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HIGH POWER FIBER LASERS

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Outline:

- Background
- History
- Key components
- Applications
- Commercial success
- Power-scaling limits
- Conclusions

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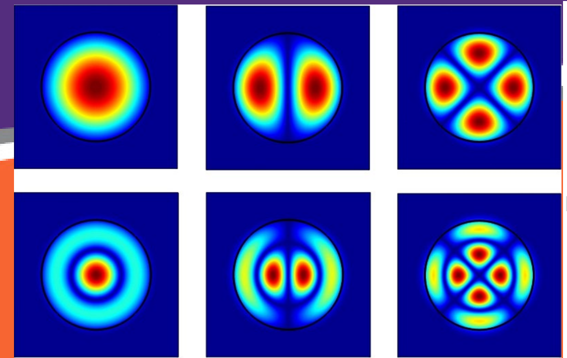
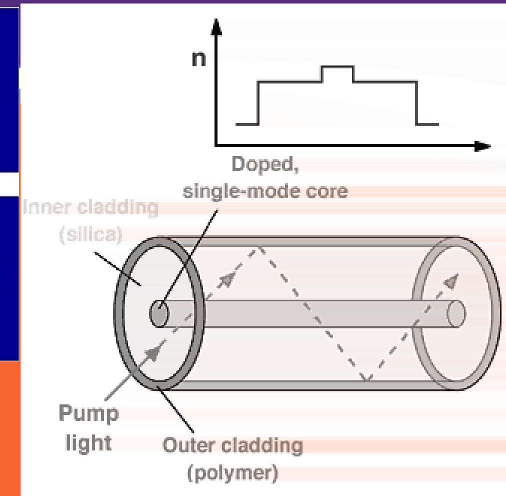
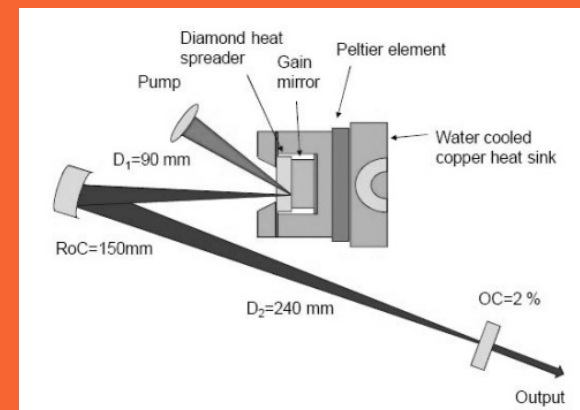
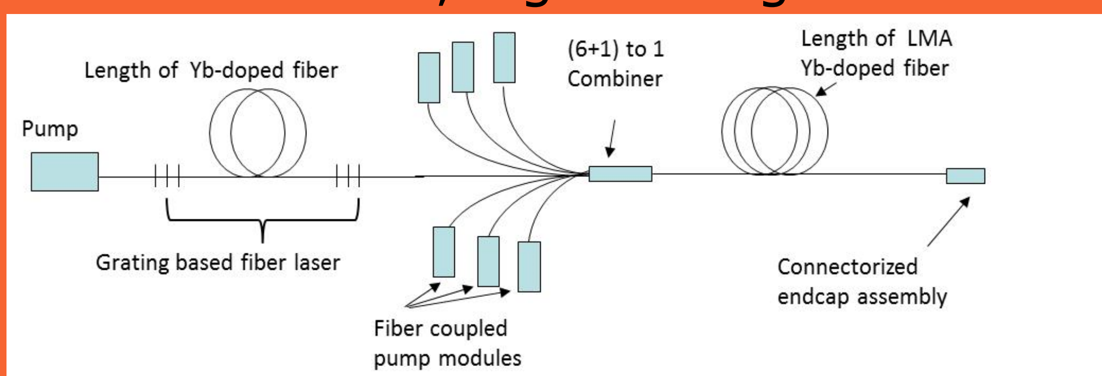


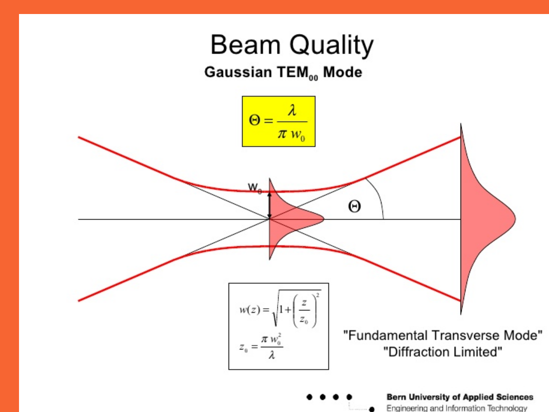


Background

- **What is fiber laser?**
  - Core is made of rare earth doped silica
  - Optical power is confined in guided mode
- **Why are we interested?**
  - Diffraction-limited mode quality
  - Efficient heat removal (small heat volume)
  - High efficiency (pump is confined)
  - Robust (potentially monolithic)
  - Low-loss silica, high damage threshold







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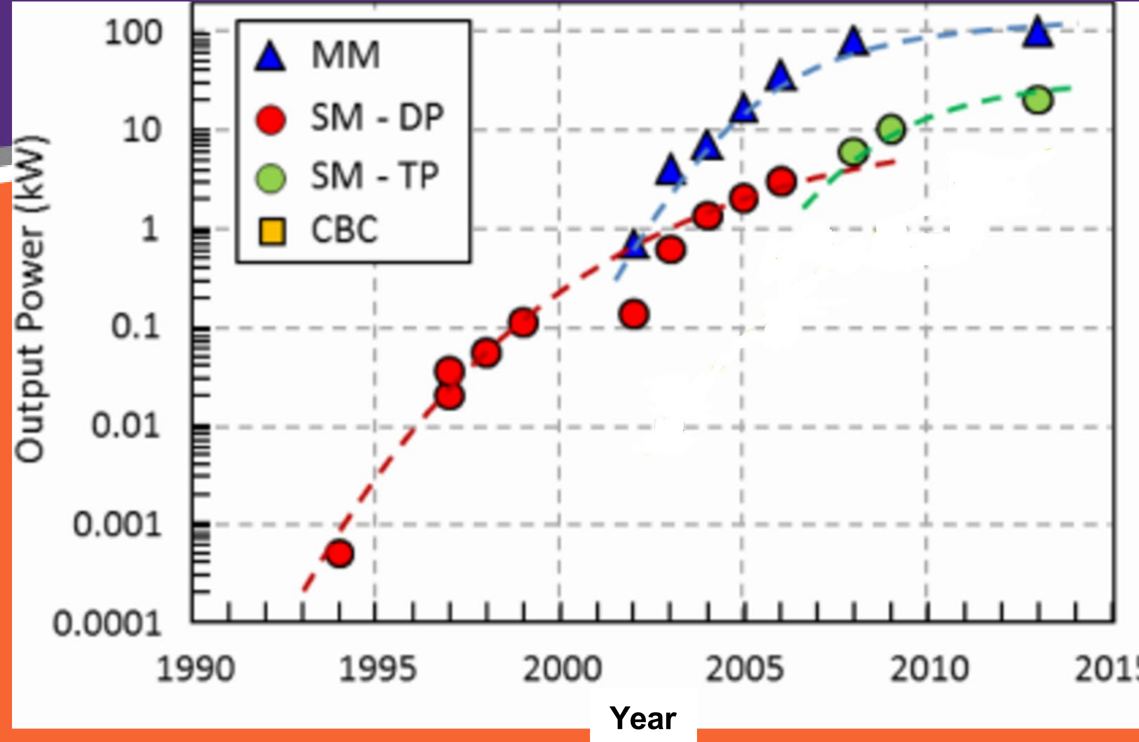
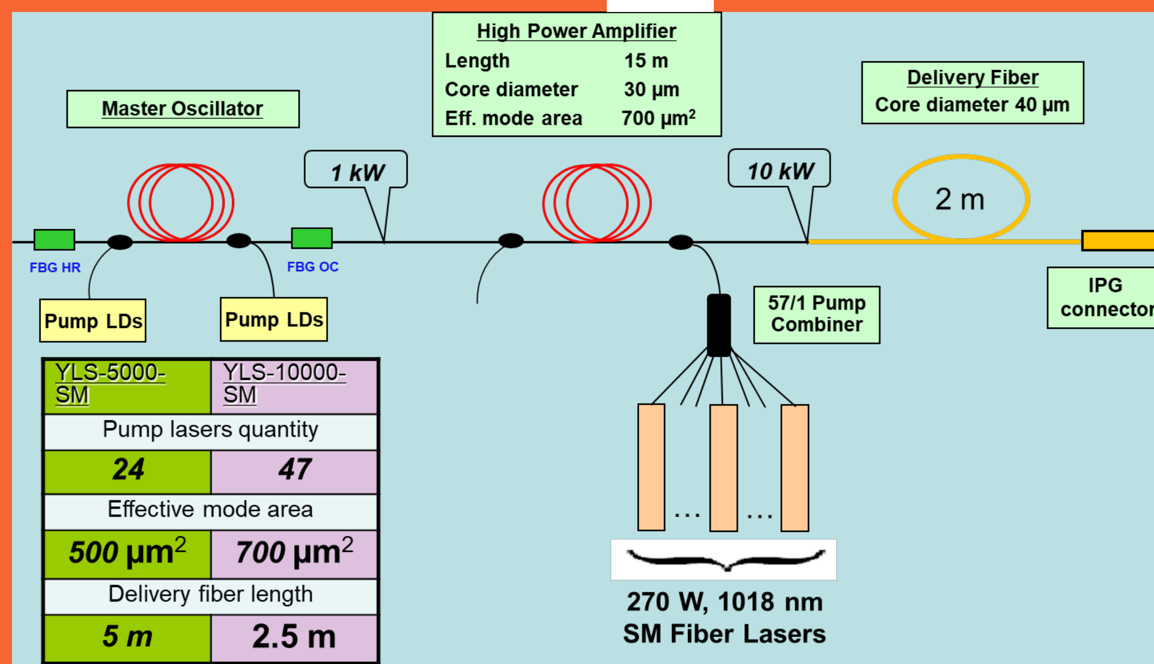
History

- **SM 20 kW**
  - Rapid SM power growth before 2010
  - Mode quality limited by thermal effect
- **MM 500kW**





YLS-5000-SM	YLS-10000-SM
Pump lasers quantity	
24	*47*
Effective mode area	
500 μm^2	*700 μm^2*
Delivery fiber length	
5 m	2.5 m

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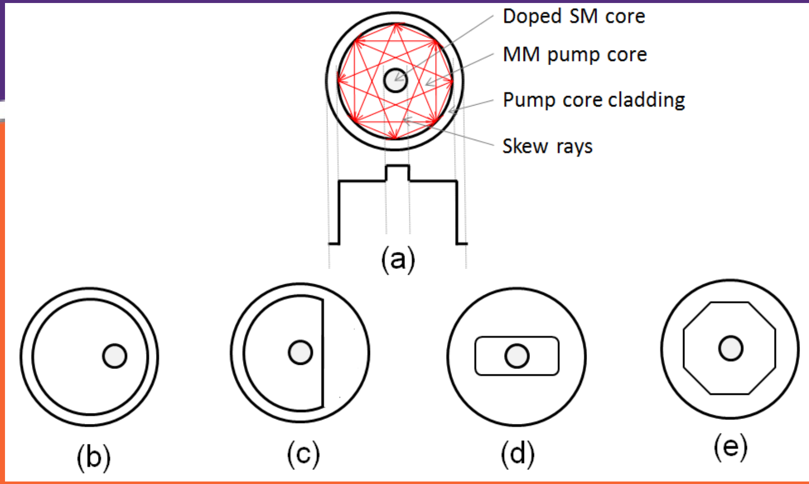
Key components

- Double-clad fibers
  - High efficiency (O-O eff. 80-90%)
  - Efficient heat removal
  - High purity/damage threshold



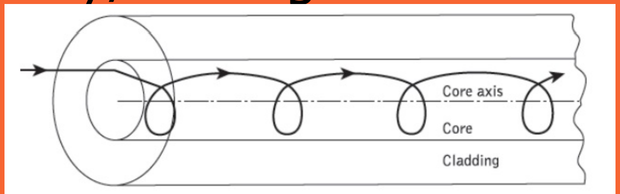
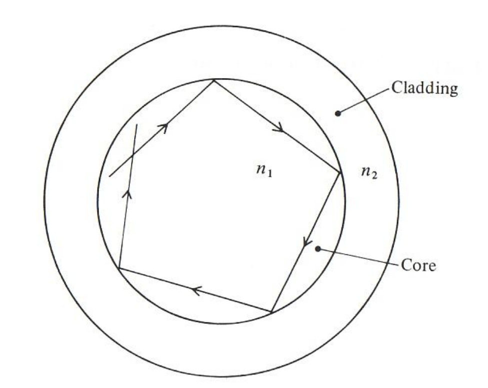
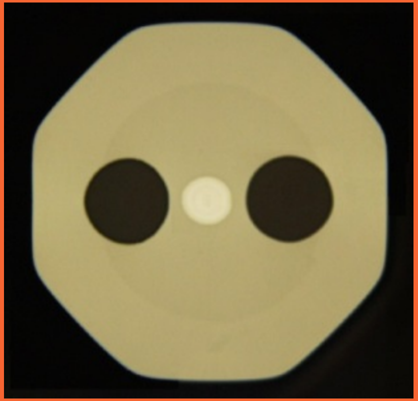
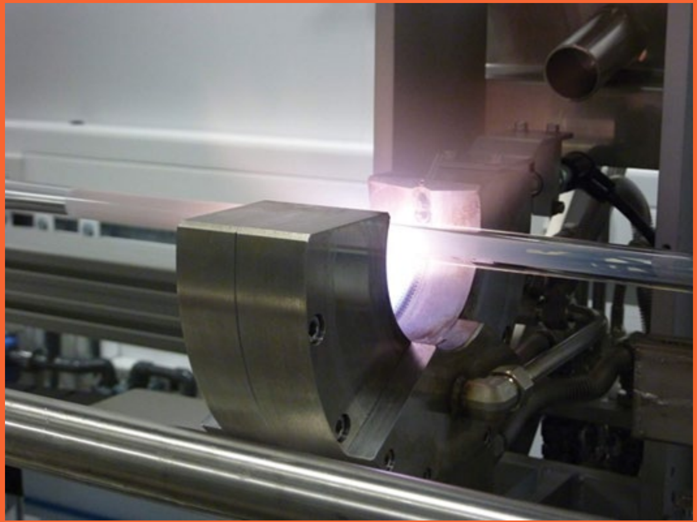
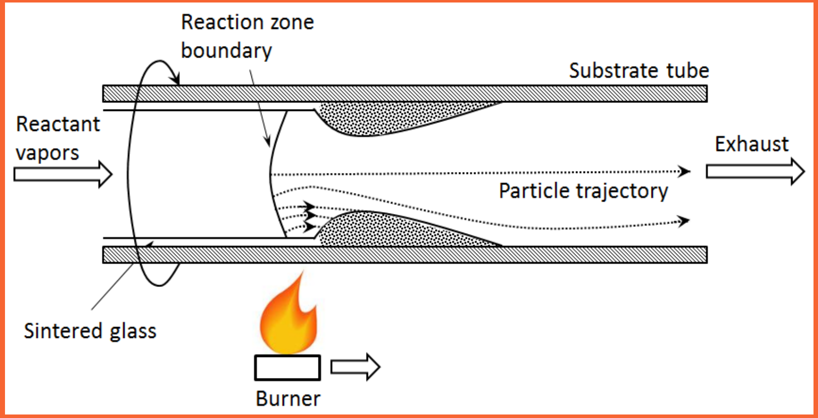


Figure 1.18 A helical skew ray path within a graded index fiber



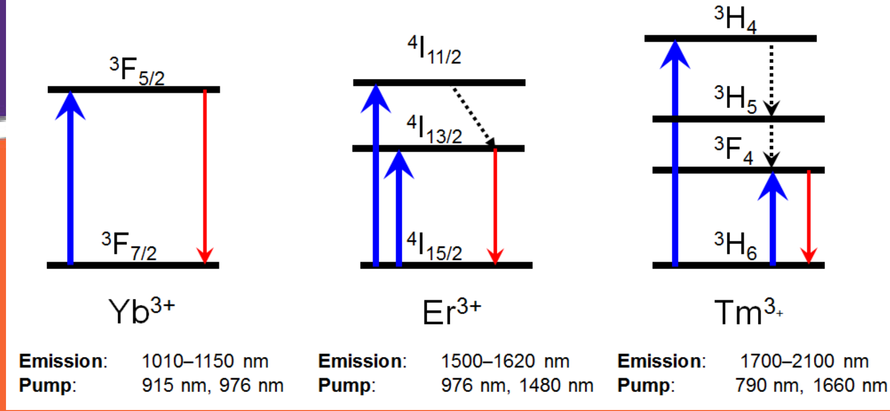


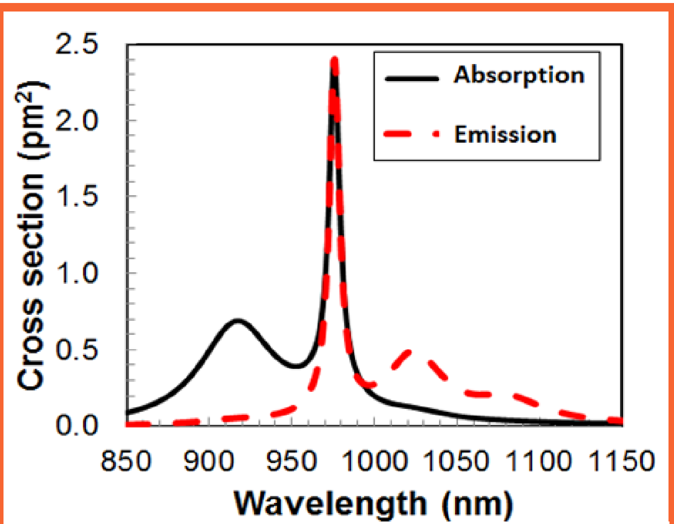


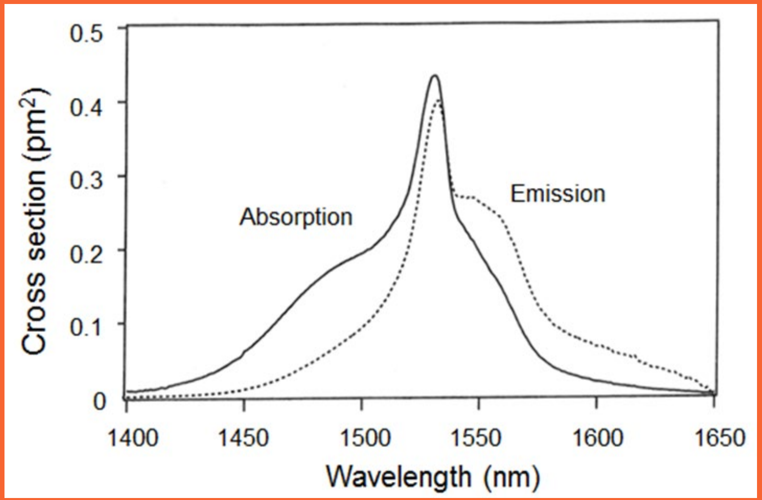


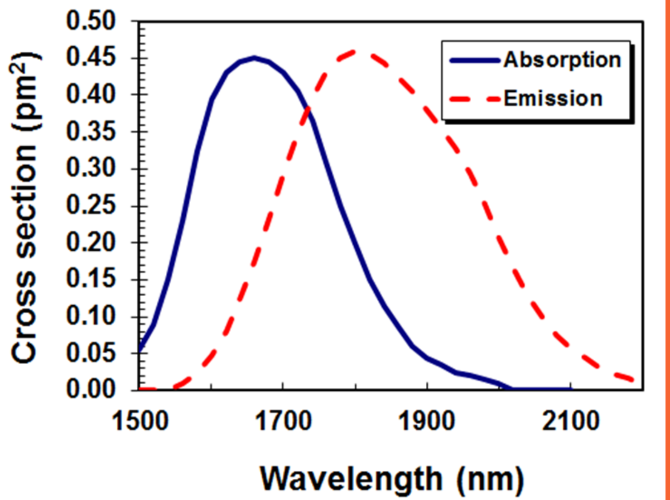
Key components

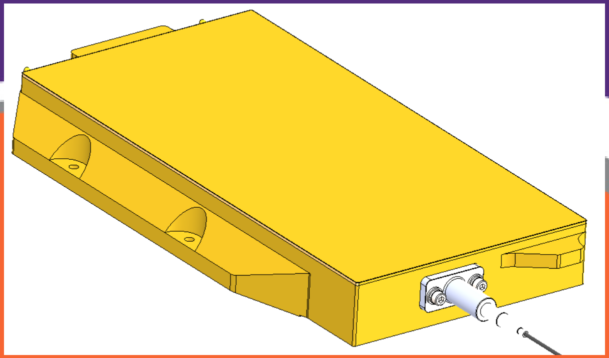
- **Rare earth doping**
  - Notable dopants: Yb^{3+}, Er^{3+}, Tm^{3+}
  - No gas phase precursors
  - Solution doping is commonly used





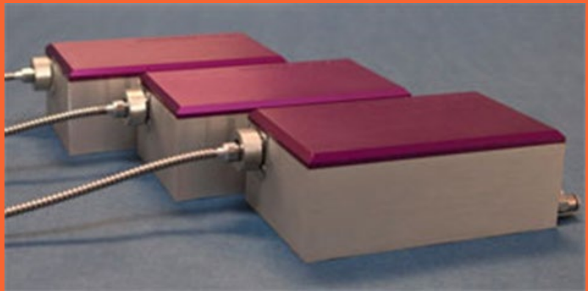






Key components

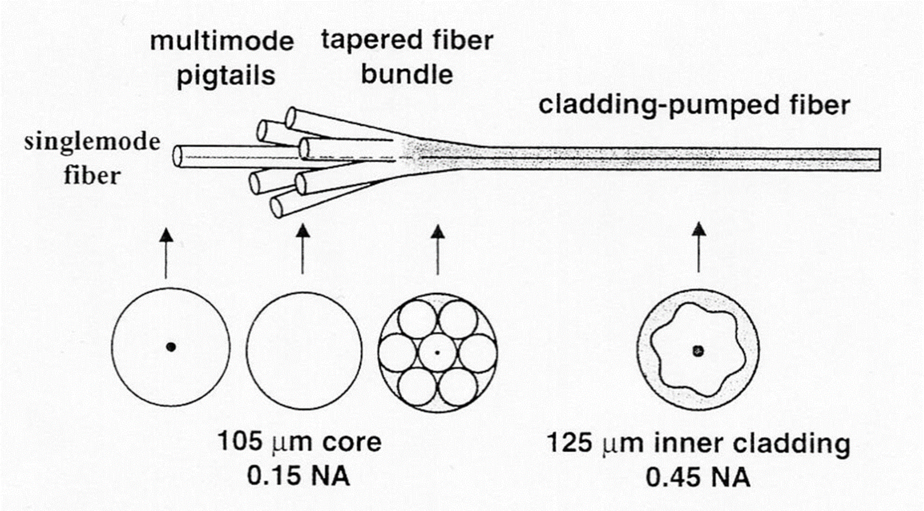
- **High-power pump diode is a key enabling factor**
  - Fiber-coupled Single emitter diode (9xx E-O eff. ~50%)
    - ~10W in 105μm/0.15NA fiber
    - ~200W in ~105μm/0.22NA fiber by combining diodes
    - ~500W in 200μm/0.22NA fiber
    - Long lifetime (100,000hrs (11 years), continuous use, IPG)
    - Used from low power to kW fiber lasers
    - Distributed architecture, ease of thermal management
  - **Fiber coupled diode bar (9xx)**
    - 1.5-3.5kW in 400μm/0.2NA
    - Single laser architecture (ease of switching pump)
    - Potentially lower cost



Key components

❖ Pump combiners

- A variety of approaches explored initially
- Standards have emerged based on standard fiber sizes



D. J. DiGiovanni US patent #5,864,644

Input fibers\ Output fiber	125 μm DCF, NA =0.46	250 μm DCF, NA = 0.46	400 μm DCF, NA =0.46
105 / 125 μm, NA = 0.15	7 x 1	19 x 1	61 x 1
105 / 125 μm, NA = 0.22	4 x 1	7 x 1	37 x 1
200 / 220 μm, NA = 0.22	1 x 1	4 x 1	7 x 1
400 / 440 μm, NA = 0.22	N/A	1 x 1	3 x 1

Assuming fully filled pump fibers

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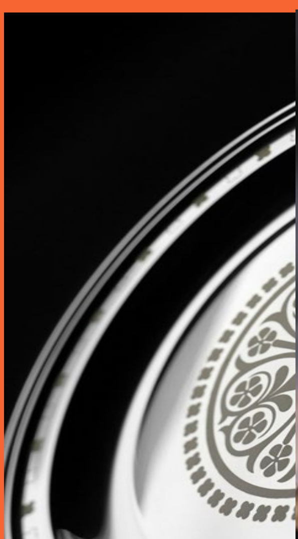
Applications

- Marking: ns pulsed fiber lasers
- Cutting and welding in manufacturing: few kW CW fiber lasers
- Micro-machining in precision machining (electronics/semiconductor/solar etc.): ps/fs fiber lasers
- Defense and security, sensing (LIDAR), Direct energy weapon: CW/pulsed
- Medical, Lasik, surgery, diagnosis: CW/pulsed



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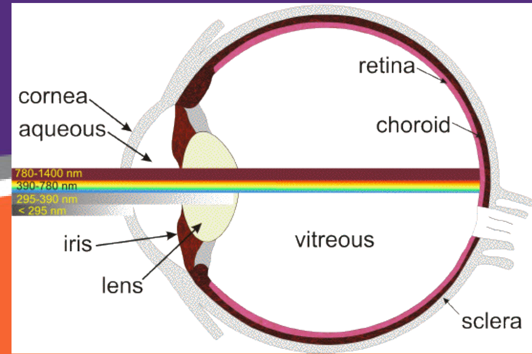
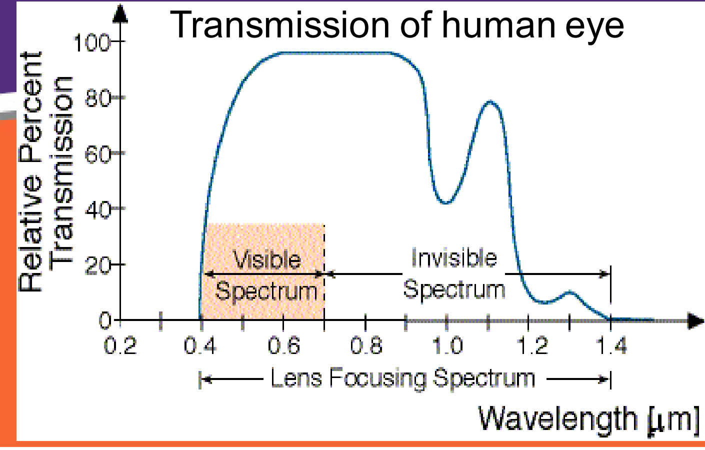
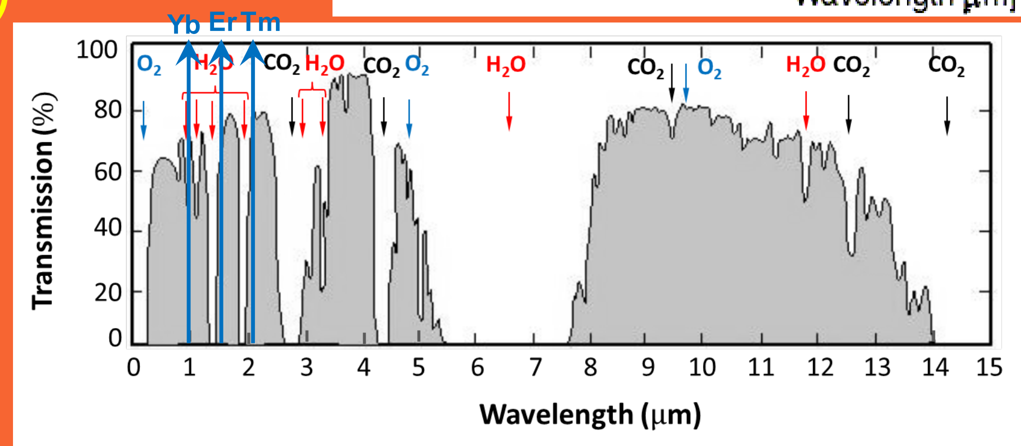
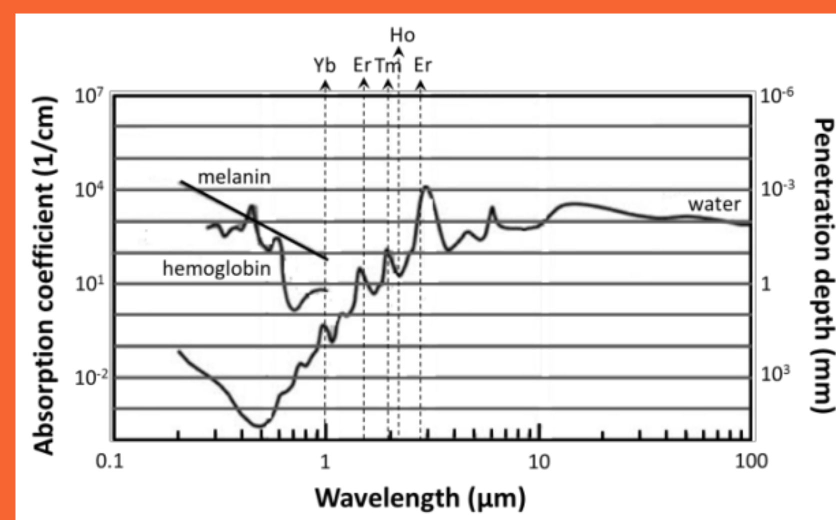
Applications





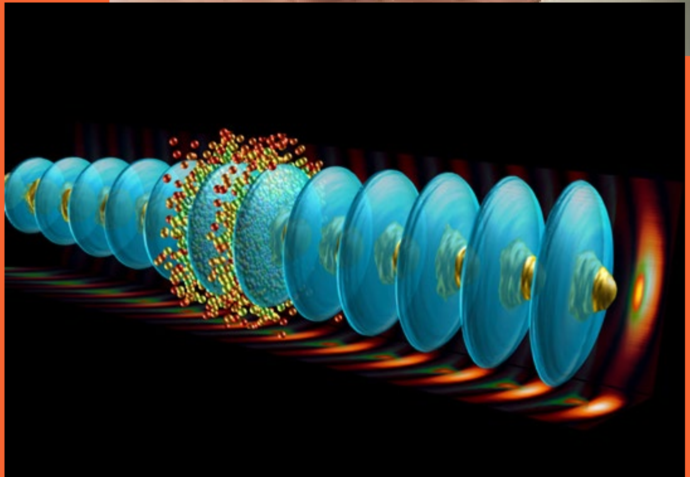
- ❑ Yb ~1.05µm (SM 20kW)
  - ➢ Highly efficient
  - ➢ Matured
  - ➢ Highest power
- ❑ Er ~1.55µm (SM 300W)
  - ➢ Eye safer
  - ➢ Lidar,
  - ➢ Laser ranging
  - ➢ Free-space communications
- ❑ Tm ~2µm (SM 1kW)
  - ➢ Lidar
  - ➢ High OH absorption
  - ➢ Surgery
  - ➢ Pumps for MWIR





Emerging Applications

- 3D printing
- Well drilling in oil industry
- cutting/welding in hazardous environment (Reactor decommission)
- Particle accelerations
- Satellite launching



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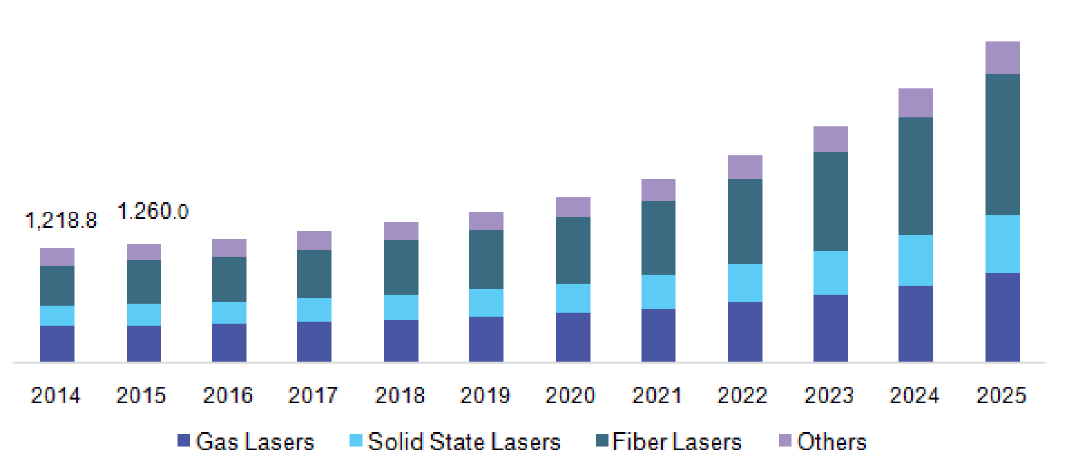
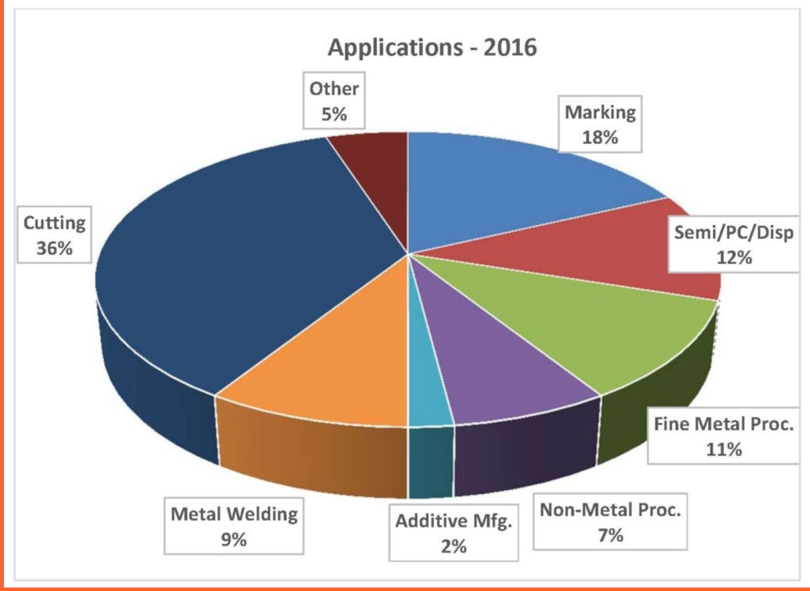
Commercial success

- Near double-digit growth
- Revenue exceeded $1B in 2015
- Largest segments: Metal cutting (36%), marking (18%), semiconductor/PC/phone display (12%), micro-machining (11%)
- Low running cost is a major factor





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Power-scaling limits

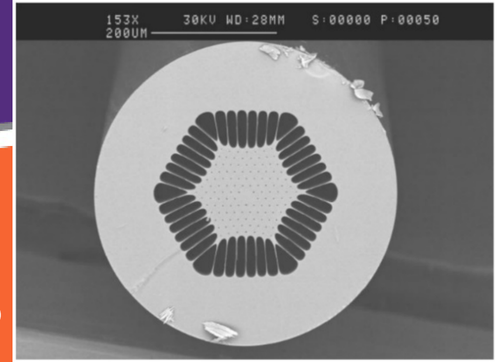
- **Further power scaling is critical**
  - Increased throughput in manufacturing
  - Emerging applications:
    - Particle accelerations
    - Satellite launch
    - Space explorations
    - Laser-induced fusion
    - Direct energy weapons
    - …
- **Most of the emerging applications also need good mode quality**

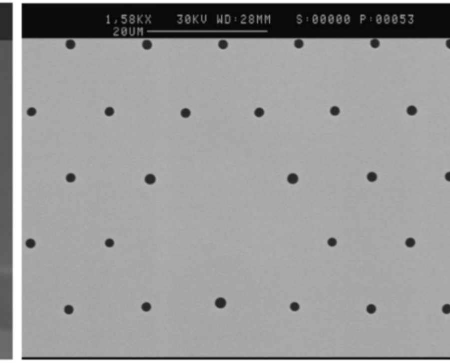
Limit to peak powers: nonlear effects

- **Nonlinear effects arise from high optical intensity is the major limit to power scaling:**
  - Stimulated Brillouin scattering (SBS)
  - Stimulated Raman scattering (SRS)
  - Four-wave mixing (FWM)
  - Self-phase modulation (SPM)

- **Need large mode area:**
  - Most effective way to mitigate optical nonlinear effects
  - High energy storage leads to higher pulse energy

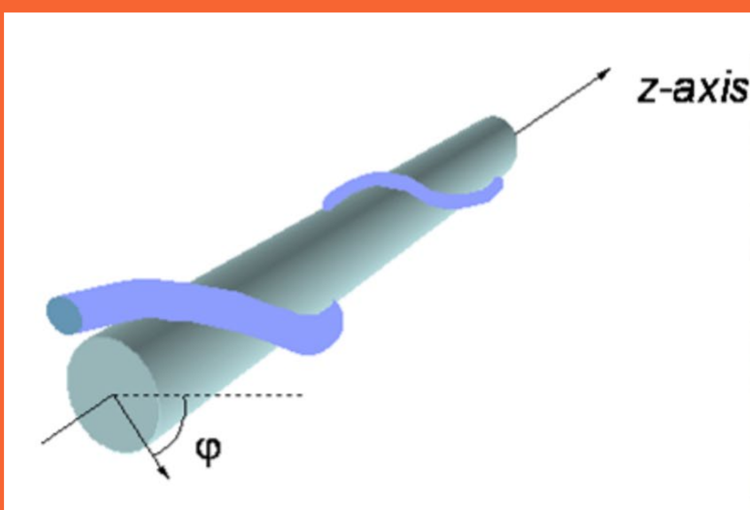
Limit to peak powers

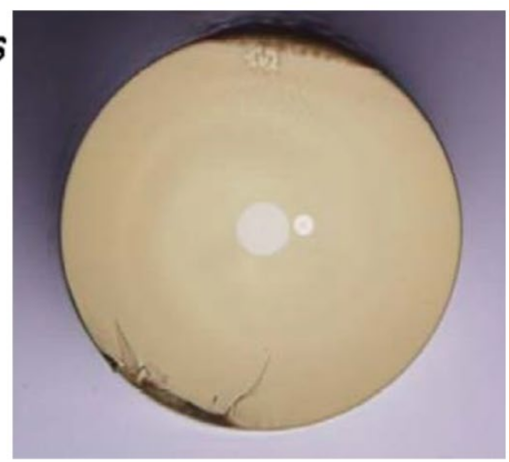


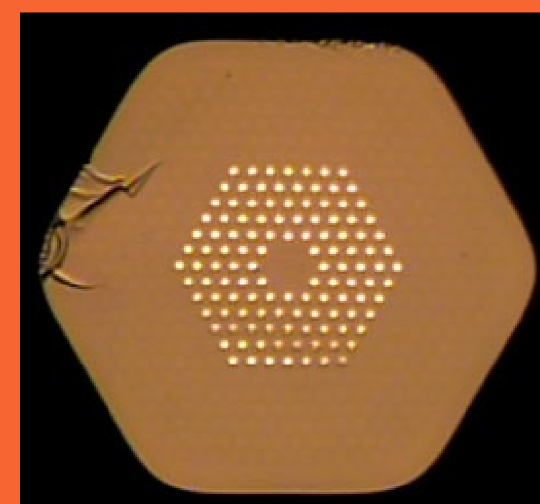


❖ Mode area scaling

- ❑ Operating in the few-mode regime
- ❑ Advanced designs to suppress high-order modes
  - ➢ Photonic crystal fiber
  - ➢ Leakage channel fibers
  - ➢ Chirally coupled core fibers
  - ➢ All-solid photonic bandgap fibers

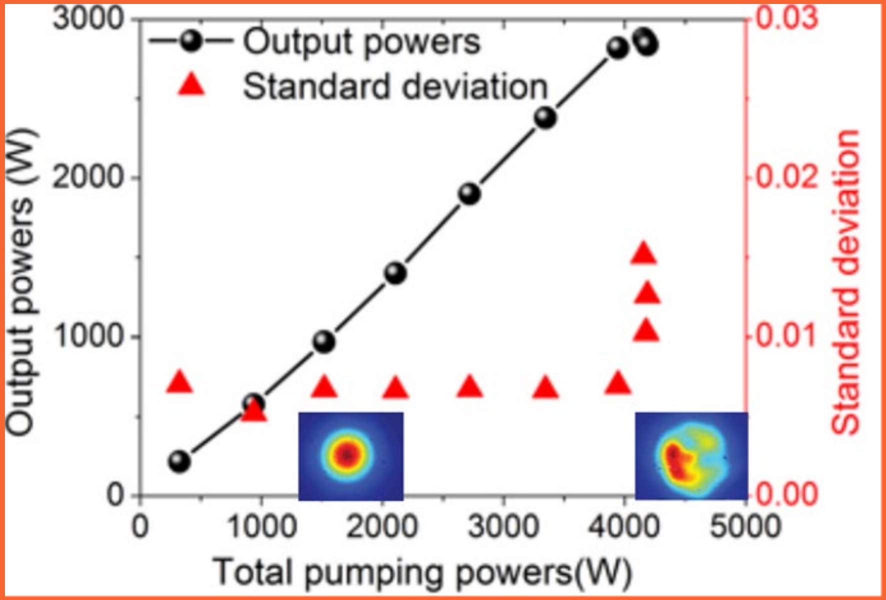






❖ Limit to average powers: transverse mode instability (TMI)

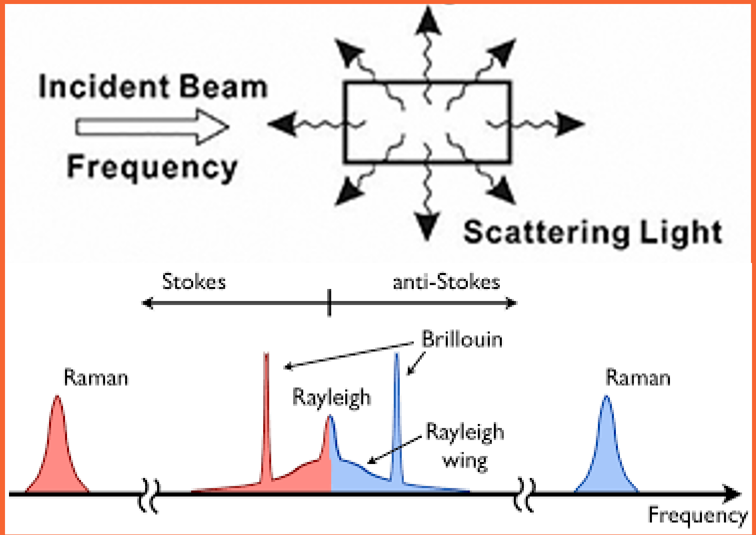
- All the key underlying physics was identified over four decades earlier as Stimulated Thermal Rayleigh Scattering
- Limited to 3-5 kW in conventional LMA fibers
- Lower quantum defect by tandem pumping used in IPG 20kW fiber lasers can mitigate this at some level
- Thresholds in the order of 100-800W observed in large-mode-area PCFs

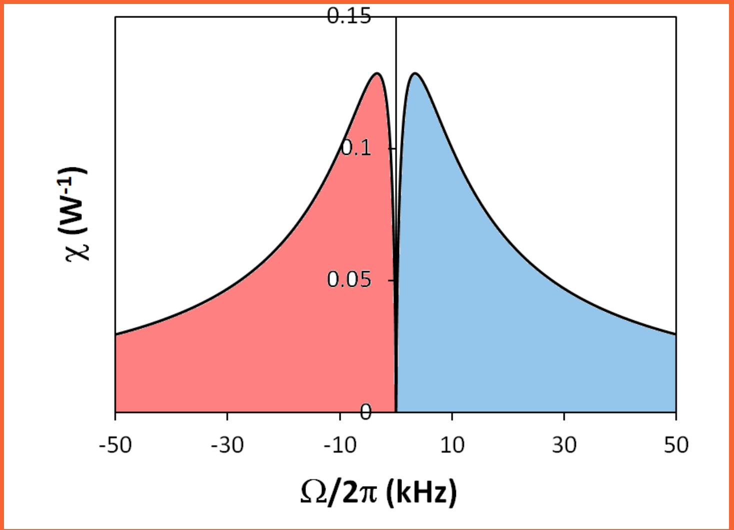


Jauregui et al, Opt. Express 20, 440-451(2012).
Jauregui et al, Opt. Express 19, 3258-3271(2011).
Hansen et al, Opt. Express 19, 23965-23980(2011).
Smith et al, Opt. Express 19, 10180-10192(2011).
Ward et al, Opt. Express 20, 11407-11422(2012).
Hansen et al, Opt. Lett. 37, 2382-2384(2012).
Dong, Optics Express 21, 2642–2656 (2013).

Stimulated Thermal Rayleigh Scattering

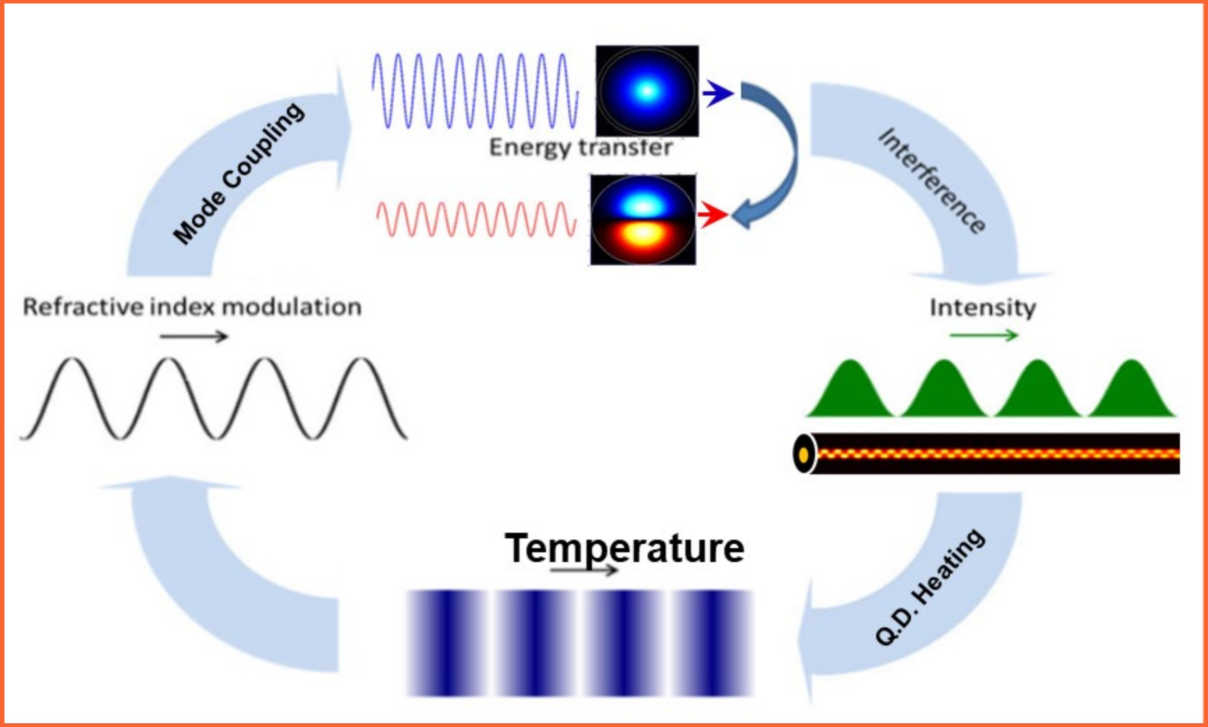
- Rayleigh scattering (or Rayleigh center scattering) is scattering of light from nonpropagating density fluctuations, no frequency shift
- Rayleigh-wing scattering is scattering from flunctuation in orientation of anisotropic molecules, rapid change and broad spectrally
- STRS is scattering of traveling temperature fluctuations which is frequency shifted. Linewidth is similar to Rayleigh scattering
- Phase-matching can only be achieved by traveling fluctuation, so there is a frequency shift, like SBS





STRS in Fiber Lasers

- Spatial modal interference gives intensity fluctuations along fiber
- Quantum heating converts intensity fluctuations to temperature fluctuations (like absorptive heating in earlier STRS works)
- Phase-matching requires traveling fluctuations, like SBS



Simple Physics Model of STRS in Fiber Lasers

- Can be described by nonlinear coupled equations

$$\frac{\partial P_{01}(z)}{\partial z} = -g_{01}\chi_{mn}P_{01}(z)P_{mn}(z) + g_{01}P_{01}(z)$$

$$\frac{\partial P_{mn}(z)}{\partial z} = g_{01}\chi_{mn}P_{01}(z)P_{mn}(z) + (g_{mn} - \alpha_{mn})P_{mn}(z)$$

- In an amplifier with uniform gain without pump depletion

$$P_{mn}(L) = P_{mn}(0)e^{(g_{mn}-\alpha_{mn})L}\,e^{\chi_{mn}\int_0^L g_{01}P_{01}(z)dz}$$

- Total nonlinear gain only depends on total thermal load for a given fiber!
- In high gain regime,

$$P_{mn}(L) = P_{mn}(0)e^{(g_{mn}-\alpha_{mn})L}\,e^{\chi_{mn}P_{out}}$$

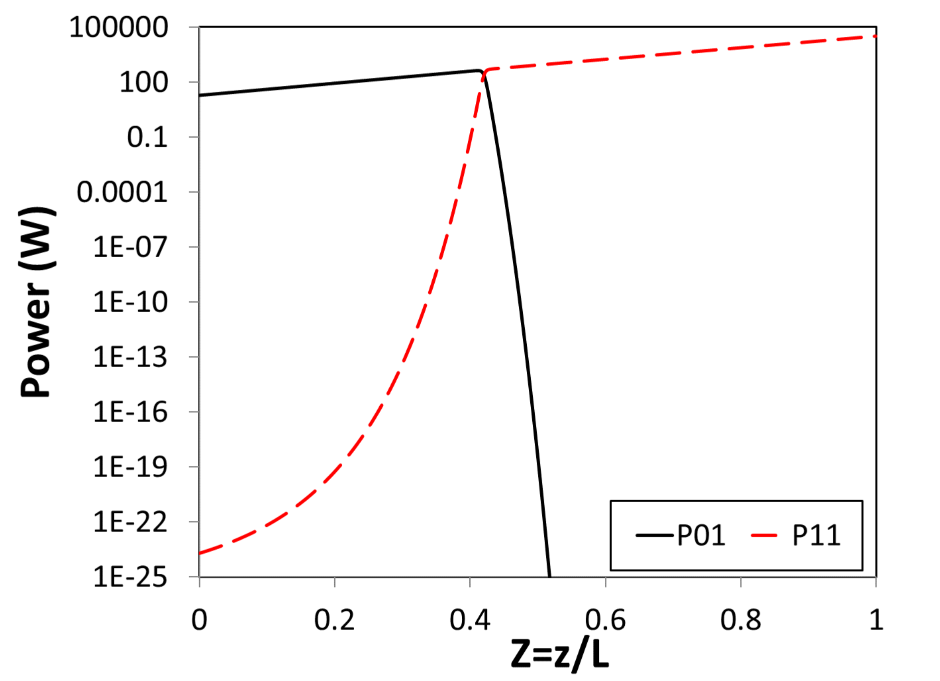
- Total nonlinear gain only dependent on output power for a given fiber!

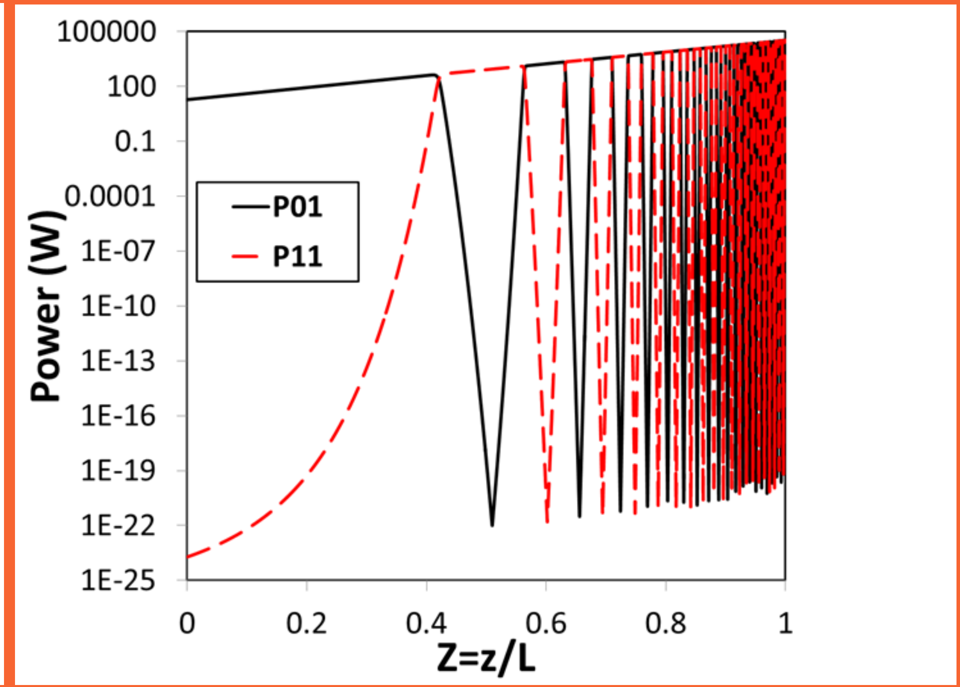
L. Dong, “Stimulated thermal Rayleigh scattering in optical fibers,” Optics Express **21**, 2642–2656 (2013).

Simple Physics Model of STRS in Fiber Lasers

- Evolution of modal powers along the fiber

$$P_{mn}(L)=P_{mn}(0)e^{(g_{mn}-\alpha_{mn})L}e^{\chi_{mn}P_{out}}$$





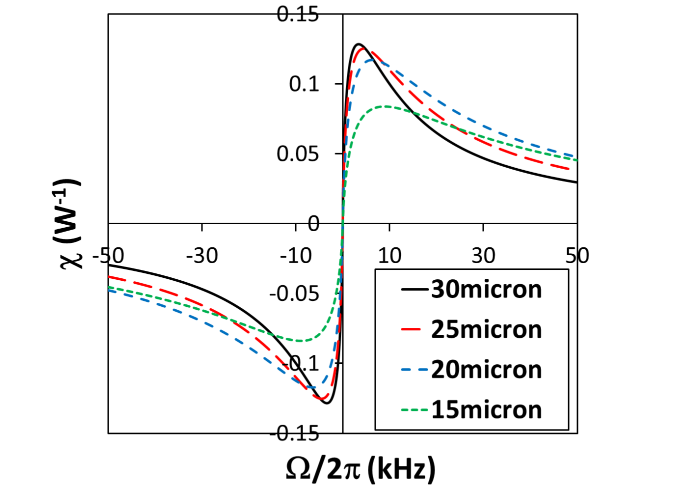
L. Dong, "Stimulated thermal Rayleigh scattering in optical fibers," Optics Express **21**, 2642–2656 (2013).

Simple Physics Model of STRS

- Nonlinear coupling coefficient χ_{mn}

$$g_{01}\chi_{mn} = \frac{2\pi k k_T}{\rho C}\left(\frac{\lambda_s}{\lambda_p} - 1\right)\sum_{l=1}^{\infty} \frac{2\left(\frac{2\Omega}{\Gamma_{ml}}\right)}{1+\left(\frac{2\Omega}{\Gamma_{ml}}\right)^2} \frac{\int_0^d g(r) f_{01}(r) f_{mn}(r) T_{ml}(r)\, r dr \int_0^b f_{01}(r) f_{mn}(r) T_{ml}(r)\, r dr}{N_{01} N_{mn} \Gamma_{ml} \int_0^b T_{ml}^2(r)\, r dr}$$

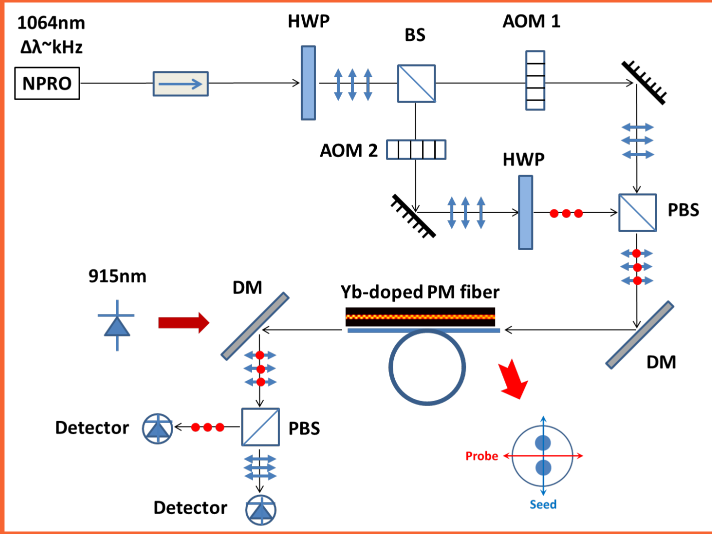
- K_T: dn/dT, C: specific heat, k: wave vector, ρ: density.
- Ω is frequency diffrenec between the two modes.
- Thermal conductivity only appears in Γ and affect only mode frequency: $\Gamma \propto \kappa$

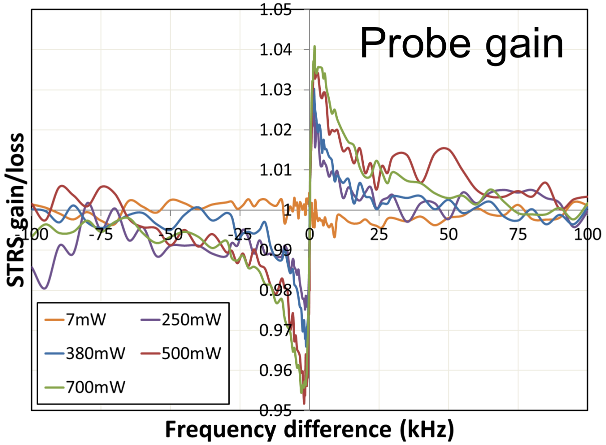


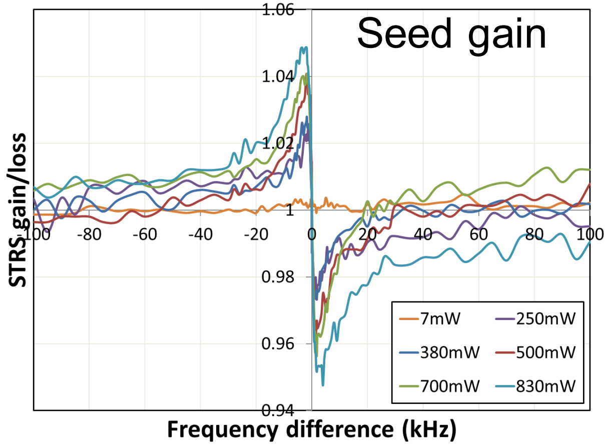
Measure STRS Gain

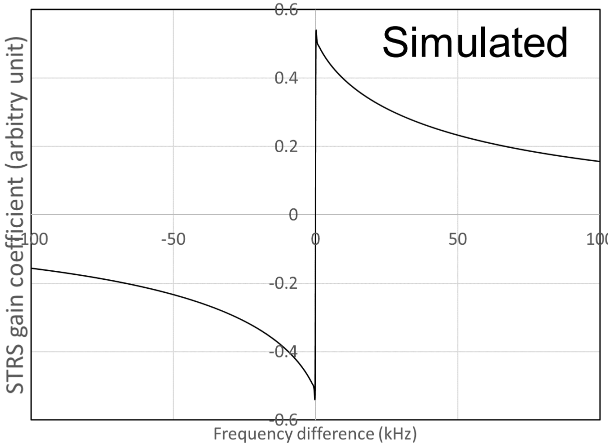
PM-YDF-5/13

- Beam spliter controls power in each mode
- AOMs control frequency difference Ω
- Seed=Probe=19mW:
  - ✓ Mode coupling driven by quantum defect, i.e. only in the presence of pump power
  - ✓ Need traveling wave for phase matching





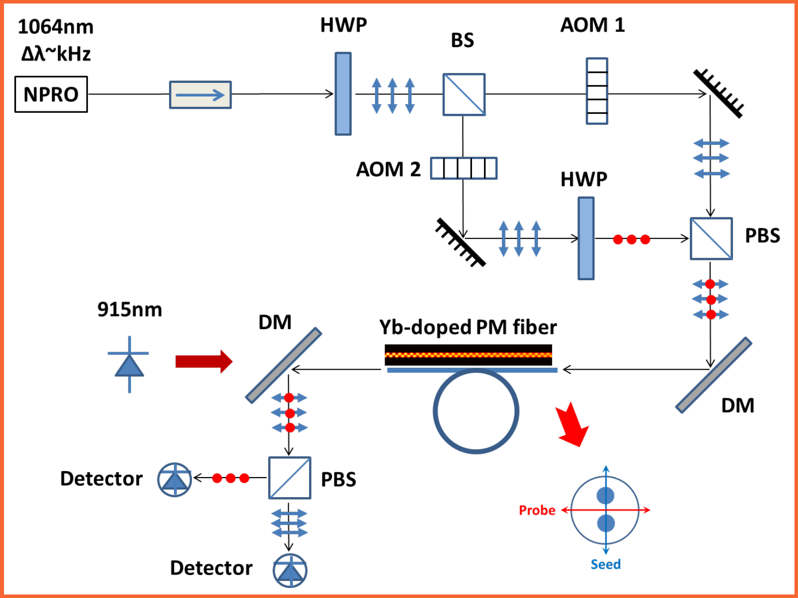


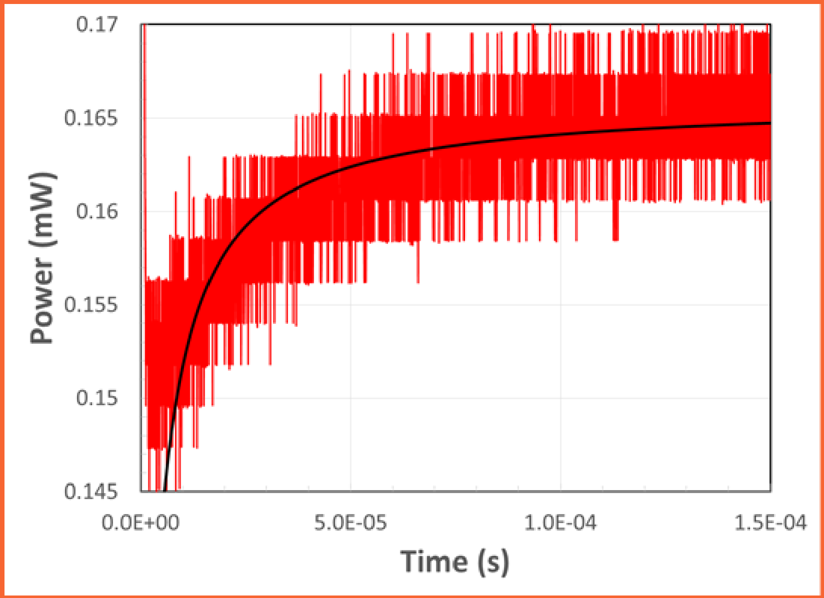


Kong et al, "Experimental Observation of Quantum-defect-assisted Polarization Mode Coupling …," Optica 3, 975 (2016).

Direct measurement of STRS gain

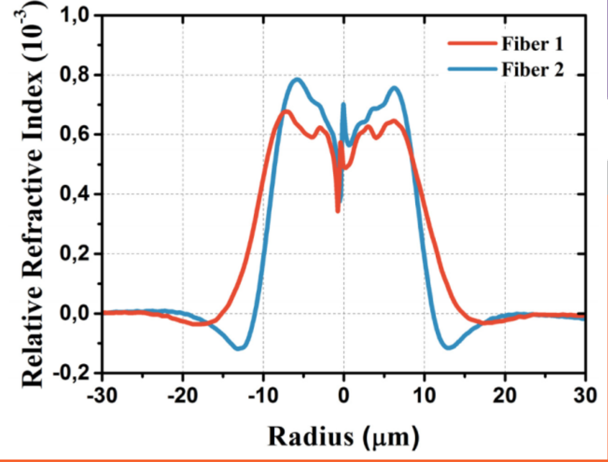
- Lifetime of the temperature grating:
  - We can turn off mode inference by turning off one polarization mode
  - Monitor the other polarization mode over time to measure grating decay over time
  - Black line is simulated thermal decay
  - Thermal in nature, decay in hundreds of μs!

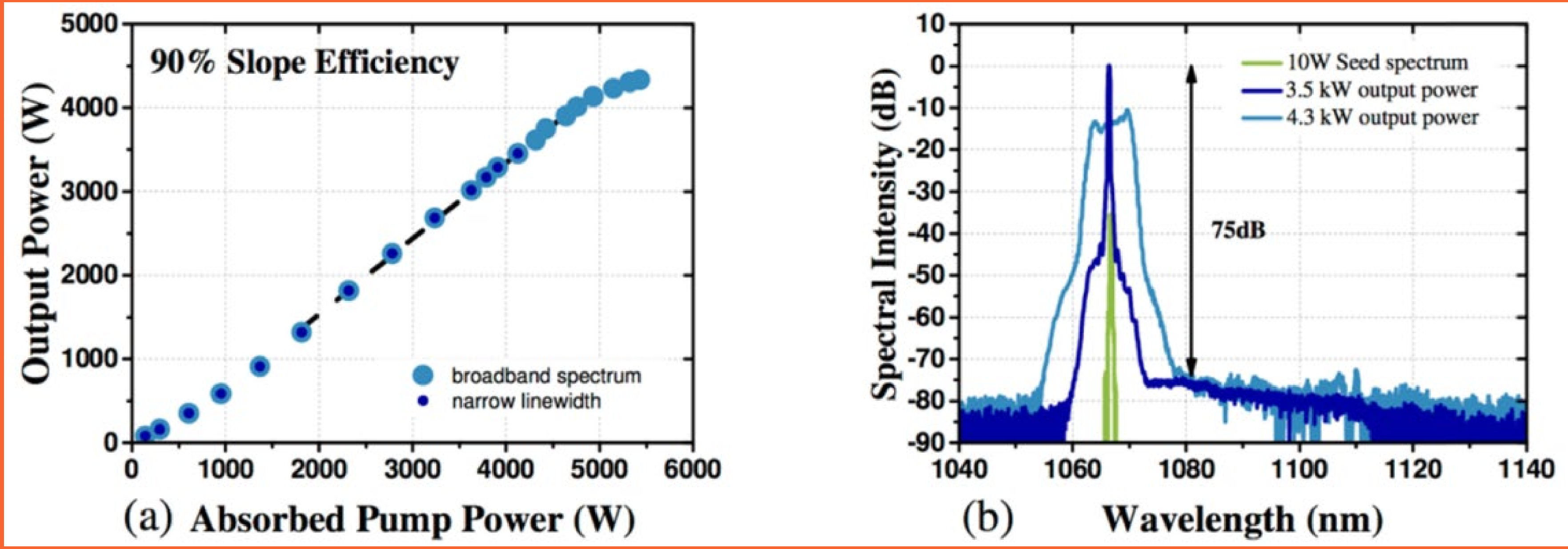




SM Yb CW power record

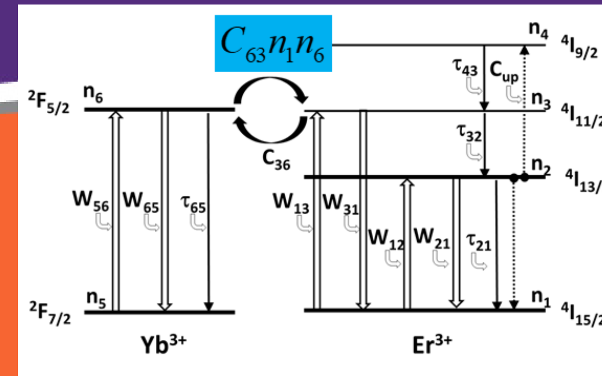
- Pump limited
- Record directly diode-pumped CW power 4.3kW
- Ultra low-NA fibers, closer to SM regime, 30m
  - 0.42NA, 23μm core, V≈2.8, M^2=1.27/1.21





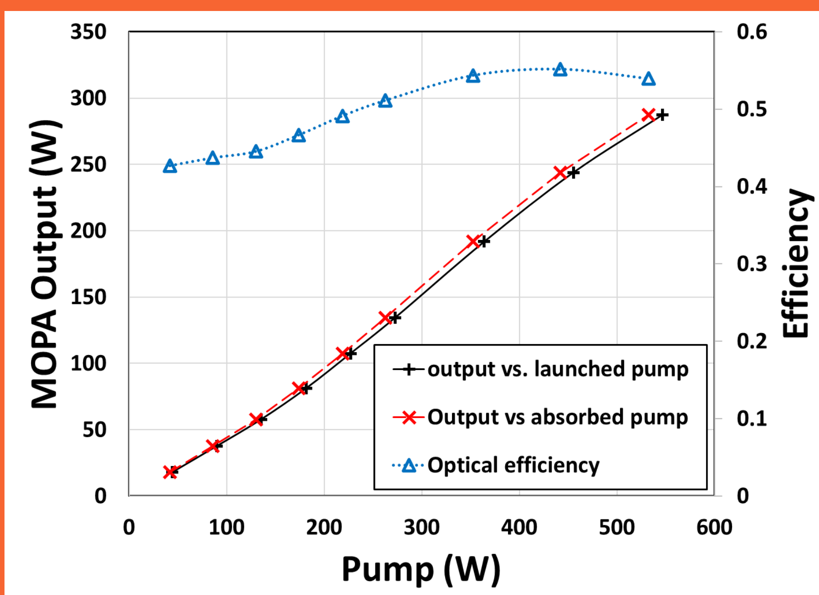
Beier et al, "Single mode 4.3 kW output power from a diode-pumped Yb-doped fiber amplifier" Opt. Express **25**, 14892-14899, 2017.

SM Er CW power record

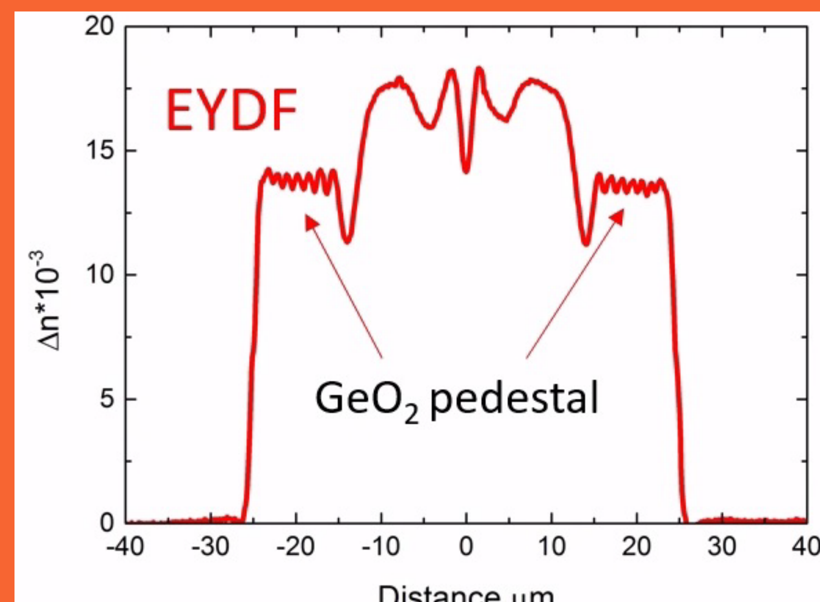


$$\sigma_p I_p > R n_1 \frac{n_6}{n_5}$$

- Thermal load limited
- Record SM CW power of 302W at 1562nm
- Near quantum-limited optical efficiency of 56%
- No Yb ASE due to high Er doping and 915nm pumping

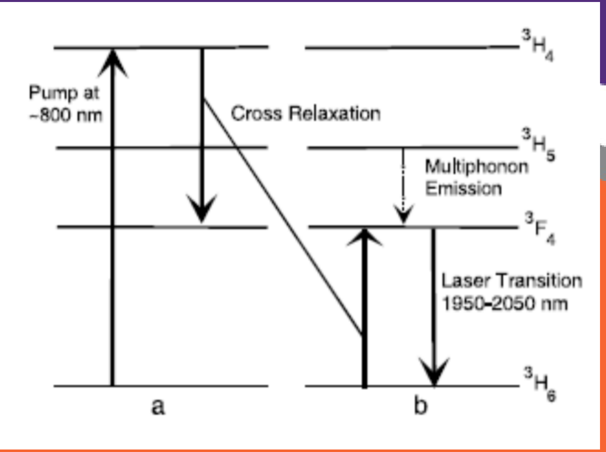


Nufern LMA-EYDF-25P/300-HE

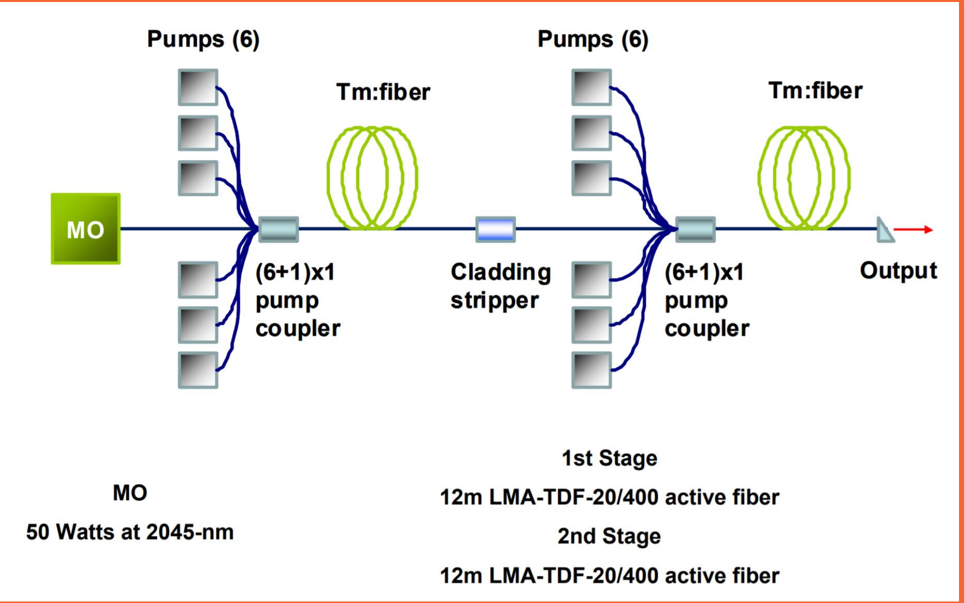


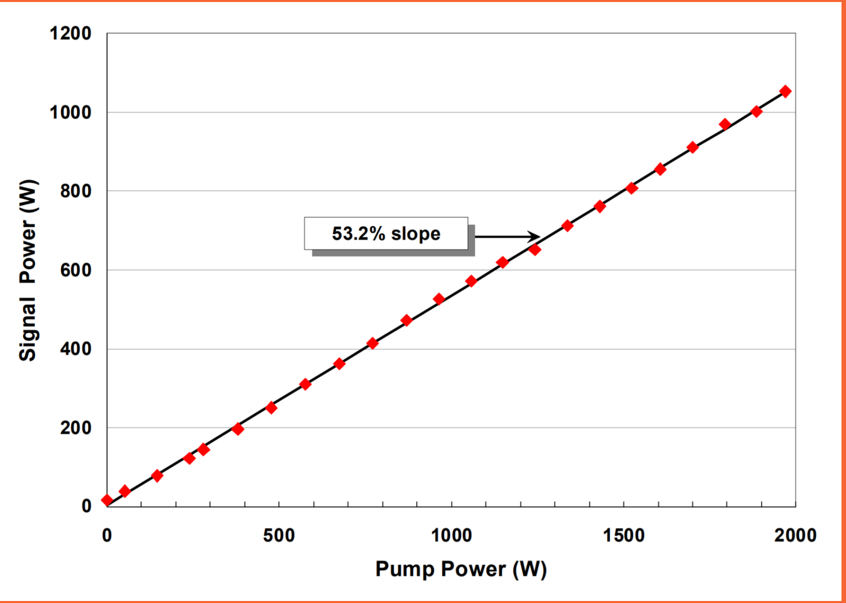
Matniyaz et al, "302 W single-mode power from an Er/Yb fiber MOPA," Optics Letters 45(10), 2910-2913(2020).

SM Tm CW power record



- Pump limited
- Record SM CW power of 1050W at 2045nm
- Optical efficiency of 53.2%
- Two-for-one pumping at 79x nm

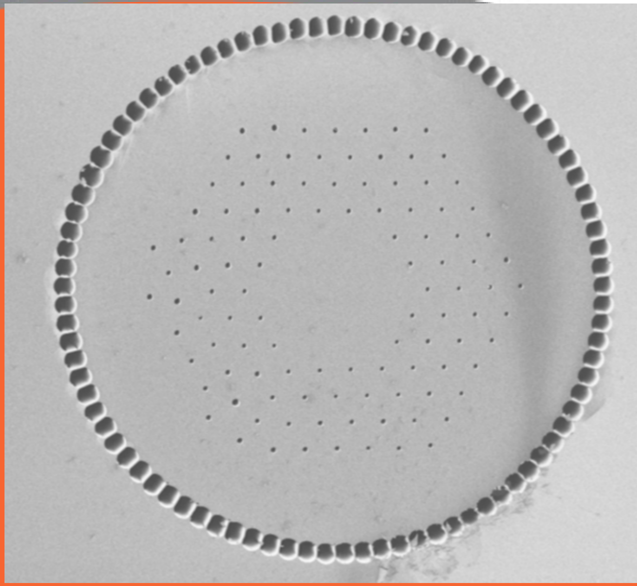


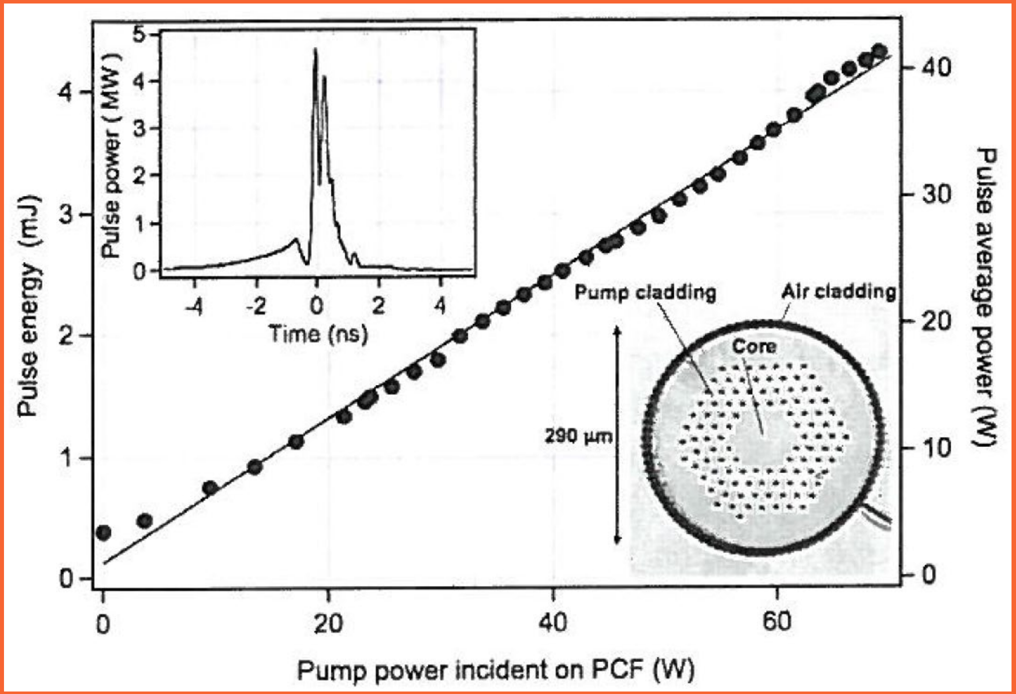


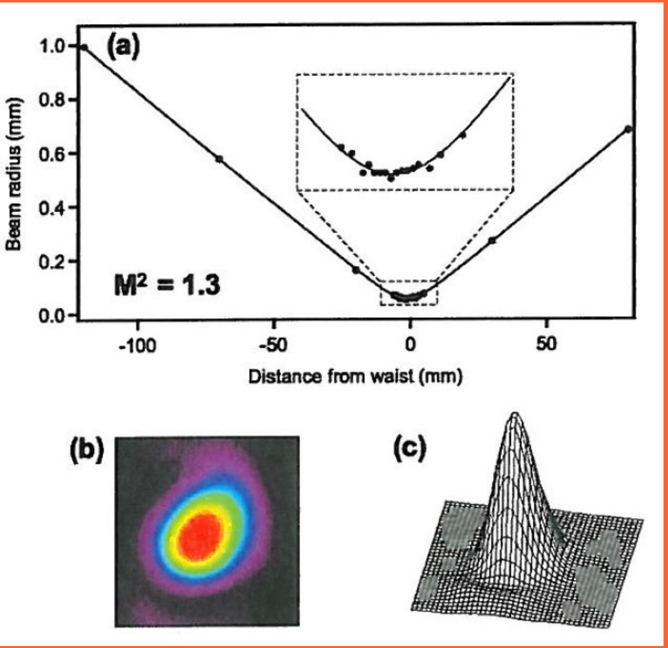
T. Ehrenreich et al., “1-kW, all-glass Tm: Fiber laser,” Proc. SPIE, vol. 7580, 2010, Art. no. 758016.

Limit to peak powers

- Record peak power of 4.5MW
- Rod-like 100μm-core PCF
- 1ns pulse, 4.3mJ, 42W average power, 9.6KHz, M^2=1.3





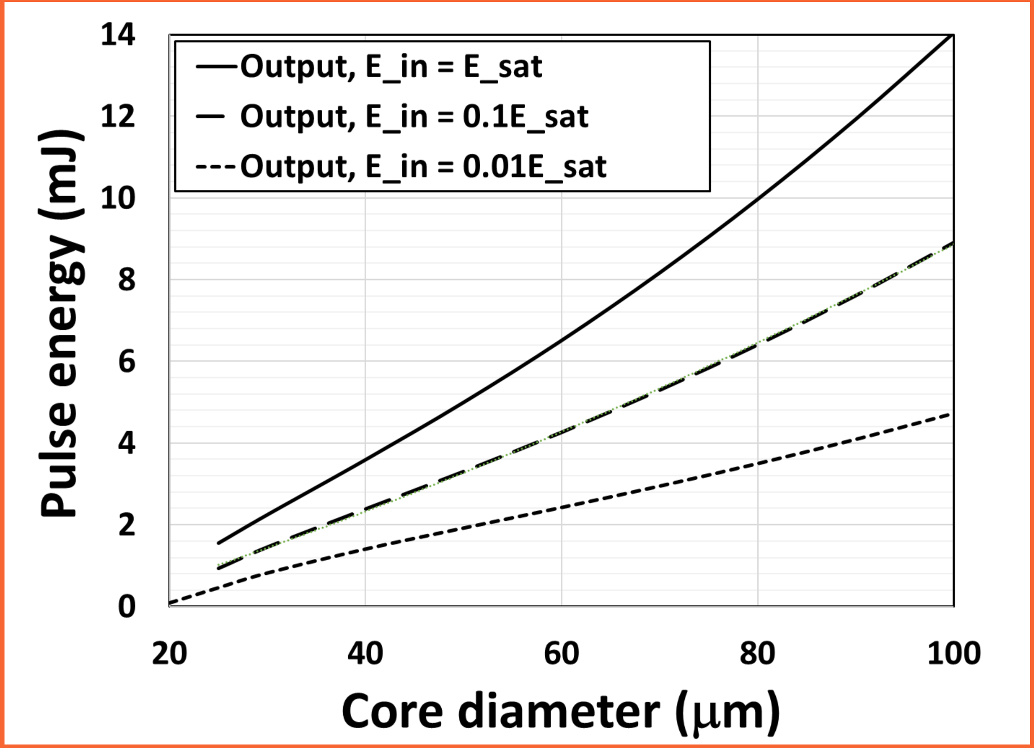


Brook and Di Teodoro, "Multimegawtt peak-power, single-transverse-mode operation of a 100μm core diameter, Yb-doped rod-like photonic crystal fiber amplifier," App. Phys. Lett. **89**, 111119-14899, 2006.

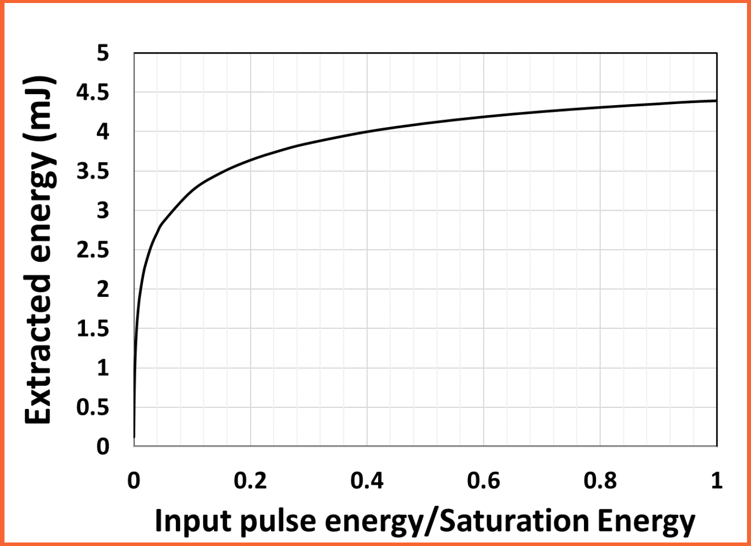
Limit to pulse energy

- Larger core → high pulse energy
- Need to seed > 20% E_{sat}

$$\widehat{E}_{sat} = \frac{h\nu \quad A_{eff}}{\hat{\sigma}_a(z) + \hat{\sigma}_e(z)}$$



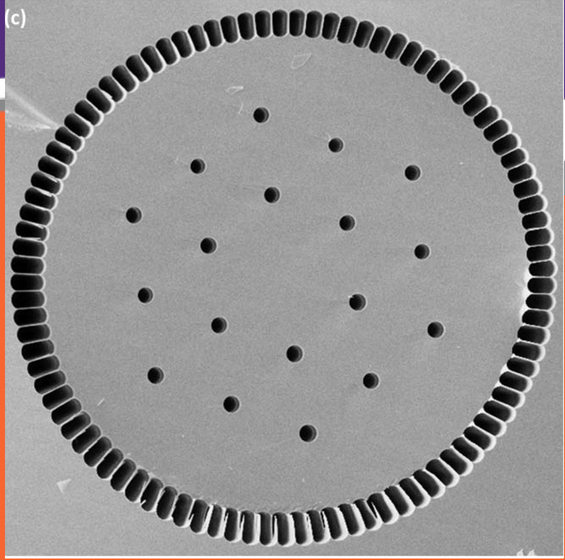
50/250 Fiber, 1035nm seed

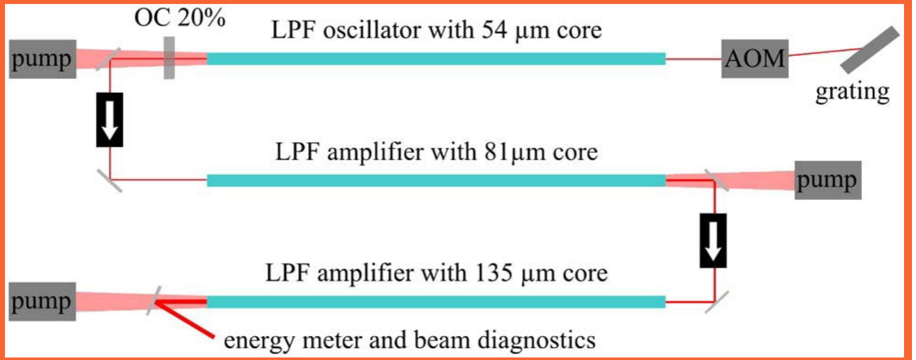


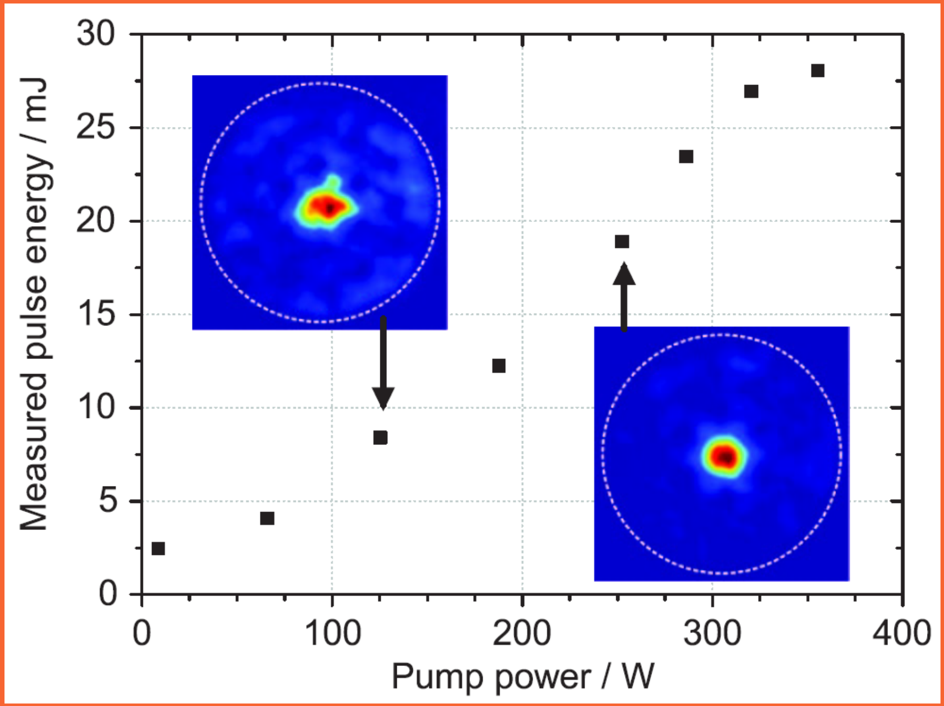
Dong, "Nonlinear propagation in optical fibers with gain saturation and gain dispersion," IEEE Journal of Lightwave Technology, **38**, 6897-6904 (2020).

Limit to pulse energy

- Record pulse energy of 26mJ
- Rod-like 135μm-core PCF
- 55ns, 130W average power, 5kHz
- M^2=1.3)



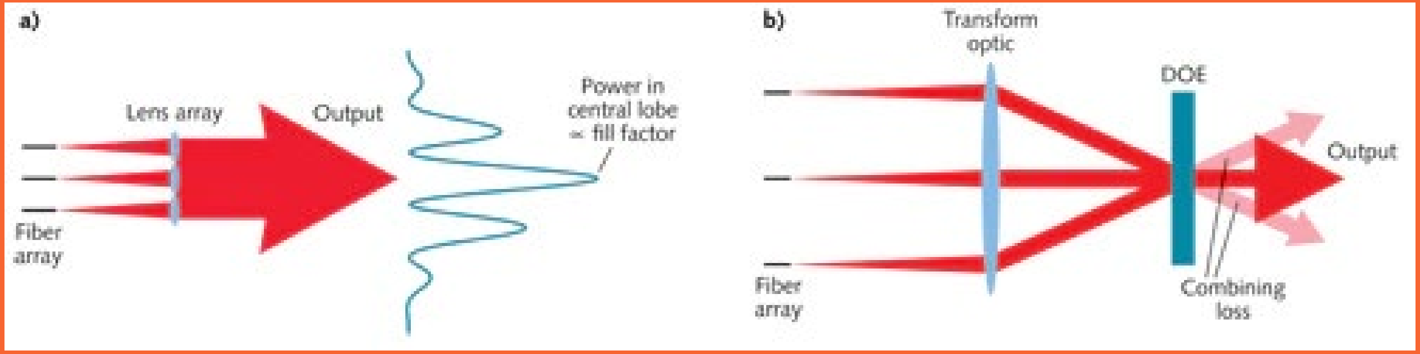




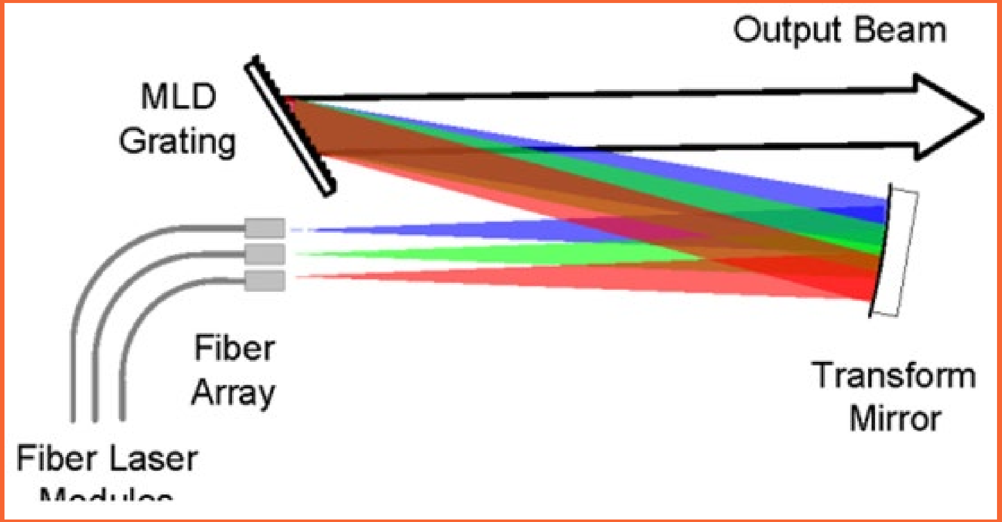
Stutzki et al, "26 mJ, 130 W Q-switched fiber-laser system with near-diffraction-limited beam quality," Opt. Lett. **37**, 1073-1075, 2012.

Further CW power scaling

- Coherent combining

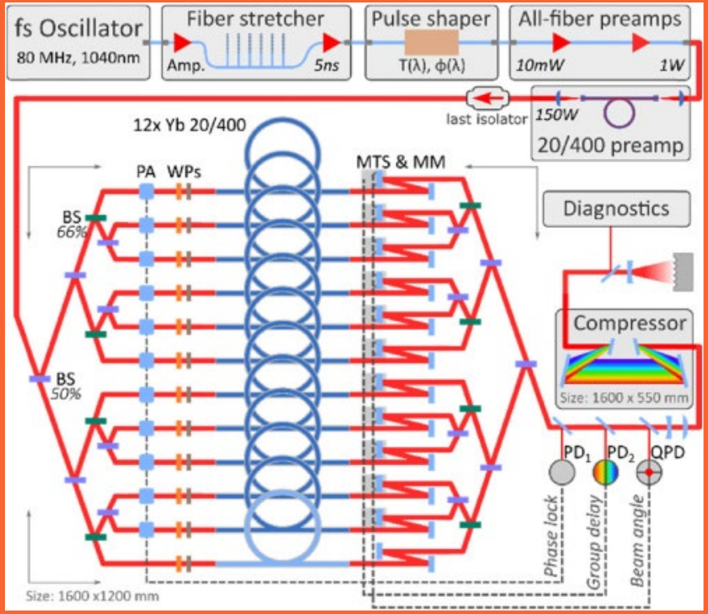


- Spectral combining



Further average power scaling of ultrafast lasers

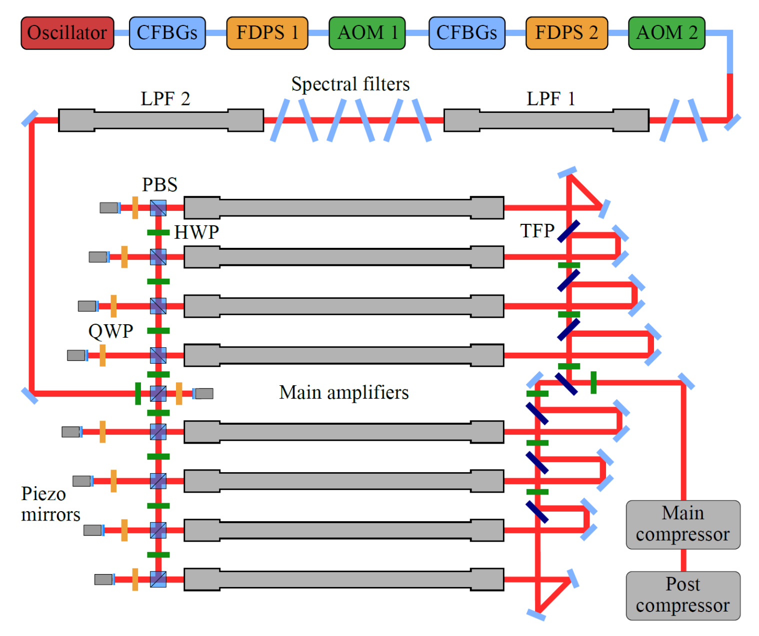
- Coherent combining of 12 pulsed lasers
- 12 main amplifiers: 11m 20/400 12cm coil diameter
- 10.4kW average power, 254fs, 130μJ, 80MHz, M^2<1.2



MÜLLER et al, "10.4 kW coherently combined ultrafast fiber laser," Opt. Lett. 45, 3083 (2020)

Further average power scaling of ultrafast lasers: record CPA pulse energy

- Coherent combining of 16 pulsed lasers
- 16 main amplifiers: 105cm, 62 MFD, stright
- 1kW average power, 120s, 10mJ, 100KHz, M^2<1.2



Stark et al, “1KW, 10mJ, 120fs coherently combined fiber CPA laser system ,” Opt. Lett. (2021)

Outline:

- Background
- History
- Key components
- Applications
- Commercial success
- Power-scaling limits
- Conclusions

Conclusions:

- Fiber lasers are reshaping our manufacturing in 21st century
- A range of very exciting emerging applications demand further power scaling
- Challenges and opportunities abound

Included below is the text of the questions asked to Liang Dong by attendees during the webinar. While several questions were answered live during the webinar, Prof. Dong provided text answers to all questions that were submitted following the conclusion of the webinar.

Question	Answer(s)
how is polarization affected by a fiber laser vs bulk laser ? is a PANDA-style fiber laser a feasible concept?	Double-clad PM fibers are widely comercially avaialble. In core size beyond 30micron, polarization is well mainatained even in non-PM fibers.
Is it possible to generate pulses in cladding-pumped high power fiber laser cavities? Instead of using a MOPA configuration?	Yes, these have been several Q-switch laser demonstrations. MOPA is commonly used due to the ease of control and better reliability (less components seeing high peak powers).
Professor Dong's "single mode" just means single spatial mode, not single-frequency (transform-limited CW,) correct?	yes
For what power level MOPA / oscillator s,will tandem pumping be better method instead of direct diode pumping?	Only when you are TMI (thermal) limited. This is typically beyond 4-5kW currently.
What are typical damage thresholds (Watts/m^2) for these fibers?	Bulk damage threshold is typically pulse width and wavelength dependent. For a 8ns pulse at 1064nm, it was measured to be ~5kW/um^2=500GW/cm^2 (see Smith and Do, "Bulk and surface laser damage of silica by ps and ns pulses at 1064nm," Applied Optics, vol 47, 4813-4832 (2008).
How does such a high power pump coupled into the output fiber of the pump diode?	Launch is optimized and fiber is then welded in place. Launch efficiency is very high. Some cooling of fiber end is still required.
Thanks for the talk. I have a question regarding creating how power fiber lasers by essentially using multiple fiber lasers and arranging them in a lattice structure, such that they are lasing in a single-spatial mode. What are the limitations for this?	When each single-mode outputs come together, they still need to be coherently combined. The phase from each core needs to be locked. This is in effect coherent combining.
At what level does one need to provide ionizing radiation shielding from beam target interaction, as well as safe distance with pulse systems?	There are significant research on high harmonic generation for producing high frequency (high energy radiation) radiations from pulsed lasers. The energy is the order of few tens of ev, high enough to be concerned. For most other applications, this is not yet an issue.
Thanks for the great presentation. what could be the cost of the fiber laser since you say its cost effective?	The main cost driver is the pump diode. This is reaching $4/W currently.
Could you comment about scaling to reach even higher powers? For example combining beams to reach higher powers, e.g. what is the limit?	Coherently combined SM record is 10kW. Spectrally combined SM record is 30-50kW with ~100kW under development.
What are your thoughts on coherently combining fiber lasers to improve power scaling? How effective are the techniques that are currently being used in the literature?	Current record is 10kW by combining 12 lasers. They may go possible another order of magnitude in controlled lab environment. Key engineering issue are resolved in phase controls. Outside lab, it will be much tougher.
What is the state of the art for overcoming the nonlinearities that limit single frequency high power fiber lasers?	The SF record is currently ~800W from a PCF.
What is the best technique to make a high power pulsed fiber laser at 1550 nm? Pulsing the pump? Mode-locking? or something else?	Depends on pulse width. Mode-locking is critical for <ps and pump modulation makes sense for >ns pulses.
Selef focusing due to Kerr effect is a power-limiting factor. Does self-focusing reduce the fiber coupling losses at all?	In the self-focusing regime, optical damage occurs and one should avoid operating near this.
what is the trend of the high power fiber laser in industry in next 5-10 years?	High average powers (100W-1kW) and high pulse energy (mJ). These would make micro-machining more economical in manufacturing.
Thanks for the great talk. What are your thoughts on new glass & transparent ceramic fiber compositions for increasing nonlinear threshold limitations in fibers?	Development in these areas can allow much higher doping levels and therefore shorten nonlinear interaction length.
what are the max power levels demonstrated with Tm-doped fibres? Are there any need for further power scaling?	Record is 1kW. Tm at 2micron can provide higher TMI threshold than Yb lasers at 1micron for the same core size due to waveguide scaling rules. It is eye-safe and has better atmosphere transmission if operated above 2.1micron.
For Coherent beam combine technolgy, both tiled aperture an filled aperature technology have their pros and cons, which technology do you think more promising? or mixed-aperture approach?	Filled aperture is winning currently. The technology are feasible and allows higher efficiency in delivering power in the bucket. But spectrally combining is winning for more robust operations outside a lab.
Does the Four-Wave Mixing impact to fiber laser?	Yes, it can generate undesired spectral components at high powers.
What's concerning point in spectral combining for power scaling? Will nonlinear effect impact to this? Thank you for the great talk	Spectral combining is more robust to nonlinear effects than coherent combining, since phase is not an issue. For coherent combining, nonlinear phase can be a big problem, as it has a wide spectral bandwidth and very hard to compensate electronically.