HIGH PERFORMANCE LARGE-MODE AREA DOUBLE-CLAD FIBERS FOR KW POWER SCALING OF FIBER LASERS FROM 1 TO 2 MICRONS

7th International Workshop on Specialty Optical Fibers

December 15th 2022

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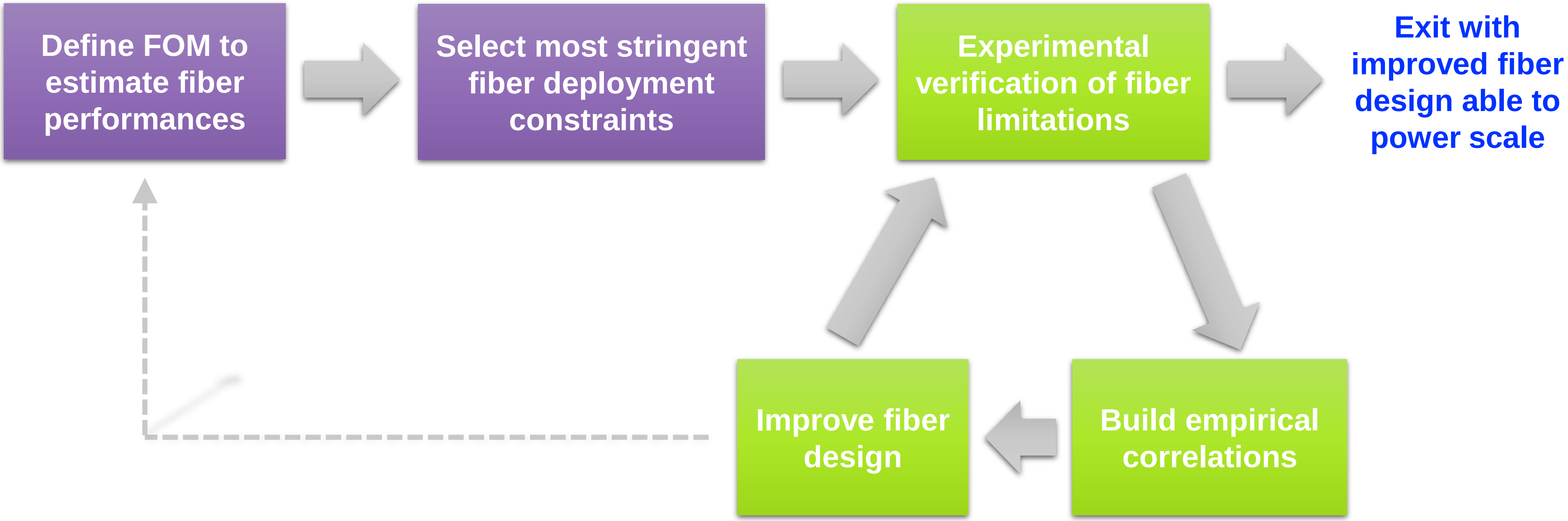
POWER SCALING OF OPTICAL FIBERS

- **Fiber laser industry relies on performance capabilities of active double (or triple) clad fibers**

- **Non-linear effects limit power scaling towards (and beyond) kW levels**
  - Transverse mode instability(TMI)
  - Stimulated Raman Scattering (SRS)
  - Stimulated Brillouin Scattering (SBS)

- **Industrial solutions from 1 to 2 µm require**
  - Performance
  - Consistency
  - Reliability

PRACTICAL APPROACH TO POWER SCALING



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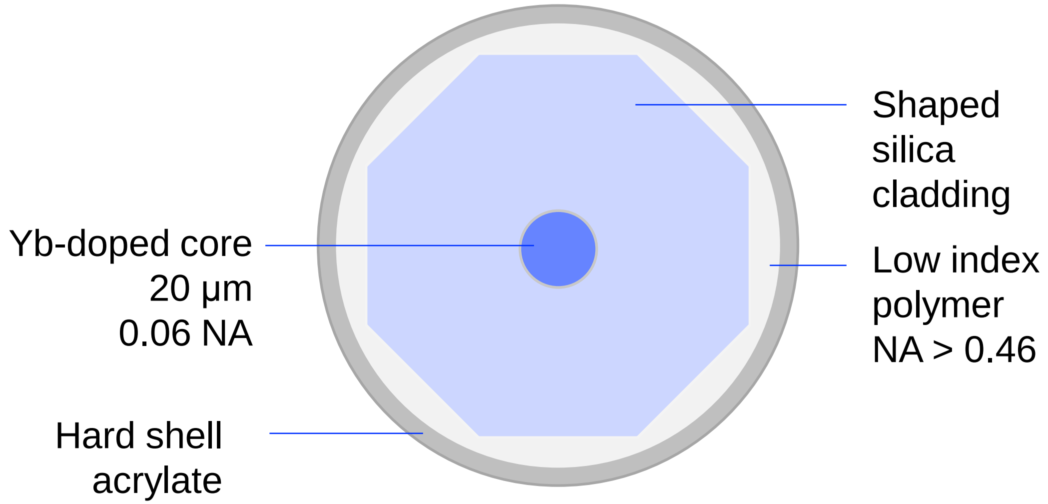
BEYOND 3 KW AT 1 µm

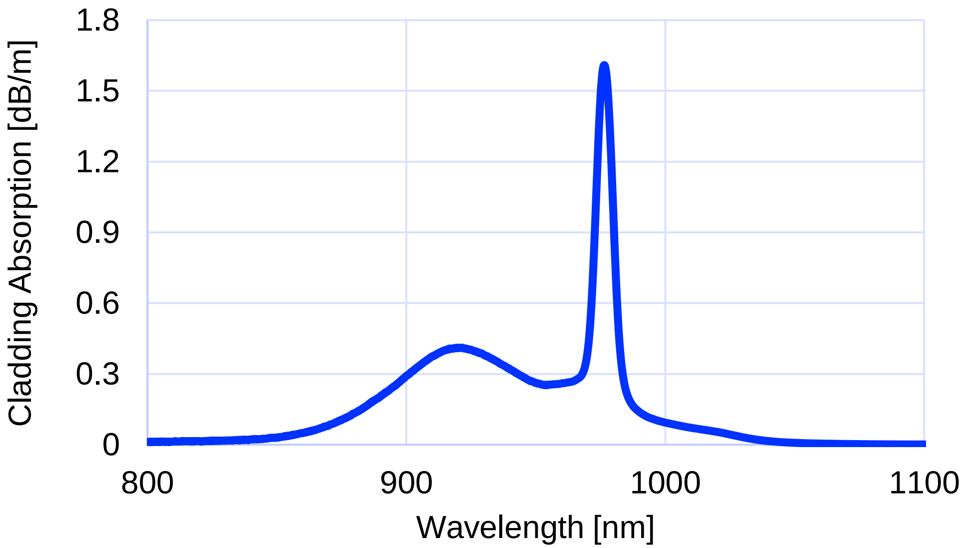
Ytterbium-doped Double-clad Fiber - YDF

YDF - OVERVIEW

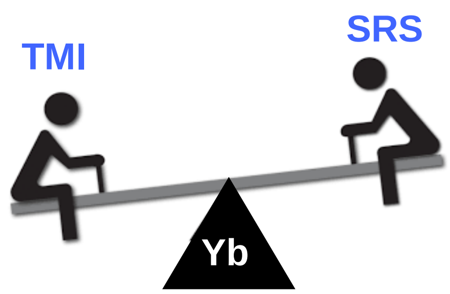
- **Typical pumping wavelength: 915 to 980 nm**
- **Laser emission between 1030 and 1080 nm**

LMA-YDF-20/400 Design





YDF - DESIGN TRADE SPACE



- **Non-linear figures of merit for multi-kW power scaling**
  - Larger implies higher performance

TMI FOM
Driven by thermal load and cavity loss

$$C_{TMI} \propto \frac{L_{eff}}{\gamma\,(1/\eta - 1)\alpha}$$

SRS FOM
Driven by laser intensity & fiber length

$$C_{SRS} \propto \frac{\alpha \pi \omega_0^2}{L_{eff}}$$

Key design Parameters

ω_0: fiber mode field radius [µm]

α: pump cladding absorption [dB/m]

L_{eff}/α: effective cavity length [m]

η: laser efficiency [%]

γ: TMI gain factor

J. Bradford et al., "TMI in High Power Lasers – Fiber Design Considerations & Mitigation Strategies", 11665-77 (invited) Photonics West 2021

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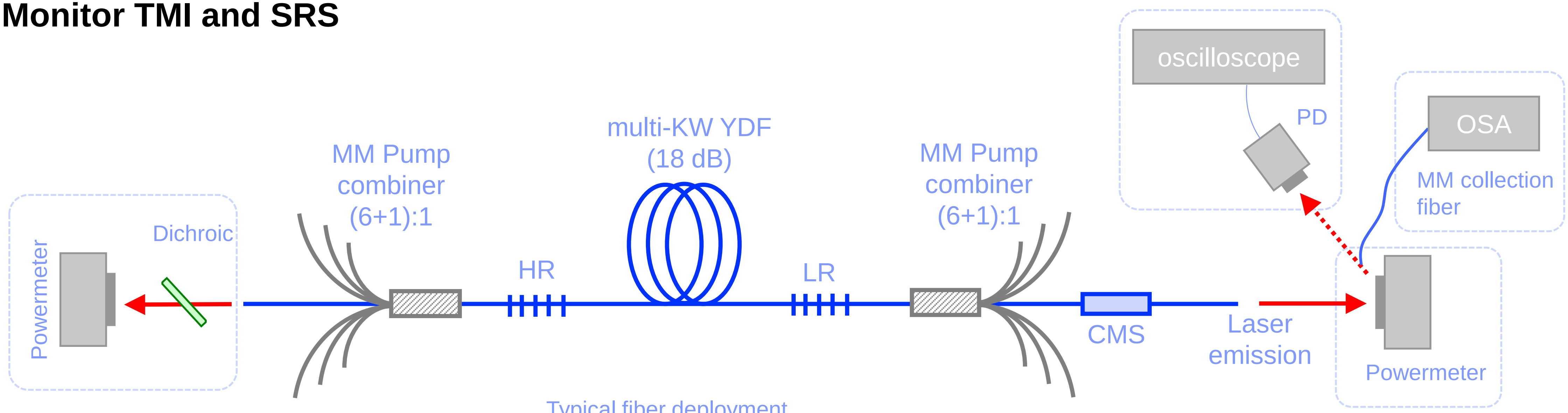
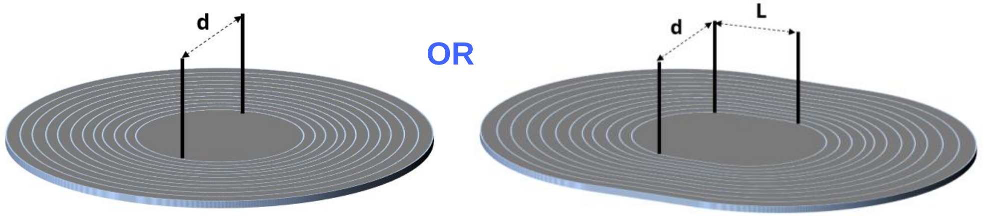
EXPERIMENTAL VALIDATION

- **Most stringent industrial fiber deployment**
- **Single oscillator with 976 nm pumping (no locking)**
- **Monitor TMI and SRS**



Typical fiber deployment



d = 80 mm, L ~ 115 mm

J. Bradford et al., “TMI in High Power Lasers – Fiber Design Considerations & Mitigation Strategies”, 11665-77 (invited) Photonics West 2021

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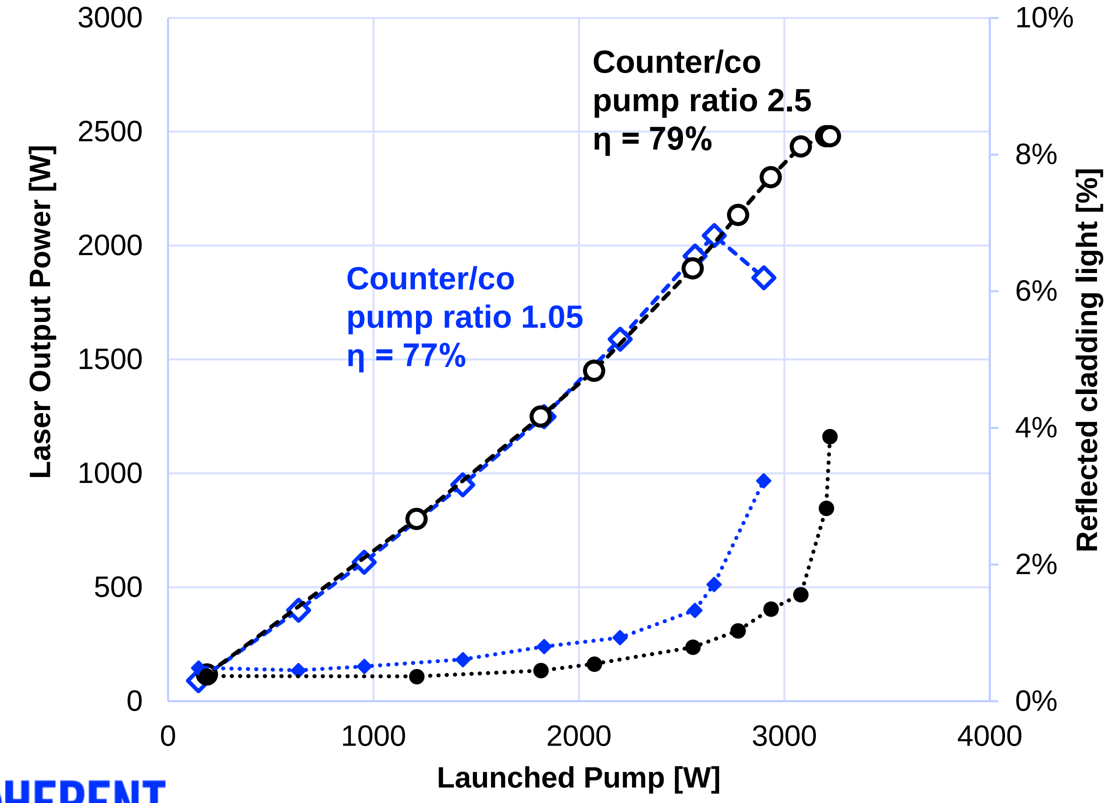
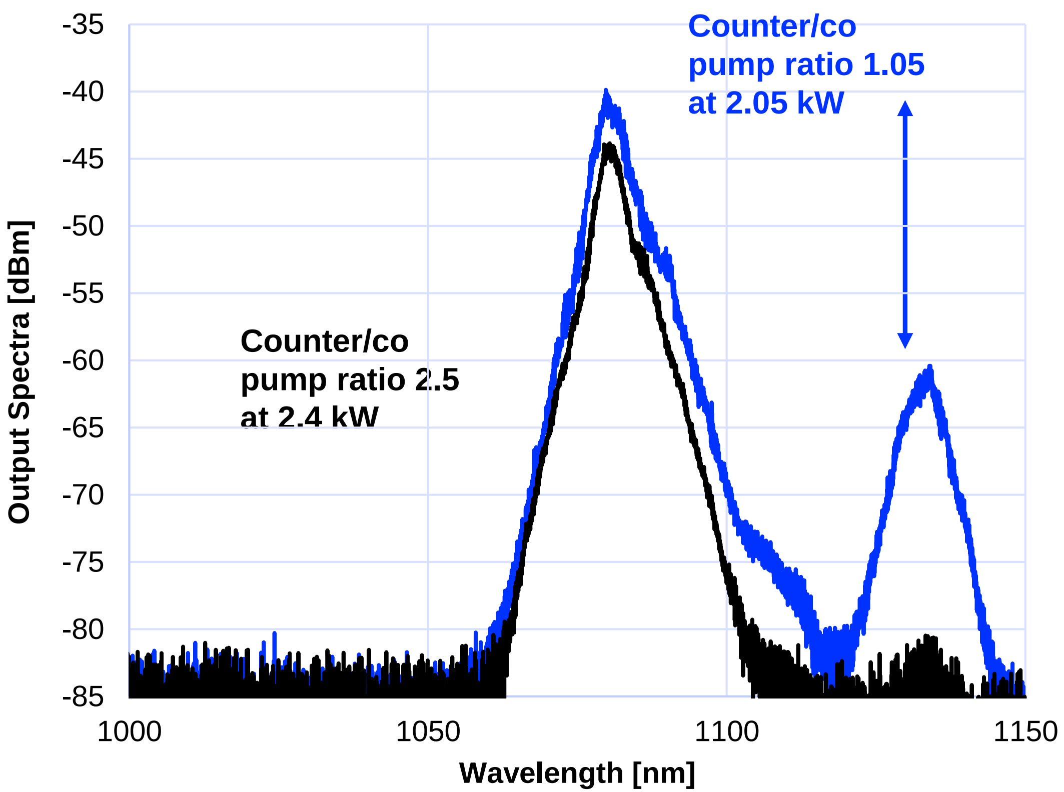
2KW POWER SCALING

- TMI and SRS thresholds strongly dependents on co & counter pumping power ratio – require optimization from the laser manufacturer
- Experimental demonstration of effective mitigation strategy to achieve 2.4 kW TMI & SRS-free

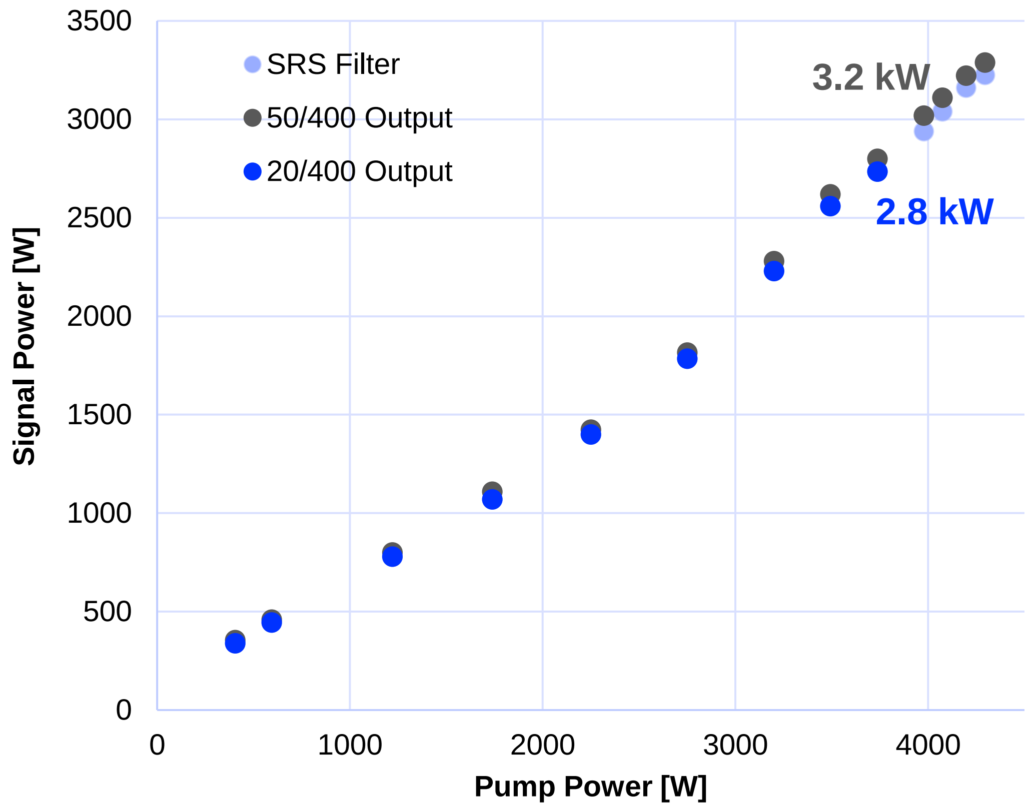


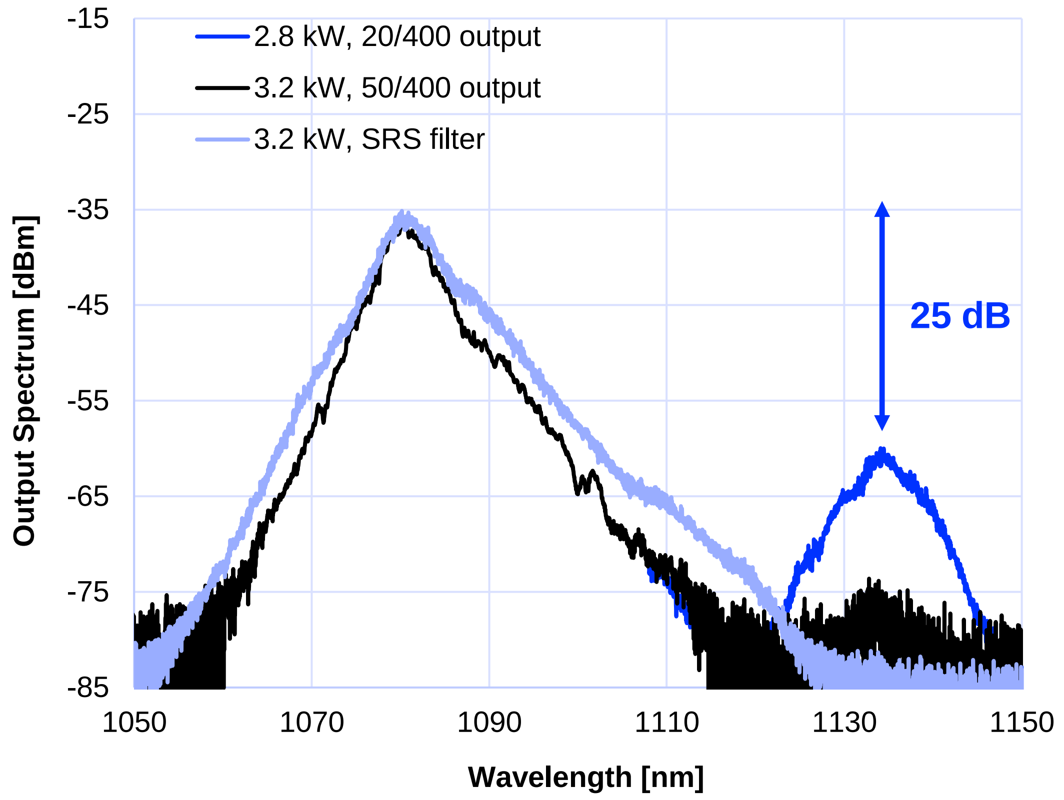


J. Bradford et al., “TMI in High Power Lasers – Fiber Design Considerations & Mitigation Strategies”, 11665-77 (invited) Photonics West 2021

BEYOND 3 KW POWER SCALING

- **Active fiber power capability demonstrated beyond 3.2 kW pump limited (3.6 kW at customer)**
- **Management of SRS relies on the customer system design**





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TOWARDS 1 KW AT 1.5 µm

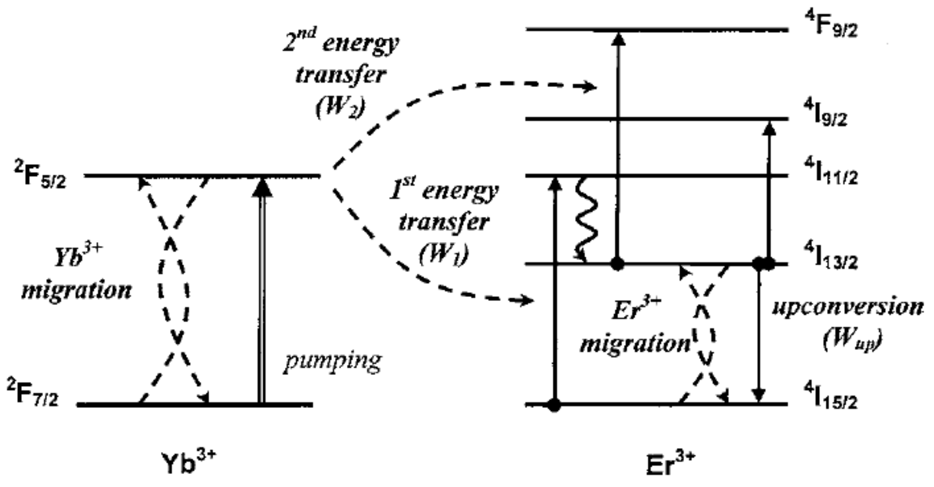
Erbium-Ytterbium co-doped Double-clad Fiber - EYDF

1.5 µm FIBER LASER APPLICATIONS

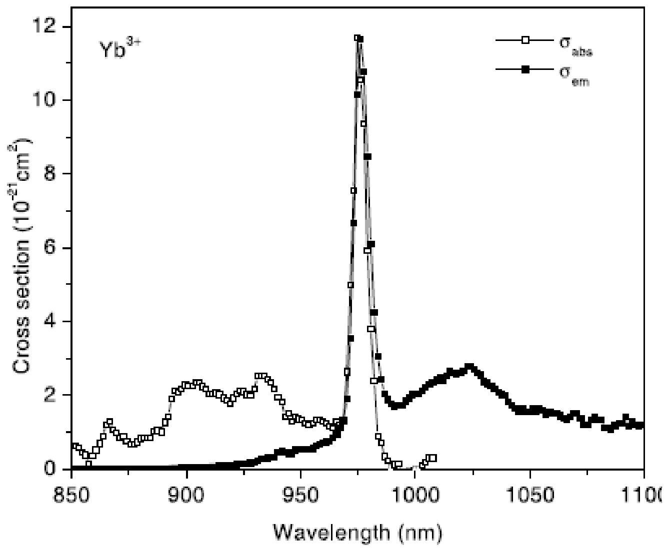
- **Key applications include**
  - LIDAR
  - SpaceTelecom
  - 3D holography
  - Sensing

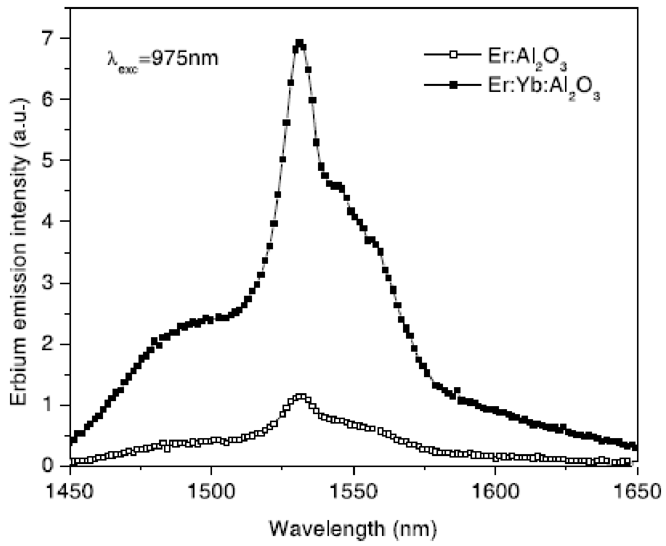
EYDF - OVERVIEW

- **EYDF available in SM, MM and LMA**
  - High core NA require pedestal designs
- **Typical pump wavelength: 915 to 980 nm**
- **Emission between 1530 and 1560 nm**
- **Limitations to power scaling in EYDF**
  - Parasitic lasing of inverted Yb ions
  - Thermal management



M. Laroche et al., "Accurate efficiency evaluation of energy-transfer processes in phosphosilicate Er3+–Yb3+ co-doped fibers", J. Opt. Soc. Am. B, vol. 23, no. 2, 2006





C. Strohhöfer et al., "Absorption and emission spectroscopy in Er^{3+}–Yb^{3+} doped aluminum oxide waveguides", Optical Materials 21 (2003) 705–712

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EYDF – PERFORMANCES AND FUTURE

- **LMA-EYDF-25P/300 fiber able to deliver 100's of W**
- **Fiber design trade space has potential for further power scaling**

Single frequency 1560nm Er:Yb fibr amplifier with 207 W output power and 50.5% slope efficiency

D. Creeden, et al., Proc. Vol. 9728, Fiber Lasers XIII: Technology, Systems, and Applications; 97282L (2016)

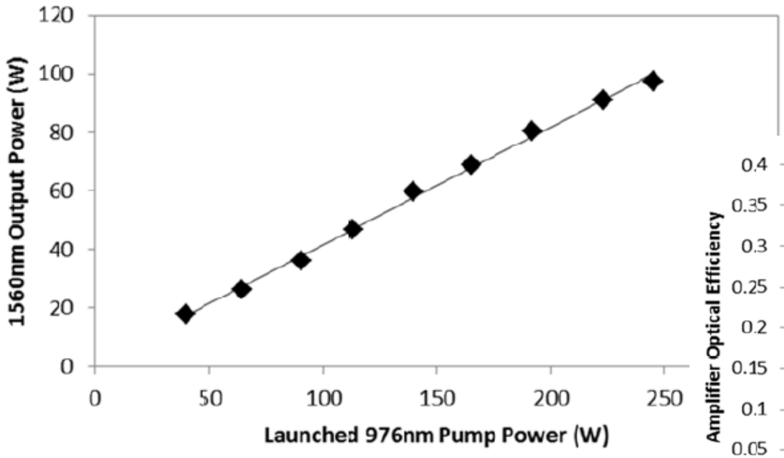

Fig. 7. Slope efficiency for EYDFA pumped at 976nm

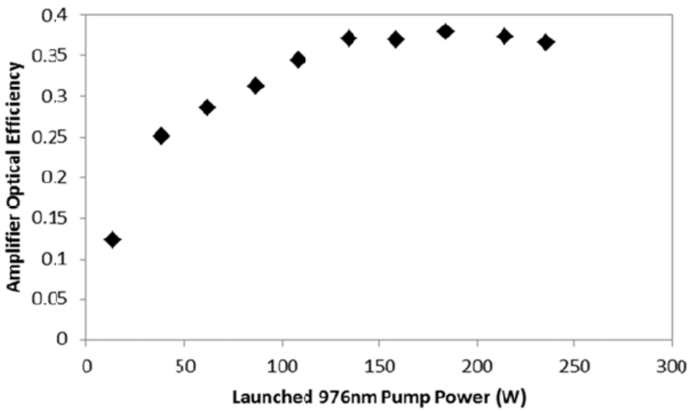

Fig. 8. Amplifier optical efficiency versus launched 976nm pump power

2910 Vol. 45, No. 10 / 15 May 2020 / Optics Letters Letter

Optics Letters

302 W single-mode power from an Er/Yb fiber MOPA

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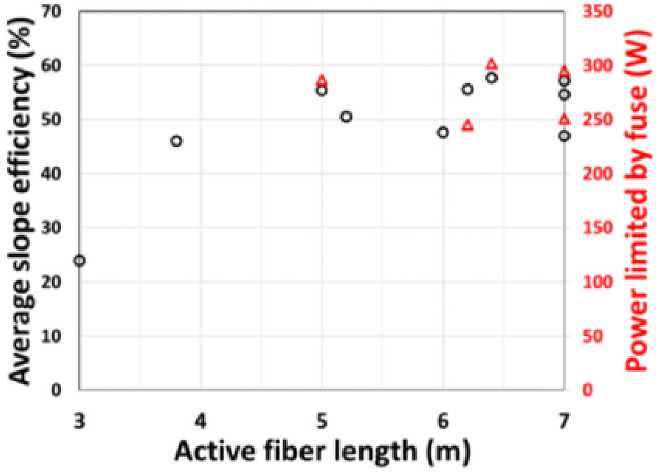

T. Matniyaz, et al., Optics Letters, vol. 45, Issue 10, pp. 2910-2913 (2020)

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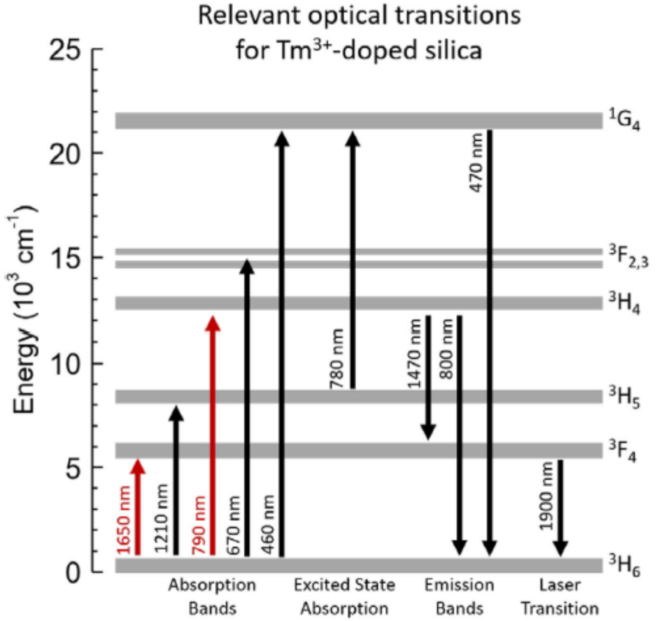
TOWARDS 1 KW AT 2 µm

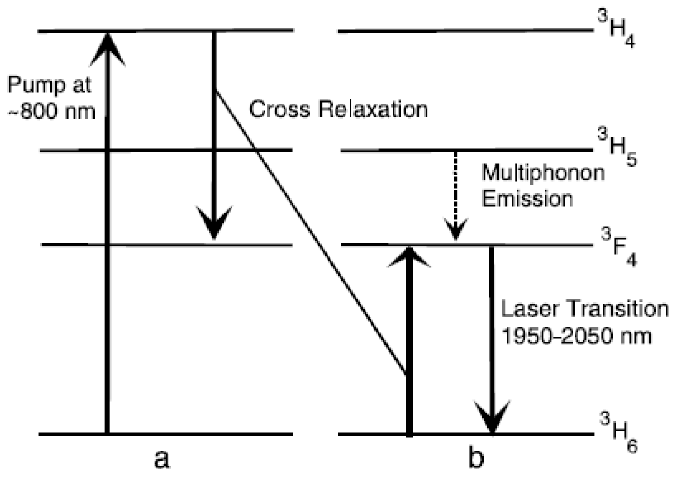
Thulium-doped Double-clad Fiber - TDF

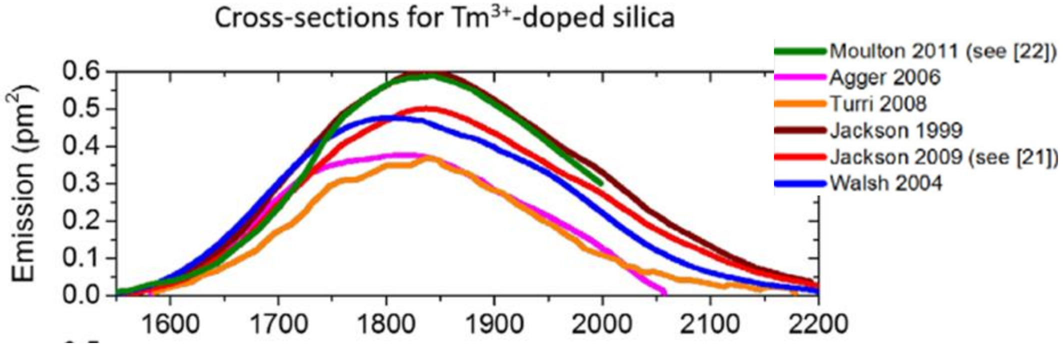
TDF OVERVIEW

- **Complex ion energy transfer processes**
- **Typically diode-pumped at ~793 nm with Stokes efficiency limit of 40%**

- **Promoting cross-relaxation process extends the theoretical efficiency limit to 80%**



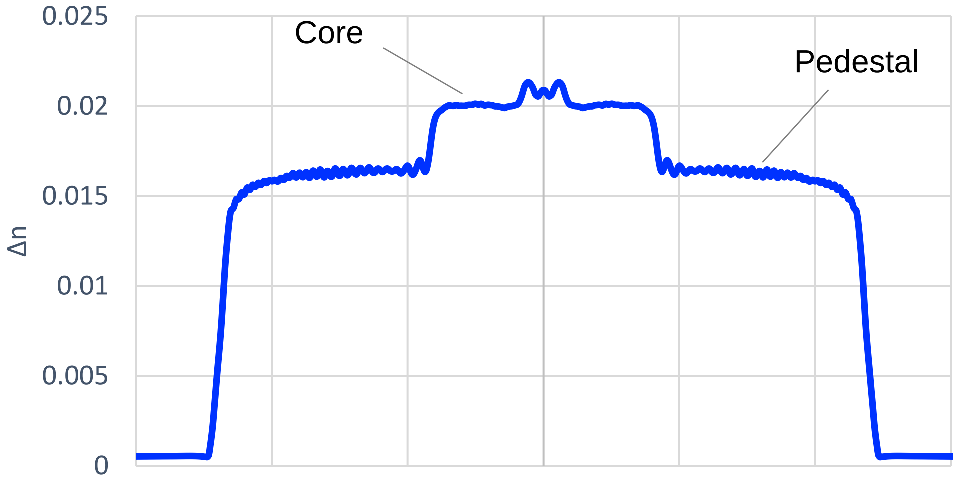


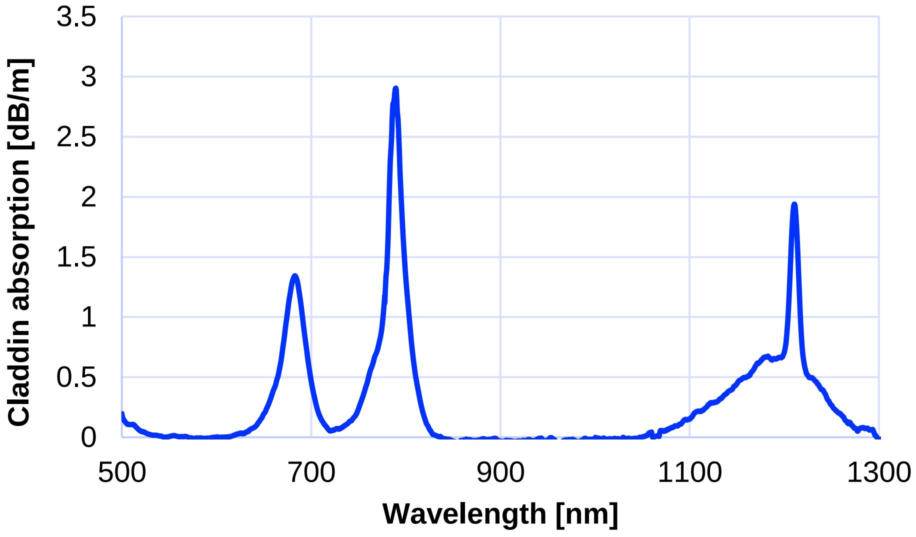


A. Sincore et al., "High Average Power Thulium-Doped Silica Fiber Lasers: Review of Systems and Concepts", IEEE JSTQE, vol. 20, no. 3, 2018

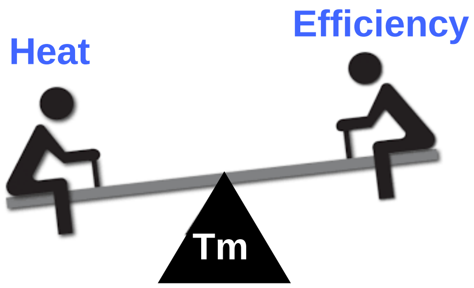
TDF OVERVIEW (CONT.)

- **LMA-TDF-25P/400-M is an established double-clad fiber for industrial applications**
  - 25 µm core diameter
  - Pedestal design ensures 0.09 core NA offers large-mode area performances
    - → Effective suppression of higher-order mode through coiling for good beam quality
  - Tm concentration and core composition enabling slope efficiency (SE) > 50%





TDF – POWER SCALING CHALLENGES



- **Power scaling LMA-TDF's beyond kW level requires balance of efficiency & heat**

Figures of merit

Larger implies higher performance

Efficiency FOM
Driven by ion density & mode overlap w/ core

$$C_\eta \propto \frac{D_{core}[Tm]}{2\omega_0 \alpha_{OH}}$$

Thermal FOM
Driven by absorption

$$C_{heat} \propto \frac{D_{clad}^2}{D_{core}^2[Tm]}$$

Fiber parameters

ω_0: fundamental mode field radius [µm]
[Tm]: Tm ion density [wt%]
D_{core}: core diameter [µm]
D_{clad}: cladding diameter [µm]
α_{OH}: OH-induced loss [dB/km]

- **Power scaling beyond kW will require TMI mitigation strategies**

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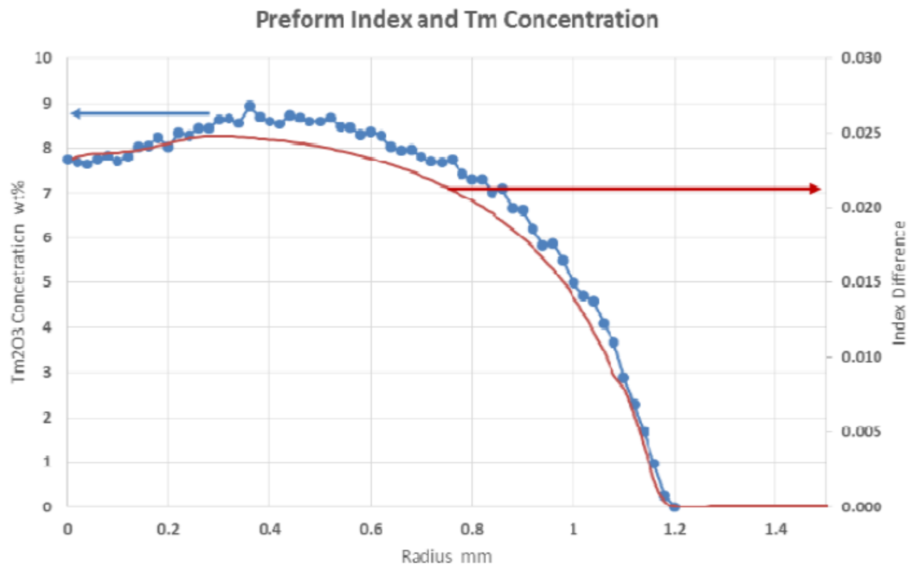
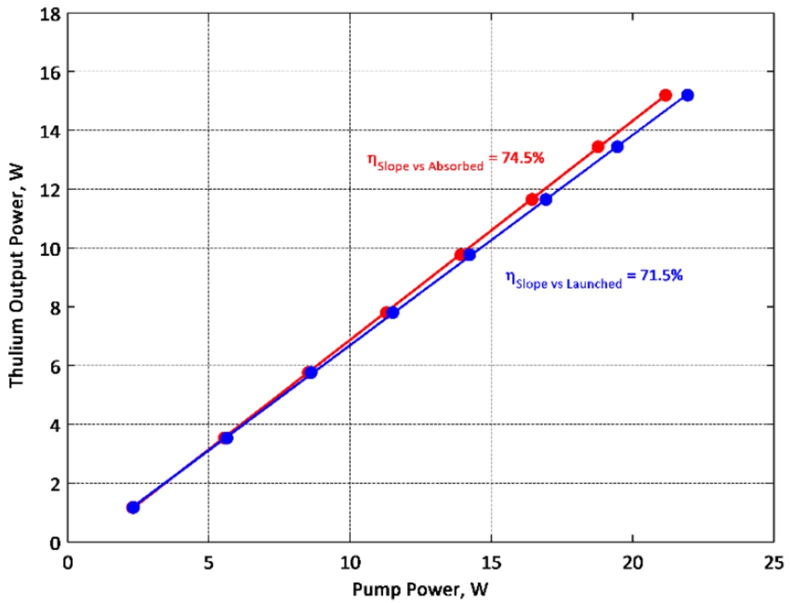
SCALING SLOPE EFFICIENCY

Efficiency FOM
Driven by ion density & mode overlap w/ core

$$C_\eta \propto \frac{D_{core}[Tm]}{2\omega_0\alpha_{OH}}$$

- **Promoting cross-relaxation process:**
  - increase [Tm] concentration
  - addition of Al_2O_3 to reduce clustering, improve solubility
- **<u>Single-mode</u> fiber with ~ 2x [Tm] concentration manufactured using all halide vapor phase (VP) modification of MCVD process demonstrated record efficiency of 74.5%**



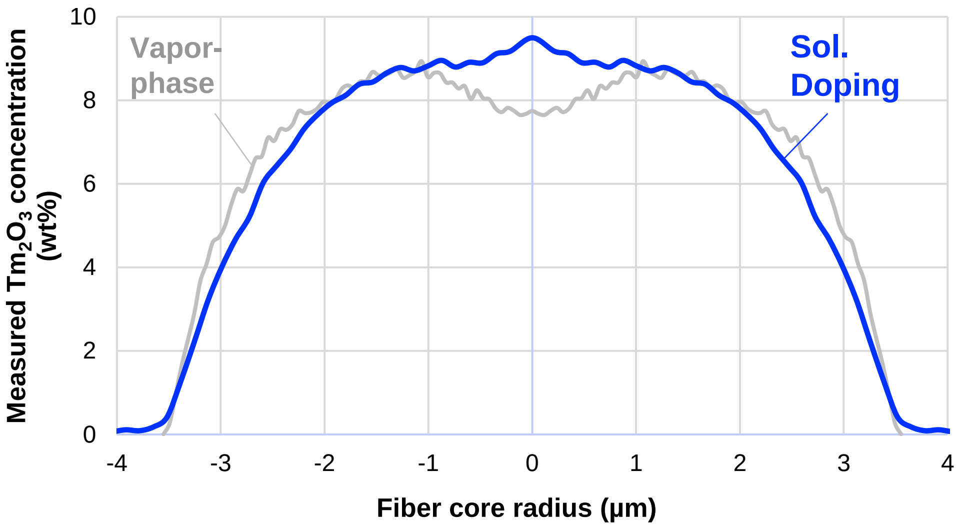


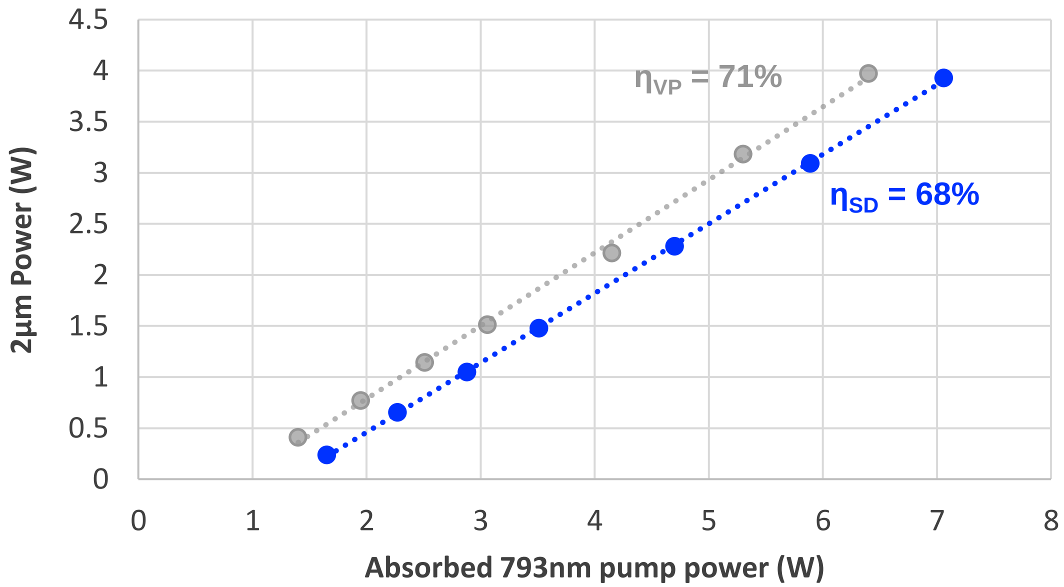
R. Tumminelli et al. "Highly doped and highly efficient Tm doped fiber laser", Proc. SPIE 10512, Fiber Lasers XV: Technology and Systems, 105120M (14 March 2018)

SCALING SLOPE EFFICIENCY (CONT.)

… can it be achieved in LMA design through solution doping (SD) MCVD?

- **Coherent developed SD-MCVD process to explore doping concentration limits in TDF**
- **Achieved > 8wt% [Tm] in single-mode glass design**
- **SM fibers tested side by side in low-power Fresnel cavity, confirm SD-MCVD is capable of manufacturing high concentration Tm-doped glass with SE comparable to VP-MCVD**





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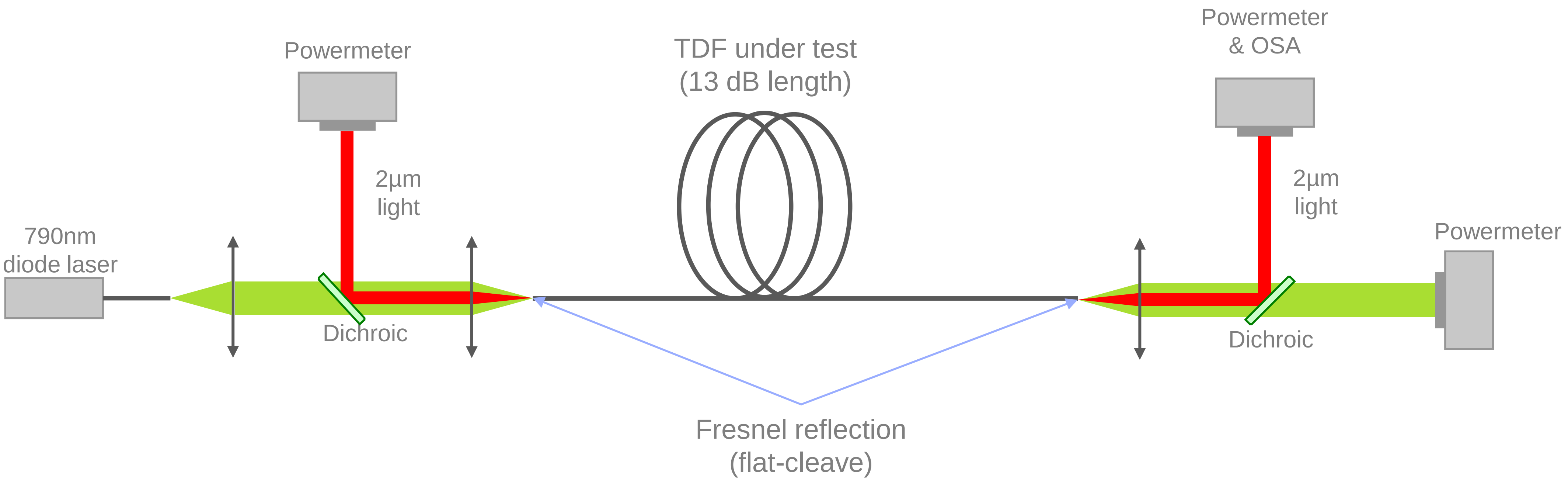
HIGH CONCENTRATION LMA-TDF

- Coherent manufactured high concentration LMA-TDF by adding a pedestal to target 0.09 core NA
- Tested HC LMA-TDF against legacy product in low-power Fresnel cavity setup



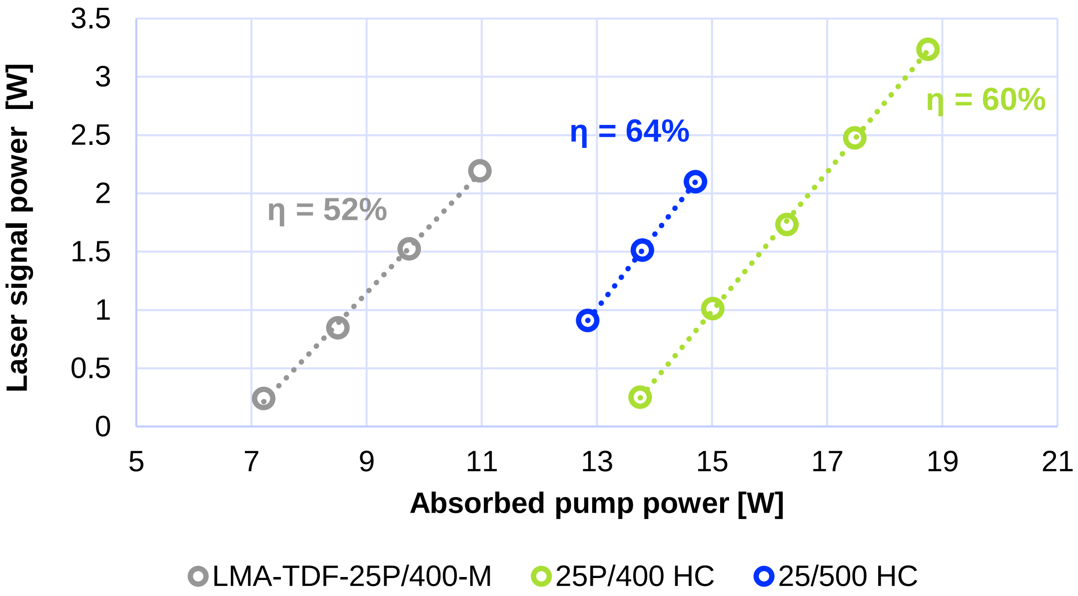
HIGH CONCENTRATION LMA-TDF (CONT.)

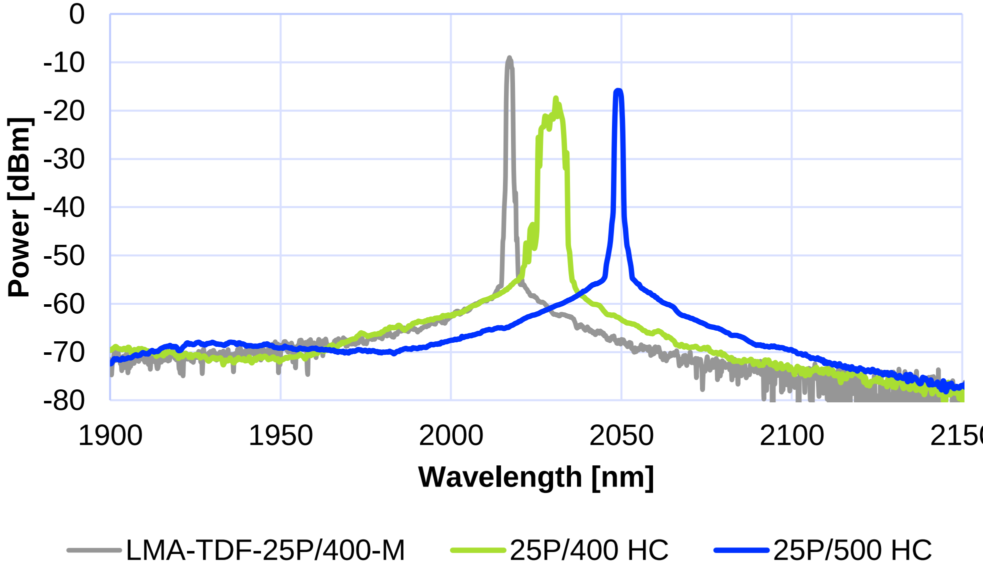
Efficiency FOM
Driven by ion density & mode overlap w/ core

$$C_\eta \propto \frac{D_{core}[Tm]}{2\omega_0\alpha_{OH}}$$

- **Lower power Fresnel cavity results in ~ 10% higher SE → room for optimization**
- **Lowering pump intensity shifts emission spectrum to longer wavelengths**

Fiber	Core [Tm]	Clad absorption 1180 (793) [dB/m]	Measured SE
Legacy 25P/400	4.5 wt%	0.7 (3.0)	52%
New 25P/400 HC	8 wt%	1.2 (5.2)	60%
New 25P/500 HC	8wt%	0.8 (3.4)	64%





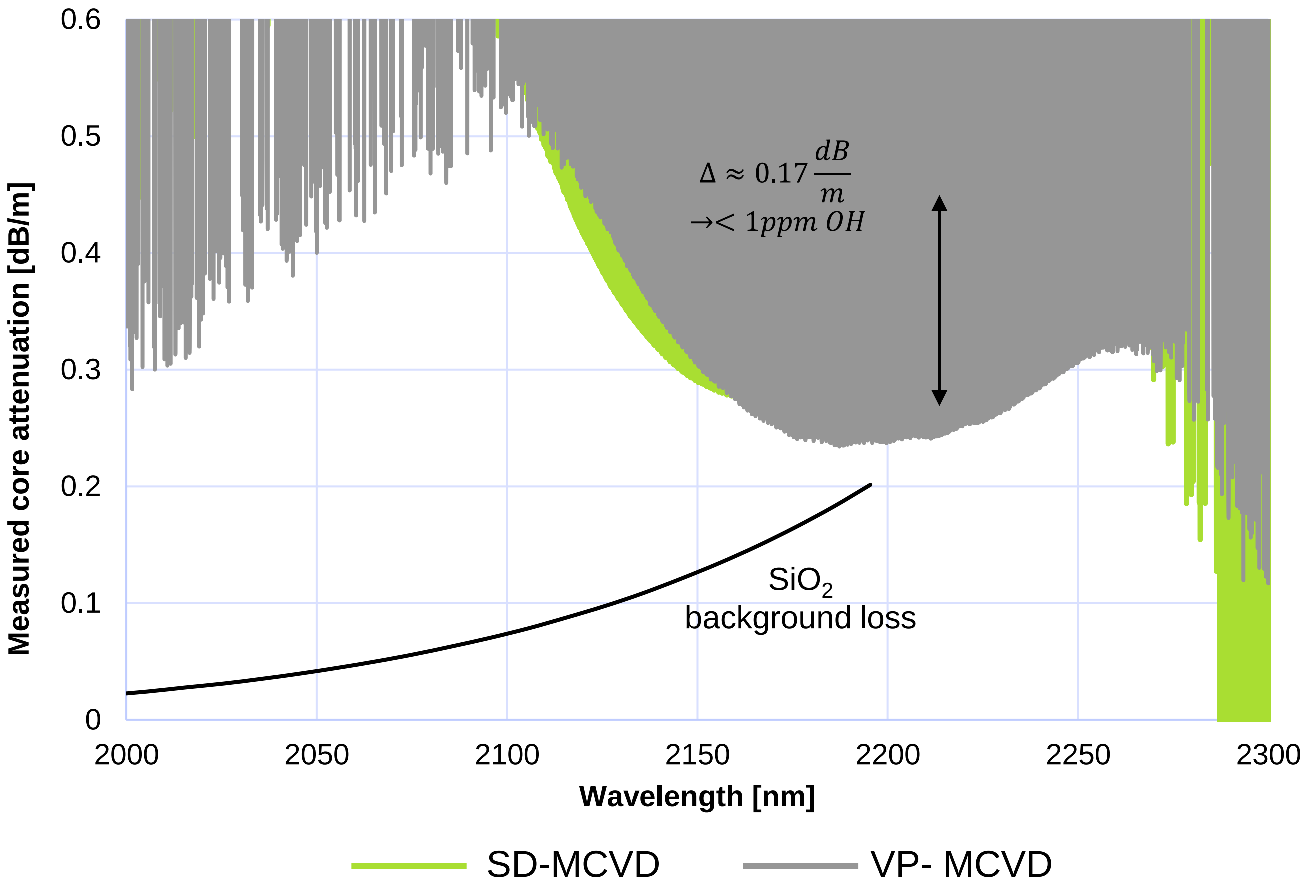
WHAT ABOUT –OH?

Efficiency FOM
Driven by ion density & mode overlap w/ core

$$C_\eta \propto \frac{D_{core}[Tm]}{2\omega_0 \alpha_{OH}}$$

- **Literature reports 1 ppm of –OH corresponds to 200 dB/km background loss at 2220 nm***
- **Measurement suggest that less than 1 ppm of –OH is added during SD-MCVD manufacturing**
- **Do not expect significant impact of –OH on SE between 1950 and 2050 nm**
- **SD-MCVD process improvements are underway**

Process impact on OH incorporation in TDF



*O. Humbach et al. "Analysis of OH absorption bands in synthetic silica", J. Non-Crystalline Solids 203 (1996) 19-26

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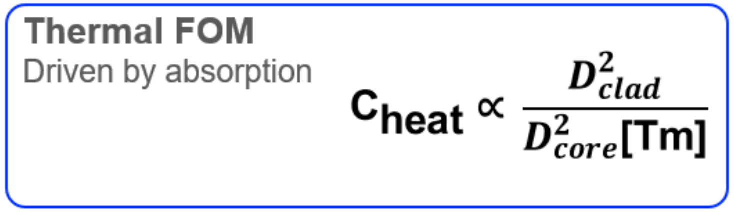
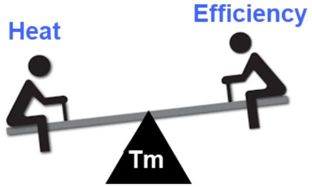
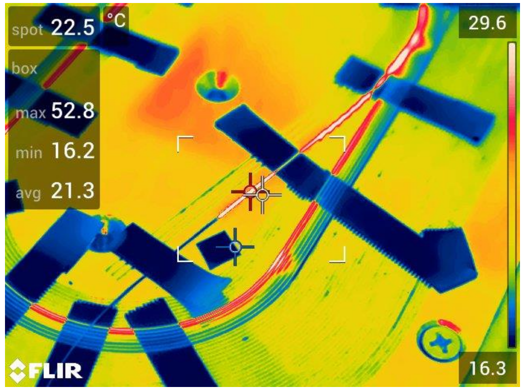
BALANCING THERMAL LOAD

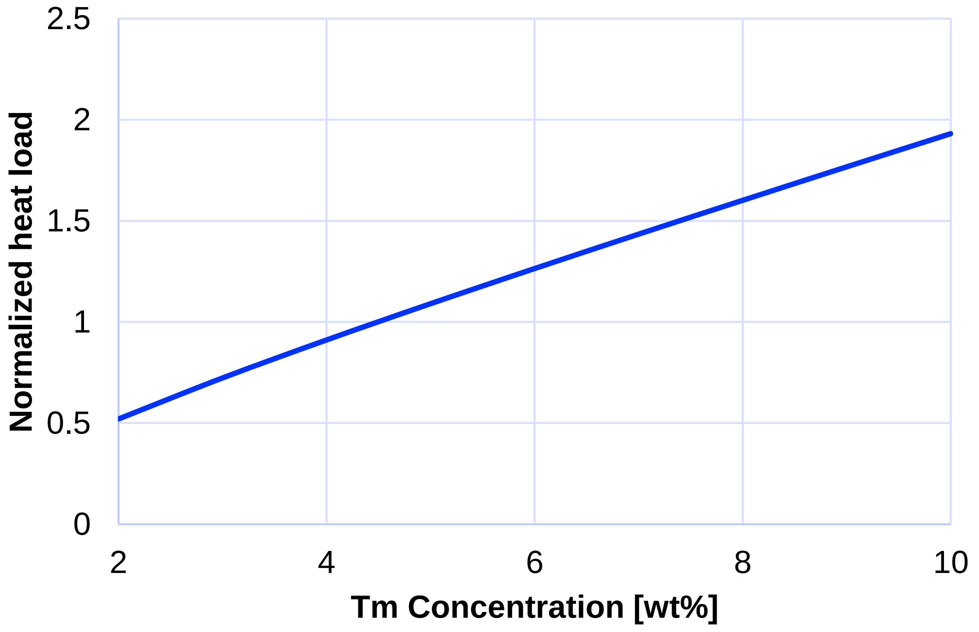


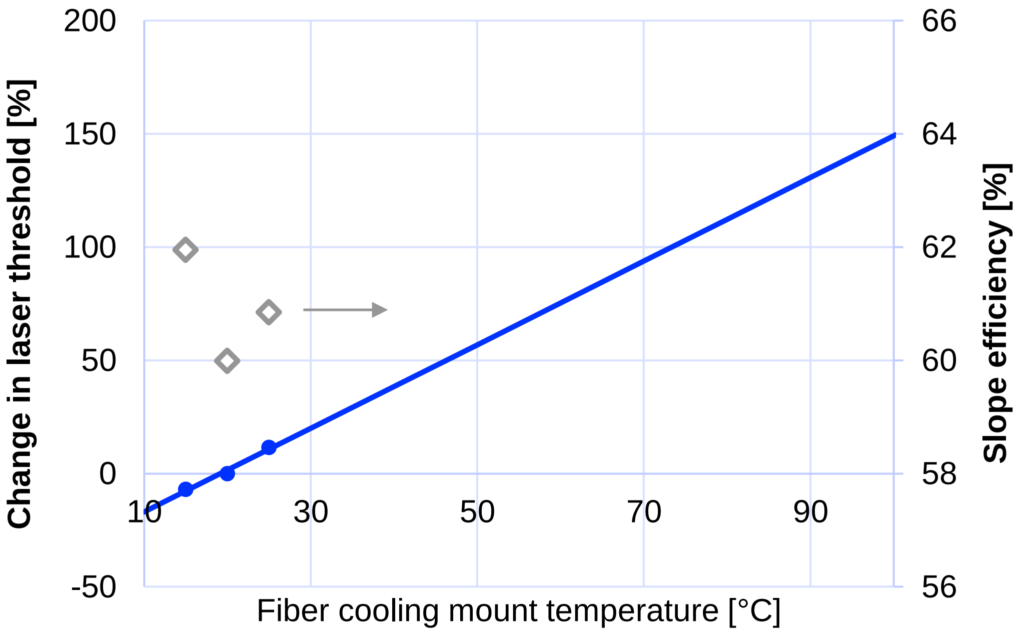
$$C_{heat} \propto \frac{D_{clad}^2}{D_{core}^2[Tm]}$$



- Expect 1.5 higher thermal load in high concentration LMA-TDF
- Laser threshold is directly impacted by fiber deployment temperature
- Requires active cooling to maintain efficiency advantages







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SUMMARY & OUTLOOK

- **Scaling power capabilities of DC active fibers using empirical models**
  - YDF > 3 kW
  - EYDF > 100's of W
  - TDF towards 1 kW

- **Future development to enable EYDF to several 100's of W**

- **First demonstration of LMA-TDF with > 8 wt% [Tm] concentration**
  - Manufactured with SD-MCVD process
  - Confirmed SE performances can be scaled compared to legacy LMA-TDF-25P/400-M
  - On-going process development to maximize SE extraction
  - Exploring fiber handling requirements towards an industrial fiber offering

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INNOVATIONS THAT RESONATE

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