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Mitigation of transverse mode instabilities

Cesar Jauregui

Average output power evolution of fiber laser systems with diffraction-limited beam quality

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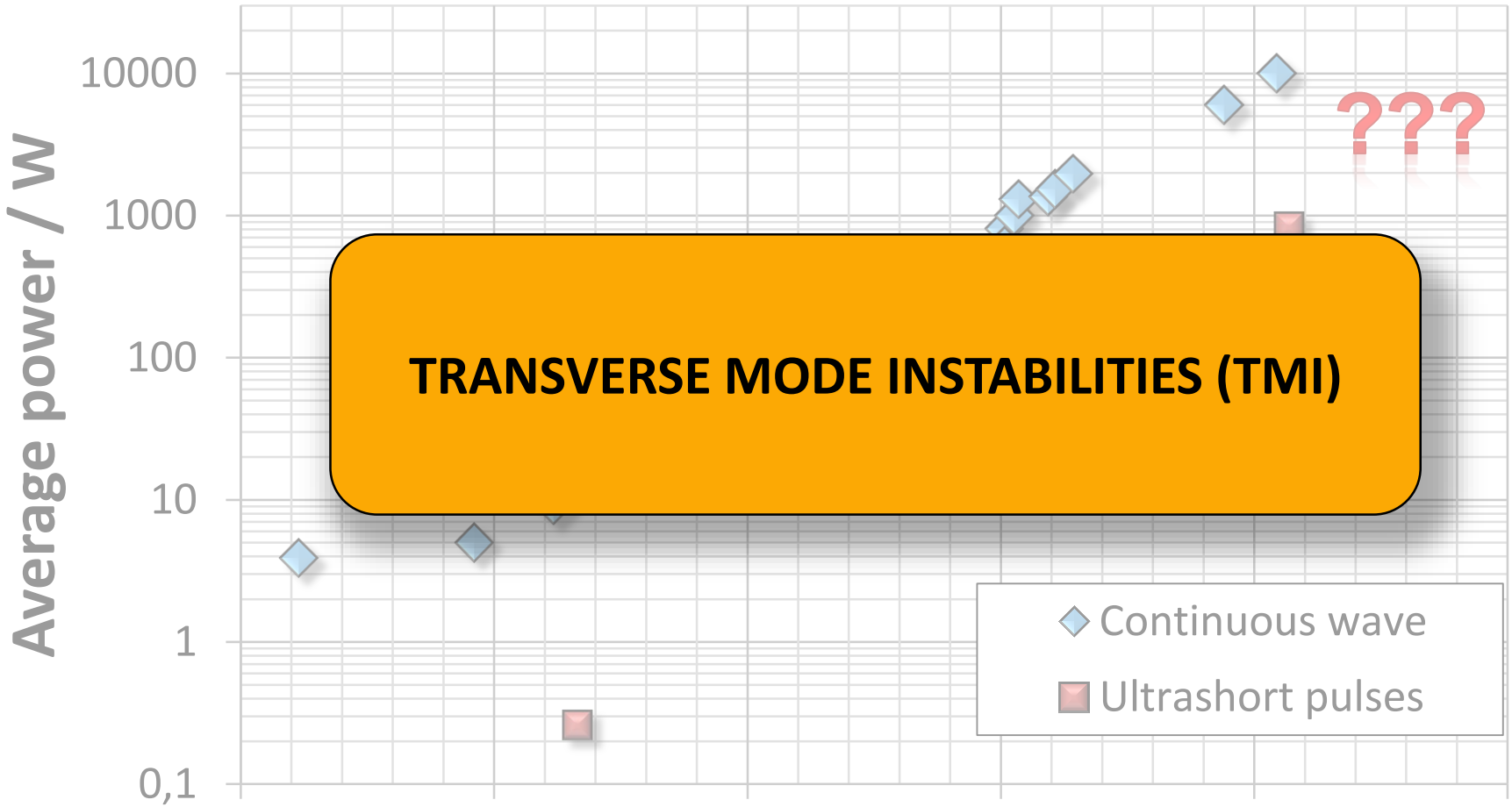

TRANSVERSE MODE INSTABILITIES (TMI)

Why has the development pace stopped?

C. Jauregui et al., "High-power fibre lasers," Nat. Photonics **7**, 861–867 (2013)

Mode Instabilities

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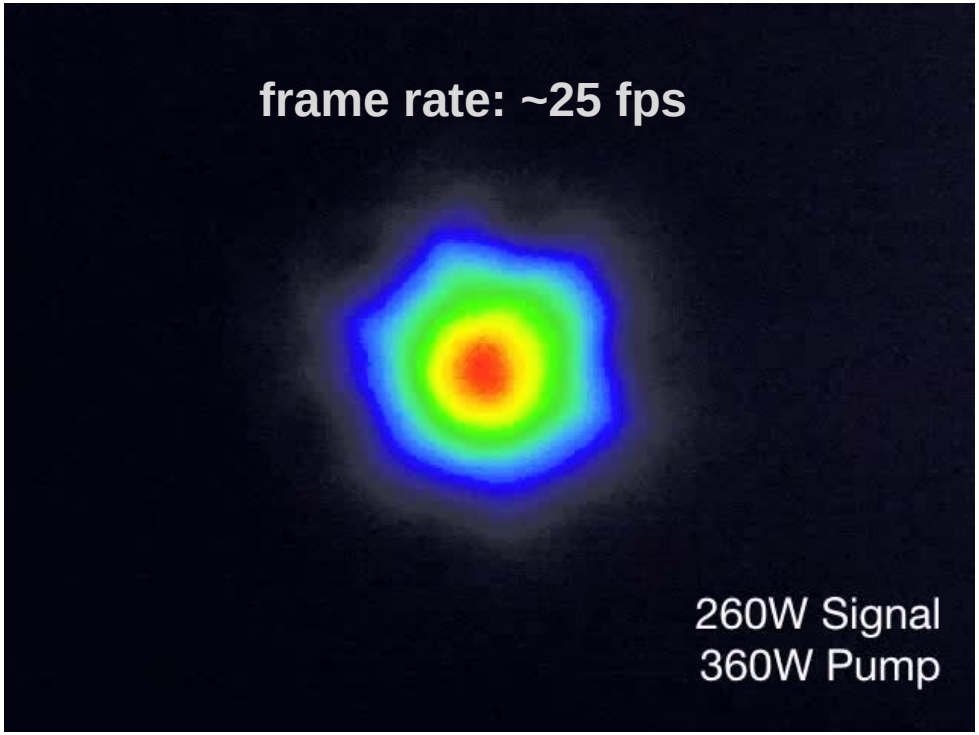
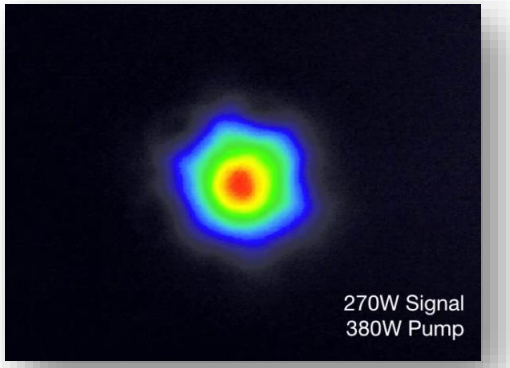


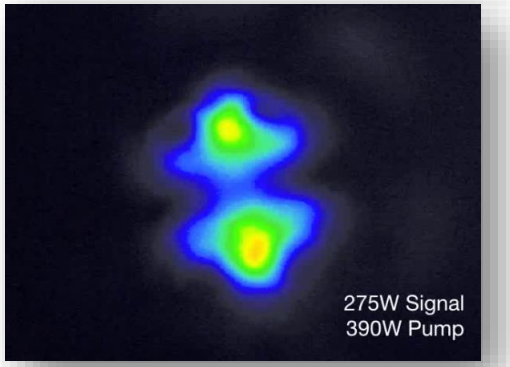
This effect threatens the very foundations upon which the reputation of fiber laser systems has been built

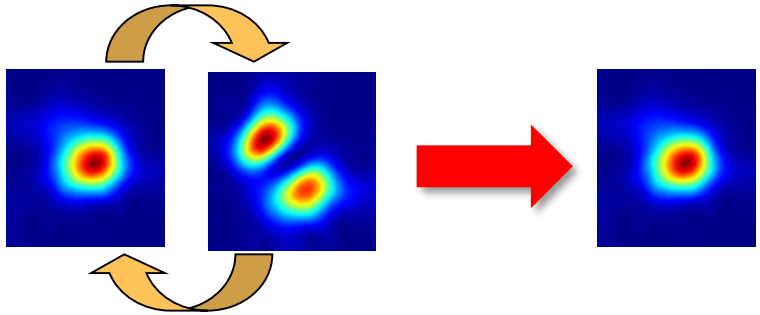
T. Eidam, C. Wirth, C. Jauregui, F. Stutzki, F. Jansen, H. Otto, O. Schmidt, T. Schreiber, J. Limpert, and A. Tünnermann, "Experimental observations of the threshold-like onset of mode instabilities in high power fiber amplifiers," Opt. Express **19**, 13218-13224 (2011)

OUTLINE

- Introduction
- Mode instabilities
- Mitigation Strategies
  - Passive
  - Active
- Conclusions







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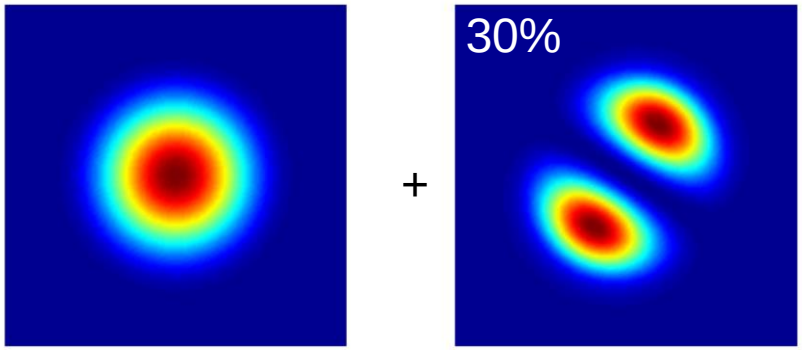
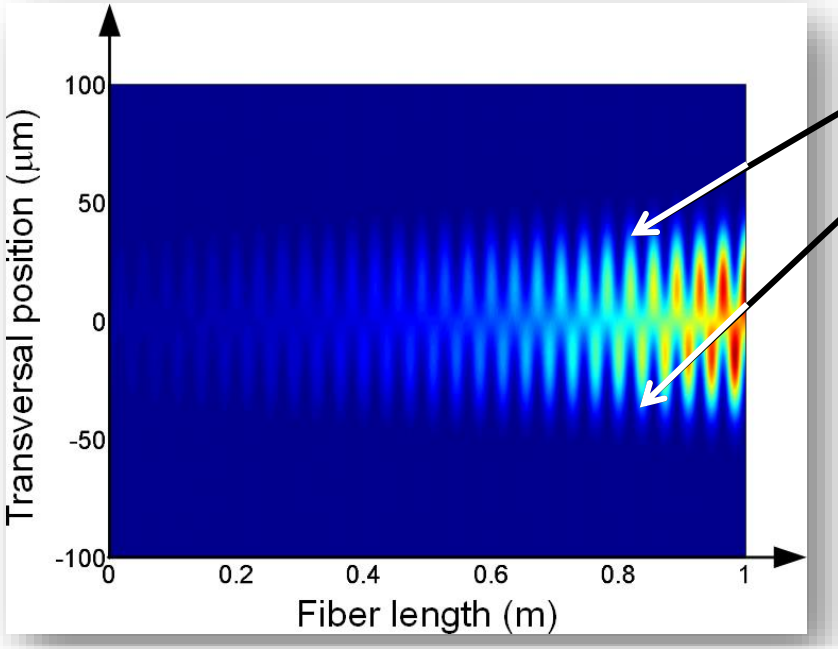
Mode instabilities: What is their origin?

Theoretical understanding

The origin of mode instabilities





Interference between modes

→ different effective indices
→ periodic interference profile

C. Jauregui et al., "Impact of modal interference on the beam quality of high-power fiber amplifiers," Opt. Express **19,** 3258-3271 (2011)

The origin of mode instabilities

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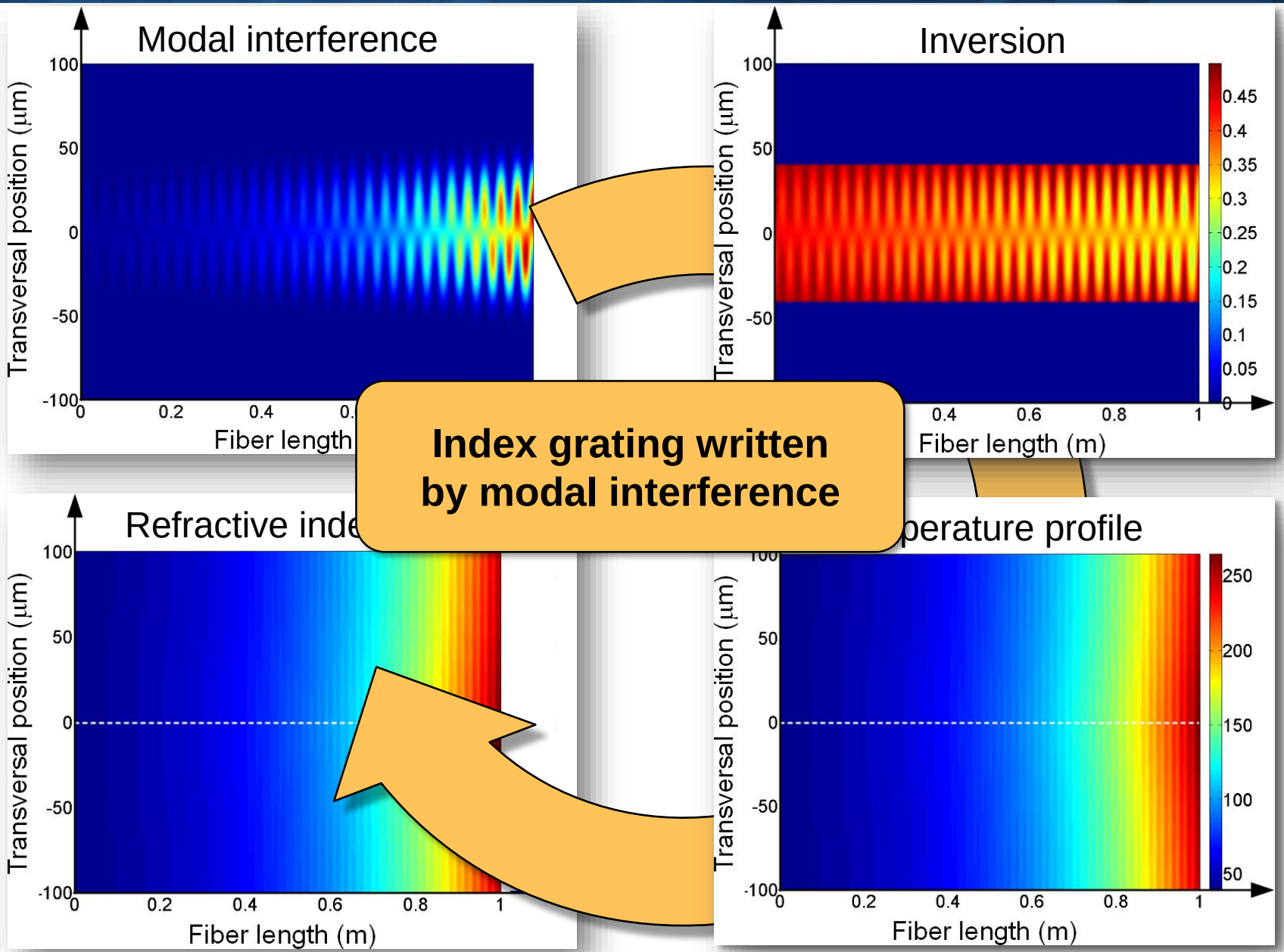


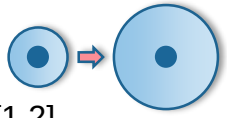
Mode instabilities: Can we do anything about them?

Mitigation Strategies

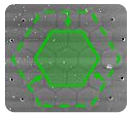
Mitigation strategies for mode instabilities

passive:

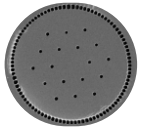
- Reduce the pump absorption [1,2]



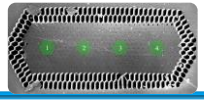
- Advanced doping geometries to reduce the grating strength [3]



- Reduce the non-productive heat-load [4]
- Improved fiber designs [5]



- Use multiple active channels [6]



[1] C. Jauregui et al., "Passive mitigation strategies for mode instabilities in high-power fiber laser systems," Opt. Express **21**, 19375-19386 (2013)
[2] A. V. Smith et al., "Increasing mode instability thresholds of fiber amplifiers by gain saturation," Opt. Express **21**, 15168-15182 (2013)
[3] T. Eidam et al., "Preferential gain photonic-crystal fiber for mode stabilization at high average powers," Opt. Express **19**, 8656-8661 (2011)
[4] C. Jauregui et al., "Simplified modelling the mode instability threshold of high power fiber amplifiers in the presence of photodarkening," Optics Express 23, 20203-20218 (2015)
[5] F. Stutzki et al., "High average power LPF amplifier with robust single-mode operation," Opt. Lett. **36**, 689-691 (2011)
[6] H.-J. Otto et al., "Scaling the mode instability threshold with multicore fibers," Opt. Lett. **39**, 2680-2683 (2014)
[7] H.-J. Otto et al., "Controlling mode instabilities by dynamic mode excitation with an acousto-optic deflector," Opt. Express **21**, 17285-17298 (2013)
[8] C. Jauregui, C. Stihler, J. Limpert, A. Tünnermann, "Mitigation of transverse mode instabilities in high-power fiber laser systems using pump modulation," paper submitted

Multicore Fiber

Passive mitigation strategies

Multicore rod-type fiber

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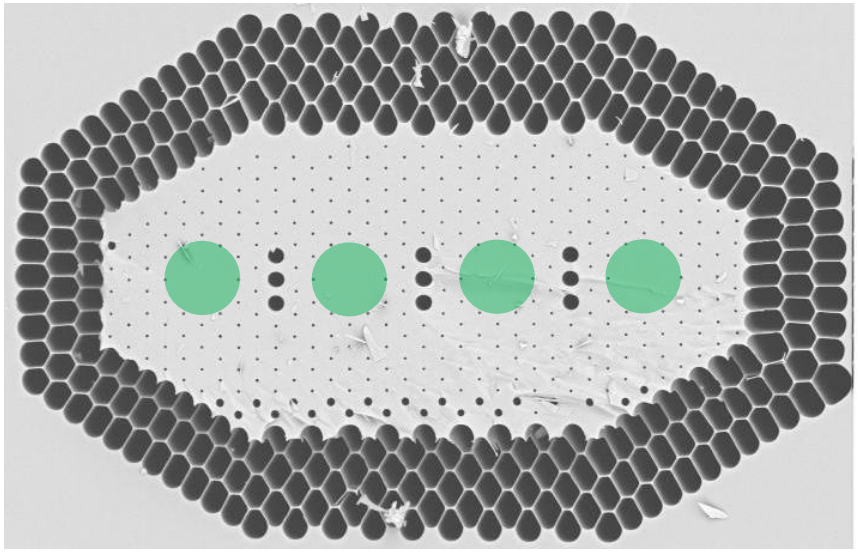
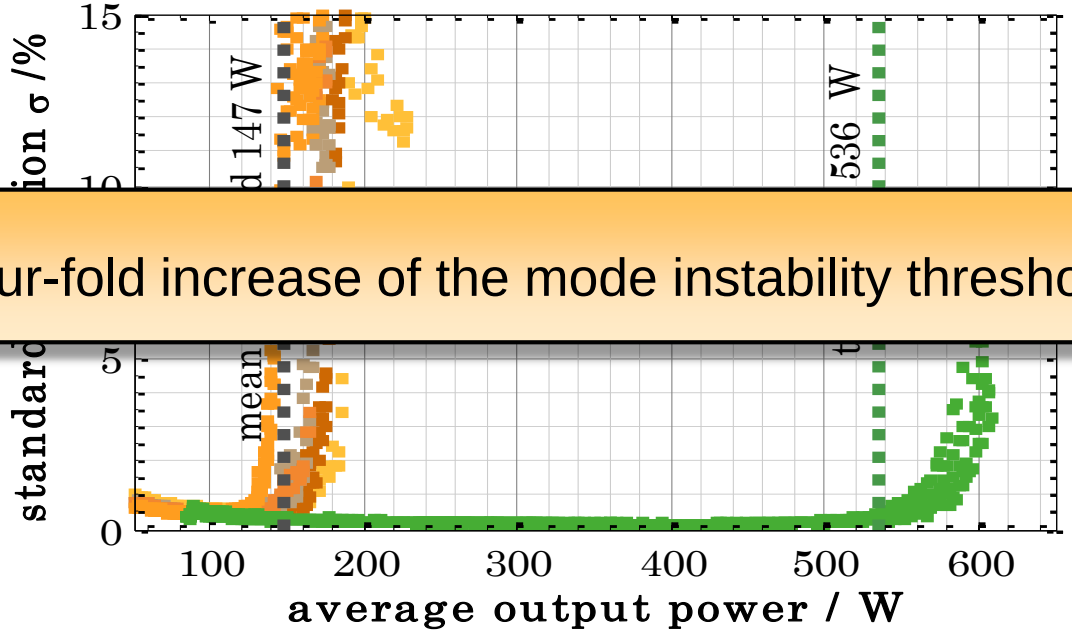


Airclad: 156 µm / 480 µm
core: 52 µm
doped: 38,7 µm
distance cores: 60 µm

length: 1,05 m



Four-fold increase of the mode instability threshold

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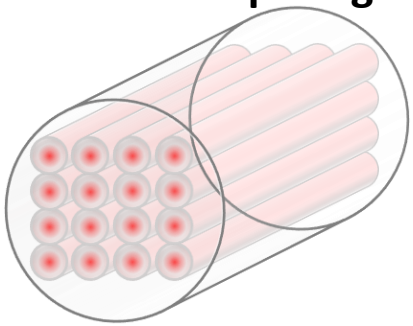
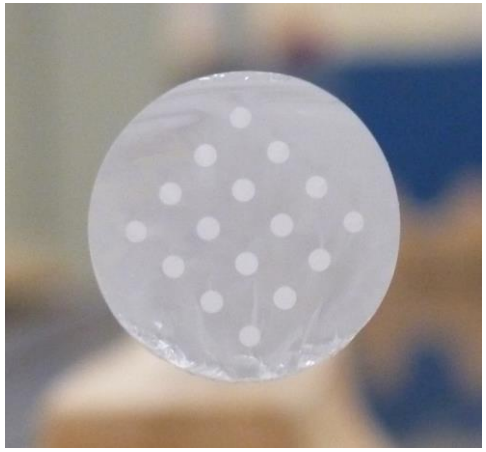
Fiber with multiple signal cores



4x4 step-index fiber



Pulse energy scaling linear with the number of cores

Previous result: Mode instability threshold for average power scaled nearly linearly in a 4 core fiber [1]

In test

[1] H. Otto, A. Klenke, C. Jauregui, F. Stutzki, J. Limpert, and A. Tünnermann, "Scaling the mode instability threshold with multicore fibers," Opt. Lett. 39, 2680-2683 (2014).

Mitigation strategies for mode instabilities

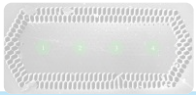
passive:

- Reduce the pump absorption [1,2]

- Advanced doping geometries to reduce the grating strength [3]

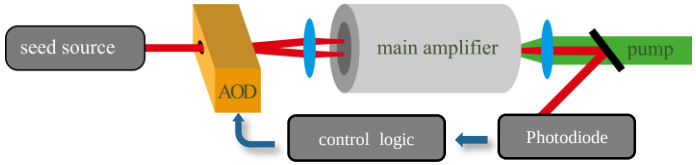
- Reduce the non-productive heat-load [4]
- Improved fiber designs [5]

- Use multiple active channels [6]

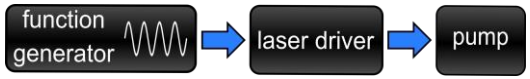


active:

- Dynamic excitation [7]



- Pump modulation [8]



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[3] T. Eidam et al., "Preferential gain photonic-crystal fiber for mode stabilization at high average powers," Opt. Express **19**, 8656-8661 (2011)
[4] C. Jauregui et al., "Simplified modelling the mode instability threshold of high power fiber amplifiers in the presence of photodarkening," Optics Express 23, 20203-20218 (2015)
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[6] H.-J. Otto et al., "Scaling the mode instability threshold with multicore fibers," Opt. Lett. **39**, 2680-2683 (2014)
[7] H.-J. Otto et al., "Controlling mode instabilities by dynamic mode excitation with an acousto-optic deflector," Opt. Express **21**, 17285-17298 (2013)
[8] C. Jauregui, C. Stihler, J. Limpert, A. Tünnermann, "Mitigation of transverse mode instabilities in high-power fiber laser systems using pump modulation," paper submitted

Pump Modulation

Active mitigation strategies

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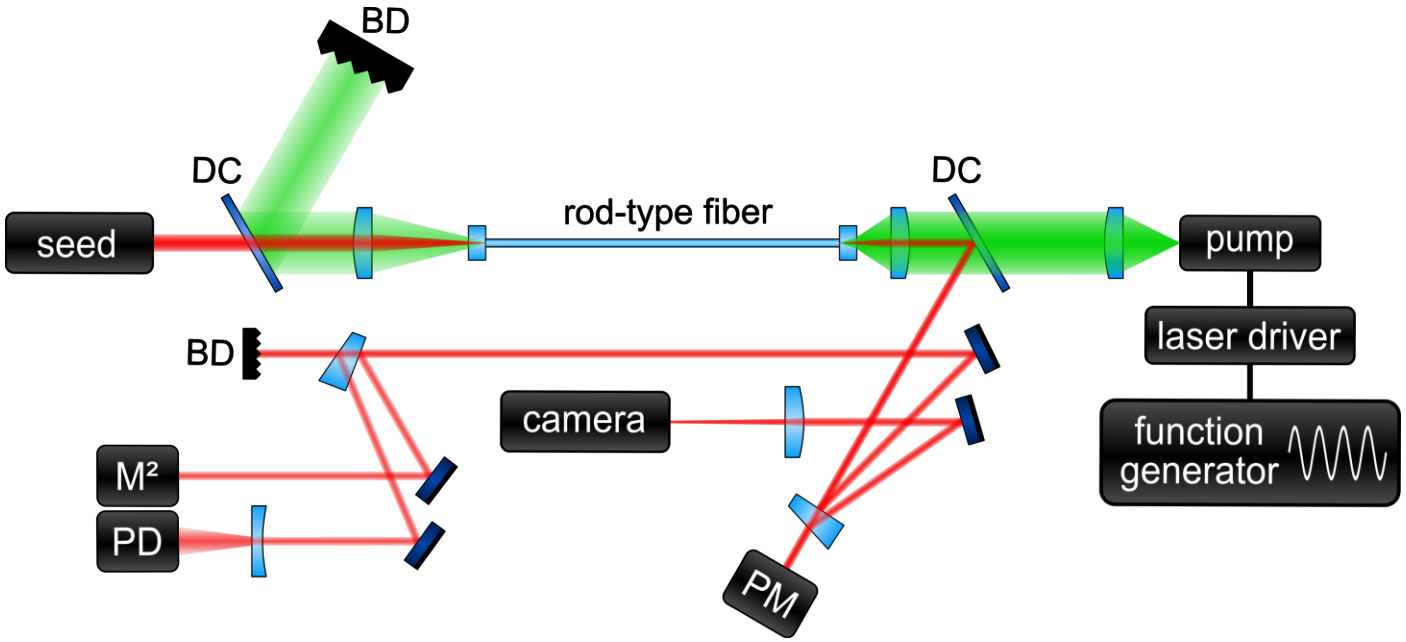


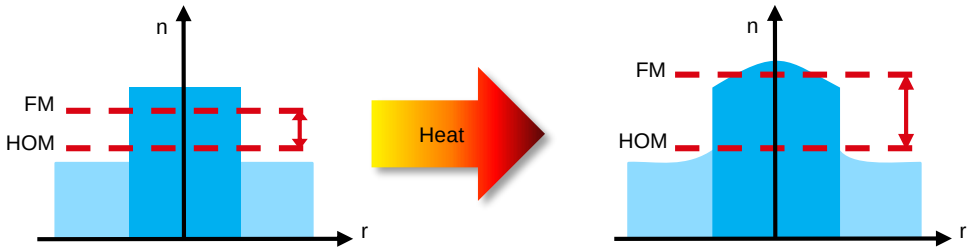
- Large-Pitch Fiber (LPF), L = 1.1 m, MFD = 65 µm, P_{seed} = 5 W, λ_{seed} = 1030 nm, λ_{pump} = 976 nm
- Pump modulation is very easy to incorporate into already existing fiber laser systems (no additional optical components)

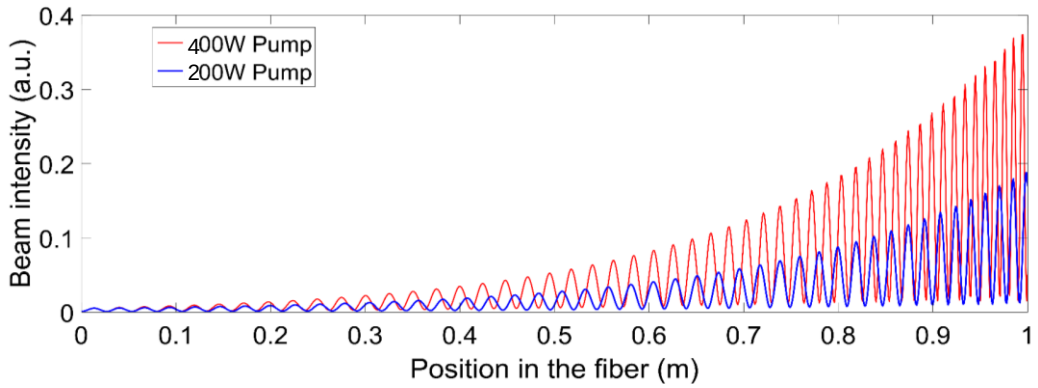
Operation Principle

- **Wash out the refractive index grating by modulating the pump power**
- Pump power modulation ➡ output power modulation

  ➡ variation of the heat load in the fiber ➡ temperature change

- Waveguide and modal set change
  ➡ Index difference between modes is changed





- Beat length of modal interference pattern is modified

- This is done periodically with the modulation frequency f_{mod}

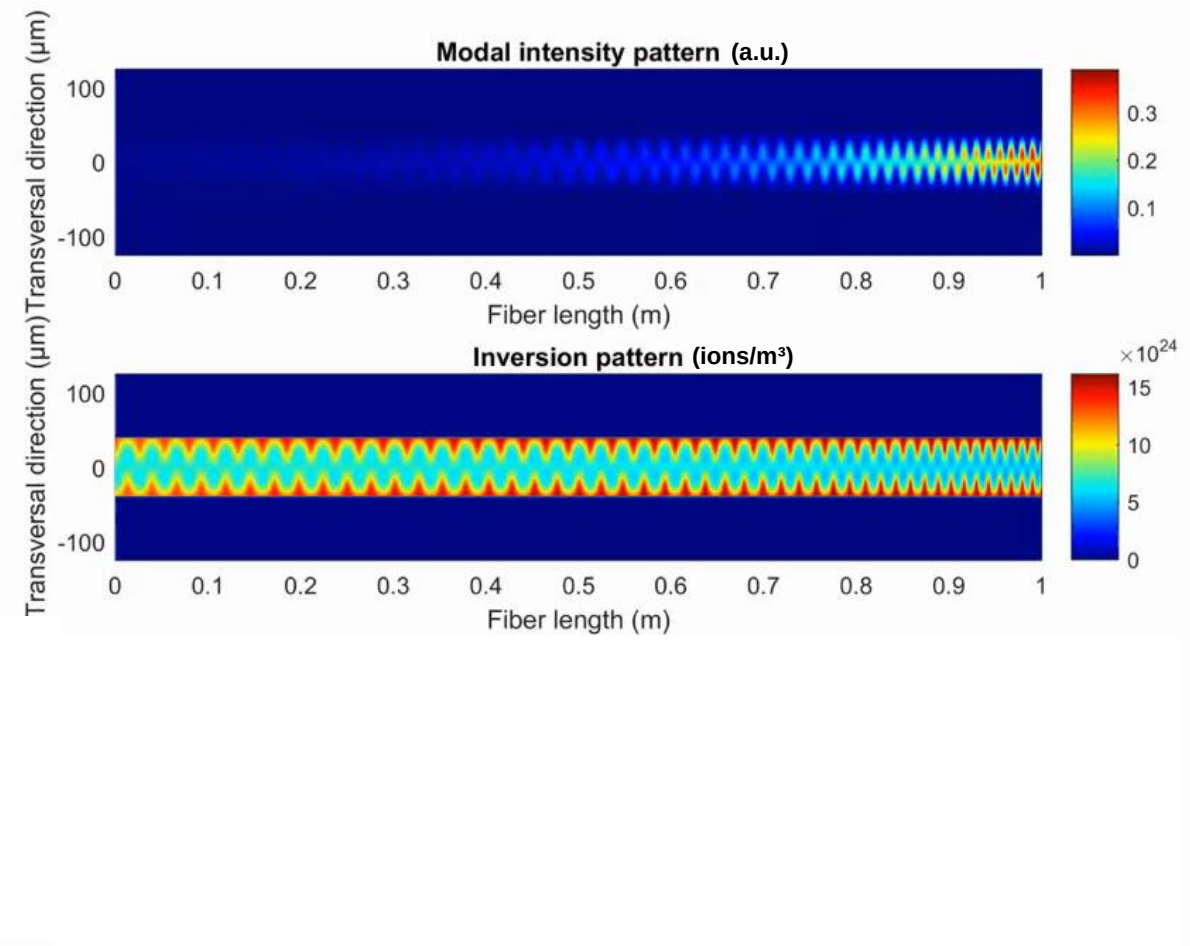
Simulations

Modulation

- P_{pump} = 300 W
- f_{mod} = 1 kHz
- ΔP_{Pump} = ± 30 %
- Sinusoidal wave

Fiber

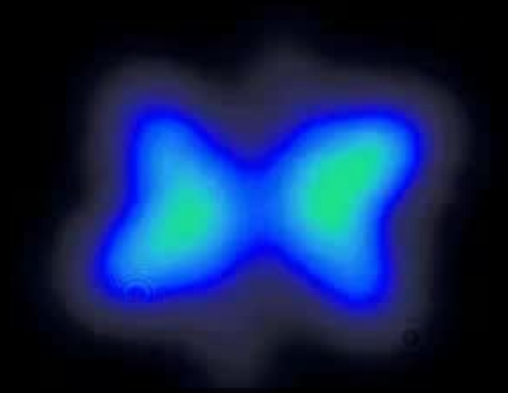
- L = 1 m
- D_{core} = 80 µm
- MFD = 65 µm
- D_{clad} = 228 µm
- V = 7
- N = $3.25 \cdot 10^{25}$ Yb-ions/m³
- P_{seed} = 5.5 W
- λ_{seed} = 1030 nm
- λ_{pump} = 976 nm



Experiments

P_{thr} = 266 W
P_{out} = 407 W (average)
pump modulation off
M^2 = 1.6

f_{mod} = 720 Hz
ΔP_{pump} = ±77 %



Stabilization done in open-loop (no-feedback loop necessary)

framerate = 30 fps

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Experiments

P_{thr} = 266 W
P_{out} = 563 W (average)
pump modulation off
M^2 = 2.5

f_{mod} = 694 Hz
ΔP_{pump} = ±81 %

Highest average output power emitted from a single-channel rod-type fiber amplifier with a high-quality stabilized beam

framerate = 30 fps

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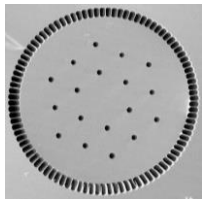
Mode instabilities: Is this the end of the road for fiber laser systems?

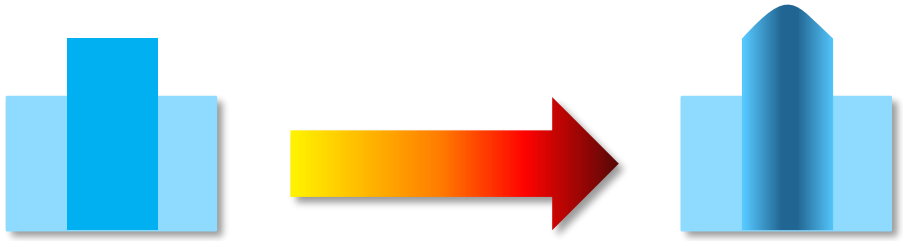
Conclusions

Conclusions

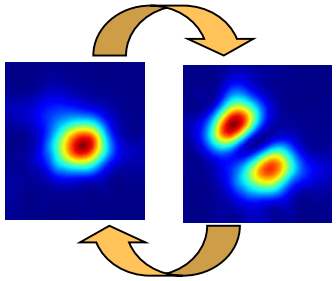
- Optical fibers are an extraordinary active medium…



- …but thermal effects cannot be simply neglected anymore.



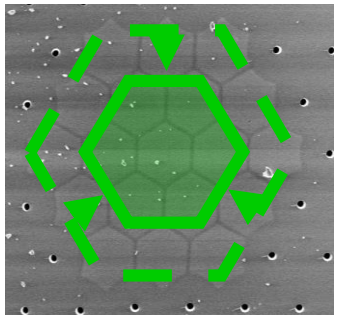
- Recently a serious new limitation has been discovered: Mode Instabilities.

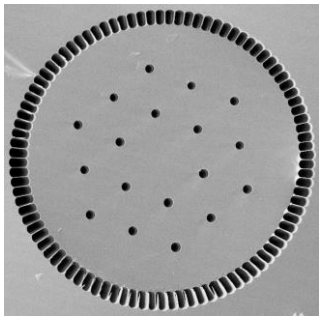


- This has quickly become the most limiting factor for the futher scaling of fiber systems.

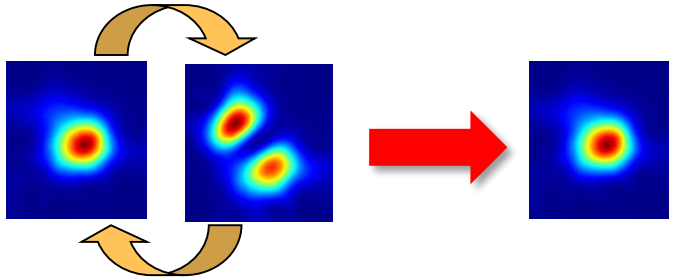
Outlook

- But fibers offer unique possibilities to control this effect.



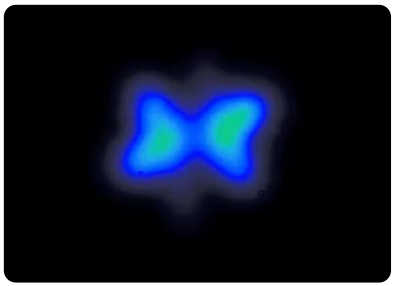


- The research on TMI worldwide has led to a rapid progress in the understanding of this effect and to the demonstration of effective methods (both passive and active) to mitigate it.



In the near future the output average power of fiber laser systems will start to rise again.

Thank you for your attention!



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