Nonlinear dynamics in intra-cavity pumped thin-disk lasers

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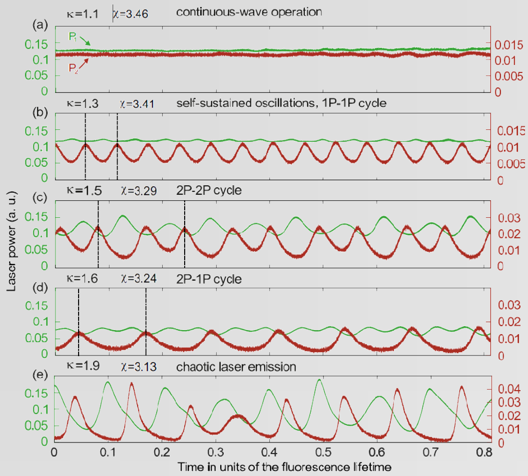
Background

Intra-cavity pumping can be used for pumping gain media with very low single pass absorption of the pump light. Experiments showed that intra-cavity pumped lasers can exhibit self-sustained oscillations and hysteresis.



Experimental Observation:

The qualitative type of dynamics in an Yb:YAG thin-disk laser depends on the resonator length of the diode-pumped laser.

Fig: Measured dynamics of the laser powers of the diode-pumped laser P_1 (green) and the intra-cavity pumped laser P_2 (red) for five different resonator lengths of the diode-pumped laser, resulting in five different beam area ratios κ and different resonator round-trip time ratios χ. Reprinted from [1]

Highlights

The output power of an intra-cavity pumped thin-disk laser shows complex dynamics:

- Stable continuous-wave pumping
- Periodic pulse trains
- Chaotic fluctuations

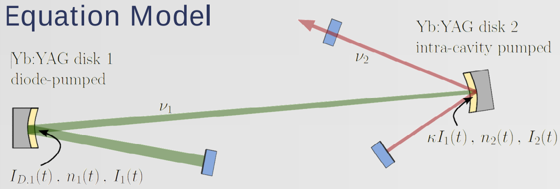
The dynamics can be understood in the framework of a rate-equation model which reproduces experimental results.

The dynamics arise naturally in the laser system due to cross-saturation effects of the two gain media. Hysteresis and multi-stability are observed.

Reference

[1] Trinschek, Vorholt, Wittrock, Optics Express, 29, 4, pp. 5755-5773

Rate Equation Model



population densities of the excited state in the disks

$$\frac{\mathrm{d}n_1}{\mathrm{d}t} = \underbrace{\frac{I_{\mathrm{D},1}}{h\nu_\mathrm{D}}\left[\sigma_{\mathrm{a},\nu_\mathrm{D}}\left(n_\mathrm{dot}-n_1\right)-\sigma_{\mathrm{e},\nu_\mathrm{D}}\,n_1\right]}_{\text{absorption and stim. emission at } \nu_\mathrm{D}} + \underbrace{\frac{M_{1,1}I_1}{h\nu_1}\left[\sigma_{\mathrm{a},\nu_1}\left(n_\mathrm{dot}-n_1\right)-\sigma_{\mathrm{e},\nu_1}\,n_1\right]}_{\text{stim. emission and reabsorption at } \nu_1} \underbrace{-\frac{n_1}{\tau_{10}}}_{\text{spont. em.}}$$

$$\frac{\mathrm{d}n_2}{\mathrm{d}t} = \underbrace{\kappa\frac{M_{1,2}I_1}{h\nu_1}\left[\sigma_{\mathrm{a},\nu_1}(n_\mathrm{dot}-n_2)-\sigma_{\mathrm{e},\nu_1}n_2\right]}_{\text{absorption and stim. emission at } \nu_1} + \underbrace{\frac{M_{2,2}I_2}{h\nu_2}\left[\sigma_{\mathrm{a},\nu_2}(n_\mathrm{dot}-n_2)-\sigma_{\mathrm{e},\nu_2}n_2\right]}_{\text{absorption and stim. emission at } \nu_2} \underbrace{-\frac{n_2}{\tau_{10}}}_{\text{spont. em.}}$$

laser intensities in the disks

$$\frac{\mathrm{d}I_1}{\mathrm{d}t} = \frac{I_1}{T_1}\Big\{\underbrace{M_{1,1}d\left[\sigma_{\mathrm{e},\nu_1}\,n_1-\sigma_{\mathrm{a},\nu_1}\left(n_\mathrm{dot}-n_1\right)\right]}_{\substack{\text{stim. emission and reabsorption}\\ \text{in the first disk}}} - \underbrace{M_{1,2}d\frac{A_1}{A_2}\left[\sigma_{\mathrm{a},\nu_1}\left(n_\mathrm{dot}-n_2\right)-\sigma_{\mathrm{e},\nu_1}\,n_2\right]}_{\substack{\text{absorption and stim. emission}\\ \text{in the second disk}}} \underbrace{-\gamma_{\mathrm{diss},1}}_{\text{diss. loss}}\Big\} + \underbrace{k_{\mathrm{sp},1}\frac{n_1}{\tau_{10}}}_{\text{spont. em.}}$$

$$\frac{\mathrm{d}I_2}{\mathrm{d}t} = \underbrace{\frac{I_2}{T_2}\Big\{M_{2,2}d\left[\sigma_{\mathrm{e},\nu_2}n_2-\sigma_{\mathrm{a},\nu_2}(n_\mathrm{dot}-n_2)\right]}_{\text{stim. emission and reabs. in second disk}} \underbrace{-\gamma_{\mathrm{diss},2}}_{\text{diss. losses}} \underbrace{-\gamma_{\mathrm{out},2}}_{\text{outcoupling}}\Big\} + \underbrace{k_{\mathrm{sp},2}\frac{n_2}{\tau_{10}}}_{\text{spont. em.}}$$

Results

The qualitative type of output dynamics of the laser system can be controlled by the ratio of the beam areas on the two disks.

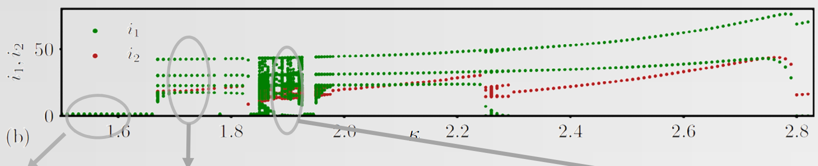
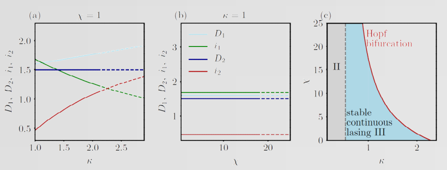


Fig: Local maxima of the intensities obtained by time simulations of the rate equation model. Each simulation run is started from the initial condition (i_1, i_2, D_1, D_2) = (0,0,0,0). Depending on the beam area ratio κ, different qualitative types of dynamics are observed. Reprinted from [1]

Stable continuous wave output

...corresponds to stable steady states of the rate equation model and can be obtained analytically.

... can be observed if the diode pumping is large enough to overcome the lasing threshold.

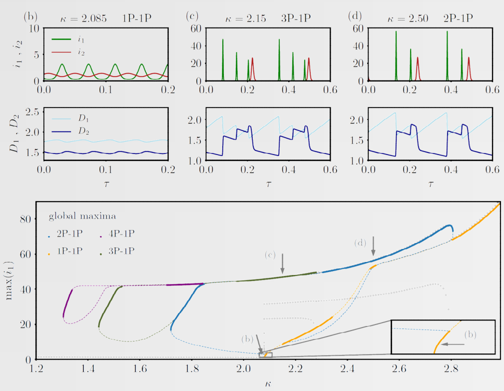


Influence of the beam area ratio κ and the resonator round-trip time ratio χ on the steady state corresponding to continuous-wave emission. Solid (dashed) lines indicate stable (unstable) states. (a) When κ is increased at fixed χ= 1, the steady state changes and looses stability in a Hopf bifurcation at κ =2.08. (b) When χ is increased at fixed κ = 1, the stationary state looses stability in a Hopf bifurcation at χ = 17.461. (c) The parameter region for which the continuous-wave emission is stable (blue region, III) is confined by the Hopf bifurcation line (red line) to the right. To the left, the lasing threshold of the second laser is not reached (grey region, II). Reprinted from [1]

Periodic pulse trains

...correspond to stable periodic orbits of the rate equation model and can be obtained by time simulations and parameter continuation.

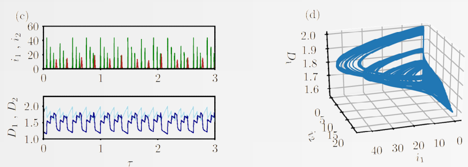
...result from cross-saturation effects in the disks.



Chaotic fluctuations

...of the peak intensity of the output power are observed in extended parameter regions.

...are verified by calculating the Lyapunov exponents of the system.



Top: Exemplary chaotic solution for κ=1.92 and corresponding attractor projected to the (i_1, i_2, D_1) phase space.

Left: Exemplary periodic cycles for three parameter values of are shown in (b)-(d). The global maxima of i_1 obtained by parameter continuation of solutions with one intensity peak in i_2 and up to four peaks in i_1 are shown in (e). Solid (dashed) lines indicate stable (unstable) states. The local maxima of i_1 obtained by time simulations are shown with grey dots for comparison. The arrows indicate the location of the solutions (b) - (d) on the periodic solution branches. The resonator round-trip time ratio is χ = 1.

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