Thin Disk based MOPA – numerical modeling and experimental results
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Outline

− Thin disk concept
− 200 kW MOPA concept
− Test of the concept in the lab
− Numerical model
− Outlook
Thin Disk concept

- Core idea: thin active material, one face cooled, used as active mirror
- thickness 0.1 – 1 mm, diameter 5 – 45 mm
- Heat flow parallel to laser beam
- Minimized thermal lens
- High output power and high efficiency simultaneously
- Power / energy scaling by scaling of pump spot area (power / energy densities and temperatures constant)
- variety of active materials
Power scalability

5.3 kW out of one disk / 20 kW with four disks

extracted volume power density > 600 kW/cm³

New high power disk module, common development of ITP and industrial partner

Courtesy TRUMPF Laser Schramberg

Courtesy Dausinger und Giesen GmbH
Concept of Neutral Gain Modules *
V-shaped resonator with 2 Relay NGMs and AO

\[ M_{x,y}^2 = 2.43, 2.91 \]

output power \( P_{\text{out}} \) (W)

pump power \( P_p \) (kW)

\[ B = 21 \frac{\text{GW}}{\text{cm}^2 \text{ sr}} \]

\[ P_{\text{out}} = 1534 \text{ W} \]

diffraction limited:
\[ P_{\text{out}} = 1.5 \text{ kW} \]
\[ M^2 = 1 \]
\[ \rightarrow B = 141 \frac{\text{GW}}{\text{cm}^2 \text{ sr}} \]

* J. Mende et. al., Concept of Neutral Gain Modules for Power Scaling of Thin-Disc Lasers, Applied Physics B, 97 (2), 2009
- Pump spot diameter, pump power and power densities similar to actual commercially used systems!

- Control of beam quality more simple than in resonator (lower power densities, linear accumulation of phase distortions, no feedback)
MOPA system aspects

System requirements:

- 200 kW output – 500 kW diode power / 1 MW electrical power
- Engagement ~ 50 s
- rechargeable battery pack: 400 – 600 kJ/kg
- 2 m³ of water (temperature rise ~ 5 K, i.e. wavelength shift 1.5 nm)
- (fibre coupled) pump modules: 1 kW / kg, 1 MW / m³

< 4000 kg & < 4 m³ for 500 kW pump power
Test of MOPA concept

Stable resonator
~ 1.5 kW
$M^2 < 3$

> 15 kW output
Test of MOPA concept

10.5% Yb:YAG, 140 µm thick
24 pump passes
20 amplification passes
1.2 cm pump spot diameter
Oscillator 360 W, $M^2 \sim 3$

Loss analysis:
~ 0.7% round trip loss

Latest tests with increased oscillator power: 2070 W
Test of MOPA concept - numerical modeling

\[ \dot{N}_2 = Q - S - \frac{N_2}{\tau} \equiv 0 \]

\[ S = \frac{\lambda_{osc}}{2\pi\hbar c} \frac{P_{osc}}{\pi r_{osc}^2 h} \left( \exp\left( m_{amp} \gamma_{osc} h \right) - 1 \right) \]

\[ Q = \frac{\lambda_p}{2\pi\hbar c} \frac{P_{pump}}{\pi r_{pump}^2 h} \left( 1 - \exp\left( -m_p \alpha_p h \right) \right) \]

\[ P_{out} = P_{osc} \exp\left( m_{amp} \gamma_{osc} h \right) \]

\[ \alpha_p = \sigma_{abs}(T)N_0 - \sigma_{abs}(T)(1 + f_{em}(T))N_2 \quad \gamma_{osc} = \sigma_{em}(T)(1 + f_{abs}(T))N_2 - \sigma_{em}(T)f_{abs}(T)N_0 \]

\[ f_{abs}(T) = \frac{Z_2}{Z_1} \exp\left( \frac{2\pi\hbar c_{vac}}{\lambda k_B T} \right) \quad f_{em}(T) = \frac{Z_1}{Z_2} \exp\left( -\frac{2\pi\hbar c_{vac}}{\lambda_p k_B T} \right) \]
Amplified spontaneous emission (ASE)

\[ \dot{N}_2 = Q - S - \frac{N_2}{\tau} - \int \int \gamma_\lambda \Phi_{\lambda,\Omega} d\lambda d\Omega \]

Photon flux density from a volume element at position \( \vec{s} \)

\[ d\Phi_\lambda(\vec{s}) = \beta_\lambda \frac{N_2(\vec{s})}{\tau} \frac{1}{4\pi s^2} G_\lambda(\vec{s}) dV \]

Requirement for model:
No back reflection from outer edges, e.g. by absorbing cladding
Test of MOPA concept

10.5% Yb:YAG, 140 µm thick
24 pump passes
20 amplification passes
1.2 cm pump spot diameter

Pump spectra from experiment

Temperatures calculated using established model
Influence of doping concentration on achievable gain

- doping-dependent, non linear loss
- additional heat generation
- intrinsic effect?
- generation of charge transfer band?
- enhanced by impurities!

M. Larionov et al., *Nonlinear Decay of the Excited State in Yb:YAG*, ASSP 2005, Vienna
Test of MOPA concept – modified rate equation

\[
\dot{N}_2 = Q - \frac{N_2}{\tau} - \gamma_{osc} \Phi_r - \int \int \gamma \Phi,\Omega \, d\lambda d\Omega - k_\Sigma N_2^2
\]

10.5% Yb:YAG, 140 µm thick
24 pump passes
20 amplification passes
1.2 cm pump spot diameter

Pump spectra from experiment

Temperatures calculated using established model

\[ k_\Sigma = 64 \cdot 10^{-20} \text{ cm}^{-3} \]
Summary & Outlook

- Thin Disk based Master Oscillator Power suitable for 200 kW with actual available components
- Auxiliary components (power, cooling) strongly dependent on engagement scenario
- Concept experimentally proven (~ 2 kW)
- Demonstration of > 5 kW, M² < 10 planned for May / June 2013 with external partner
- Demonstration of ~ 5 kW, M² < 5 end of 2013 with improved multipass setup