Virtual long term testing of high-power fiber lasers

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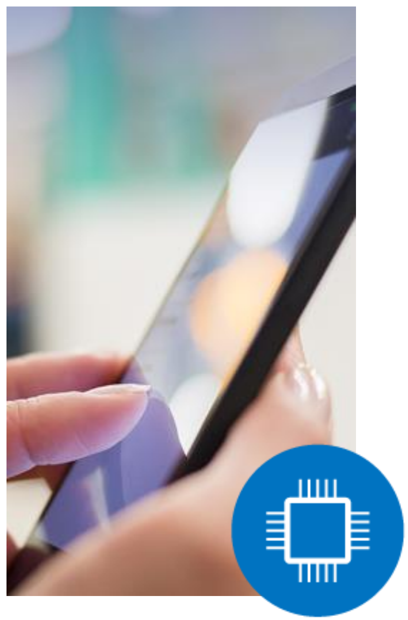
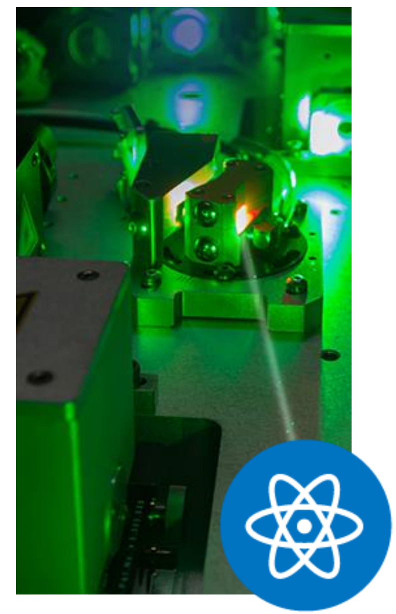
Core Markets

Materials Processing



Microelectronics

OEM Components
& Instrumentation



Scientific Research
& Government Programs

Hamburg: High Power Lasers

Automotive,
Machine Tool,
Metal Cutting/Welding,
Medical Device

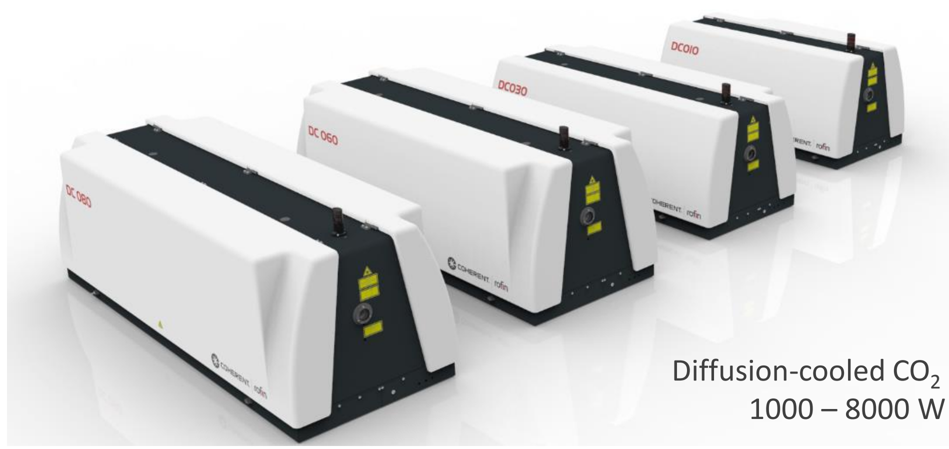
Materials Processing

Fiber Lasers (HighLight FL series)

Compact version
up to 8000 W

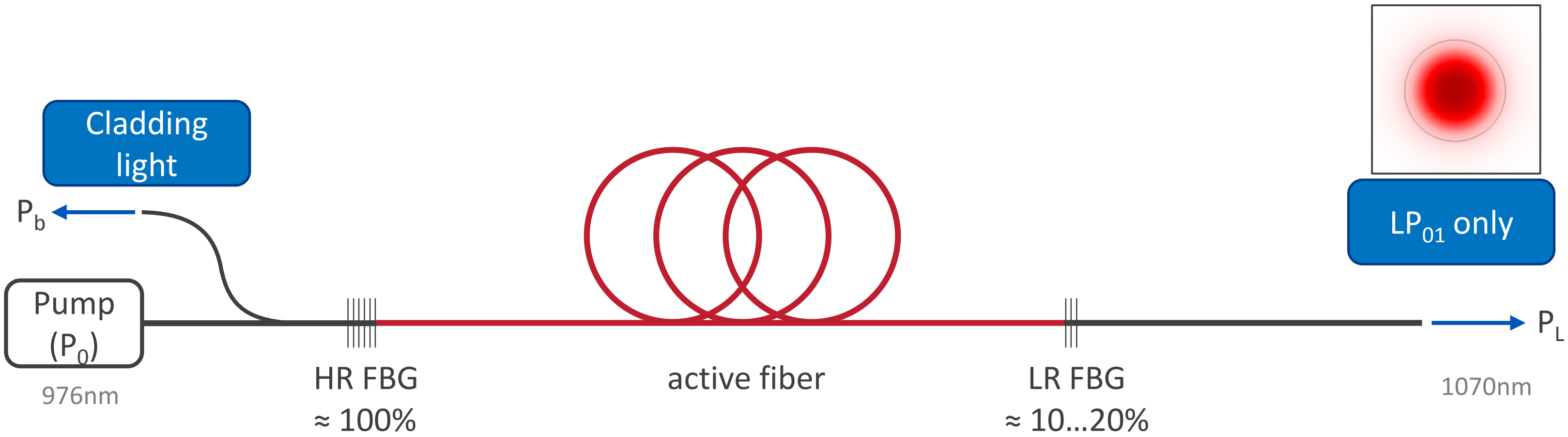
Standard version
up to 10000 W

CO_2 Lasers (DC series)



Diffusion-cooled CO_2 lasers
1000 – 8000 W

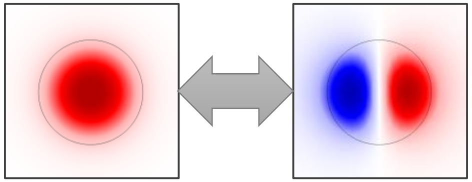
Fiber laser principle



Fiber laser (kW class):

- Active (pumped) fiber doped with Yb^{3+} ions
- Bragg gratings inscribed into fiber (FBGs) as mirrors
- Fiber is coiled to remove higher order modes

Motivation



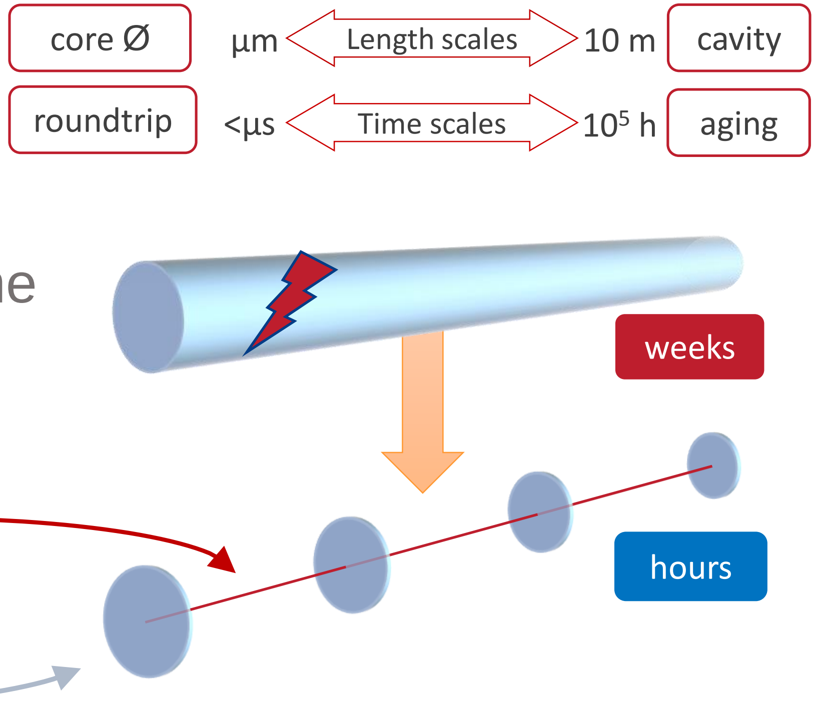
- Transverse Mode Instability (TMI)
  - Thermo-optical effect → energy transfer between fundamental and higher order
- Photodarkening (PD)
  - Increasing absorption over time (1000…100 000h)
  - Increasing heat load lowers TMI threshold → limits laser power

- It can take very long to observe the effect!

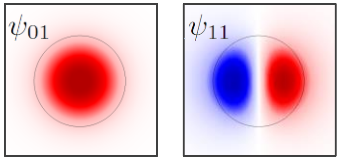
  → Reduce testing time by simulation

Multiscale Modeling

- Huge range of scales
- Full 3D simulation takes lots of time
- Separation of scales / dimensions
- Sequential 2D / 1D models



Modeling approach



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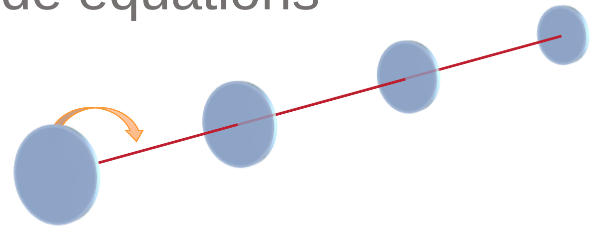
2D

1) Calculate mode shapes
2) Stationary inversion distribution
3) LP_{01} / LP_{11} gain and bend losses
4) Photodarkening over time (100.000 h)
5) Thermal profile and mode coupling

Interpolation functions $\alpha(P_p, P_{01}, P_{11}, t)$

1D

6) Coupled mode equations



Electromagnetic Waves Frequency Domain (ewfd)

Algebraic equations
Parametric Study

Heat Transfer in Solids (ht)

Model Coupling / Average Domain Probe

Coefficient Form PDE (c)

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Transverse Model – Gain

$$\frac{N_2(r,\varphi)}{N(r)} = \frac{I_p\nu_s\sigma_{ap} + I_s\nu_p\sigma_{as}}{I_p\nu_s(\sigma_{ap}+\sigma_{ep}) + I_s\nu_p(\sigma_{as}+\sigma_{es}) + h\gamma_{se}\nu_s\nu_p}$$

inversion

$$\alpha_{p,s} = -(\sigma_{es,p}+\sigma_{as,p})N_2(r,\varphi) + \sigma_{as,p}N(r)$$

local gain / absorption

$$\alpha_{01,11}^{eff} = \langle \psi_{01,11}^2(r,\varphi)\left(\alpha_s(r,\varphi)+\alpha_{PD}(r,\varphi)\right)\rangle$$

effective mode gain (scalar)

$$\langle \ldots \rangle = \frac{1}{\pi r_0^2}\int_0^{2\pi}\int_0^{r_0} \ldots r\,dr\,d\varphi$$

transverse average (integration coupling)

Cross sections σ_{xy}: x ϵ (absorption, emission), y ϵ (signal, pump), I_p, I_s: pump/signal intensity
Frequencies ν_y, spontaneous emission rate γ_{se}, h = Planck constant

Transverse Model – Photodarkening

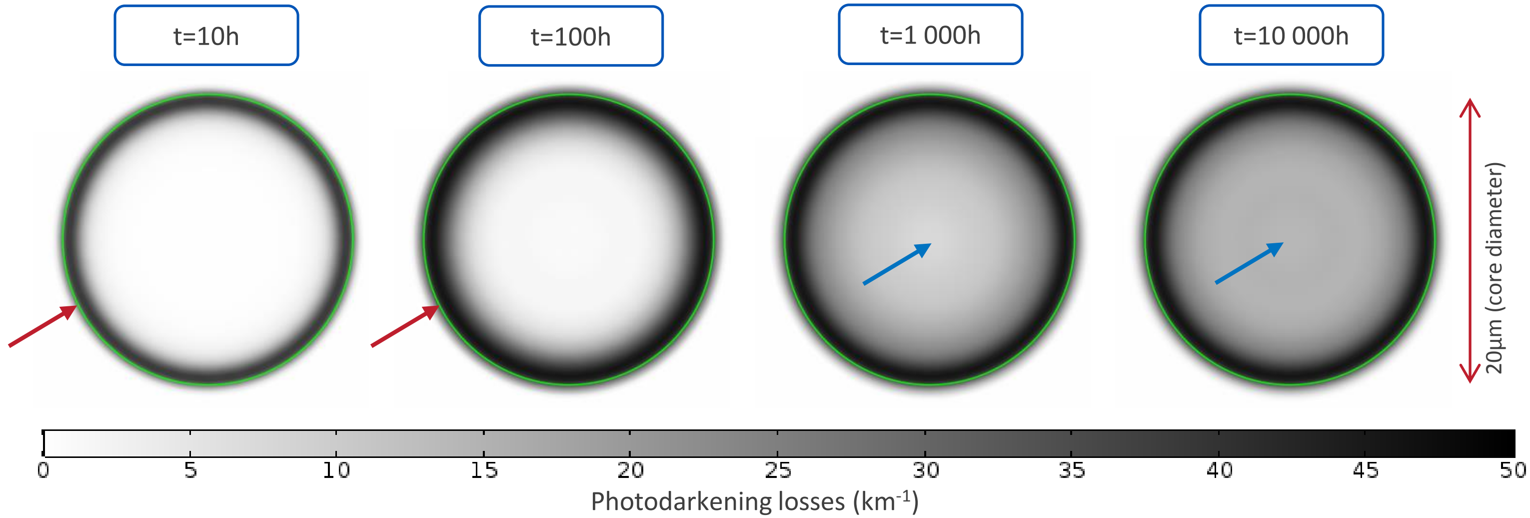
- Additional absorption
- Local description (r,φ,t)
- Time scale and saturated value depend on inversion

$$\alpha_{PD}(t) = \alpha_{sat}\left(1 - \exp\left(-(t/\tau)^{\beta}\right)\right)$$

$$\frac{1}{\tau} = \frac{1}{\tau_0}\left(\frac{N_2}{N}\right)^{C}$$

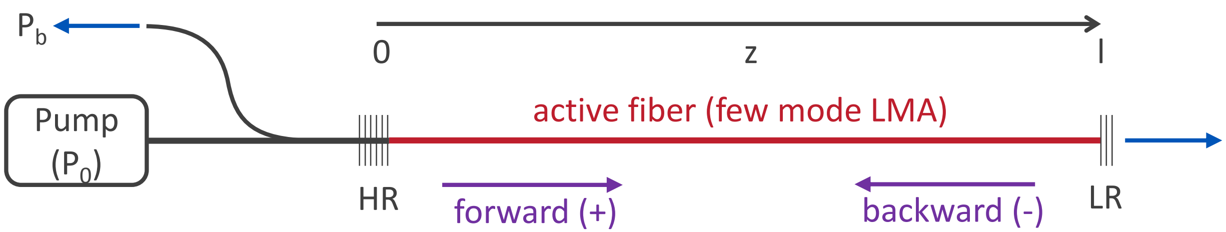
$$\alpha_{sat} = \frac{A}{\mu}\left(\frac{N}{N_{ref}}\right)^{S \frac{N_2/N}{0.46}}$$

Virtual Aging of the Fiber



- Higher inversion at the core edge
- PD starts and saturates quickly at core edge
  - Slower aging in the center
  - Saturated value lower in the center

Longitudinal Model

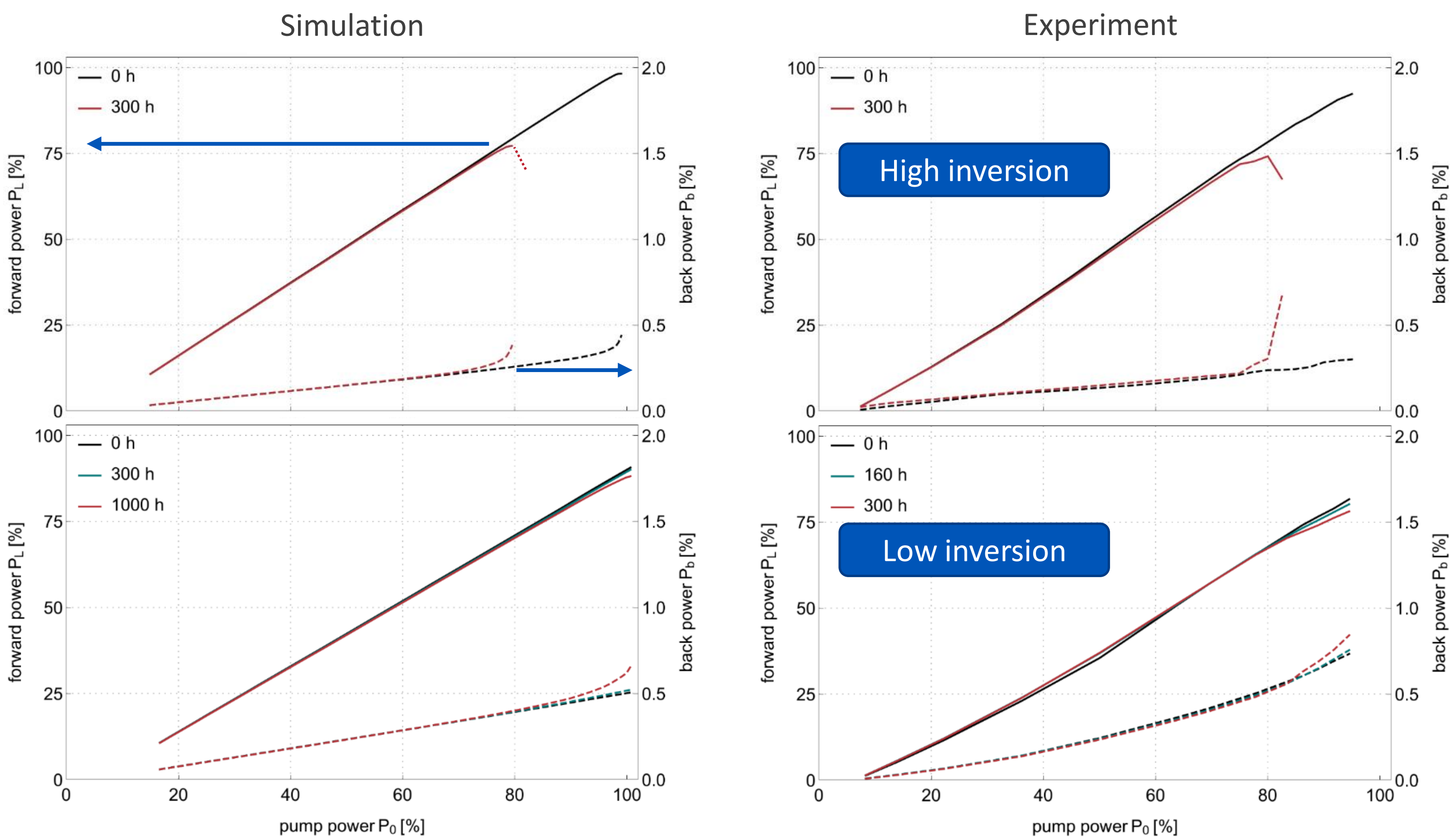


$$P_L = (1 - \rho_{LR}) P_{01}^{+}(z = l)$$

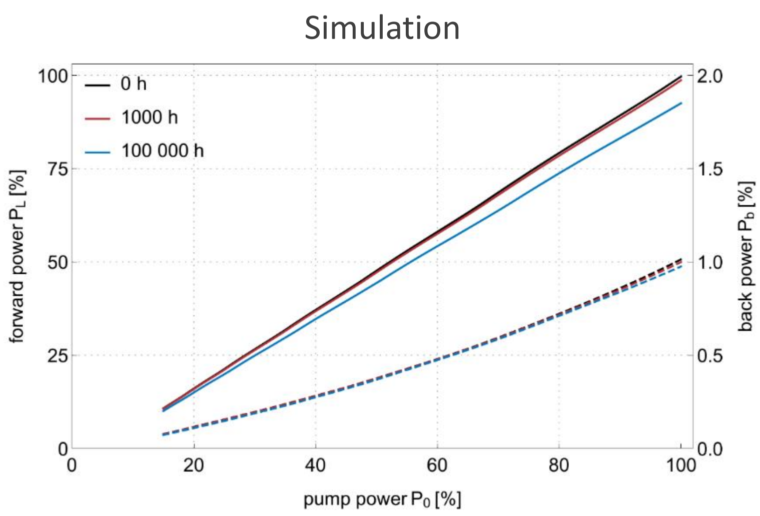
Scalar coefficients:

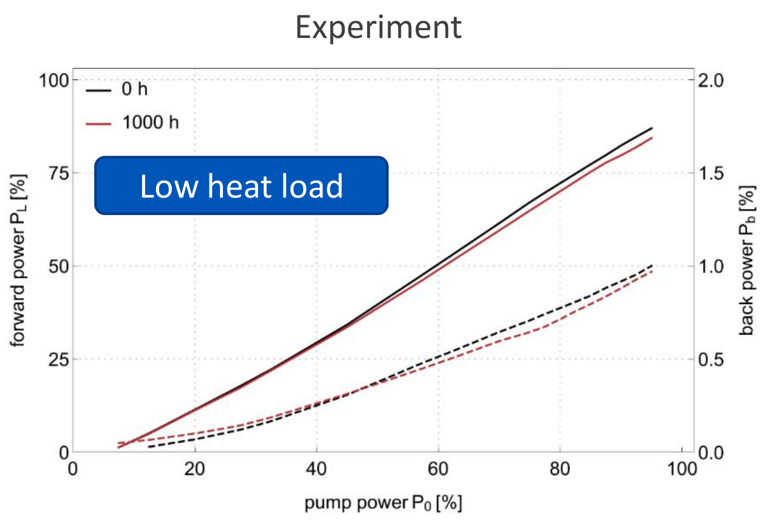
pump power	$$\frac{\partial}{\partial z} P_p = -\alpha_p^{eff} P_p \,,$$	pump absorption
LP_{01} ($A_{01}^2 = P_{01}$)	$$\pm \frac{\partial}{\partial z} A_{01}^{\pm} = -\frac{\alpha_{01}^{eff}}{2} A_{01}^{\pm} - \gamma_{MC}^{eff} A_{11}^{\pm} \,,$$	signal gain (LP_{01} and LP_{11})
LP_{11} ($A_{11}^2 = P_{11}$)	$$\pm \frac{\partial}{\partial z} A_{11}^{\pm} = -\frac{\alpha_{11}^{eff}}{2} A_{11}^{\pm} + \gamma_{MC}^{eff} A_{01}^{\pm} - \frac{\alpha_{BL}}{2} A_{11}^{\pm}$$	mode coupling LP_{01} ⇔ LP_{11}
cladding	$$\pm \frac{\partial}{\partial z} P_c^{\pm} = \alpha_{BL} P_{11}^{\pm}$$	bend losses LP_{11} ⇨ cladding

Validation: Power Ramps



Validation: Power Ramps





- With optimized design (reduced heat load and inversion) no mode instability is observed
- Simulation predicts desired linear power curve even after 100 000 h of operation

Summary

- Multiscale model and numerical scheme for virtual long term testing of high-power fiber lasers

- TMI threshold and long-term degradation well predictable
- Simulation of 100 000h laser operation in only a few hours
- Fast testing of design variants

THANK YOU FOR YOUR ATTENTION

QUESTIONS?

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