Novel trends in semiconductor-laser pumped rare-earth-doped solid-state lasers

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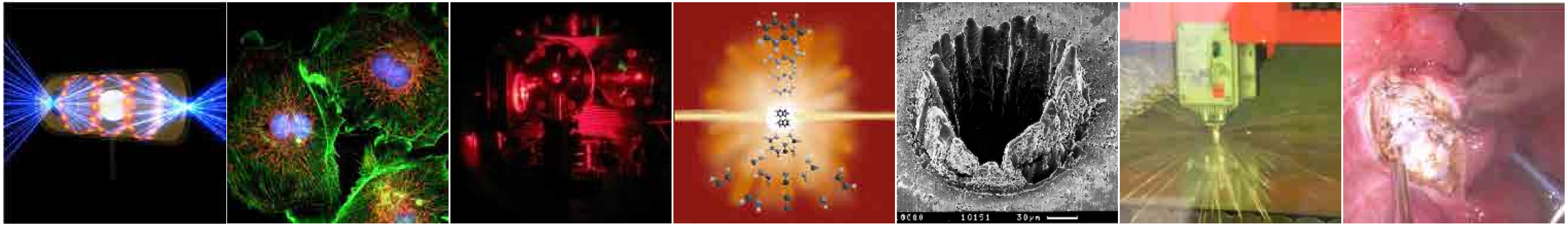
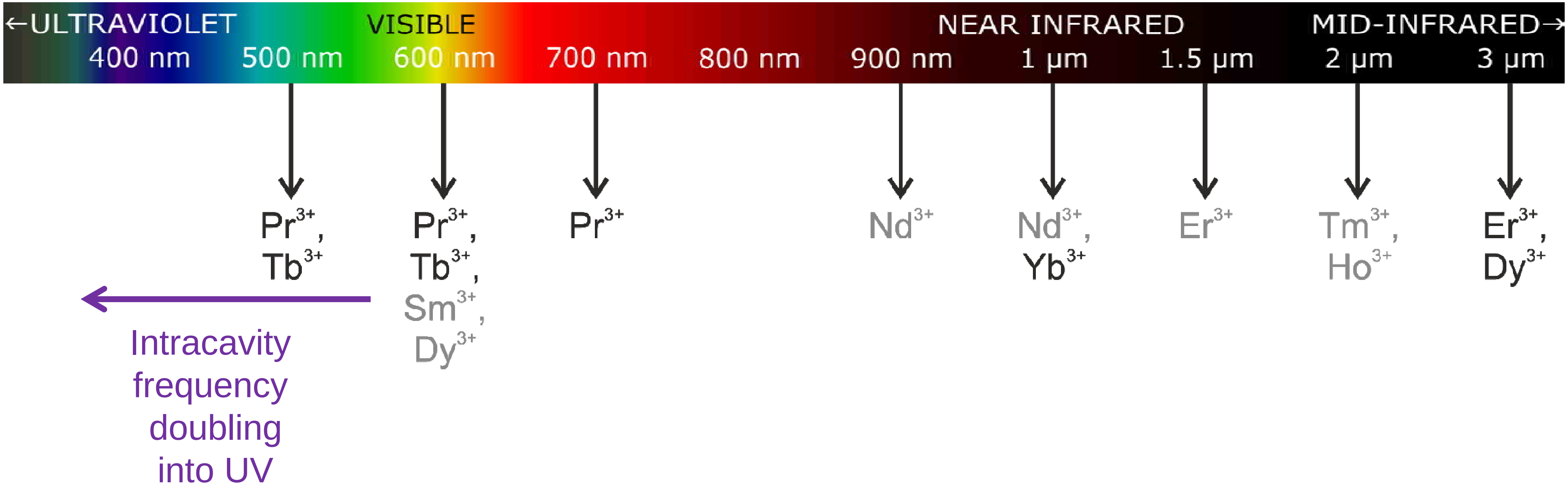
Buchs, Switzerland, 12.02.2017

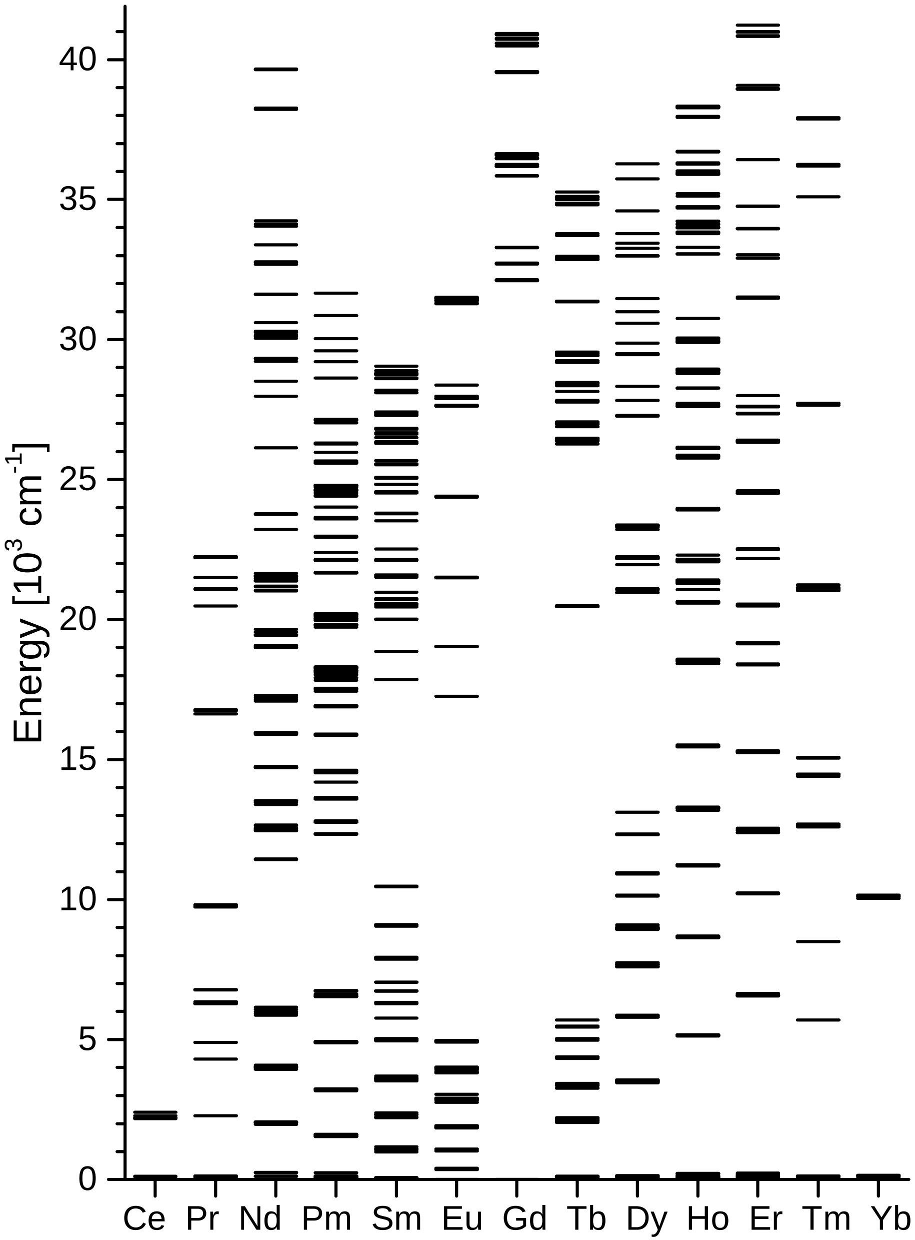
Introduction

Applications of lasers



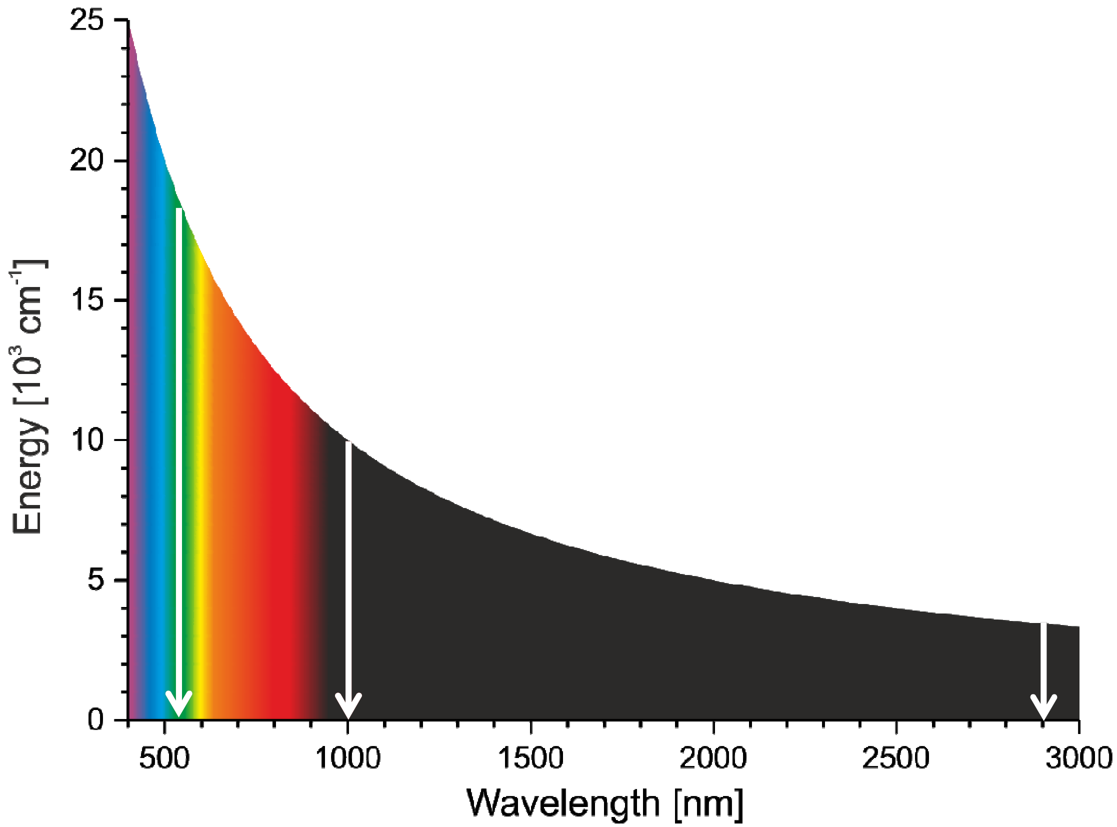


Introduction



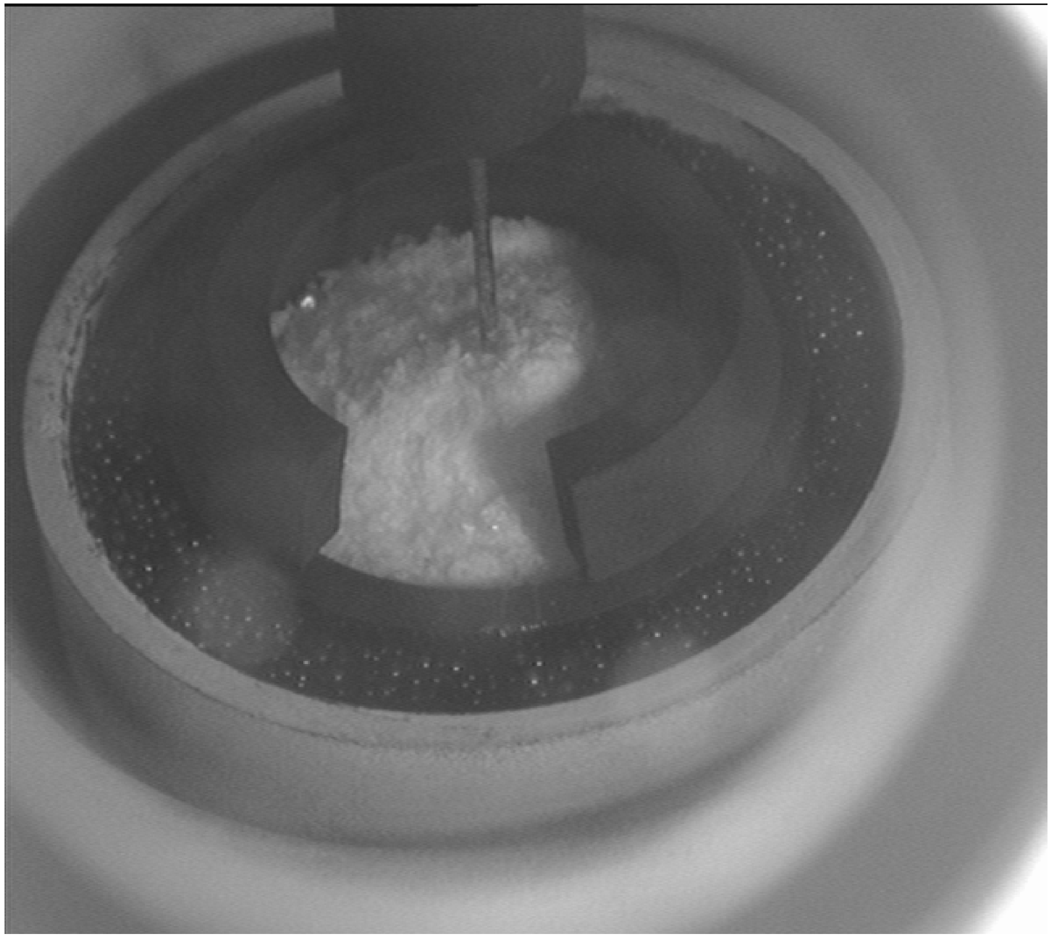
Rare earth ions in the Diecke diagram

- *4f* energy levels of all trivalent rare earth ions in $LaCl_3$
- *4f* shell shielded by 5*s* and 5*d* shells: characteristic spectroscopic fingerprint for each rare earth ion



Introduction

Czochralski-growth for fluoride and oxide laser crystals



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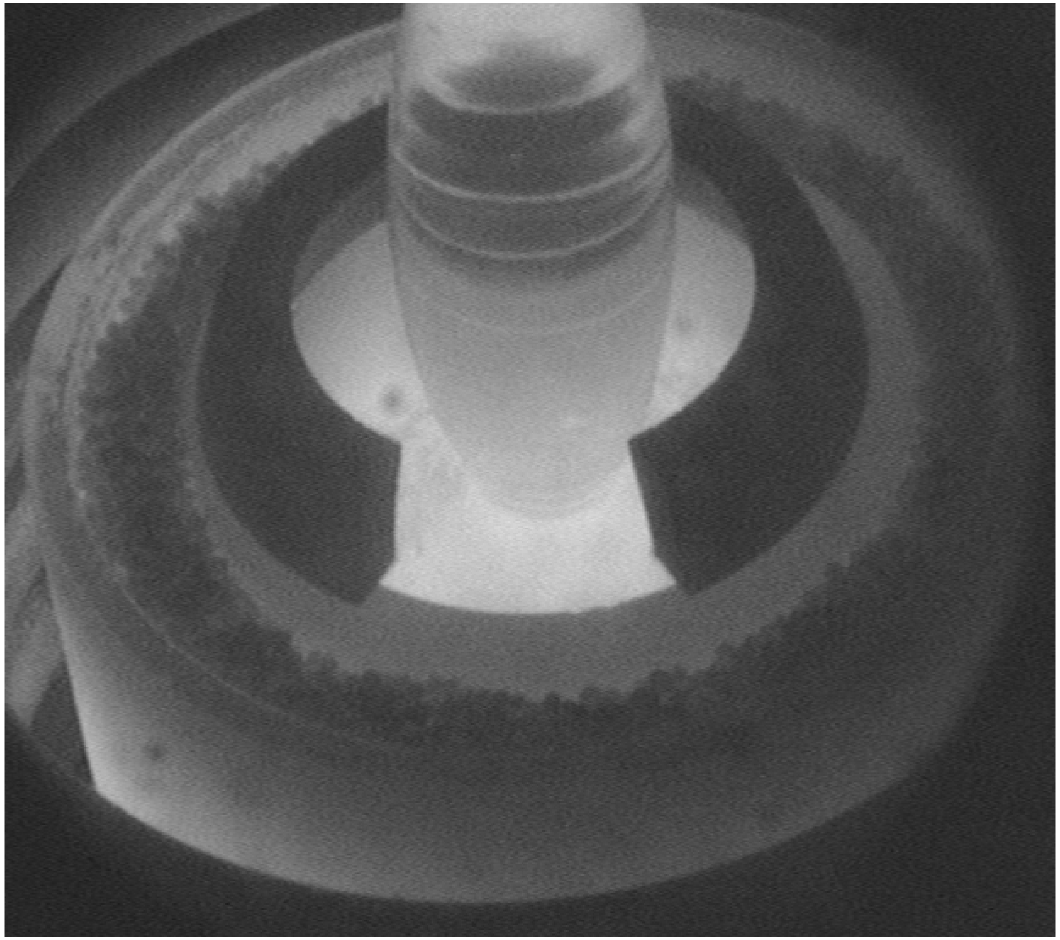
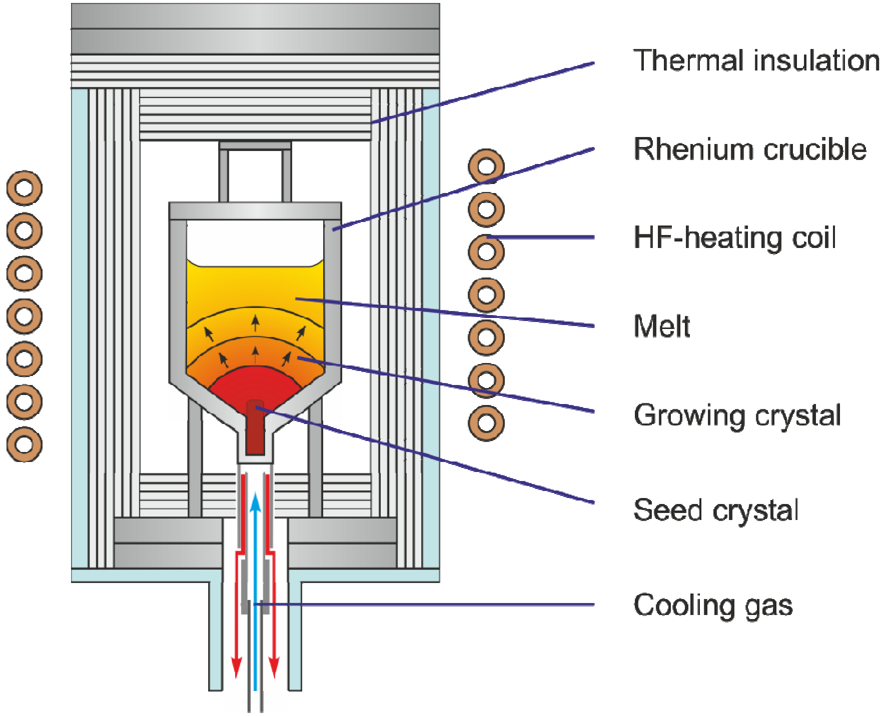
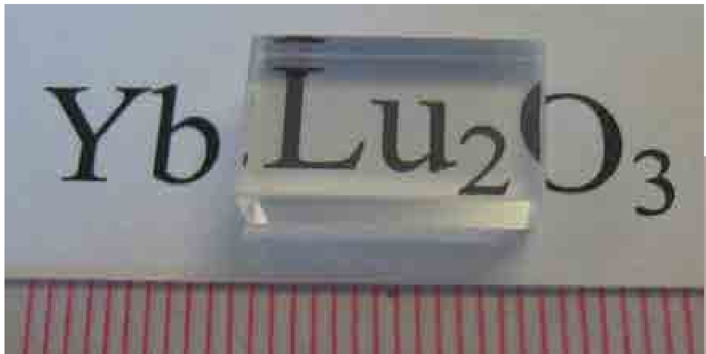
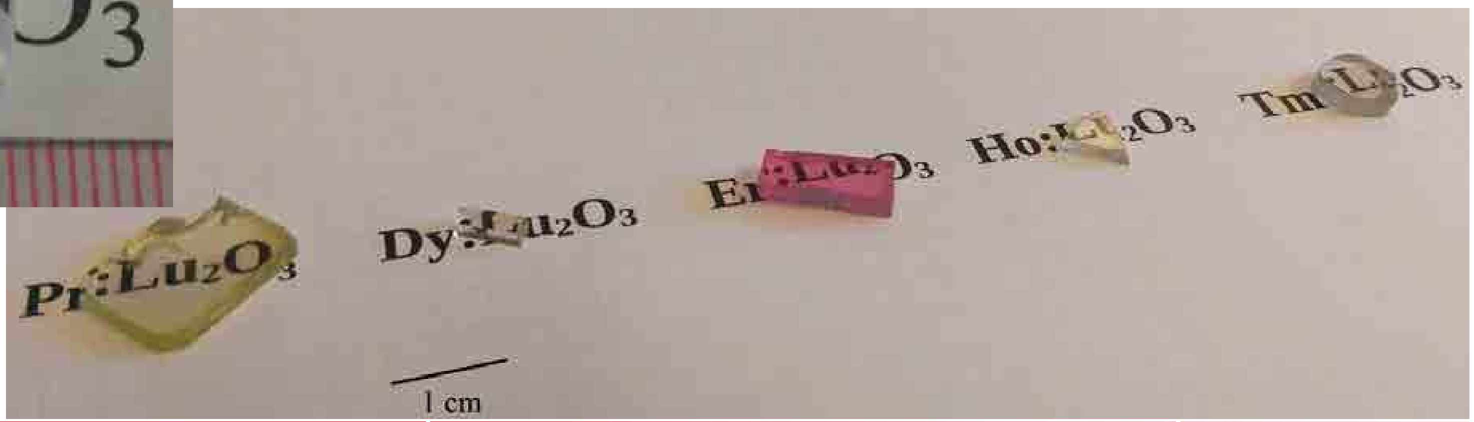


Growth by the heat exchanger method (HEM) for cubic sesquioxides

- Melting points exceeding 2400 °C make crystal growth very demanding
- Rhenium is the only suitable crucible material
- Precise control of growth atmosphere (very low O_2-partial pressure)







R. Peters, C. Kränkel, et al., J. Cryst. Growth **310** (7-9), 1934-1938 (2008)

Introduction

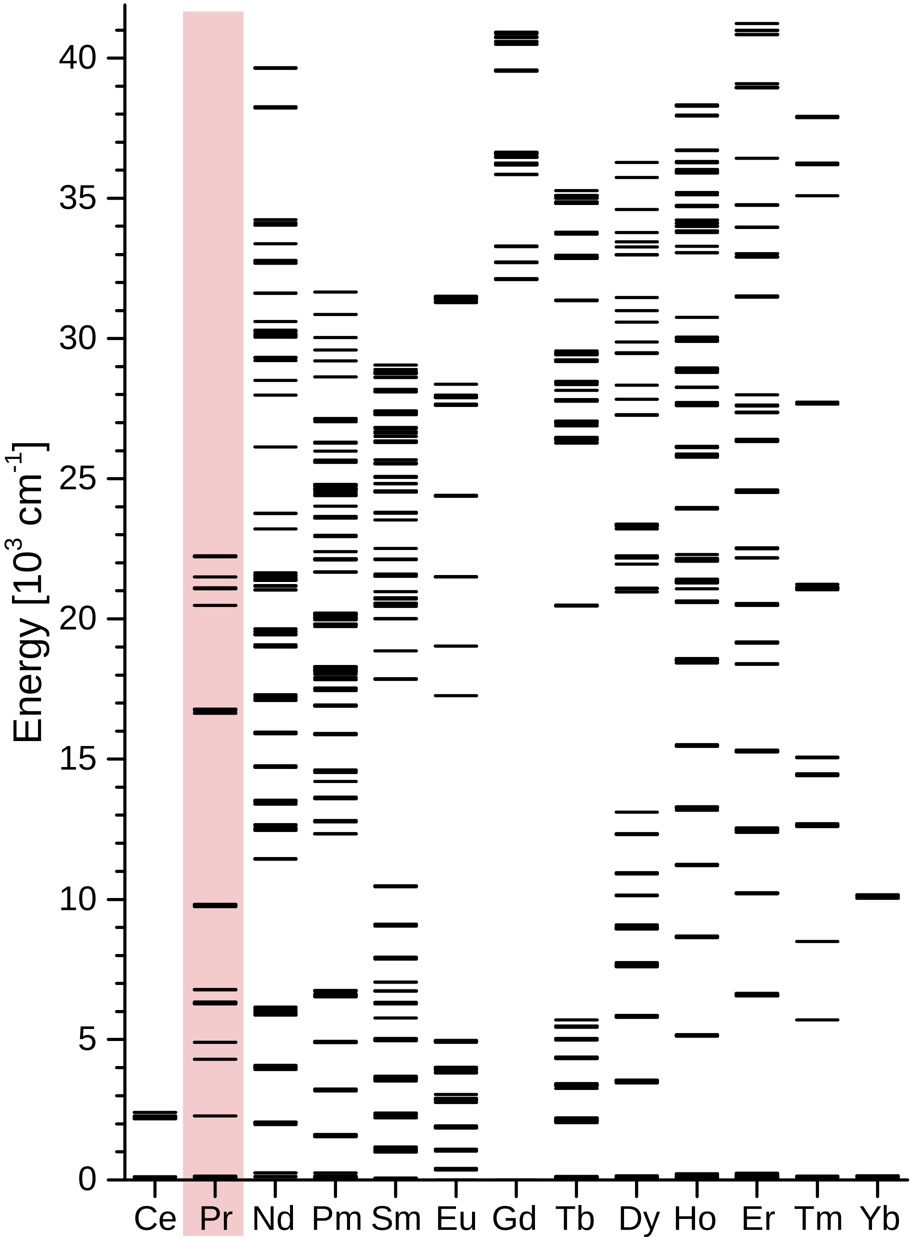
Influence of the host material on the laser properties

Issue	Requirement for the host material
Parity forbidden 4*f*-4*f*-transitions	Acentric site symmetry
Non-radiative decay of mid-IR transitions	Low phonon energy host materials
Broad gain spectrum for fs-pulses	Disordered host or multiple RE^{3+}-sites
Thermal management of high power lasers	Good thermal conductivity
Need for particular laser wavelength	Crystal field shifts emission to required value

These requirements cannot be fulfilled by only one host material!

Outline

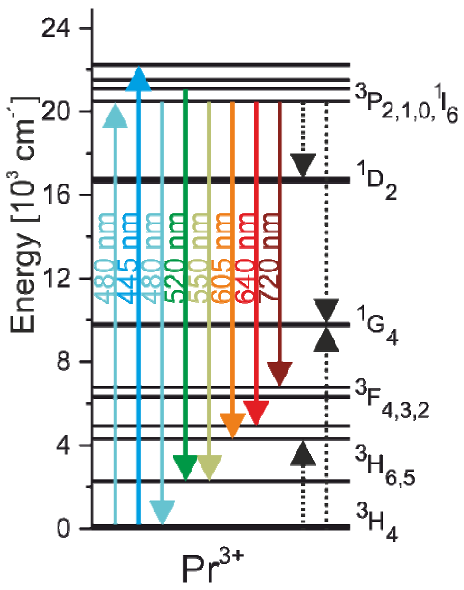
- Introduction
- Visible lasers based on Pr^{3+}
- Mid-IR lasers based on Er^{3+} and Dy^{3+}
- High intracavity power lasers based on Yb^{3+}
- Pulsed waveguide lasers based on Yb^{3+}
- Conclusion

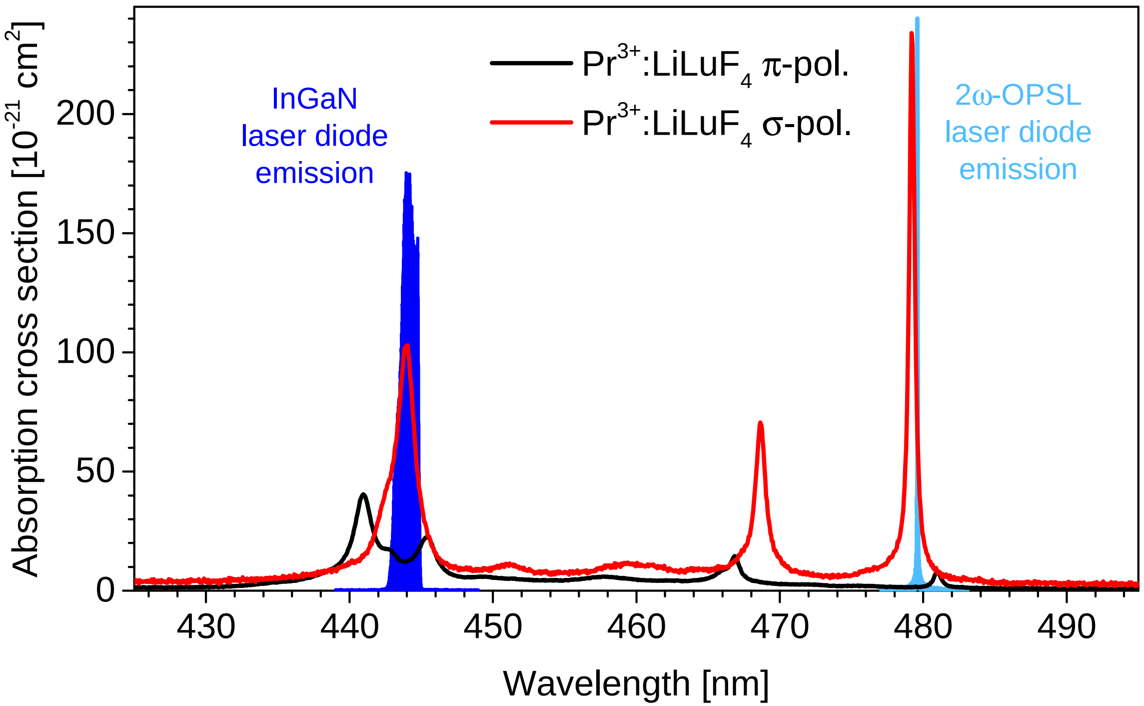


Visible lasers based on Pr^{3+}

Visible lasers based on Pr^{3+}

Absorption cross sections of Pr^{3+}



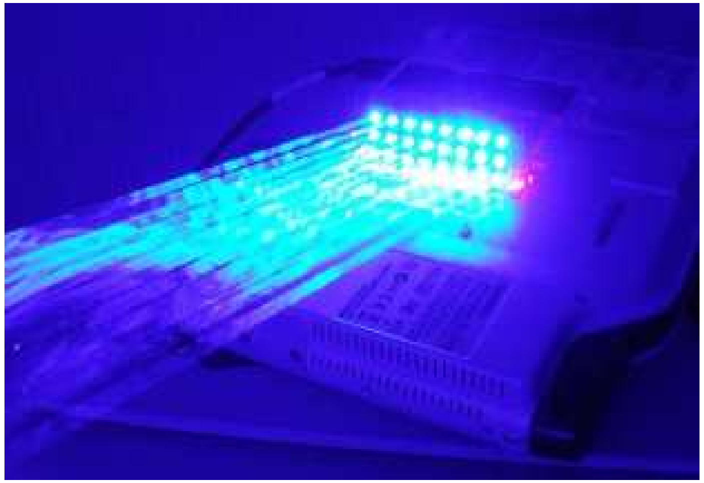


- Broad absorption at 445 nm → suitable for InGaN-laser diode pumping
- ZPL absorption around 480 nm → suitable for pumping with 2w-OPSL

Blue-emitting pump sources for Pr^{3+}-lasers

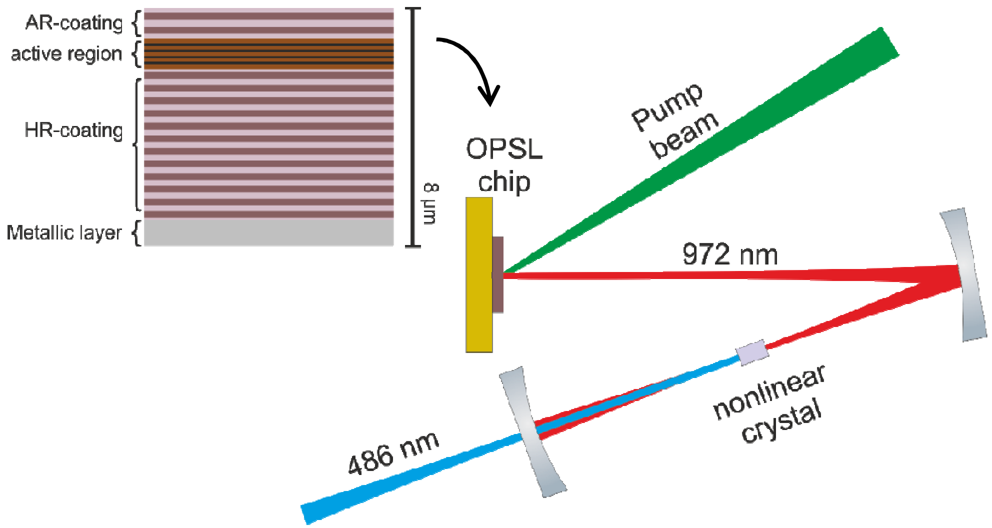
InGaN-laser-diodes at ≈ 450 nm

- Applications in BluRay, projectors and headlamps drive development
- Up to 3.5 W per emitter available



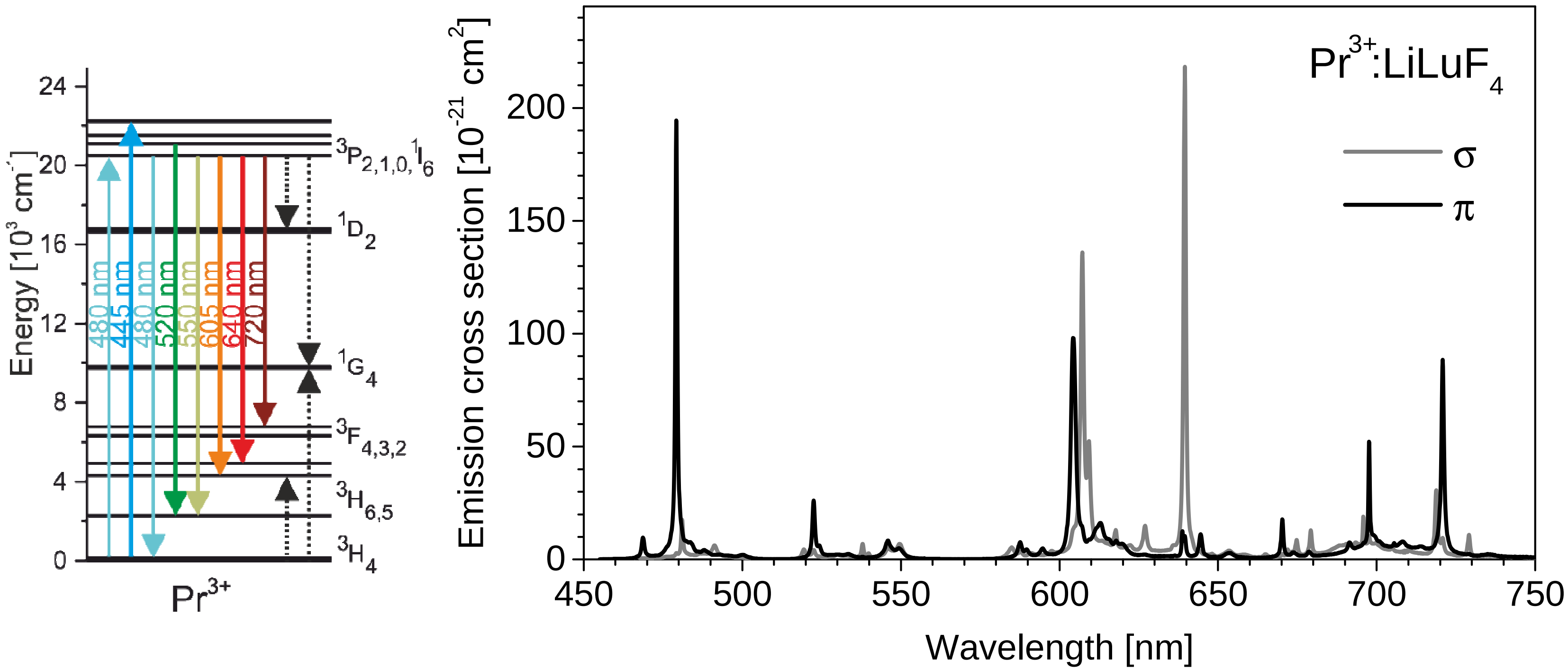
Frequency doubled InGaAs-based optically pumped semiconductor lasers (2w-OPSL)

- InGaAs disk laser at ≈ 970 nm
- Intracavity frequency doubled to ≈ 486 nm
- >5 W of output power with excellent beam quality commercially available



Visible lasers based on Pr^{3+}

Stimulated emission cross sections of Pr^{3+}



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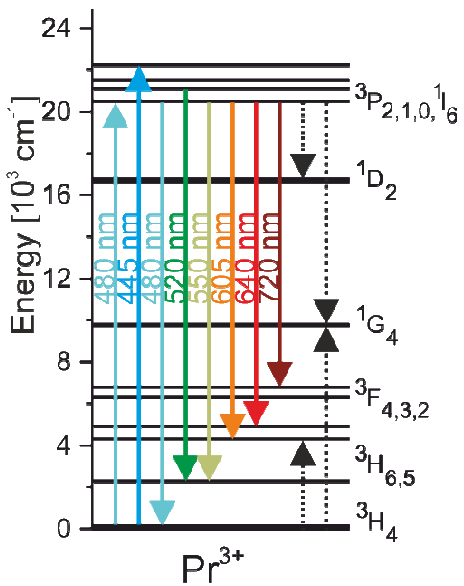
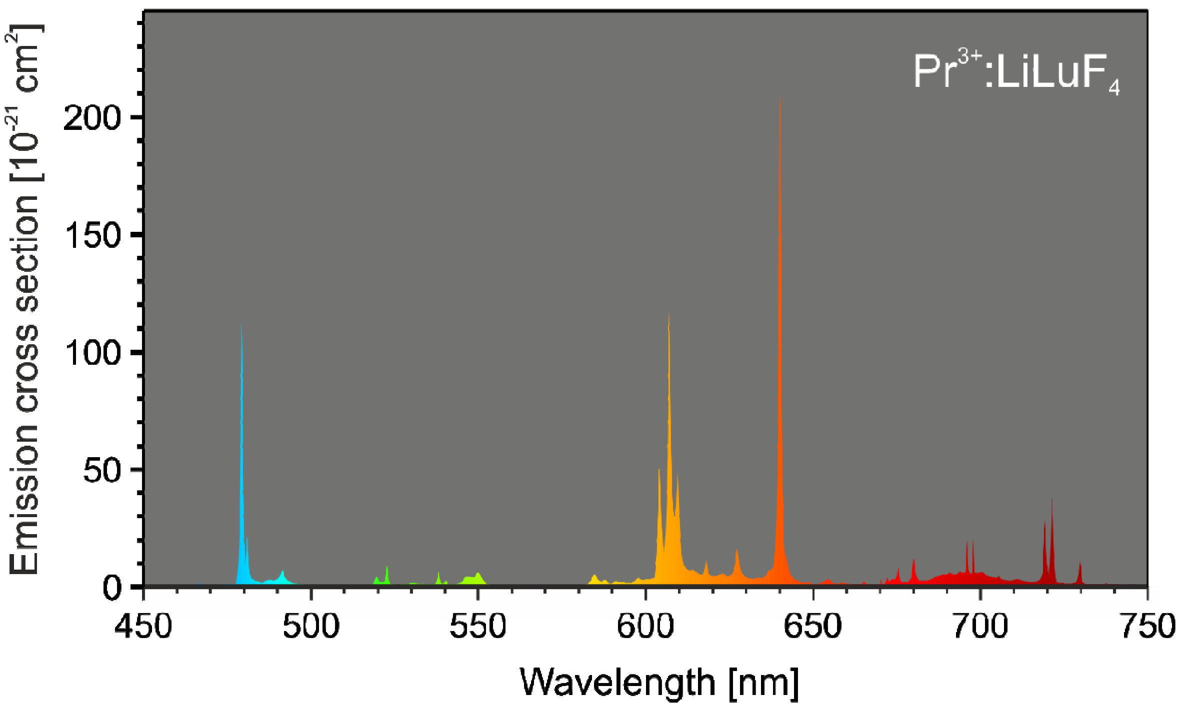


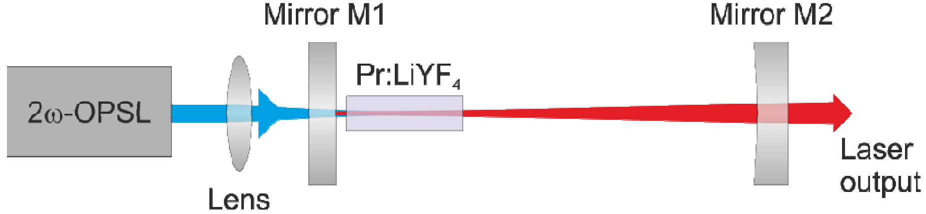


- Pr^{3+} exhibits emission cross sections throughout the whole visible range
- Emission cross sections similar to those of Nd:YAG at 1064 nm
- True 4-level-laser schemes at green, orange, red and deep-red transitions
- Cross relaxation negligible at doping concentrations < 0.5%

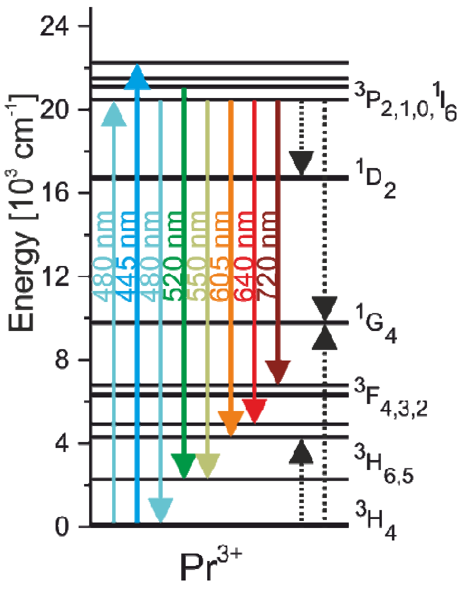
Visible lasers based on Pr^{3+}

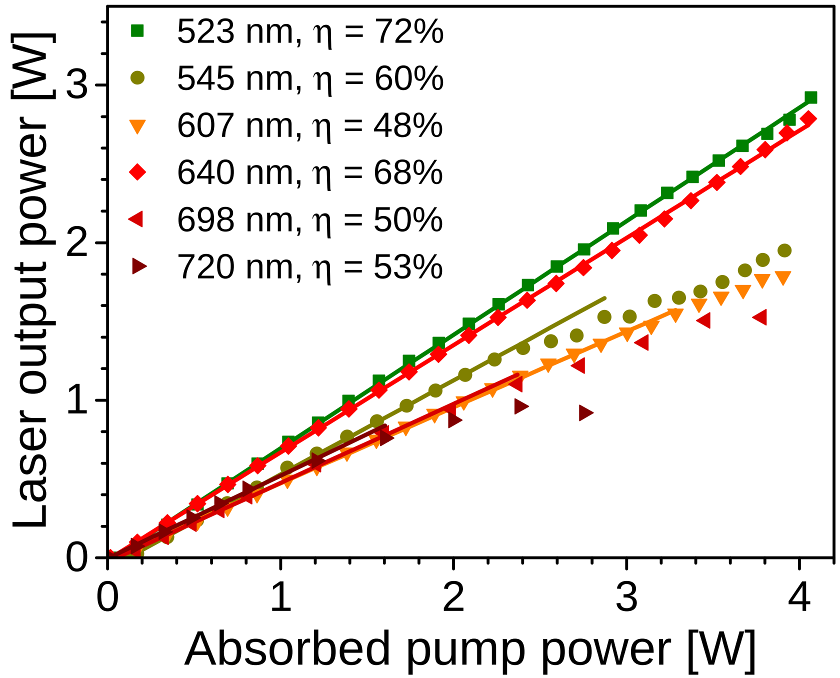
2w-OPSL-pumped visible cw lasing with $Pr^{3+}:LiYF_4$

- Up to 5 W of pump power at 480 nm
- Nearly 3 W of visible output
- Optical-to-optical efficiencies >60%



Pr^{3+} is "the Nd^{3+} of the visible"

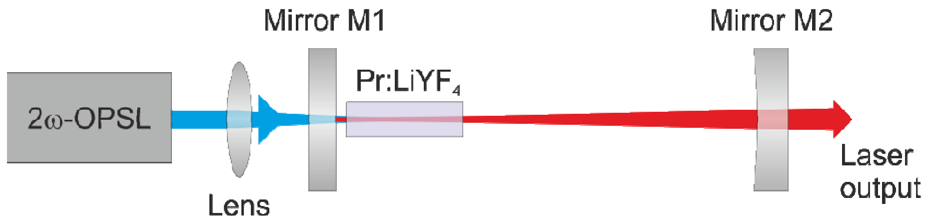


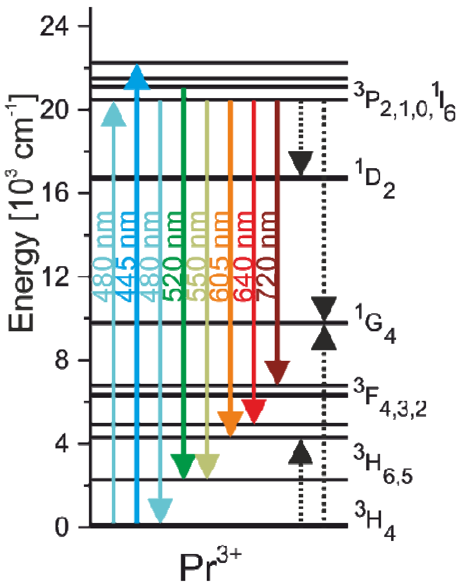


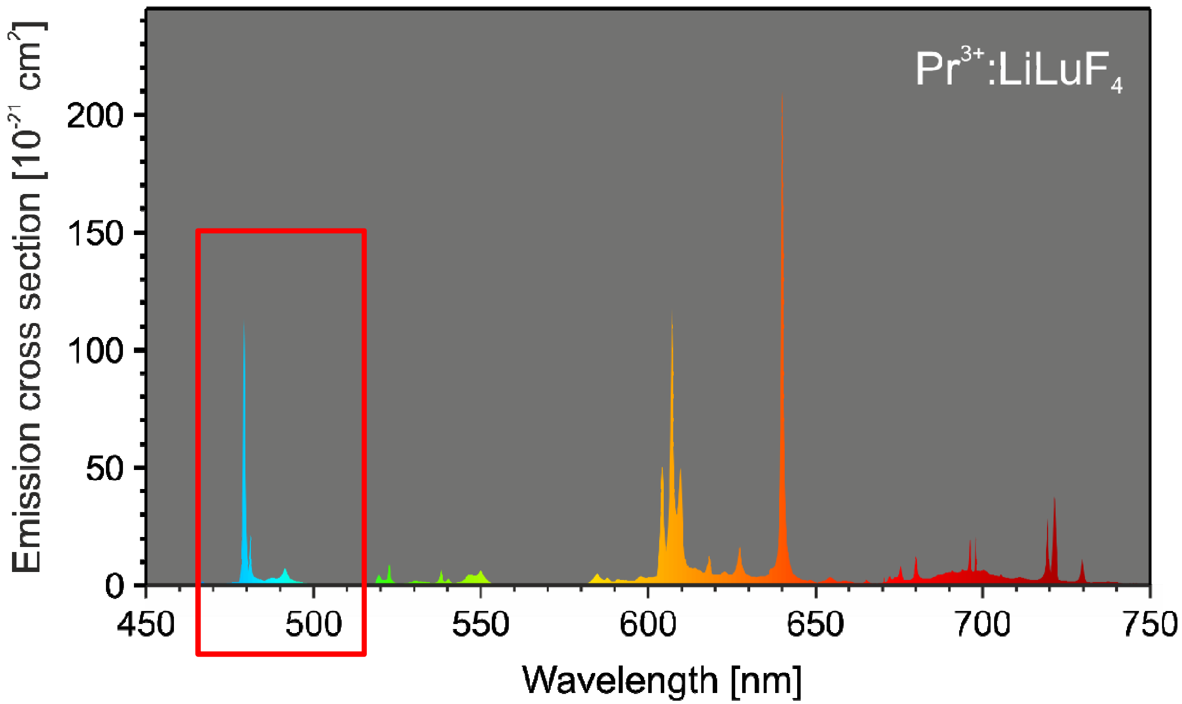
P. W. Metz, C. Kränkel, G. Huber, *et al.*, Opt. Lett., **39** (11), 3193-3196 (2014)

Visible lasers based on Pr^{3+}

2ω-OPSL-pumped **blue** cw lasing with $Pr^{3+}:LiYF_4$





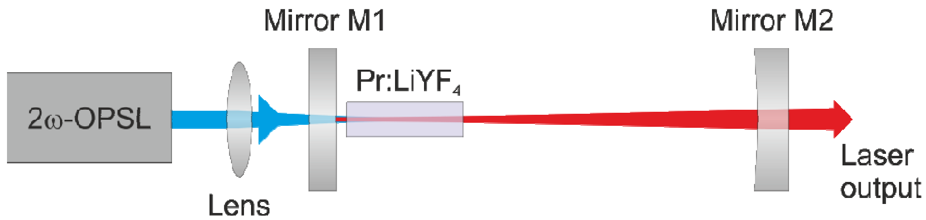


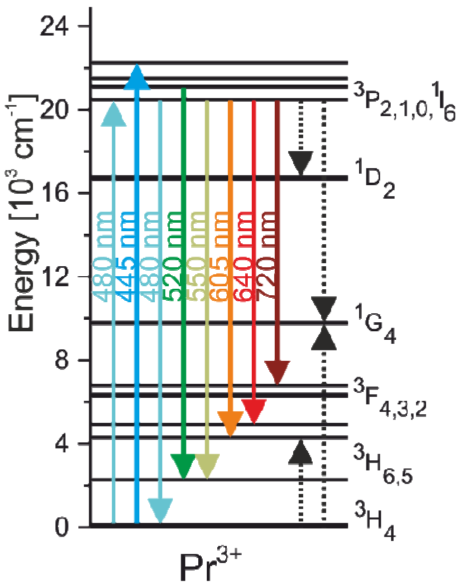
P. W. Metz, C. Kränkel, G. Huber, *et al.*, Opt. Lett., **39** (17), 5158-5161 (2014)

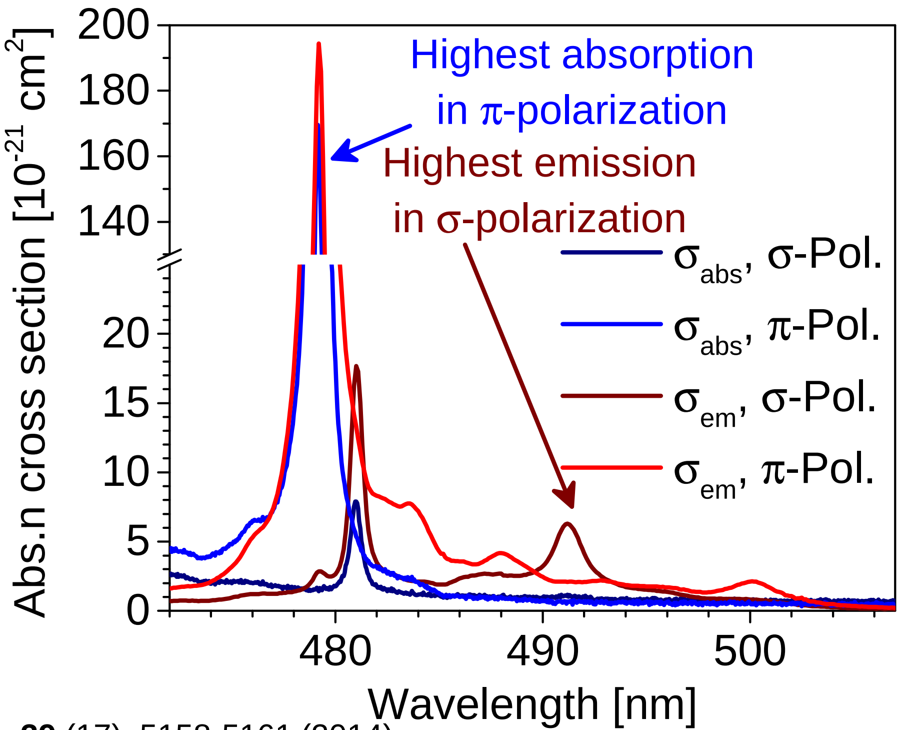
Visible lasers based on Pr^{3+}

2ω-OPSL-pumped blue cw lasing with $Pr^{3+}:LiYF_4$

- 491 nm emission is polarized perpendicular to 480 nm absorption







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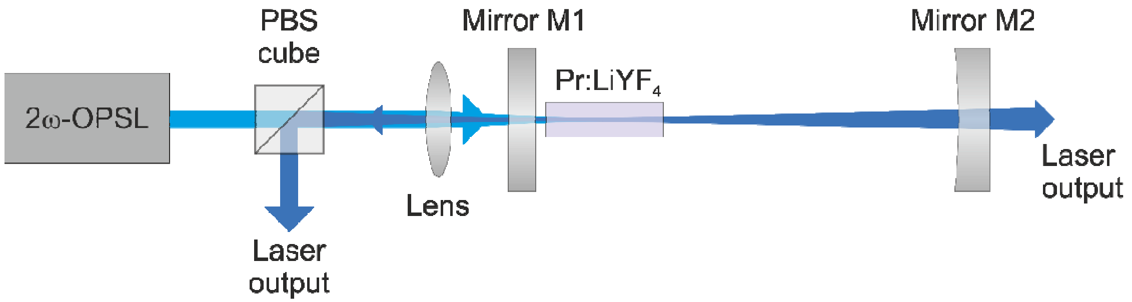
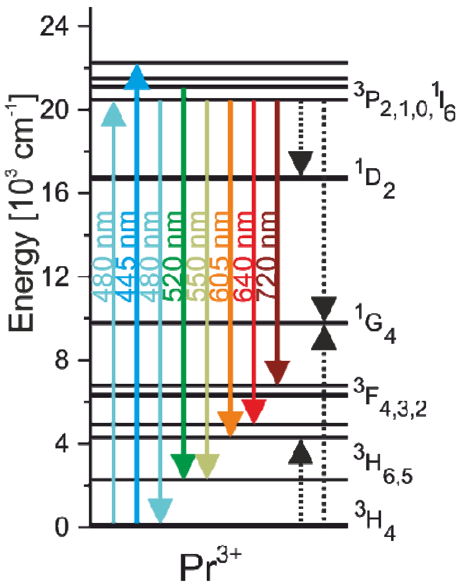
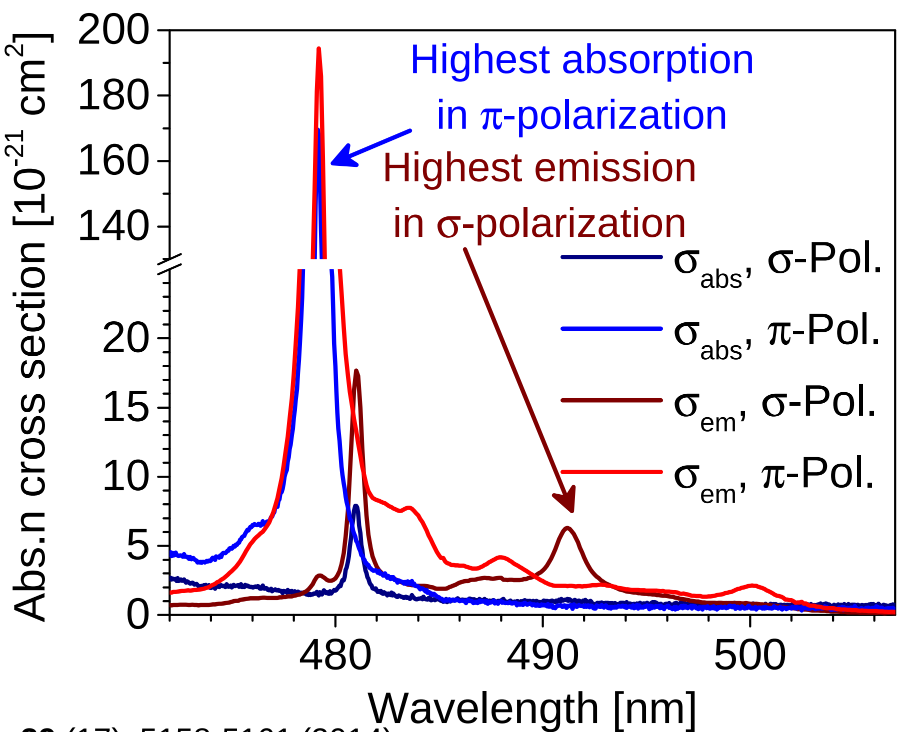
Visible lasers based on Pr^{3+}

2ω-OPSL-pumped blue cw lasing with Pr^{3+}:$LiYF_4$

- 491 nm emission is polarized perpendicular to 480 nm absorption
  → Outcoupling via PBS cube







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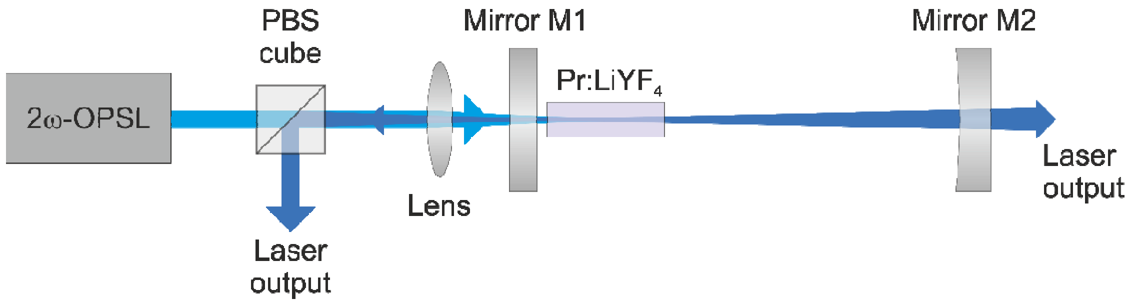

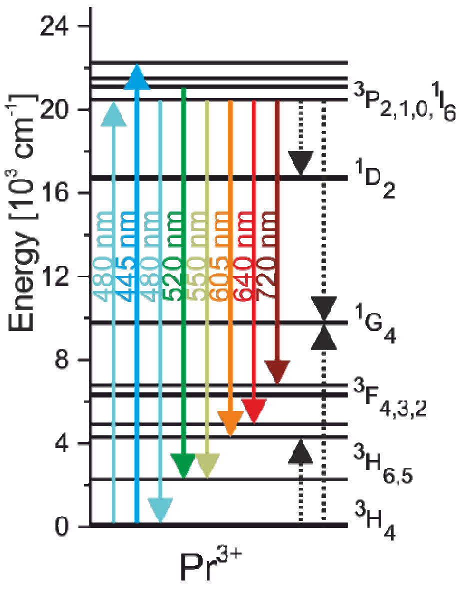

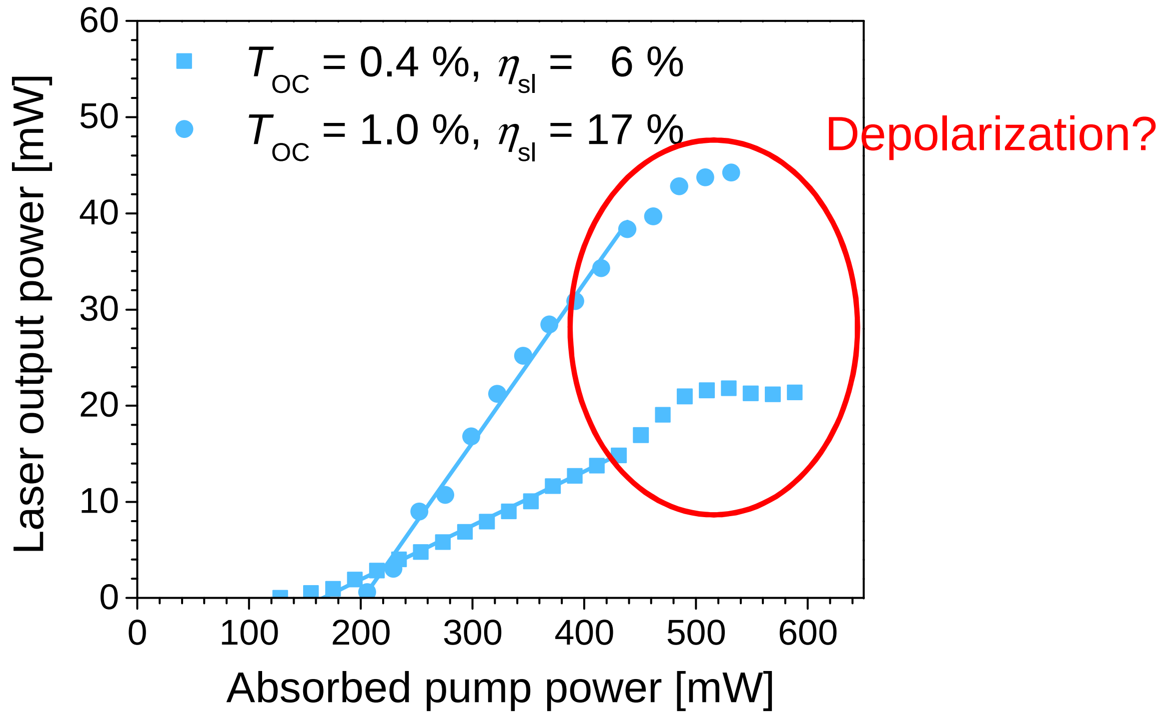

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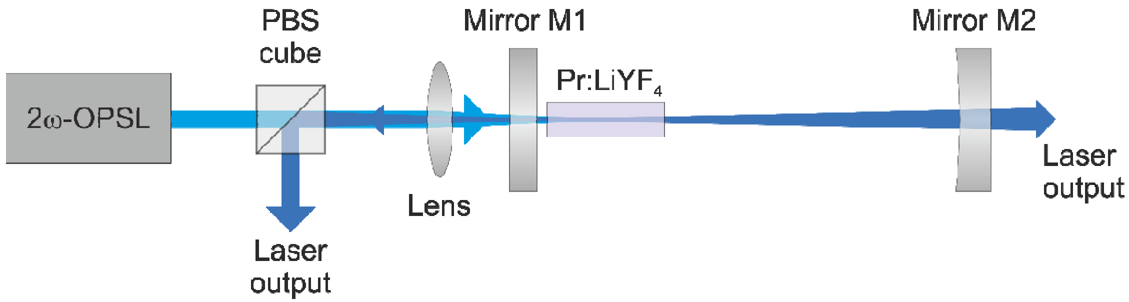
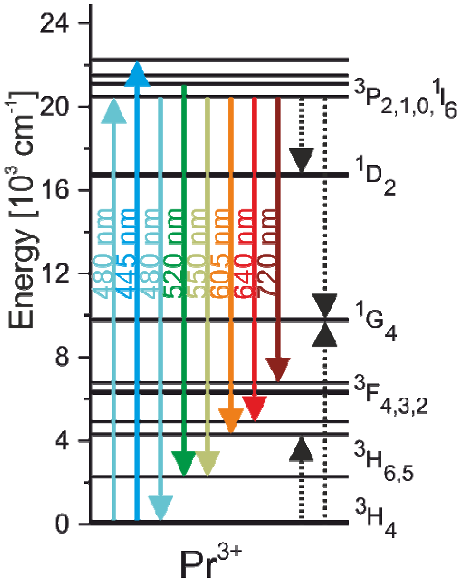
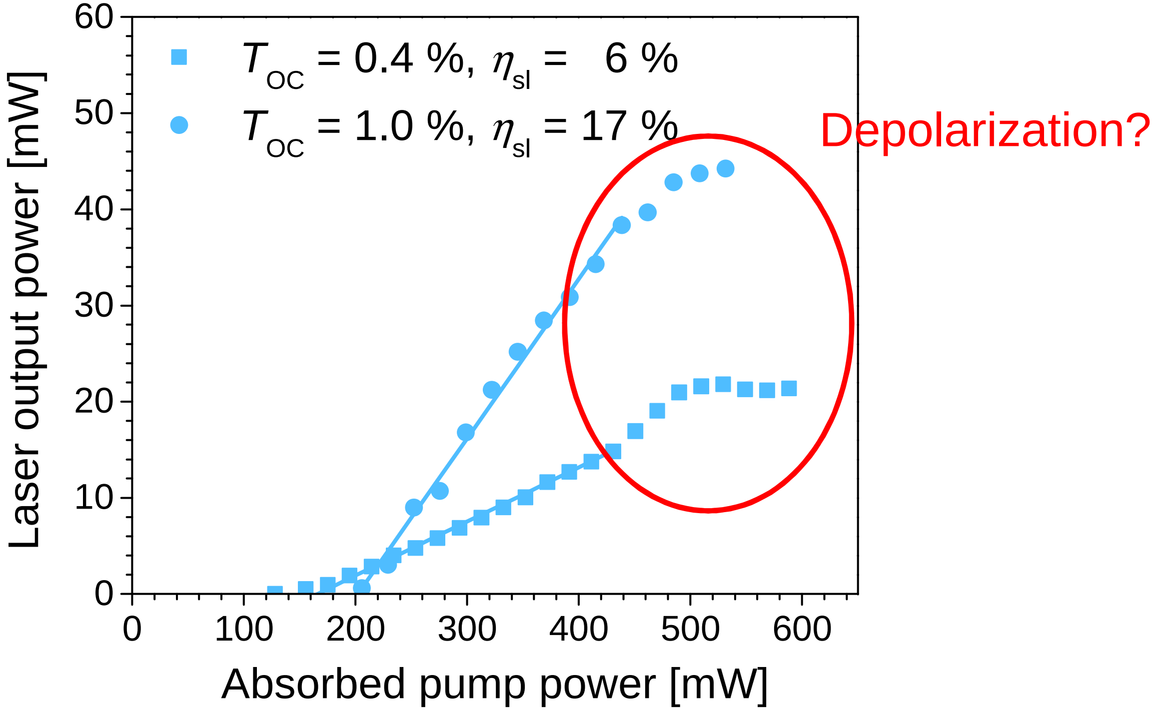
Visible lasers based on Pr^{3+}

2ω-OPSL-pumped blue cw lasing with $Pr^{3+}:LiYF_4$

- 491 nm emission is polarized perpendicular to 480 nm absorption
  → Outcoupling via PBS cube
- Mirror HT for 480 nm and HR for 491 nm required for further scaling
- Frequently observed damage on pump mirror







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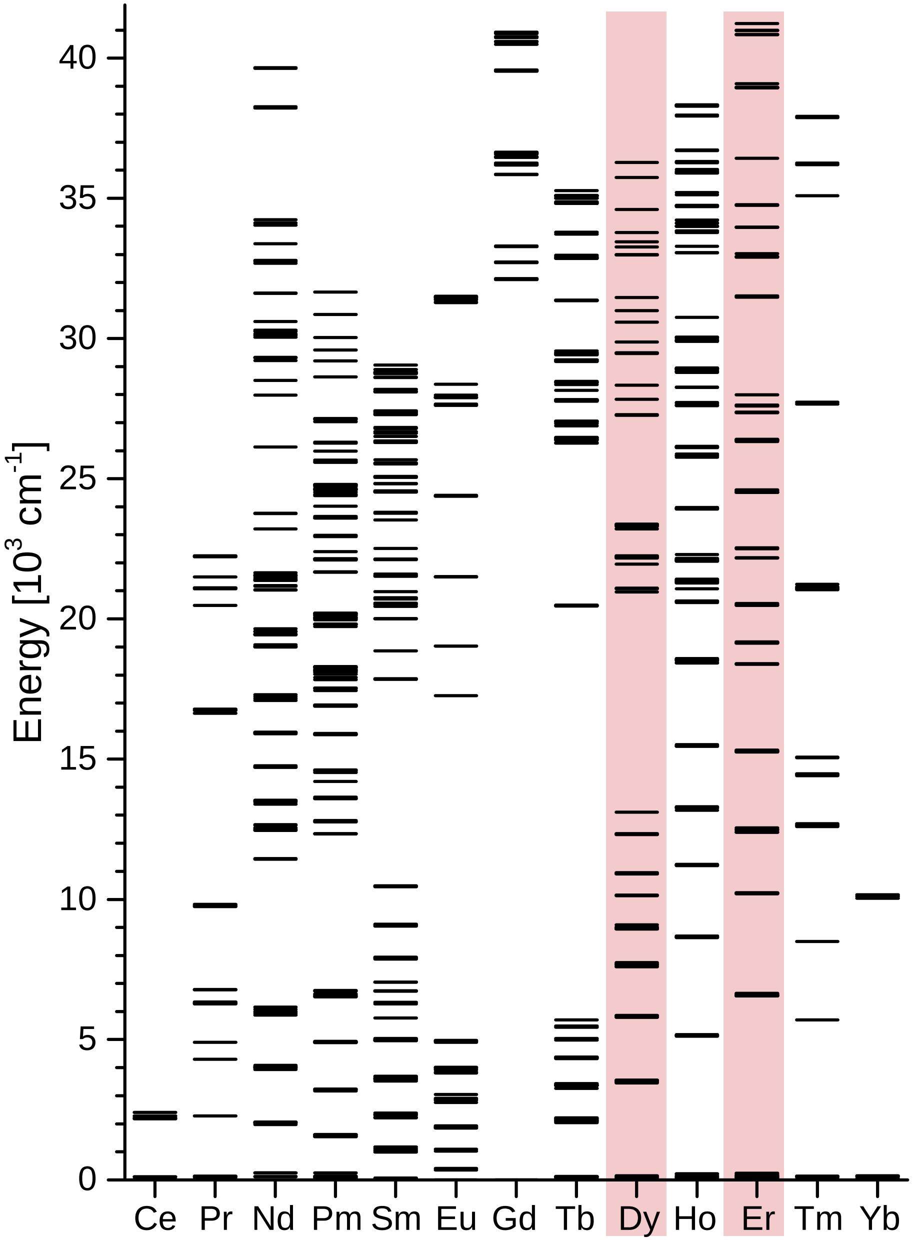
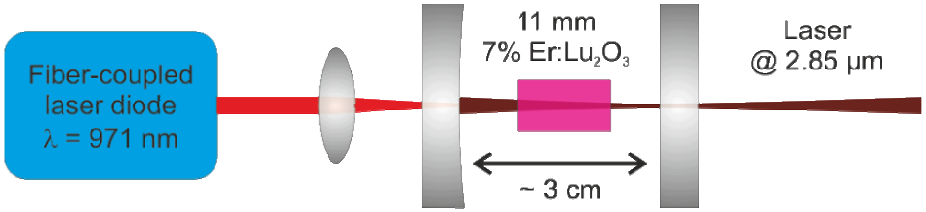


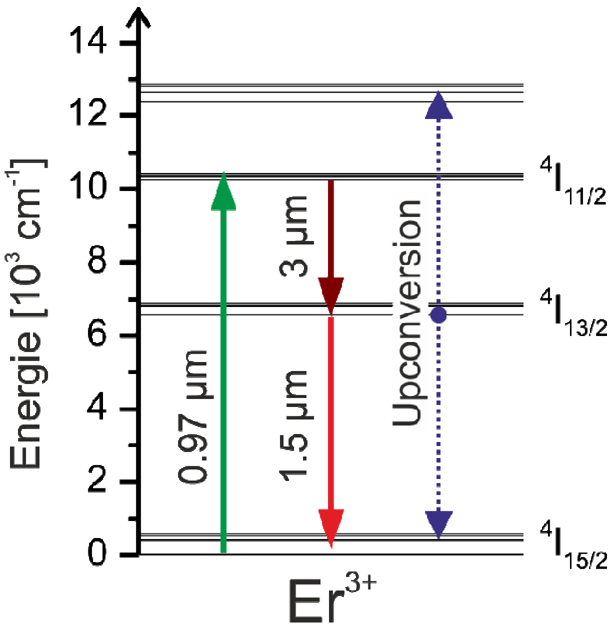
Mid-infrared lasers based on Er^{3+} and Dy^{3+}

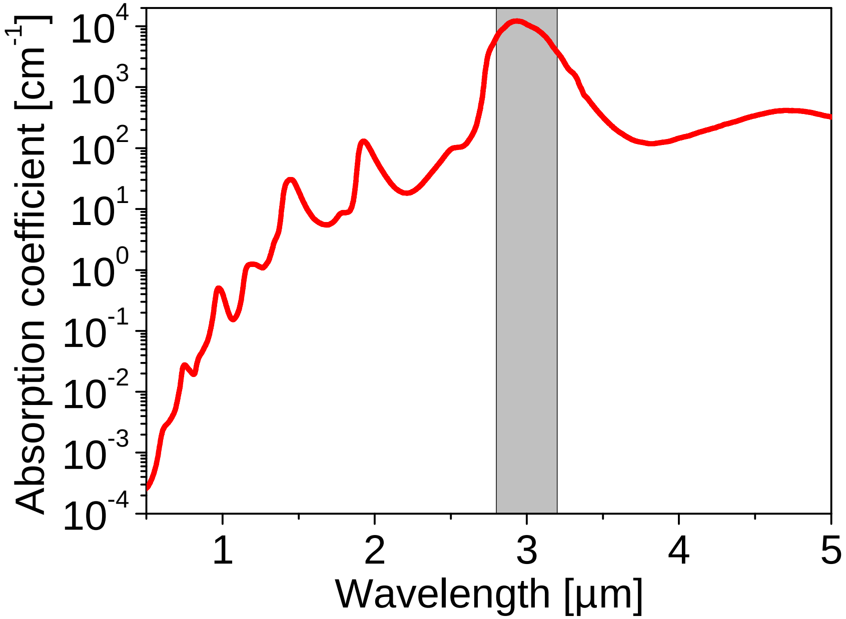
Er^{3+}-doped Lu_2O_3 for 3 µm lasing

High power room temperature 2.85 µm $Er:Lu_2O_3$ laser

- Main motivation for 3 µm lasers
  Strong water absorption → Laser surgery
- Ordered mirrors for 3 µm lasers:







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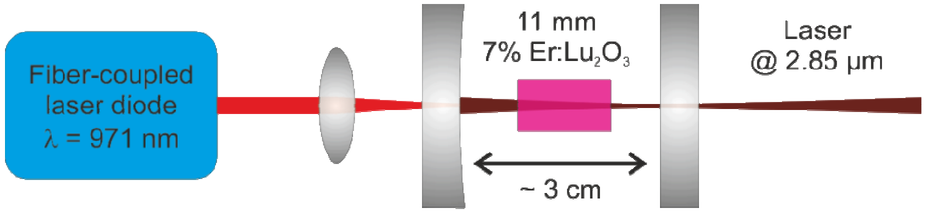
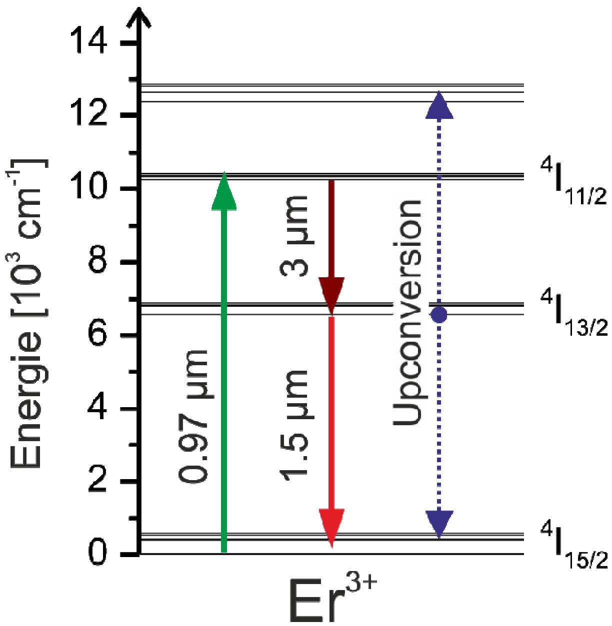
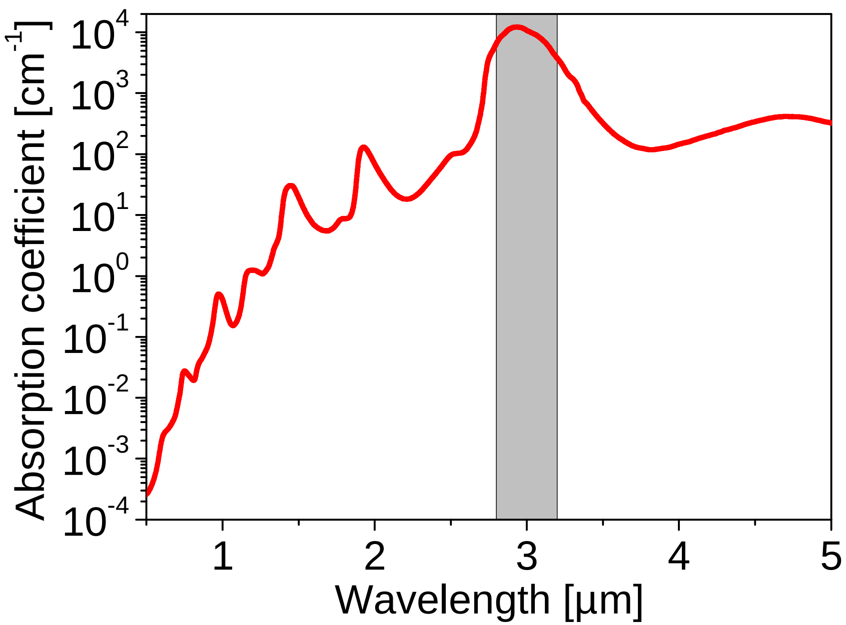
  - 1[st] batch delivered on glass substrates…







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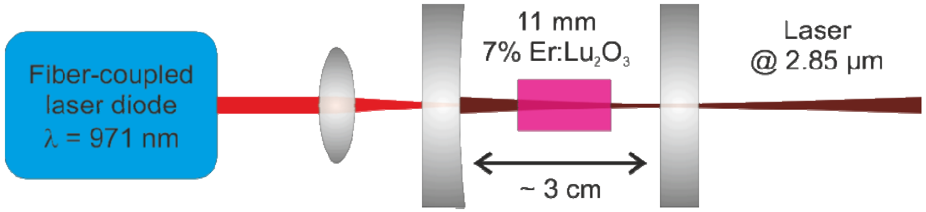
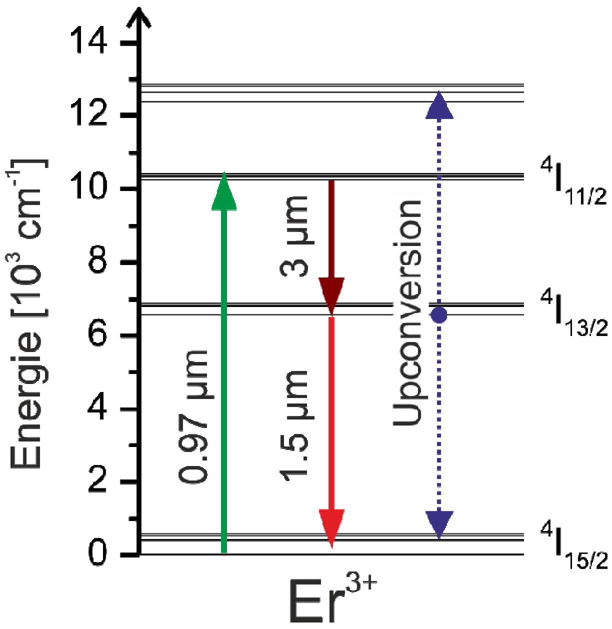
  - 2nd batch on YAG with characteristic water absorption lines…





Er^{3+}-doped Lu_2O_3 for 3 µm lasing

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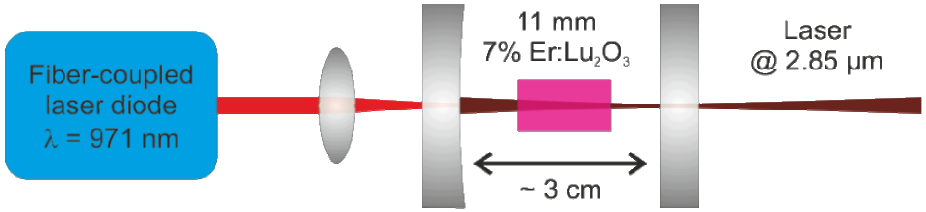
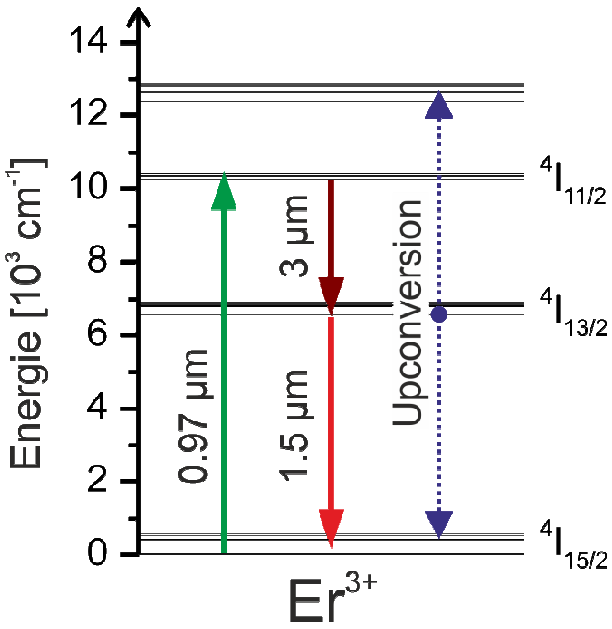
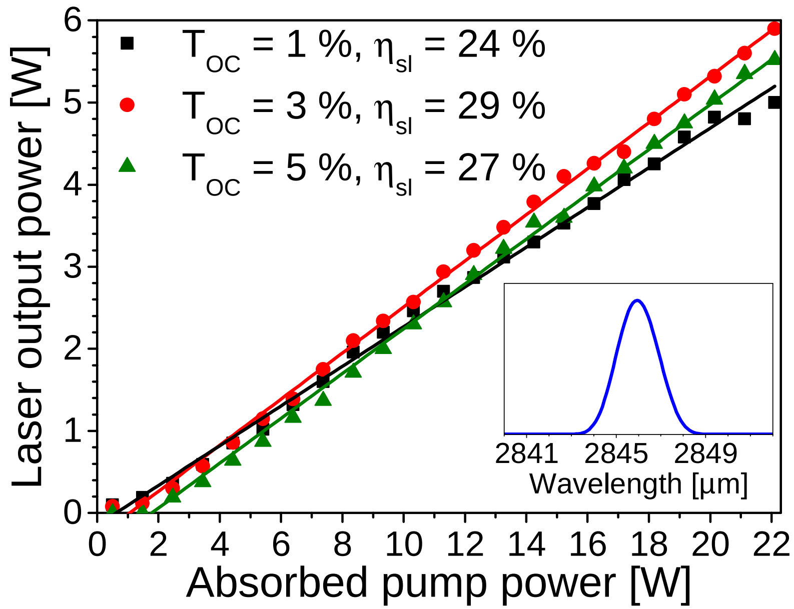
  Strong water absorption → Laser surgery
- Ordered mirrors for 3 µm lasers:
  - 1st batch delivered on glass substrates…
  - 2nd batch on YAG with characteristic water absorption lines…
  - **3rd batch allowed for record performance!**





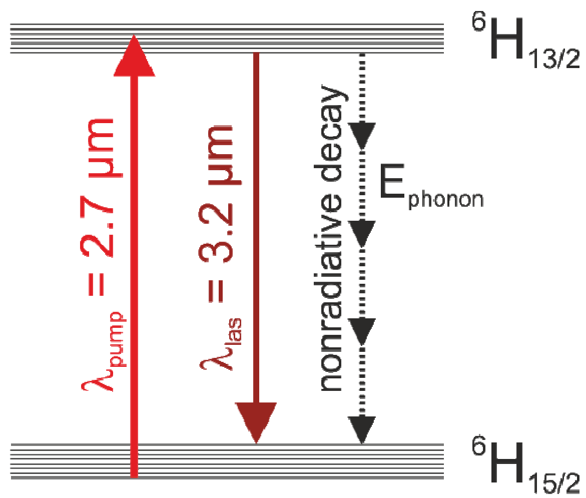


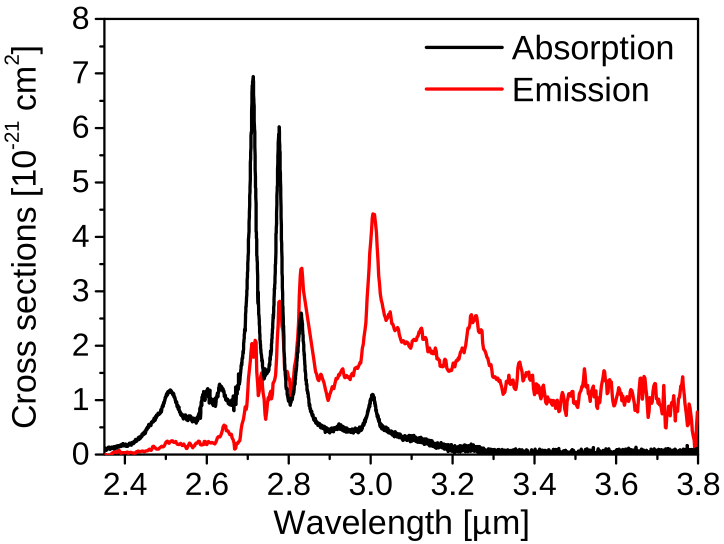
T. Li, C. Kränkel, *et al.*, Opt. Lett. **37** (13), 2568-2570 (2012)

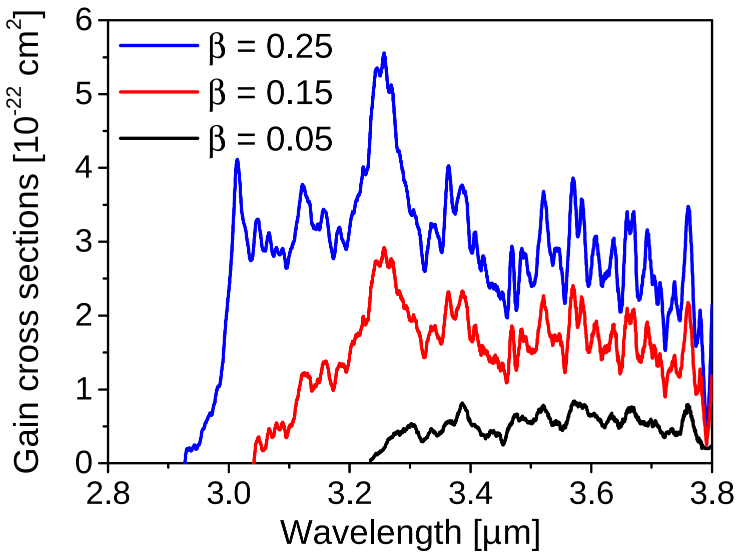
Dy^{3+}-doped Lu_2O_3 for >3 µm lasing

Toward 3.5 µm lasing in $Dy^{3+}:Lu_2O_3$

- $Dy^{3+}:Lu_2O_3$ single crystals grown for the first time
- Gain for quasi-3-level lasing between 3.0 µm and 3.6 µm





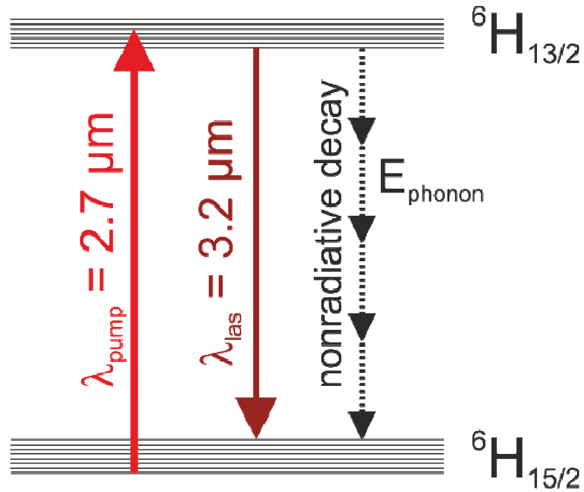


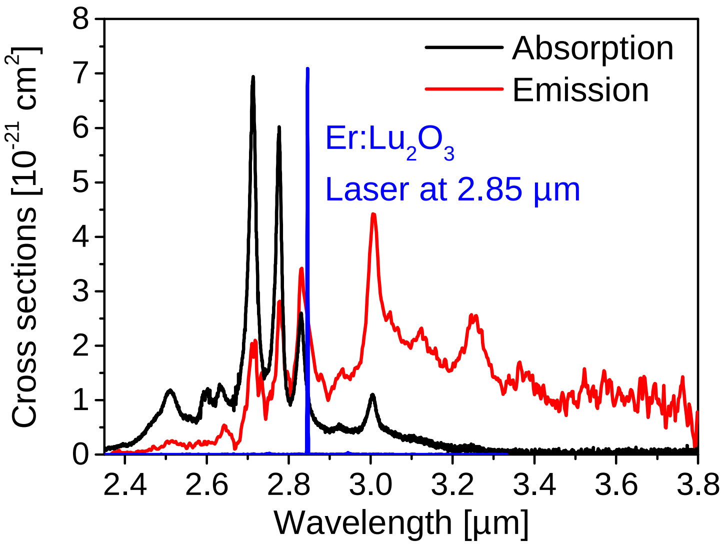
A. M. Heuer, P. von Brunn, C. Kränkel, EPS Europhoton Conference 2016, Poster 33.22

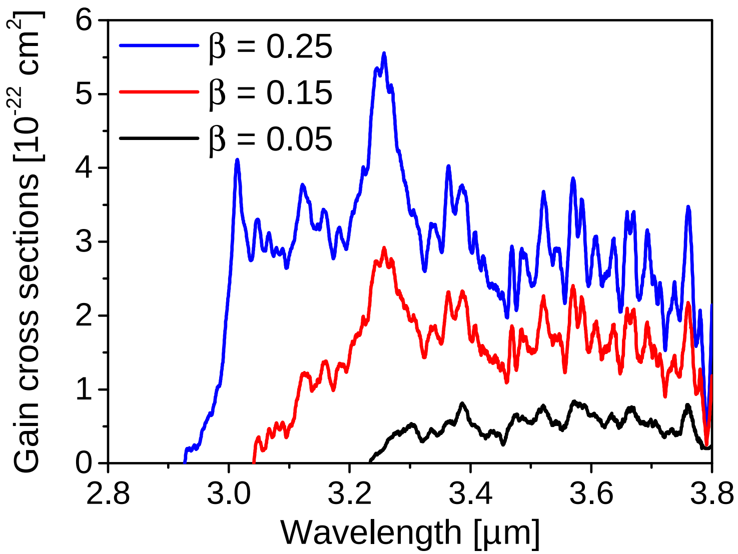
Dy^{3+}-doped Lu_2O_3 for >3 µm lasing

Toward 3.5 µm lasing in Dy^{3+}:Lu_2O_3

- Dy^{3+}:Lu_2O_3 single crystals grown for the first time
- Gain for quasi-3-level lasing between 3.0 µm and 3.6 µm
- Possible pump source: Er:Lu_2O_3 laser at 2.85 µm
- Coating HR for >3 µm and AR for 2.85 µm → Thickness?







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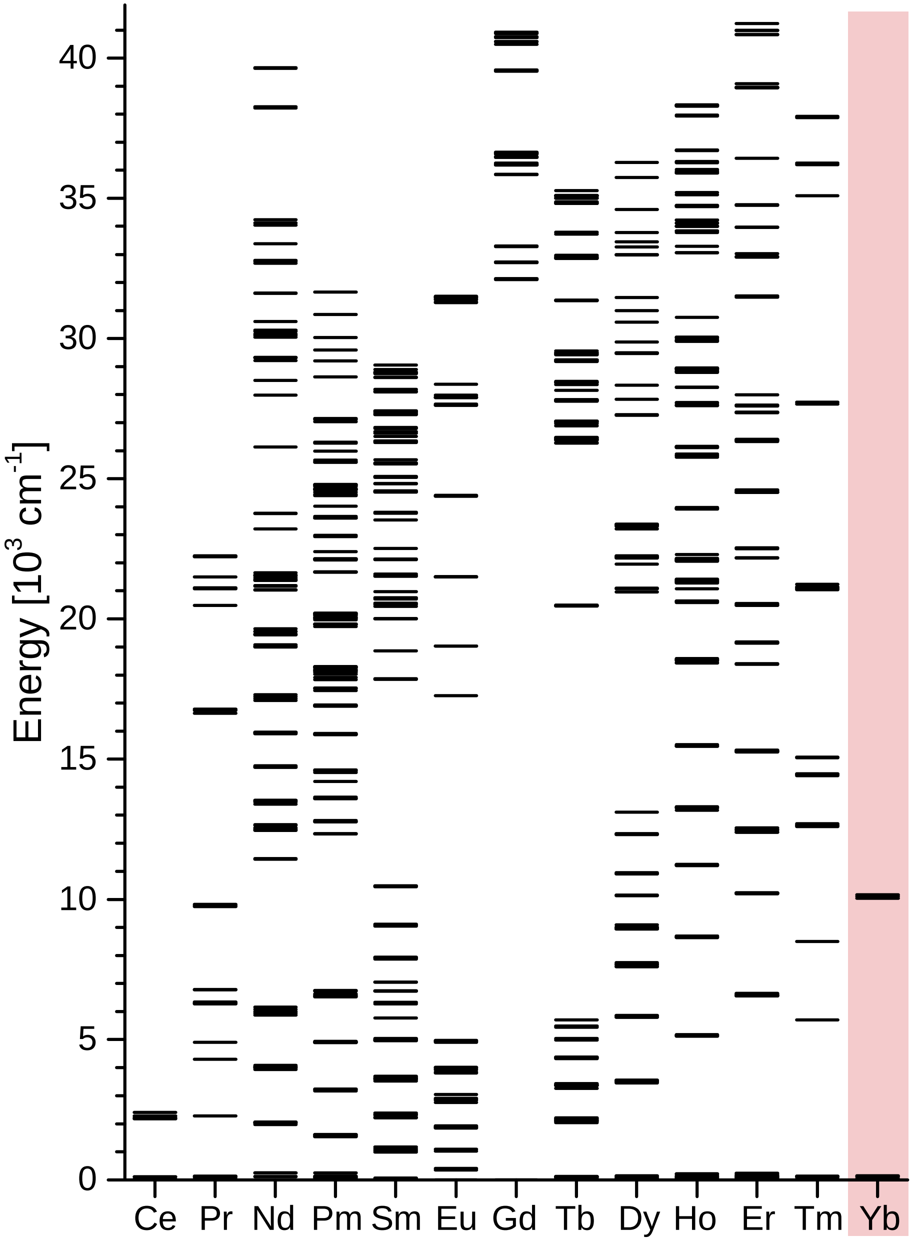
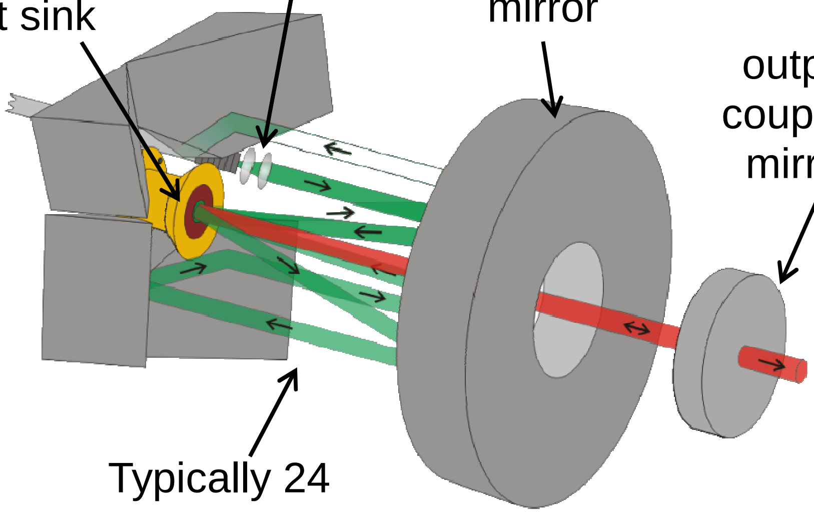


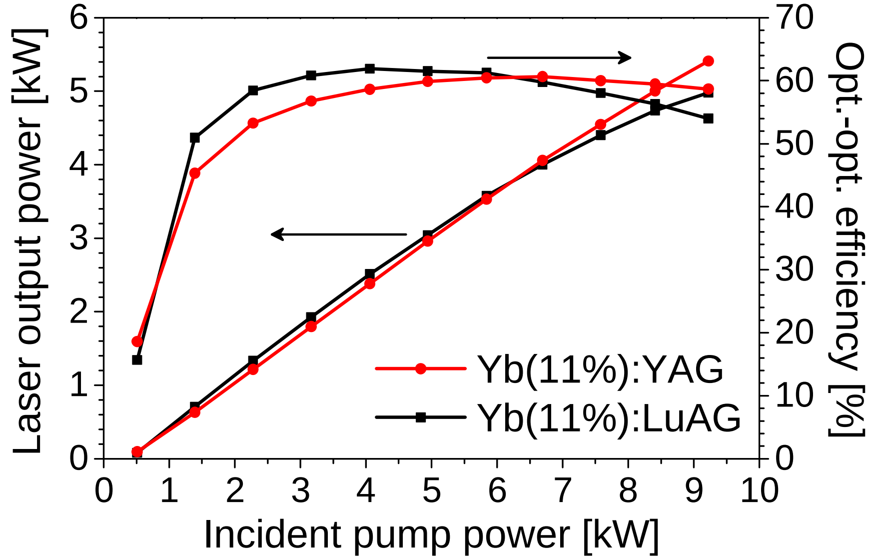
High intracavity power lasers based on Yb^{3+}

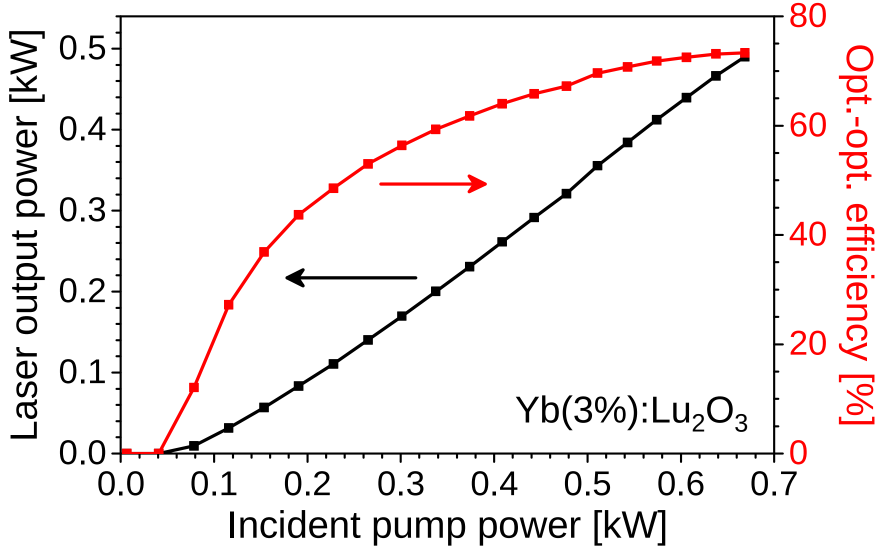
High intracavity power thin disk laser

The thin disk laser

- Multi-pass pumping scheme for very high output power
- kw output power with Yb:YAG and Yb:LuAG
- Few 100 W output power with Yb:Lu_2O_3







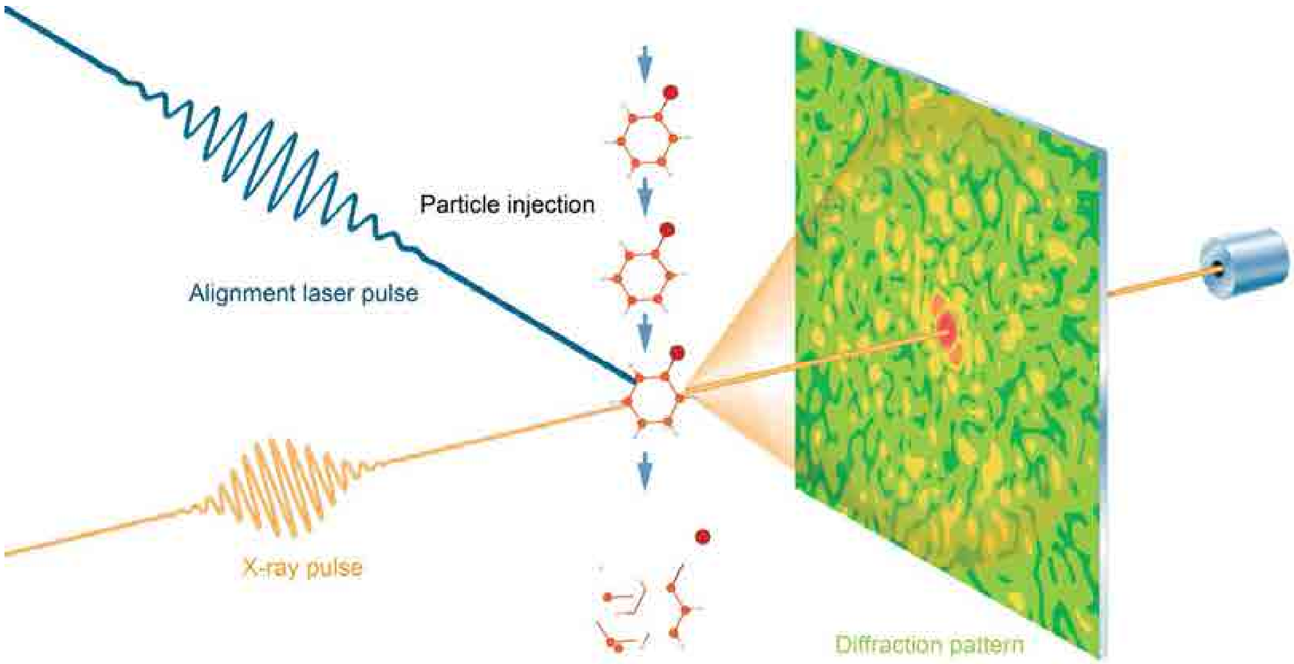
K. Beil, C. Kränkel, et al. Opt. Express 18 (20), 20712-20722 (2010)
C. Kränkel, IEEE JSTQE **21** (1), 1602013 (2015)

High intracavity power thin disk laser

Adiabatic alignment of molecules in the electric field of a laser

Requirements:

- ns-pulse durations and >10^{11} W/cm^2 intensity → mJ pulse energies
- Probing e.g. by Hamburg's XFEL MHz repetition rates → multi-kW average power
- Alignment at arbitrary repetition rates with cw laser → MW cw output power



B. Deppe, C. Kränkel, *et al.*, Opt. Express **23** (22), 28491ff (2015)

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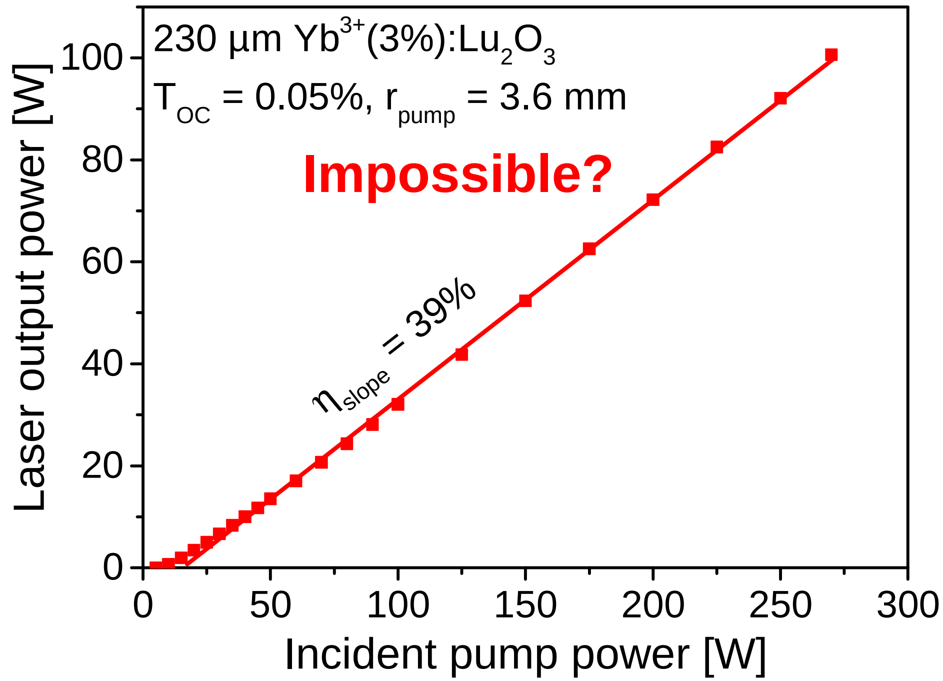

C. Kränkel et al., ALT'16, talk LSM-3-3

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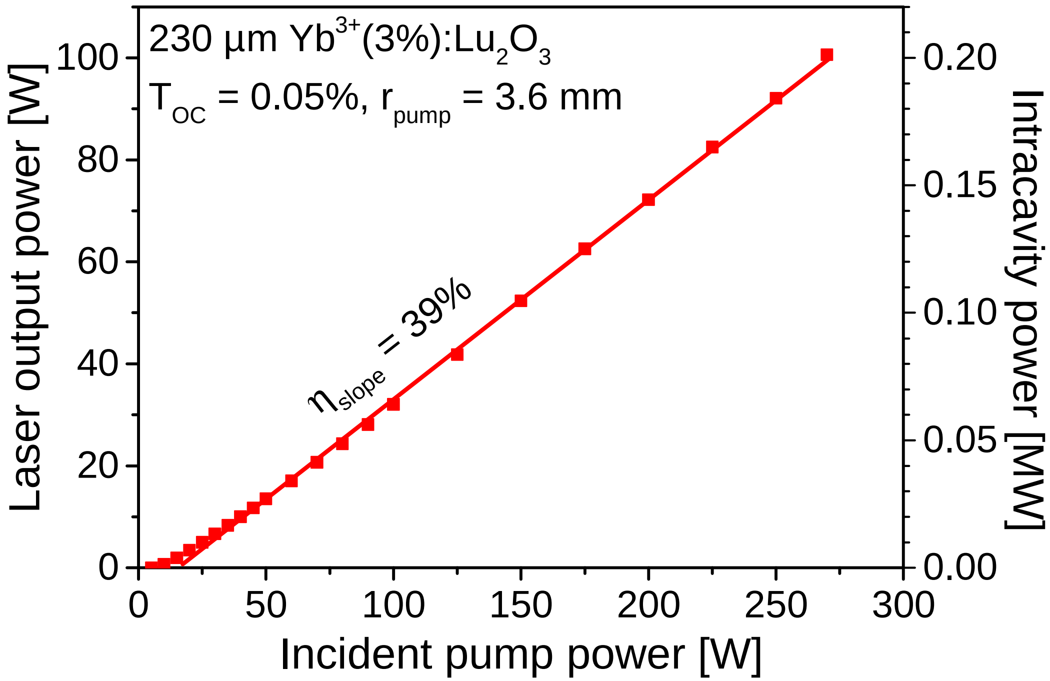


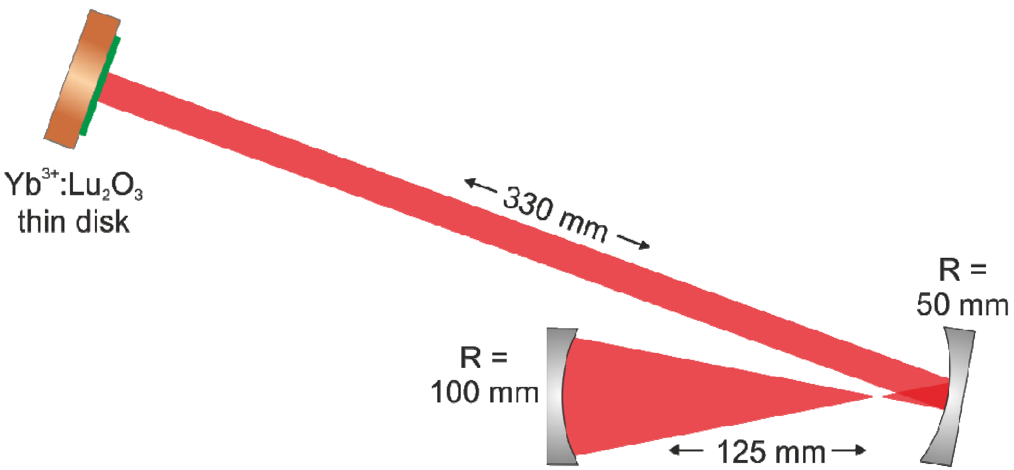
- High **intracavity** power thin disk laser for molecular alignment
- Commercial TDLs operate at r_{pump} = 10 mm → MW cw intracavity power feasible

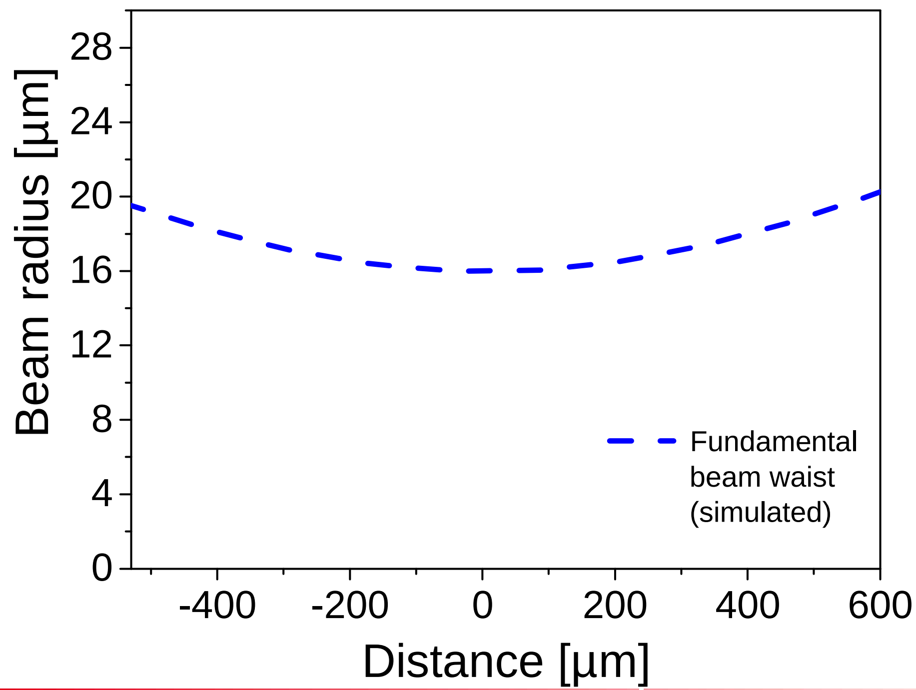
C. Kränkel et al., ALT'16, talk LSM-3-3

High intracavity power thin disk laser

High intracavity power thin disk laser for molecular alignment

- Theoretical beam waist radius of ≈ 15 µm at 10 kW intracavity power
- Measured beam waist radius of ≈ 20 µm → Intracavity cw intensity ≈ 10^9 W/cm²





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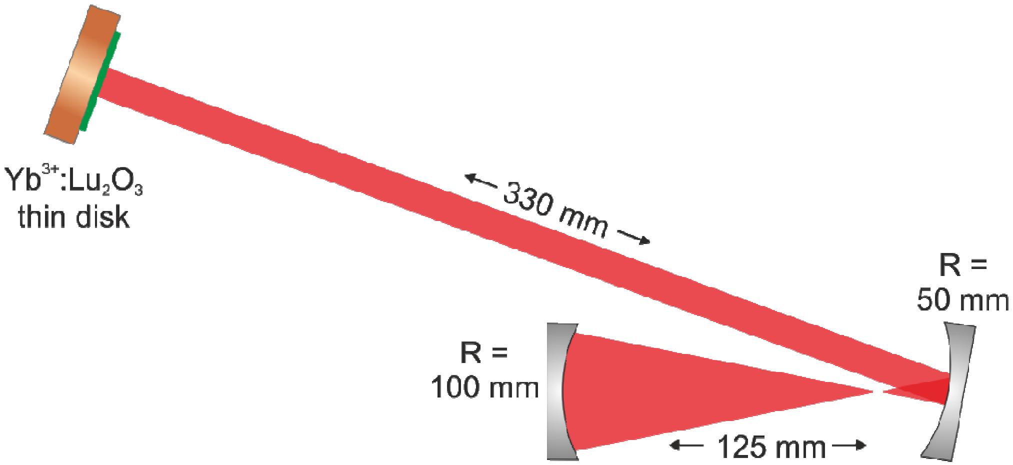

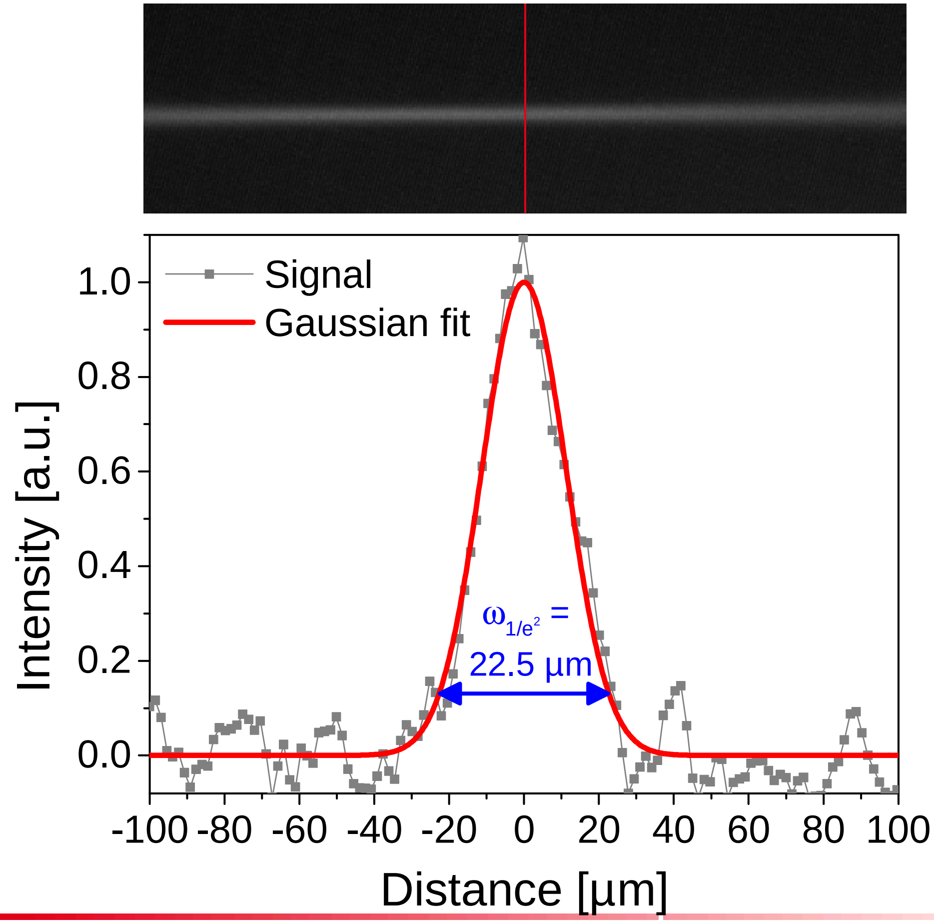

C. Kränkel et al., ALT'16, talk LSM-3-3

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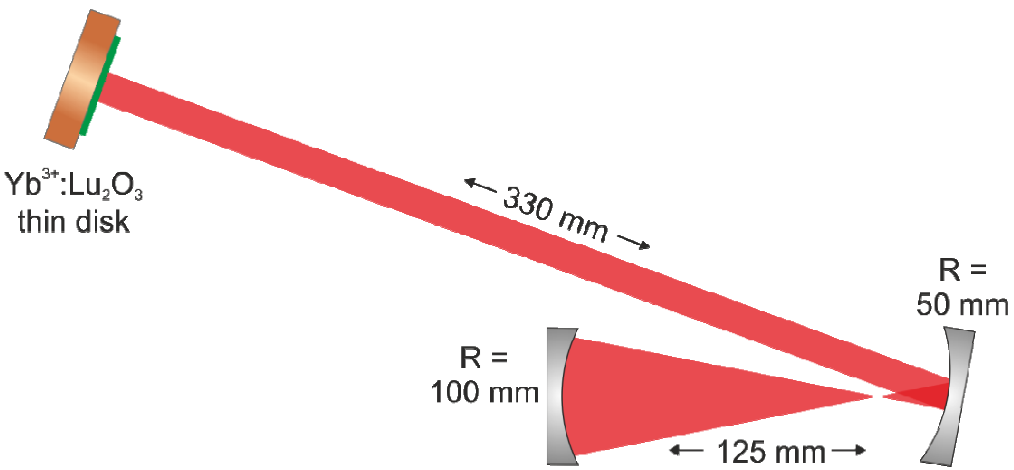
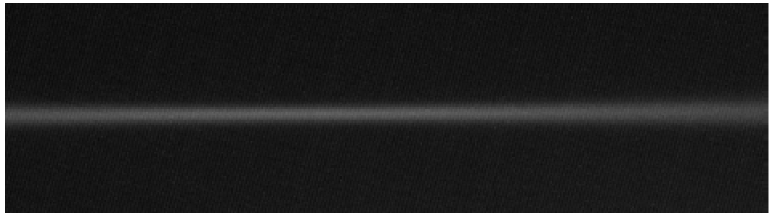
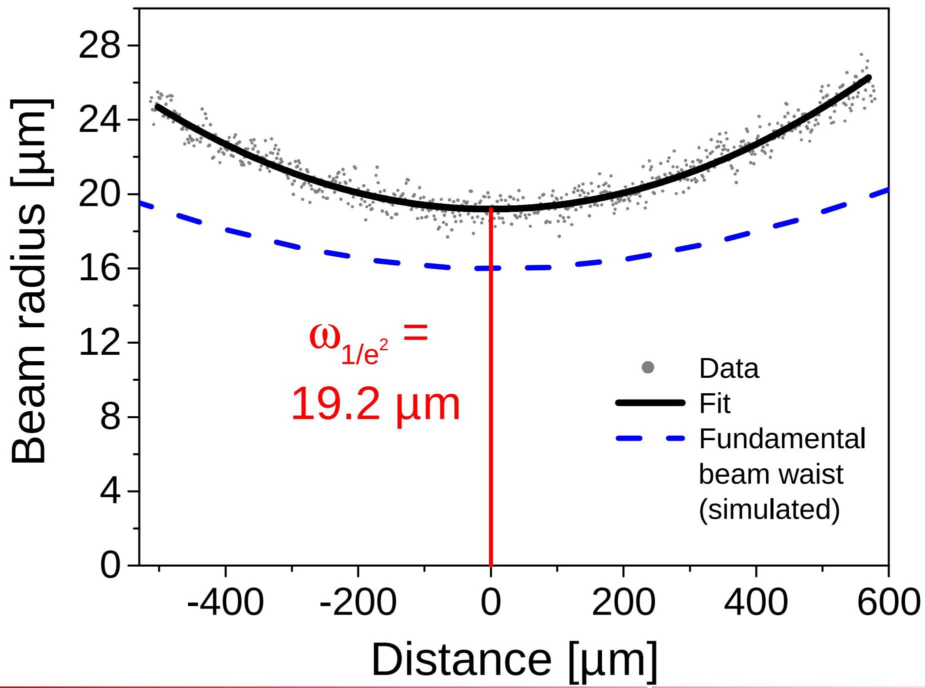


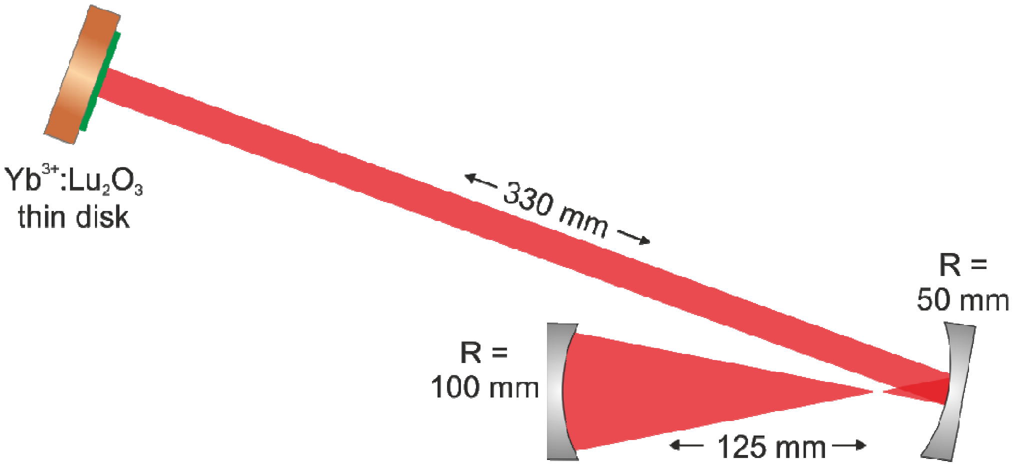


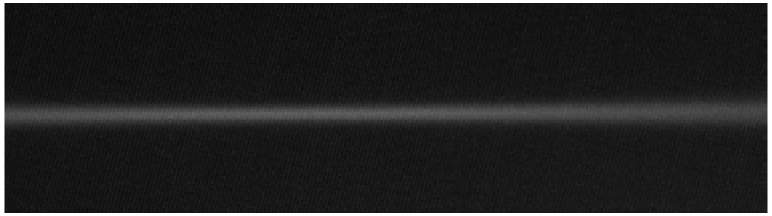


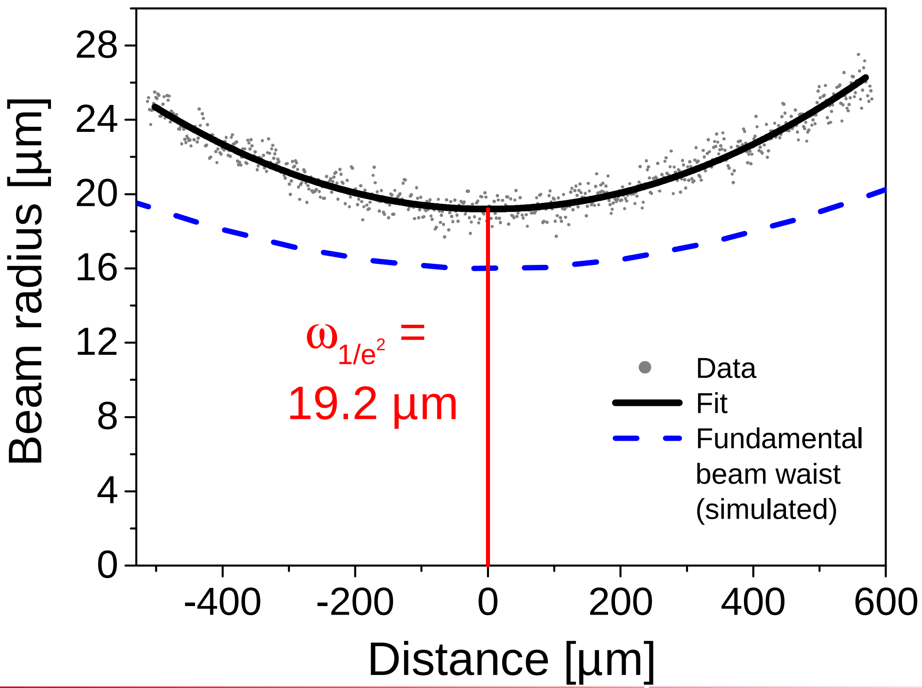
C. Kränkel et al., ALT'16, talk LSM-3-3

High intracavity power thin disk laser for molecular alignment

- Theoretical beam waist radius of ≈ 15 µm at 10 kW intracavity power
- Measured beam waist radius of ≈ 20 µm → Intracavity cw intensity ≈ 10^9 W/cm²
- Intensities > 10^{11} W/cm² require further scaling
  - 1 cm pump spot diameter
  - 1 MW intracavity power
  - 1.5 kW pump power





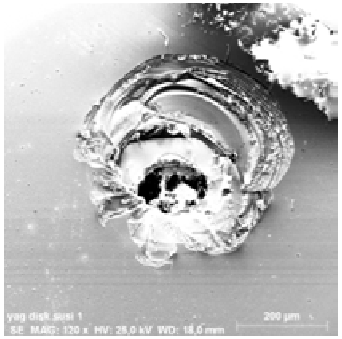


C. Kränkel et al., ALT'16, talk LSM-3-3

High intracavity power thin disk laser

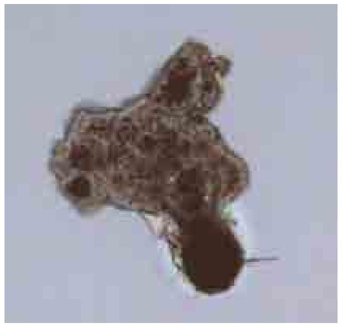
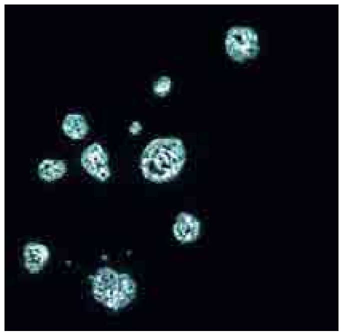
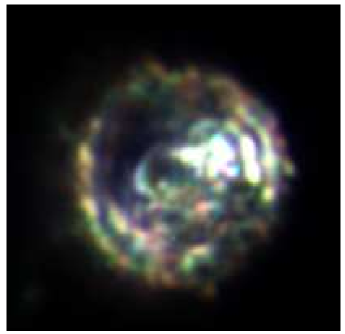
Main issue

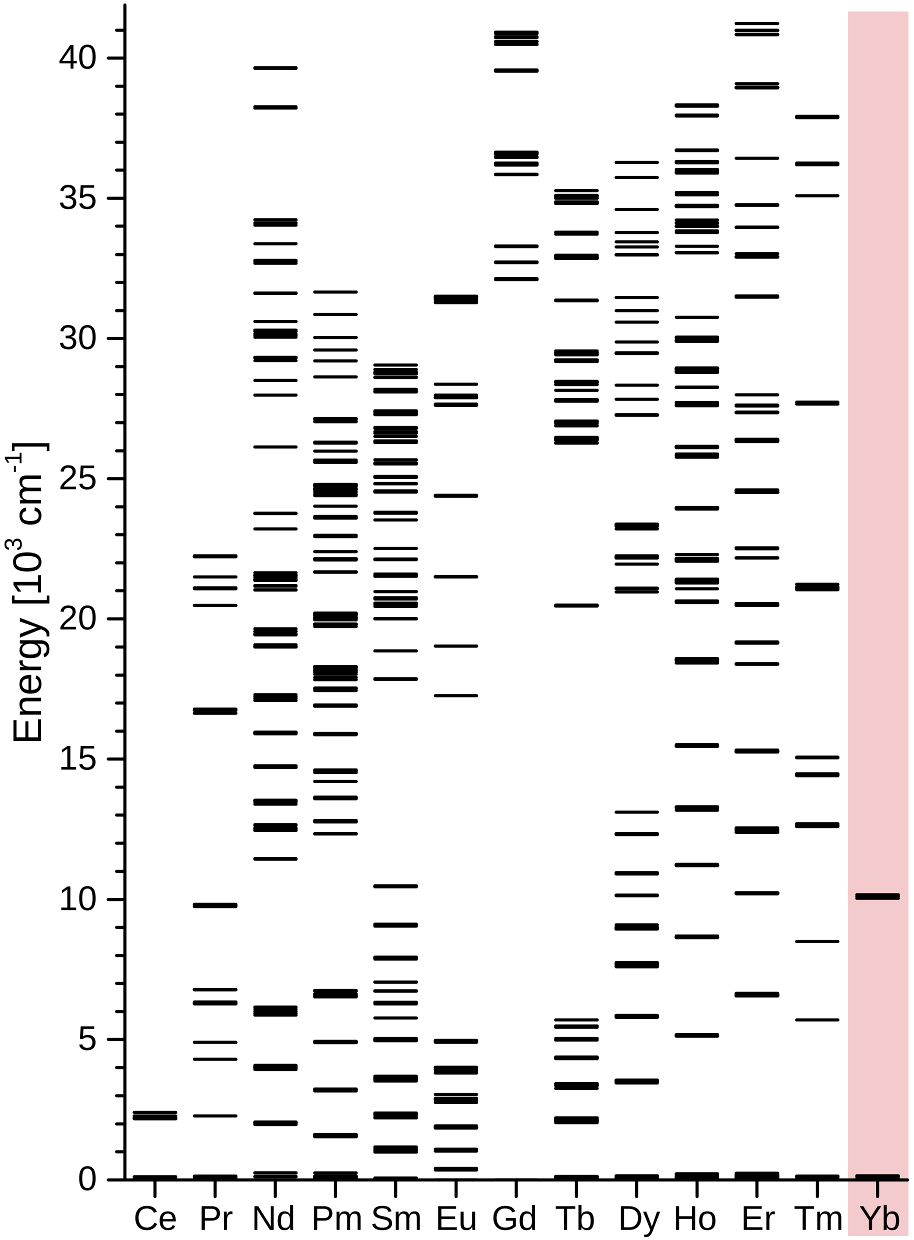








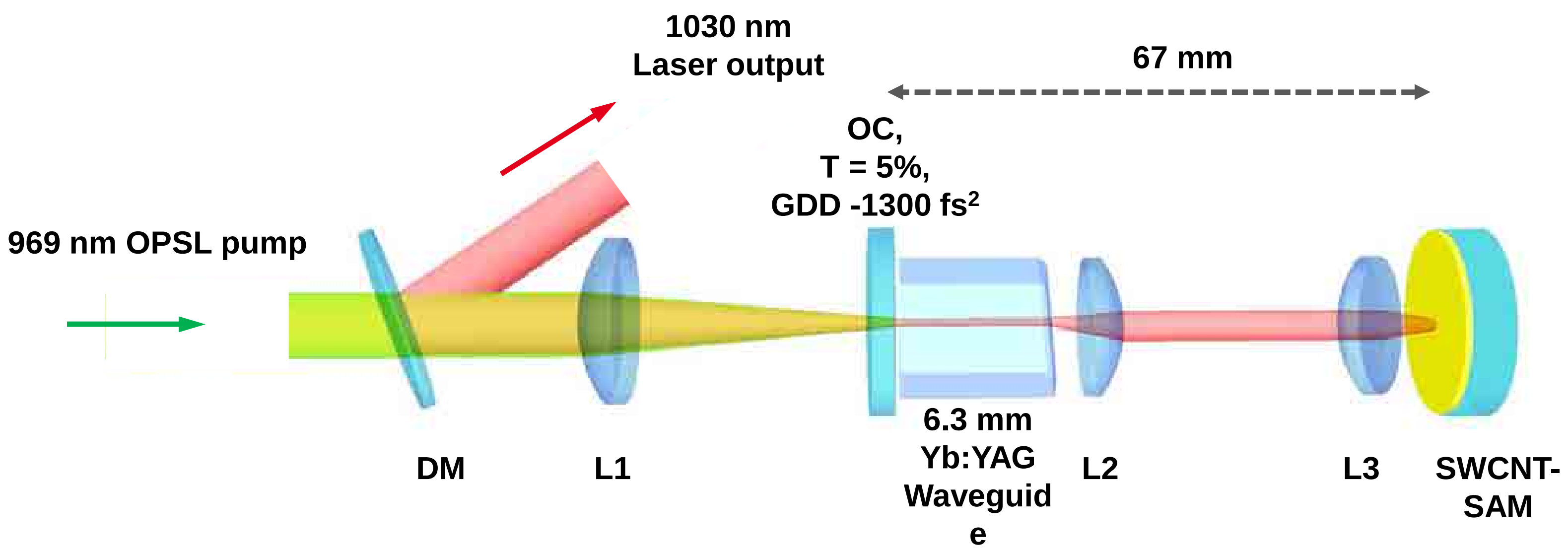





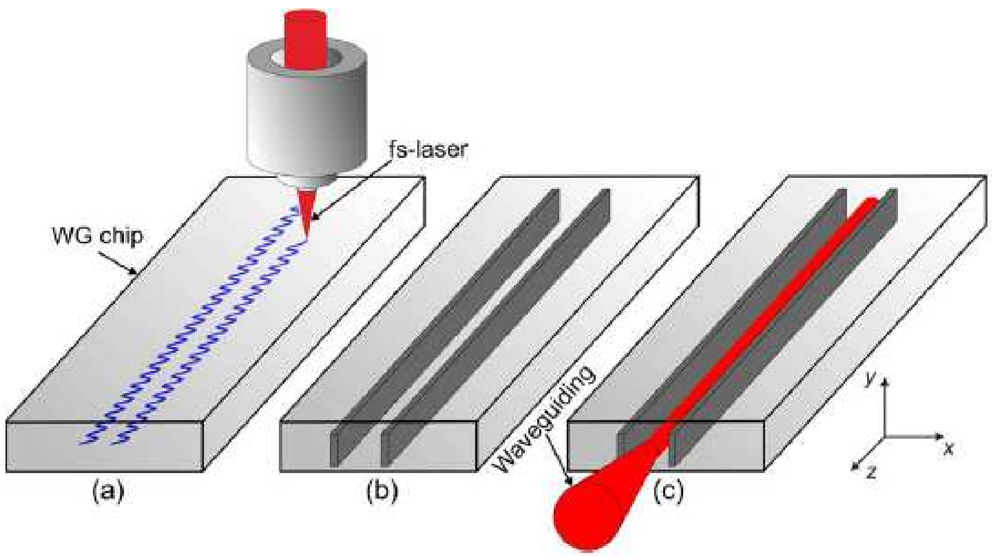


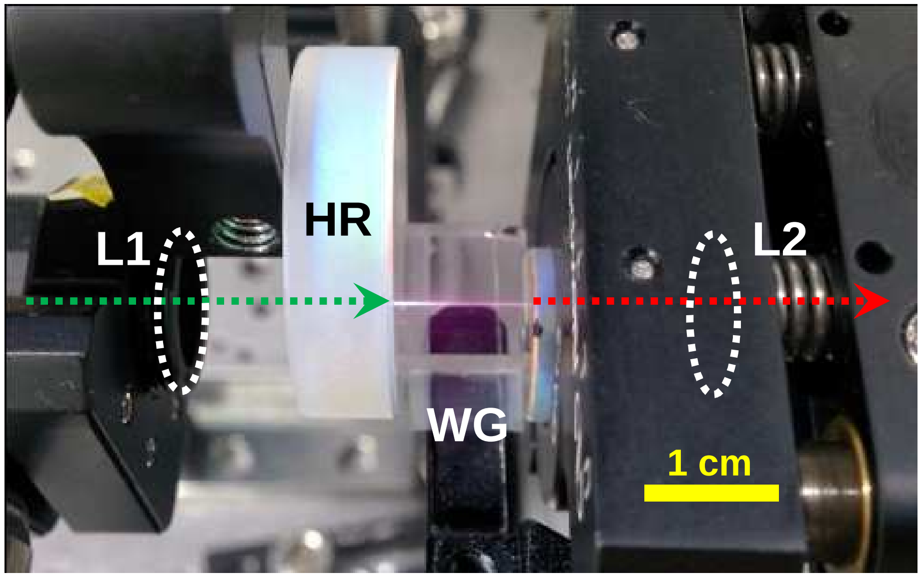
Pulsed waveguide lasers based on Yb^{3+}

Pulsed Yb^{3+} waveguide lasers

fs-laser-inscribed Yb:YAG waveguide laser



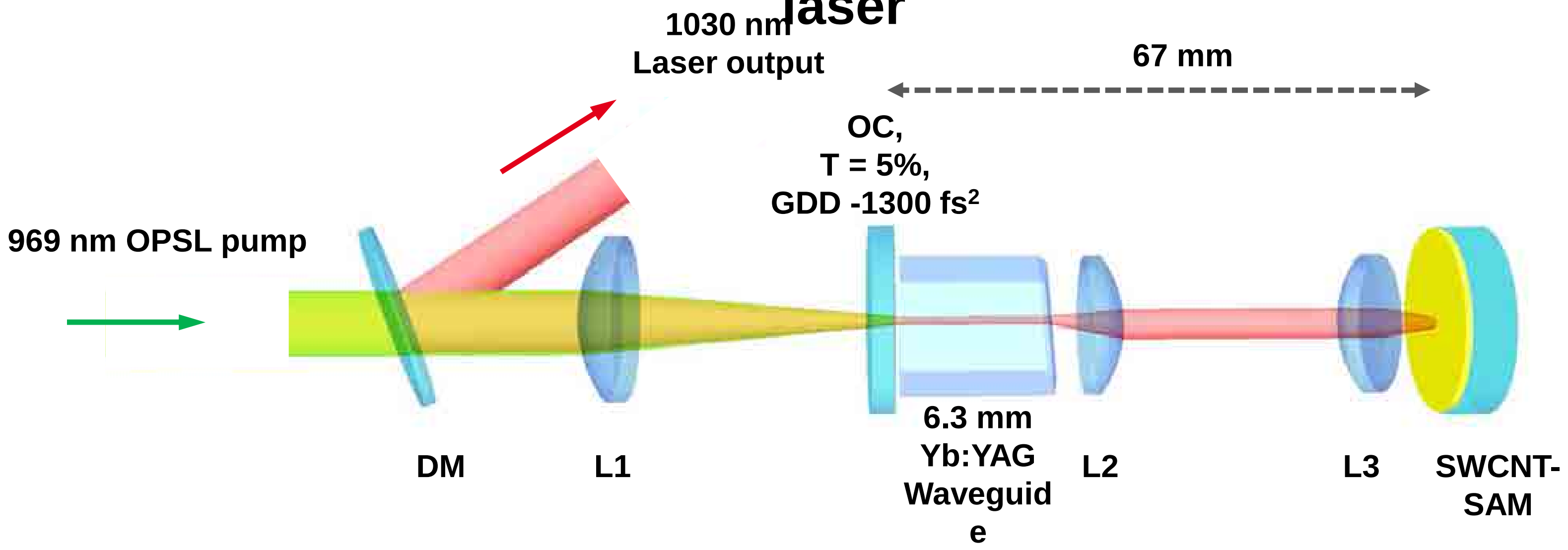


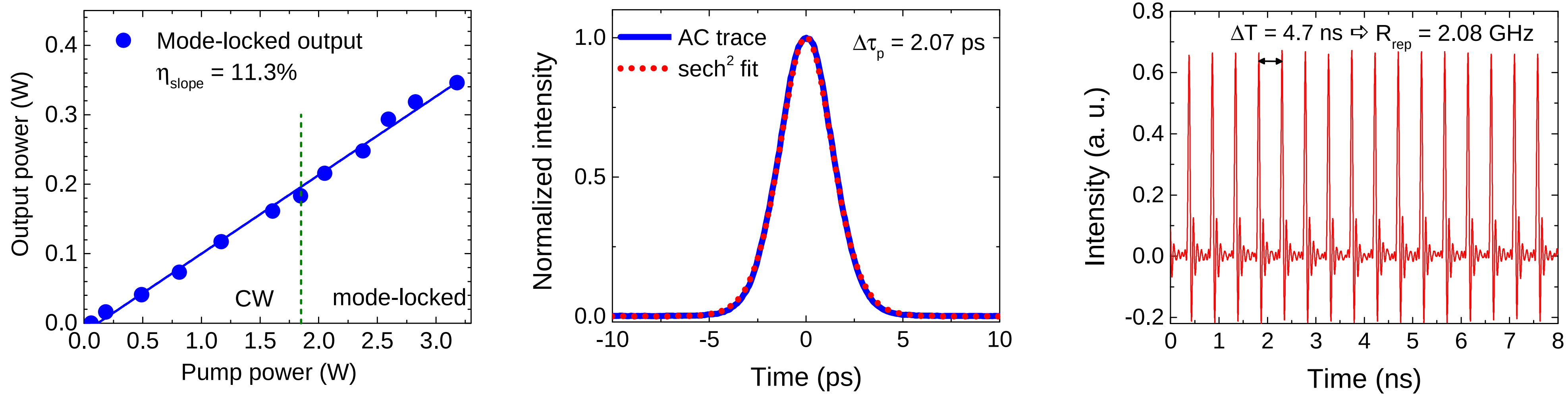


S. Y. Choi, C. Kränkel, *et al.*, ECLEO 2017, Talk CJ-10.4

Pulsed Yb^{3+} waveguide lasers

Single walled carbon nanotube modelocked Yb:YAG waveguide laser





S. Y. Choi, C. Kränkel, *et al.*, ECLEO 2017, Talk CJ-10.4

Conclusion

Visible lasers

- Pr^{3+}-lasers are as highly efficient materials for visible lasers
- Further scaling of blue Pr^{3+} lasers requires special coatings

Mid-IR lasers

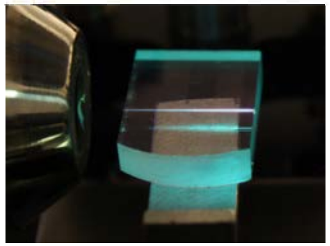
- 3rd mirror batch allowed record 3 µm performance of Er^{3+}:Lu_2O_3
- Dy^{3+}:Lu_2O_3 is a very promising laser material, waiting for mirrors!

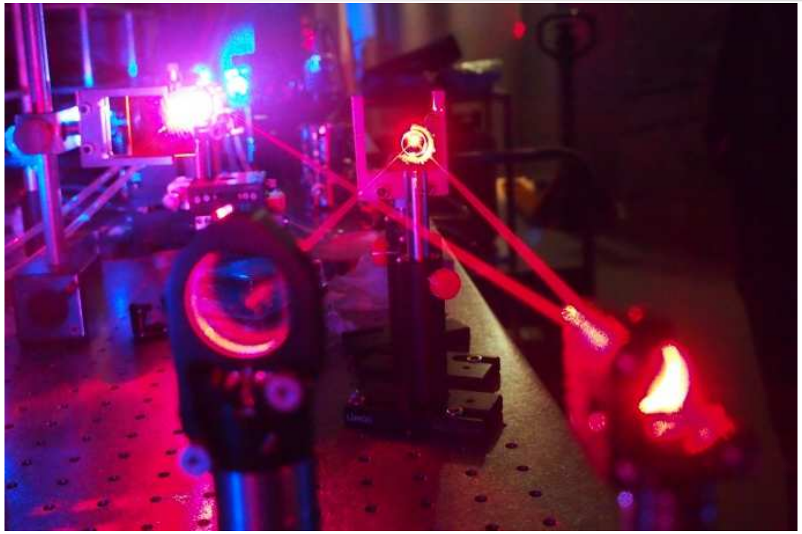
Infrared lasers

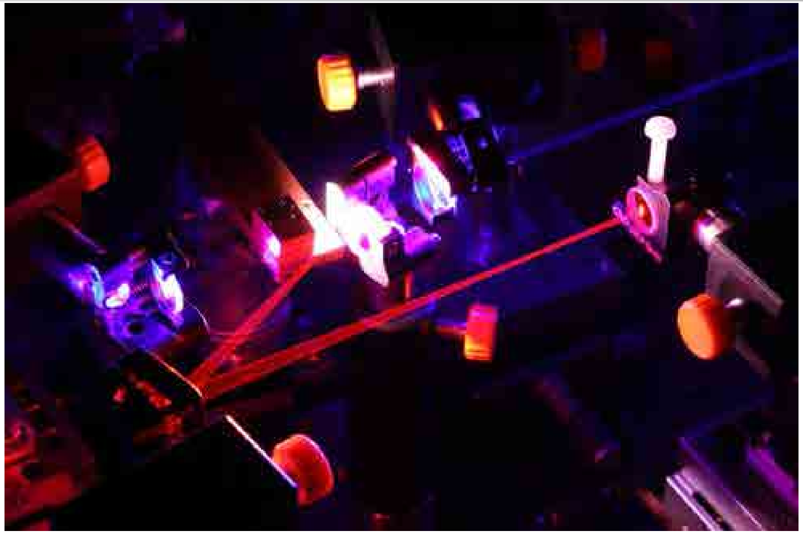
- Yb^{3+}:Lu_2O_3 allows for record efficiencies and kW-class cw output
- Coatings as show-stopper for reaching required intracavity power

Waveguide lasers

- fs-laser inscribed waveguides enable efficient & compact ps-lasers
- Exploring the full potential requires very sophisticated coatings







Thank You for Your Attention

This work was supported by the DFG Graduate School 1355 –“Physics with new advanced coherent radiation sources“, the BMBF project TSUNAMI (FKZ 13N13050) and the Hamburg Excellence Cluster “Centre for Ultrafast Imaging”

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GRK 1355: Physik mit neuartigen kohärenten Strahlungsquellen

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