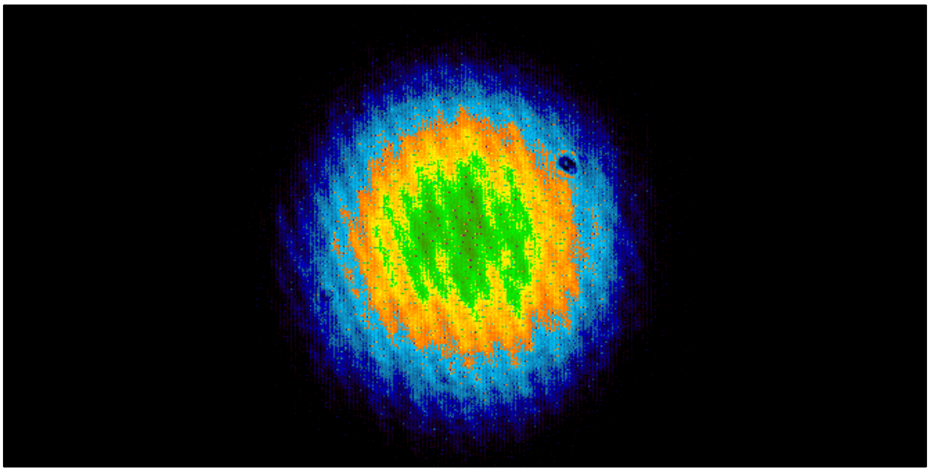
Unsynchronized Lasers



Near field: Sum of intensities

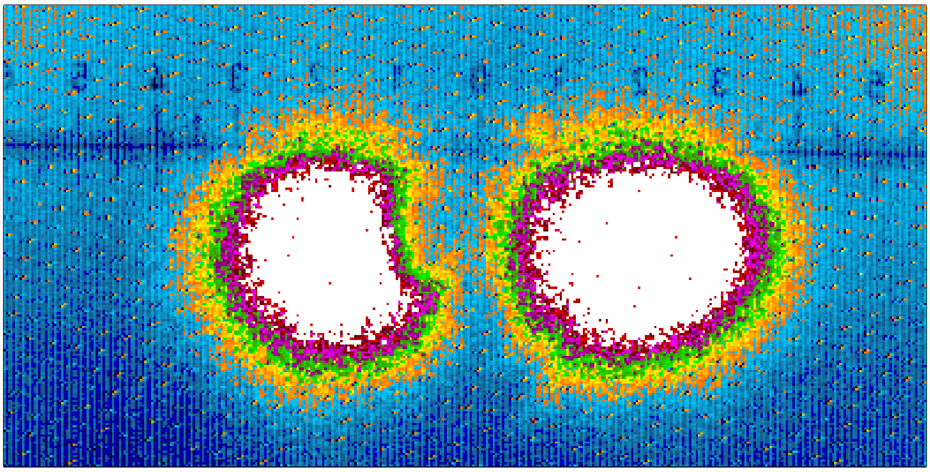


Far field: Gaussian

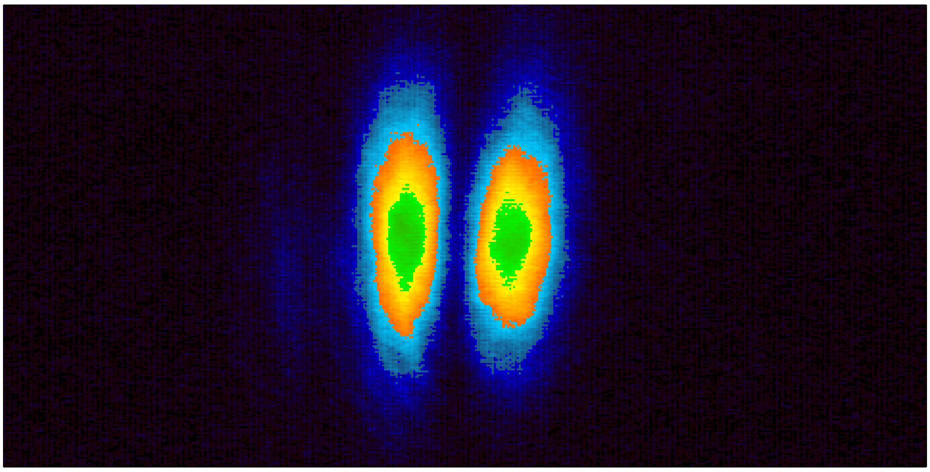


Fringes: Visibility V = 0

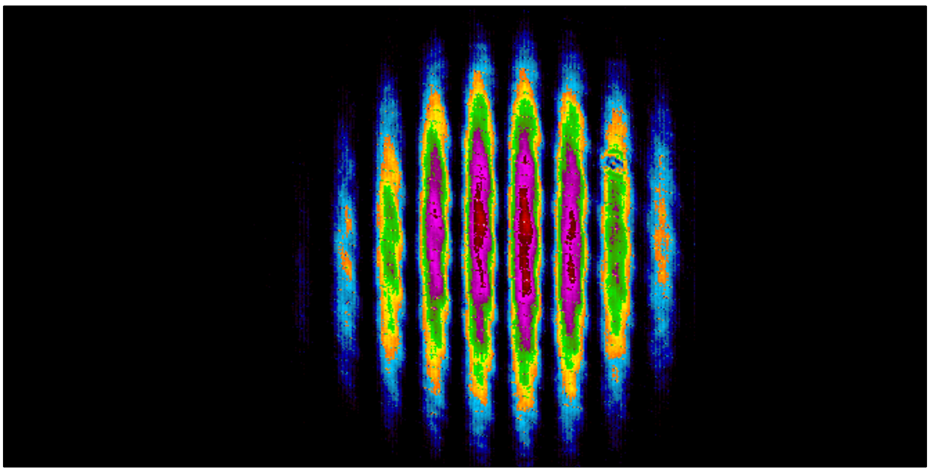
Synchronized Lasers



Near field: Destructive interference

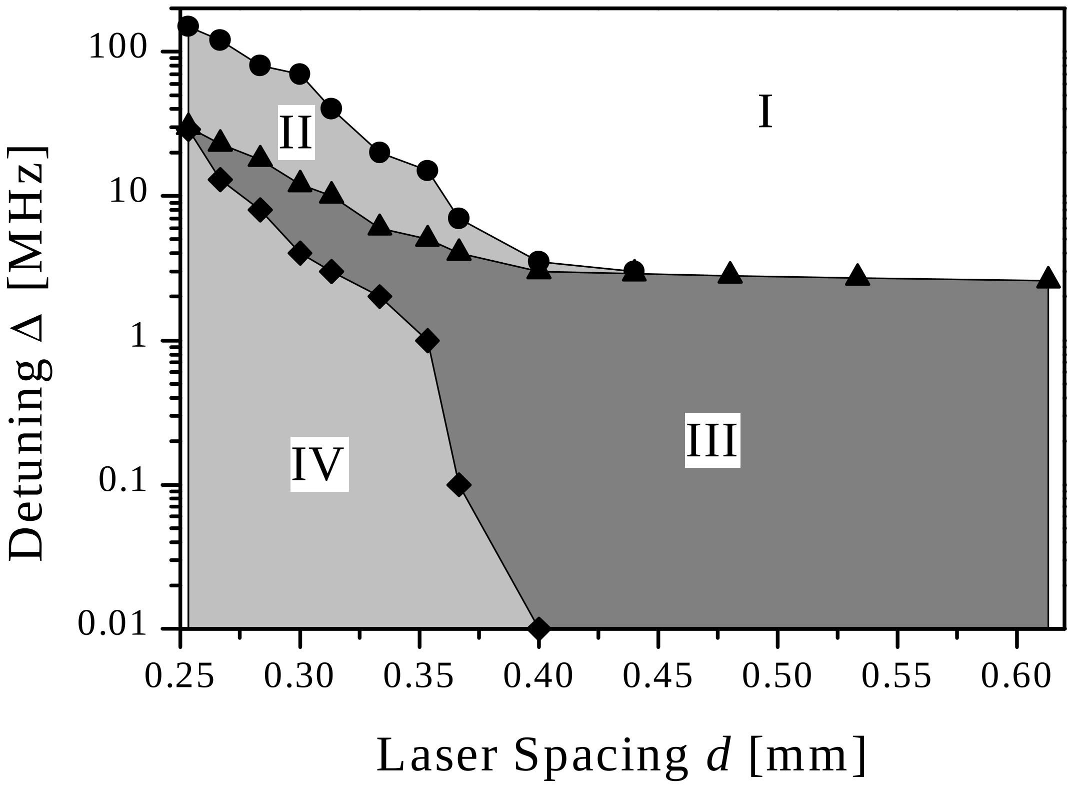


Far field



Fringes: Visibility V = 1

Parameter Space



I stationary intensity, zero fringe visibility

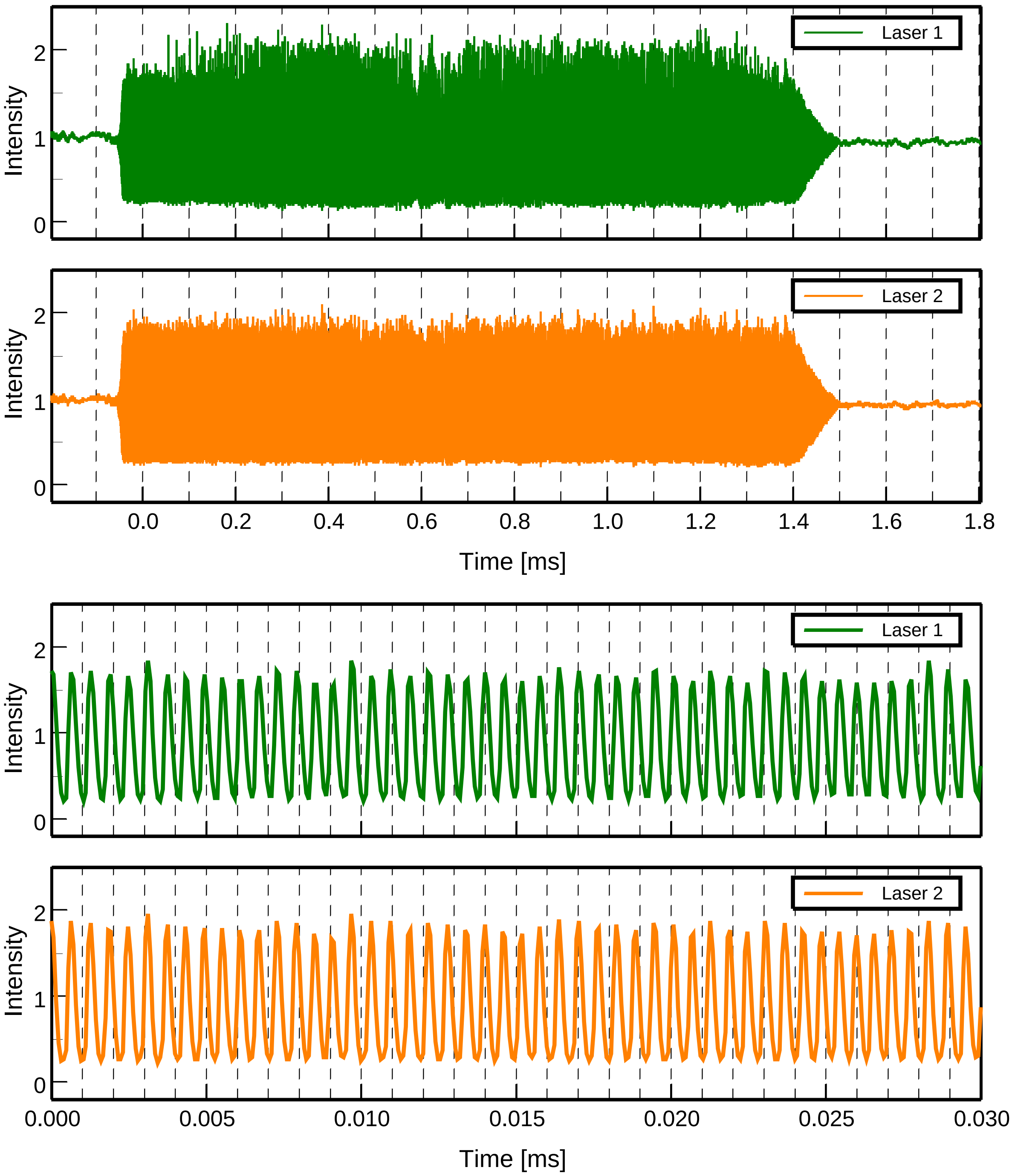
II intermediate visibilities

III amplitude instability, maximum visibility

IV stationary intensity, maximum visibility

Synchronous pulsations

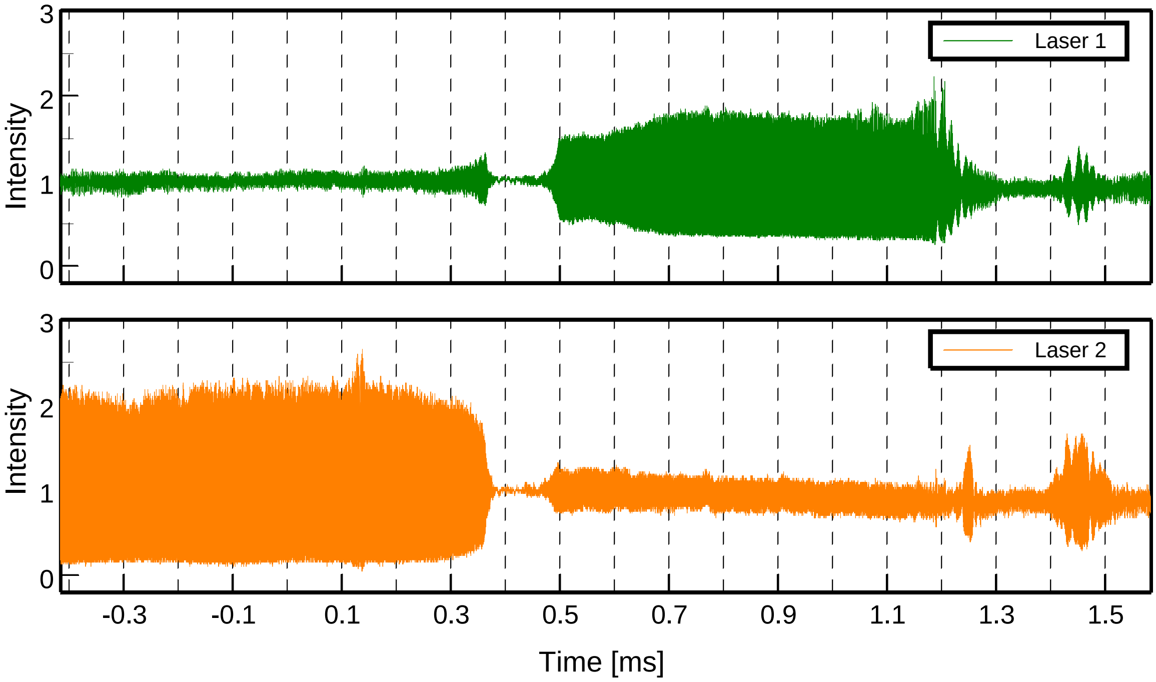
(strong or weak coupling)

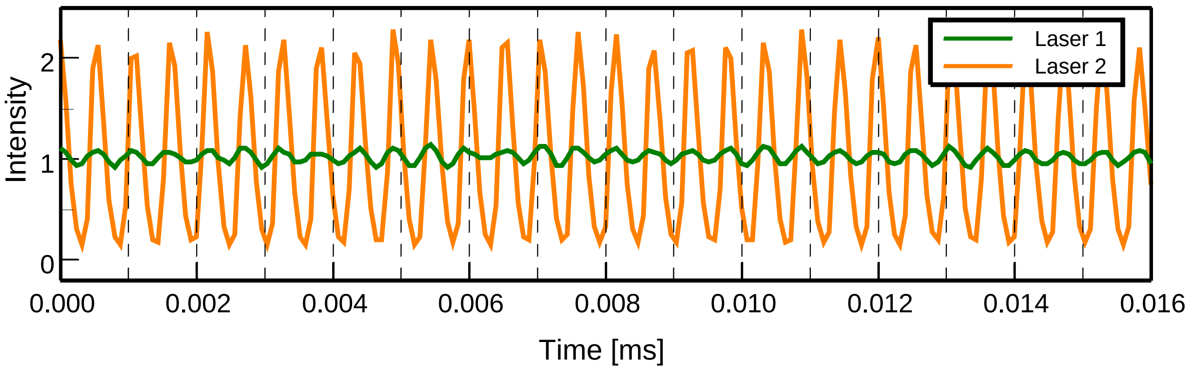


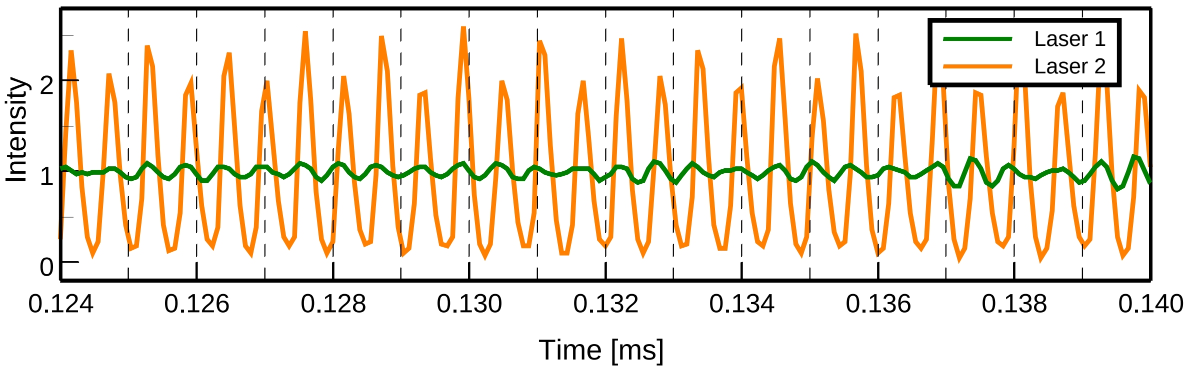
- pulsation frequency is of the order of laser relaxation oscillation frequency
- laser pulsations are in phase
- long undisturbed intervals of pulsations can be observed

Alternating Pulsations

(weak coupling only)

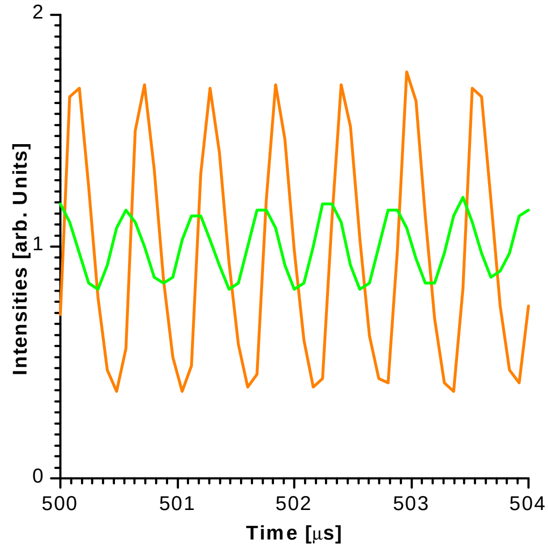




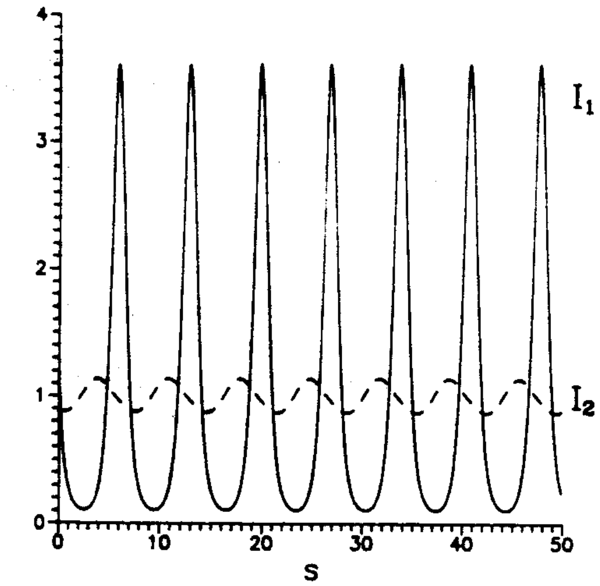


- laser pulsations are out of phase
- pulsation amplitudes alternate
- system is sensitive to detuning fluctuations

‘Localized Synchronization’ ?



Experiment

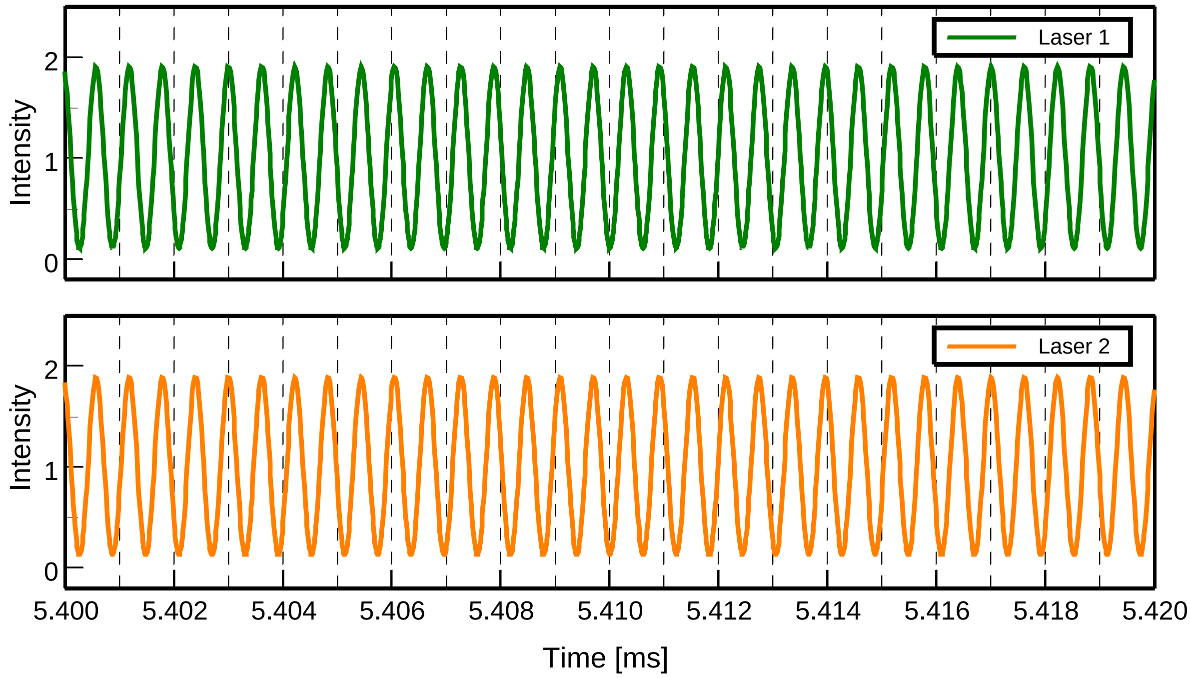


Theoretically predicted oscillations in ‘localized synchronization’ state

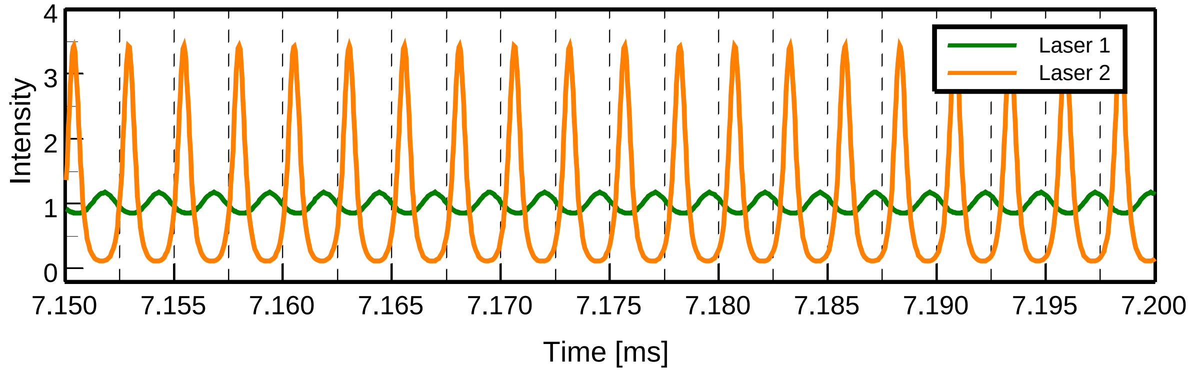
R. Kuske u. T. Erneux, Opt. Commun. 139 , 125 (1997)

Numerical Simulations

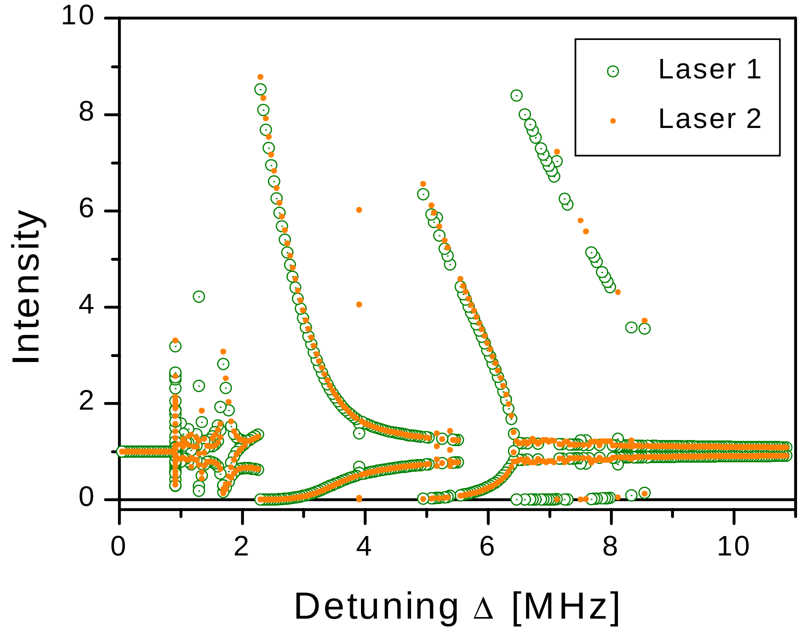
Synchronous Oscillation



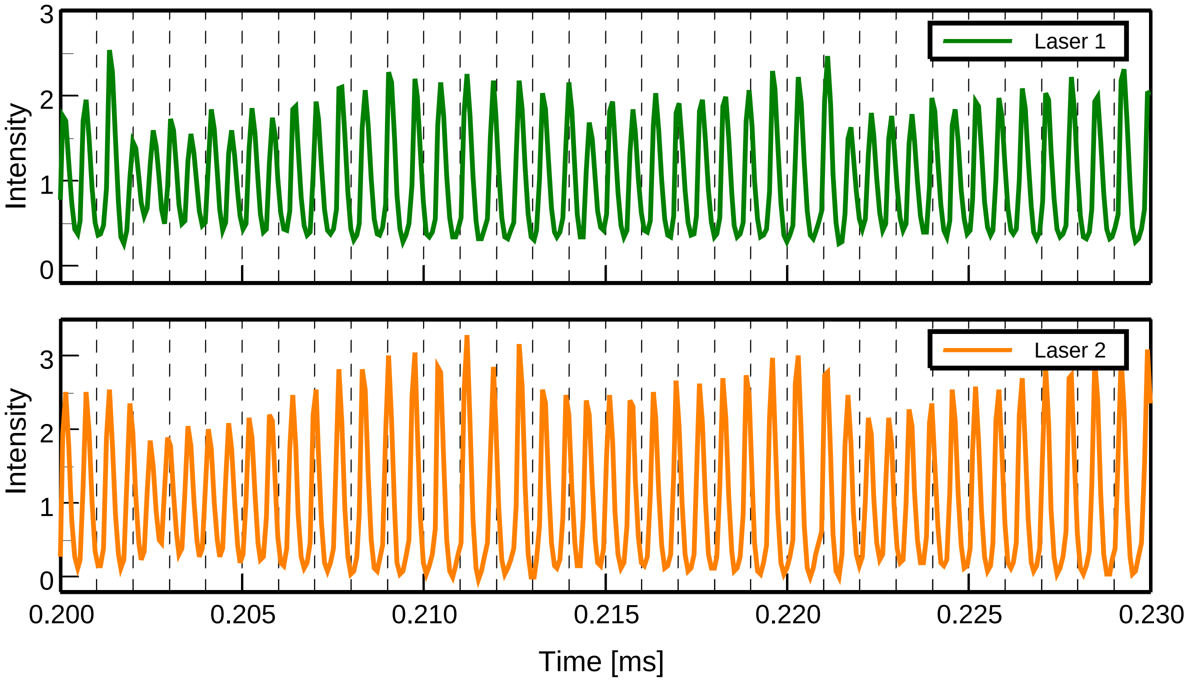
Localized Oscillation



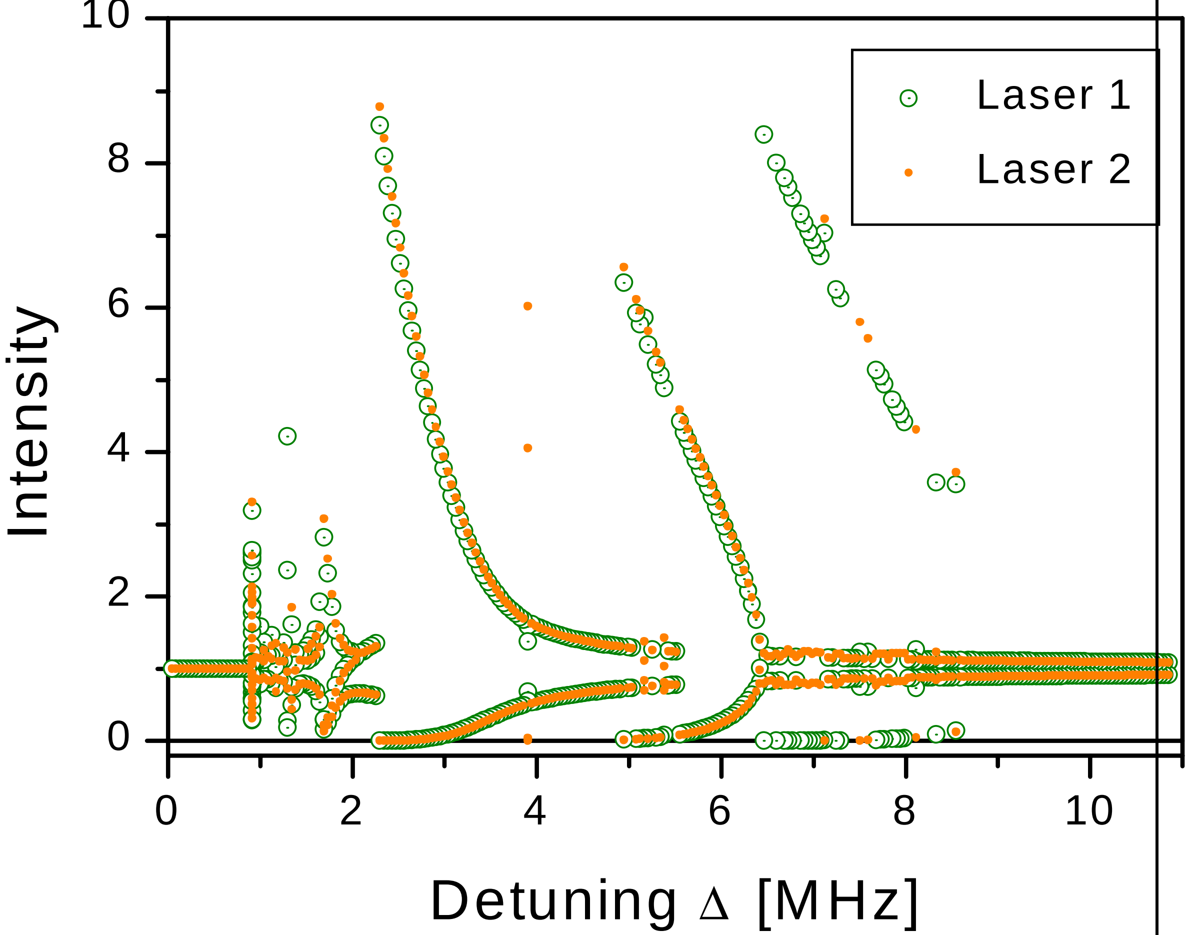
Bifurcation Diagram



Anharmonic Oscillations



Bifurcation Diagram



- xxx
- yyy
- zzz

Summary

- A semimonolithic Nd:YVO_4 microchip resonator is very well suited for studying the dynamics of coupled lasers
- Different types of instabilities can be found in the vicinity of the emergence of phase synchronization of two lasers
- For the first time, a type of amplitude pulsations resembling the recently predicted 'localized synchronization' type could be observed

Outlook

- Replacement of free-space pump setup by single-mode glass fibers
- Study of larger numbers of lasers in one- and two-dimensional arrangements
- Use of laser diode(s) as pump source

$\rightsquigarrow$ Nd:YVO_4 microchip laser array pumped by VCSEL array

to appear in *Chaos, Solitons and Fractals, forthcoming issue on 'Pattern formation in nonlinear optical systems'*

Three coupled lasers