2µm fiber development

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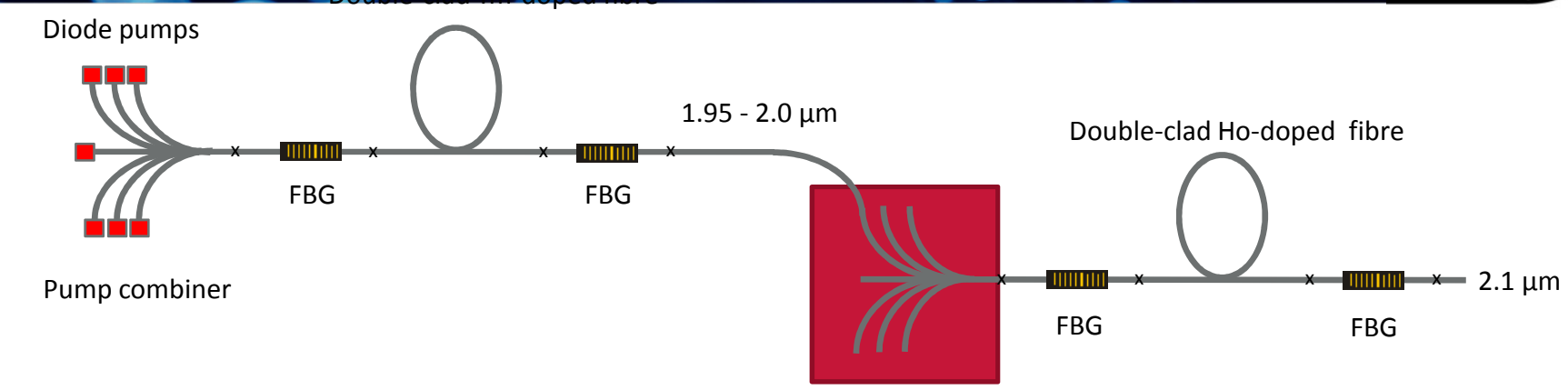
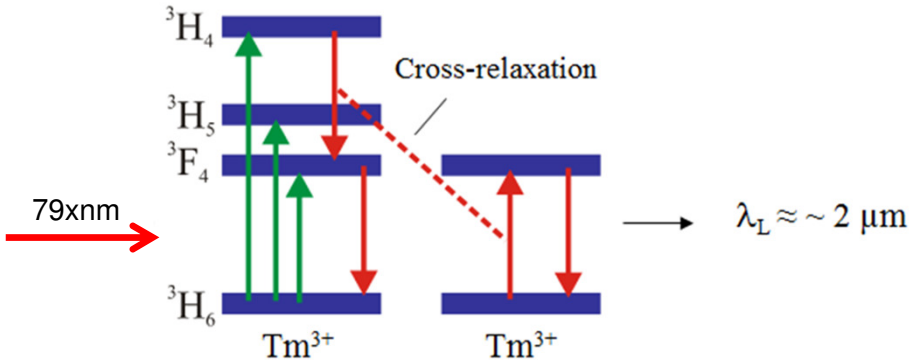
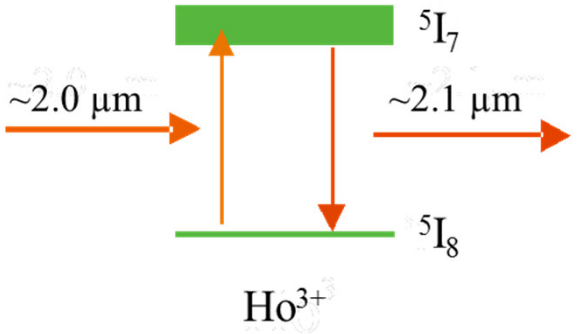
OVERVIEW

- ISLA Concept
- Holmium Fiber Progress
  - Cladding Materials
  - Cladding Shaping
  - Triple Clad Design
- Tm Fiber
  - Efficiency for 793nm pumping
  - Laser demonstration

The ISLA fibre approach







- Two-stage pumping scheme
- Intermediate brightness-enhancement and wavelength-conversion stage
- Exploits 2-for-1 cross-relaxation process in Tm fibre
- High efficiency low-quantum-defect Ho fibre stage

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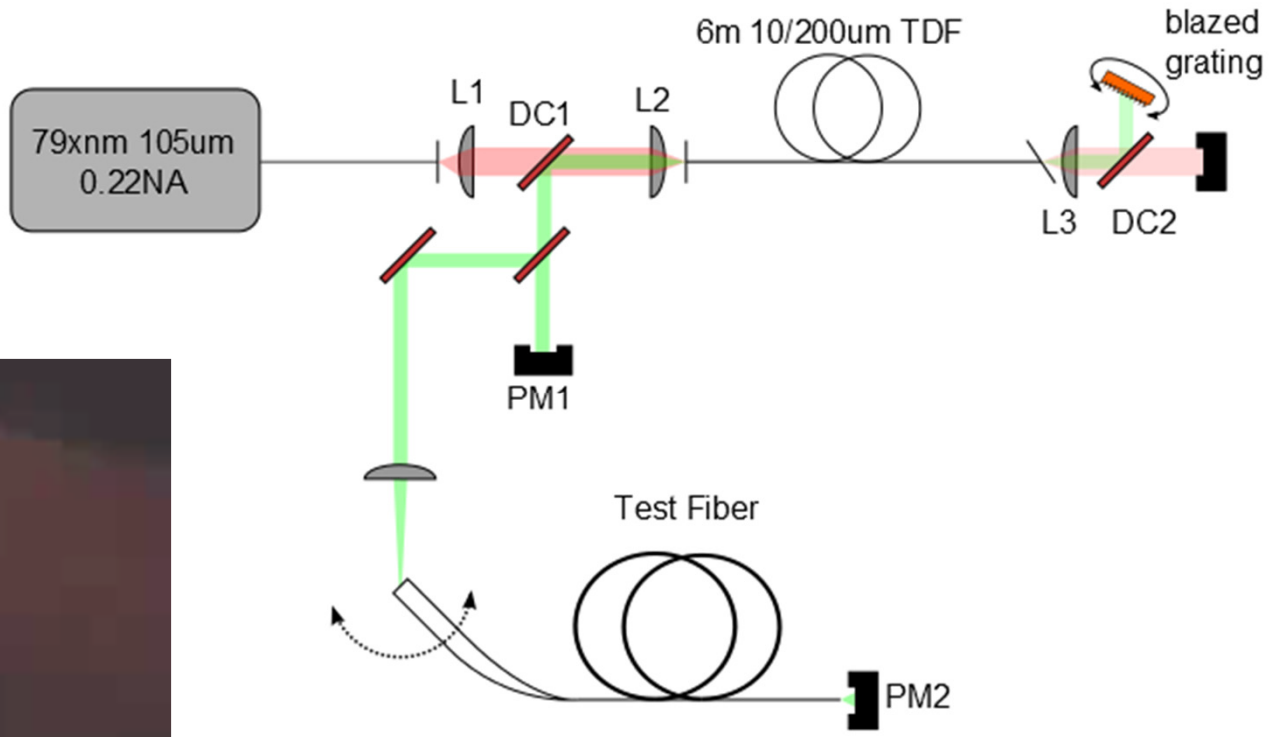
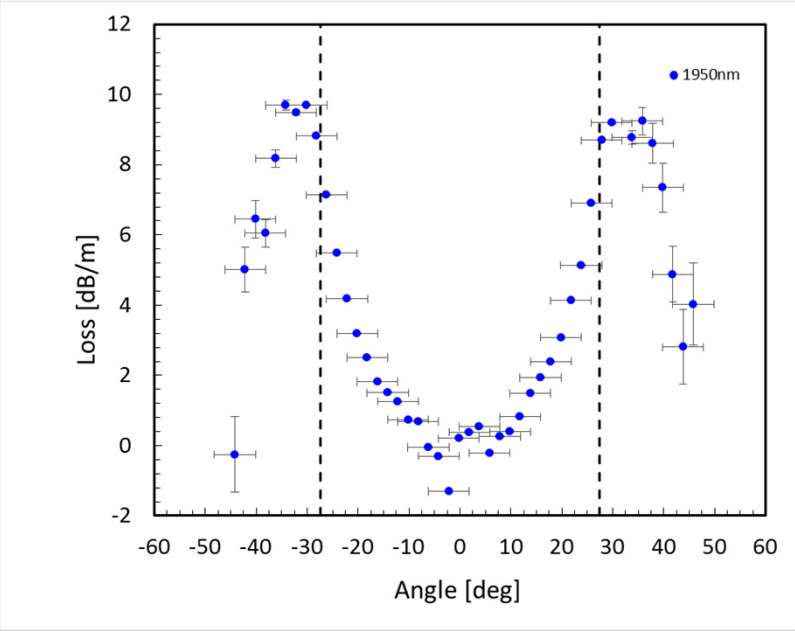
Cladding material investigation



Cladding material investigation

200µm matched passive
Low index PC-373 coating



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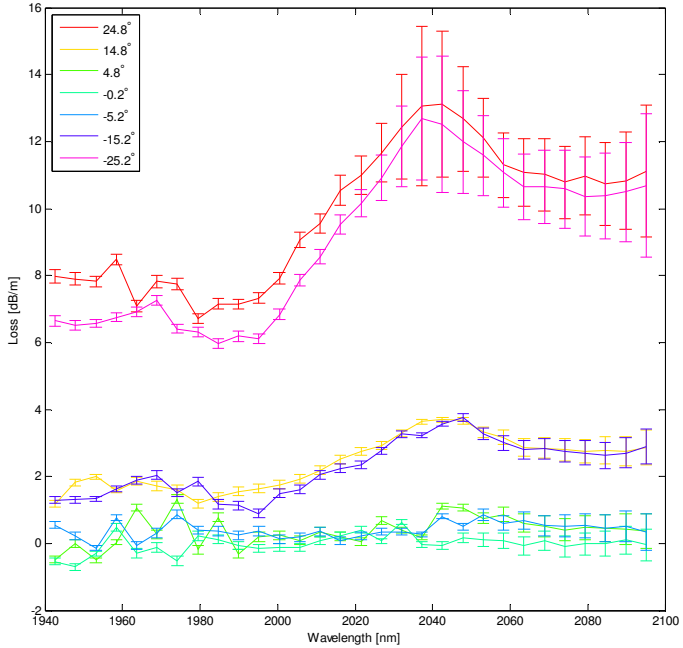
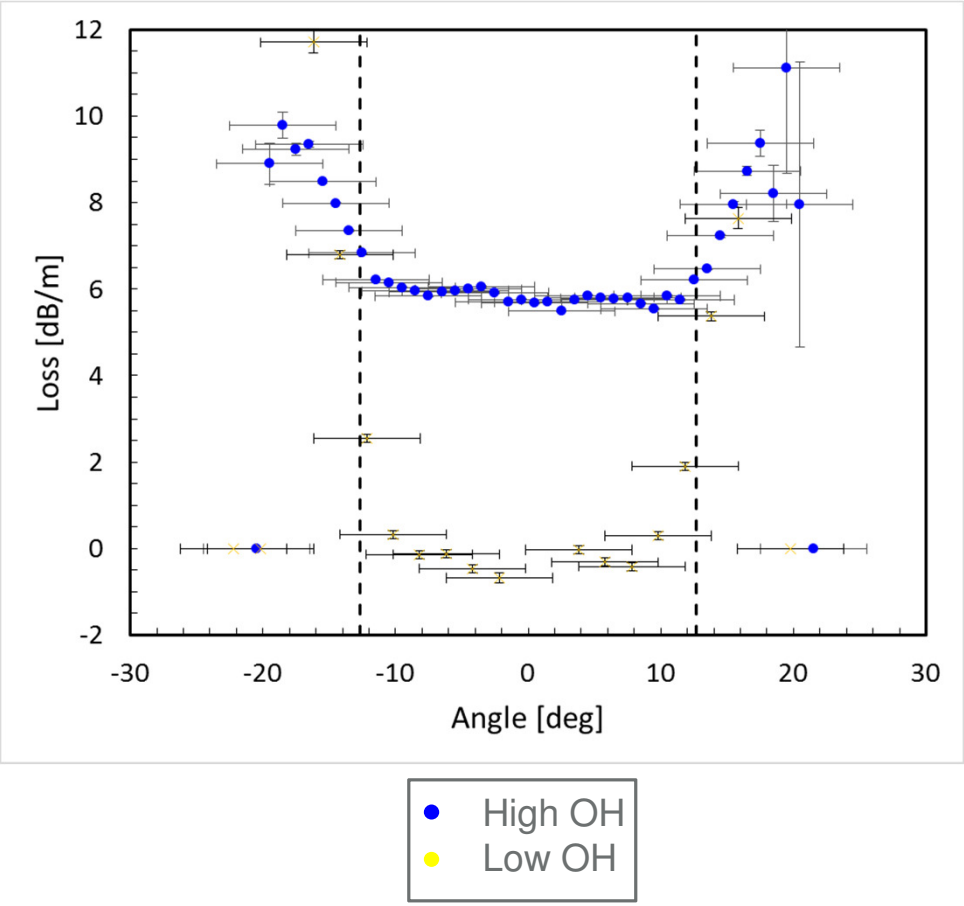


Cladding material investigation

Fluorine doped guidance

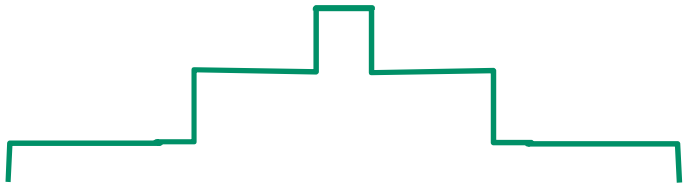
Flat attenuation until NA limit reached

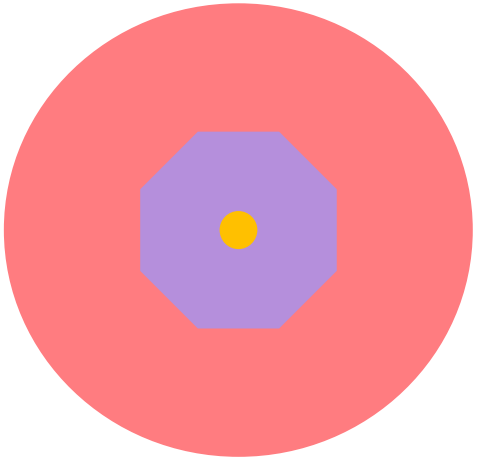


Double clad Ho design

- Plan
  - » Ho preform etched down to correct core to cladding area ratio
  - » Machined cladding for pump mixing
  - » Overjacketed with 0.17NA F-doped tube

- Triple clad draw
  - » Single mode -> 12.5/60/150
    - Point to point 61±1µm
    - Flat to flat 55±1µm
  - » Expected attenuation
    - 1.6dB/m @ 1950nm

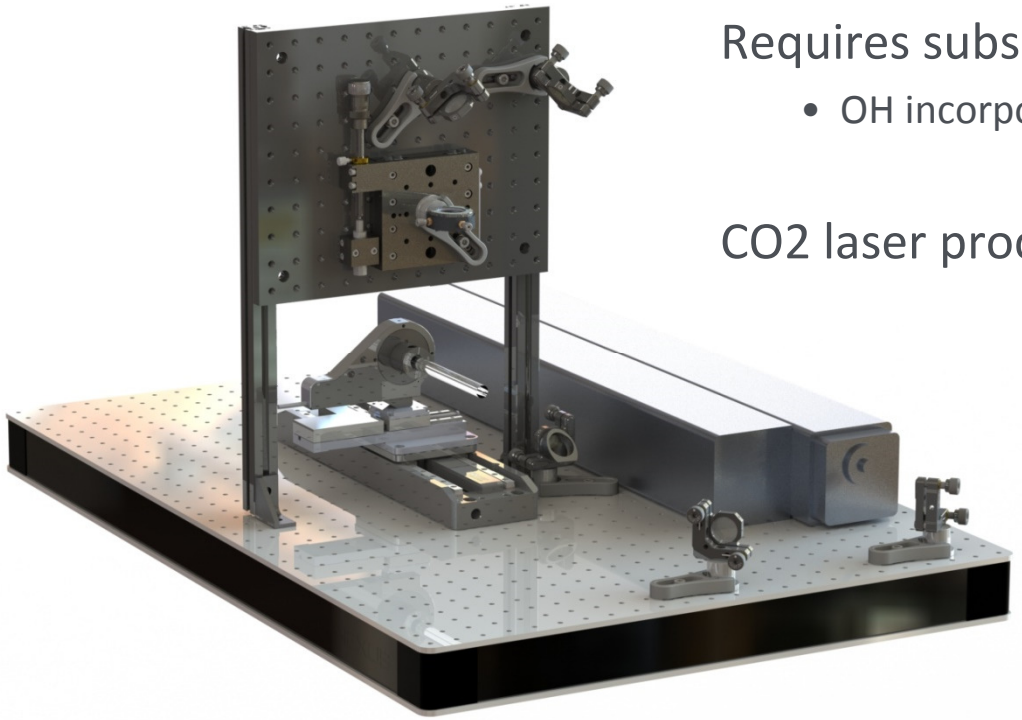




Cladding machining

Current machining undertaken by diamond mill

Time consuming



Requires subsequent fire polishing

- OH incorporation from H2 torch

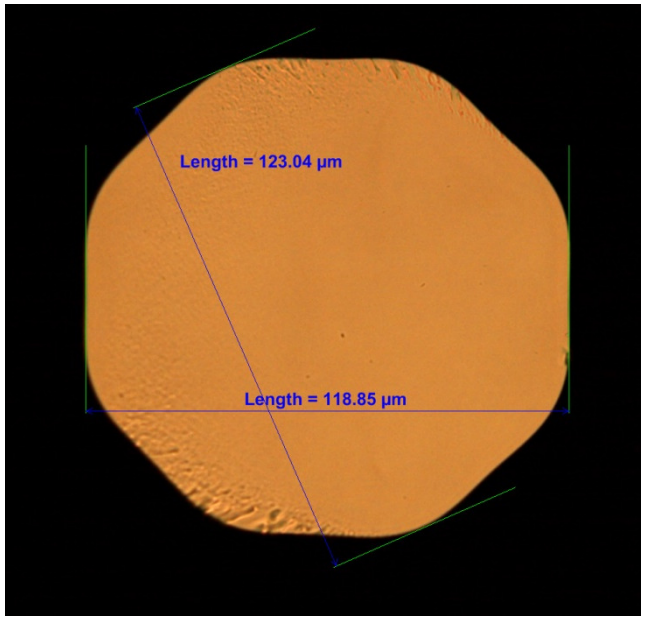
CO2 laser processing?

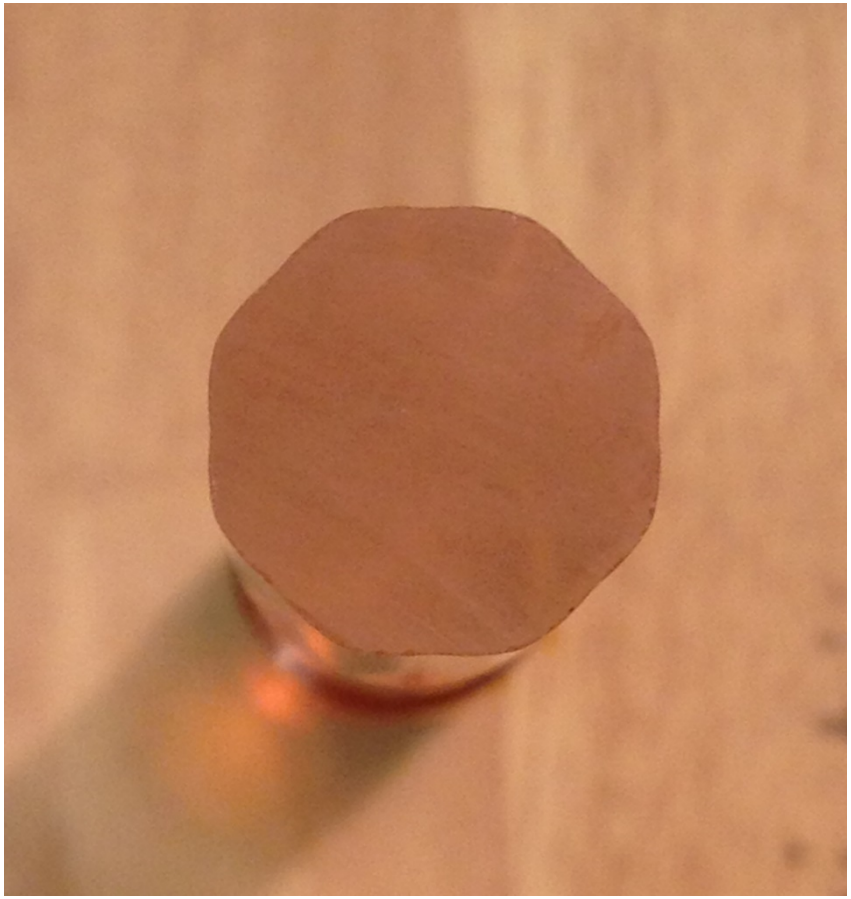
Cladding machining

Polygon shape machining

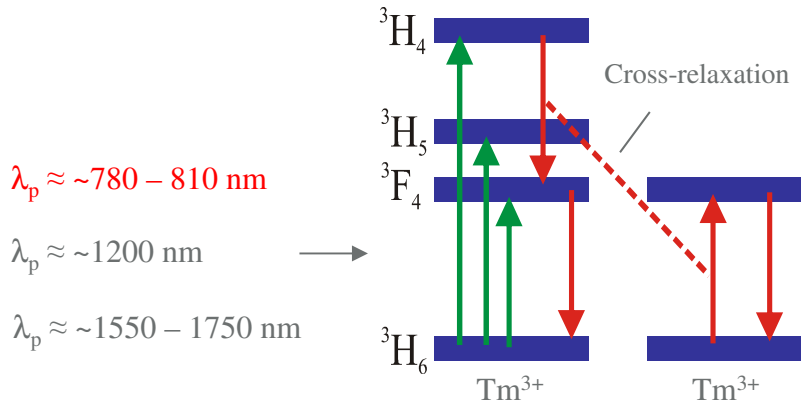
Fully Automated

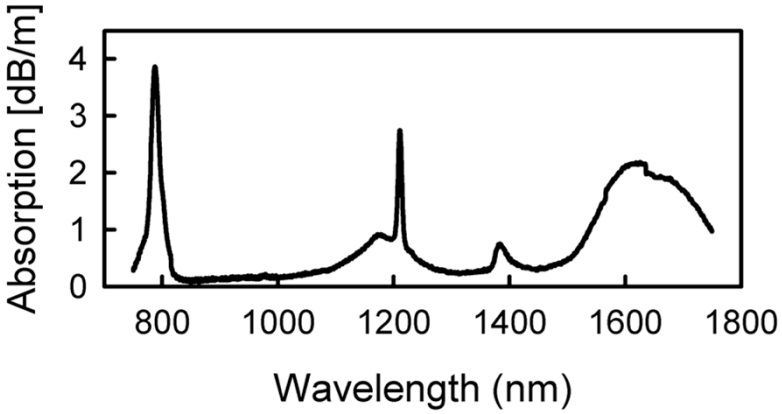
High speed





THULIUM PUMPING SCHEMES





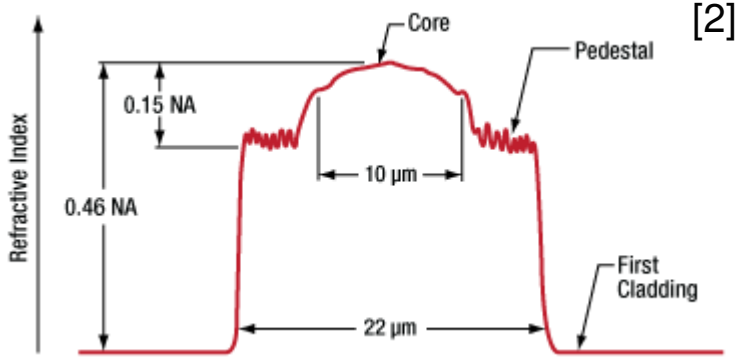
- Readily available high power 793nm pump diodes
- Tm/Al Concentration optimisation allows 2 for 1 cross relaxation [1]
- Potential high efficiency for
  - Direct 2µm applications
  - Generation further into the IR
    - Tandem pumping,
    - OPO
    - Supercontinuum
    - etc

[1] S. Jackson et. Al. 'Efficiency dependence on the Tm^{3+} and Al^{3+} concentrations for Tm^{3+}-doped silica double-clad fiber lasers. App. Opp. 42, 15, p2702-2707 (2003)

TM DESIGN PLAN

Commerically available fiber

- High Tm doping leads to high NA
- High NA addressed with 'pedestal structure' to reduce NA.
  - Challenging to Splice
  - Beam quality compromised [1]



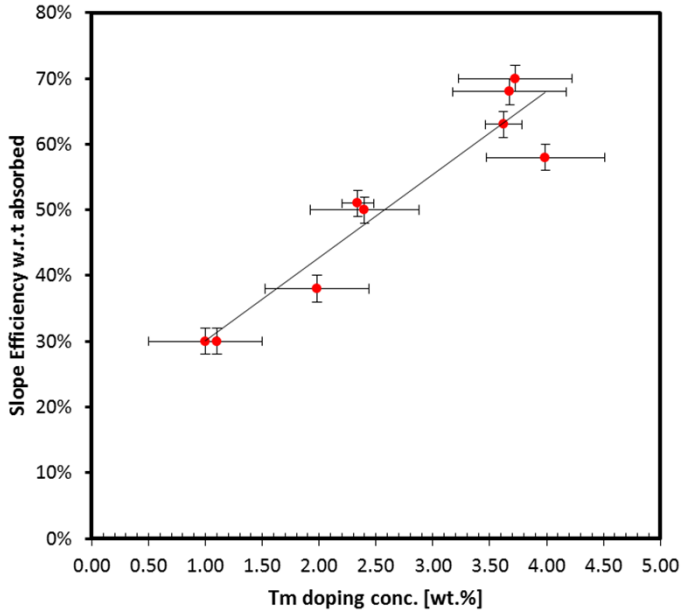
[2]

Our design strategy

- Solution doped MCVD fabrication
- Single mode preferable
  - not imperative
- Design High NA
  - Optimise for 2-for-1 793nm pumping efficiency
  - No pedestal
  - Minimise core propagation losses due to OH contamination

[1] N. Simakov et.al 'Design of experimental demonstration of a large pedestal thulium doped fibre', Opt. Expr. 23, 3, p3126 (2015)
[2] Nufern Tm fiber. Image from Thorlabs website accessed June-2015

CONCENTRATION



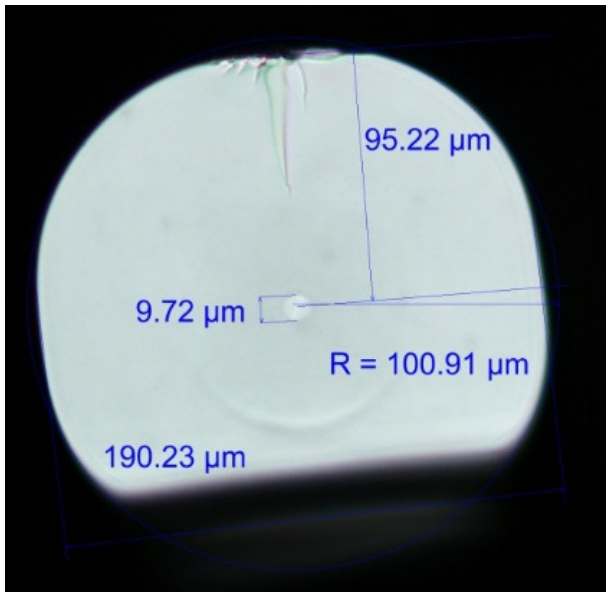
*Tm conc. calibrated from a combination of EDX and absorption measurements

- Up to 70% slope efficiency w.r.t. absorbed pump realised.
  - 4.1±0.2wt% Tm concentration
- Optimised core attenuation ~1000dB/m @789nm.
- Further increase in Tm concentration attempted
  - Cores elliptical
  - Evidence of poor collapse
  - Likely due to mechanical property mismatch between high doped core and silica cladding.

REDUCING CLADDING ATTENUATION

Intial Preform Parameters

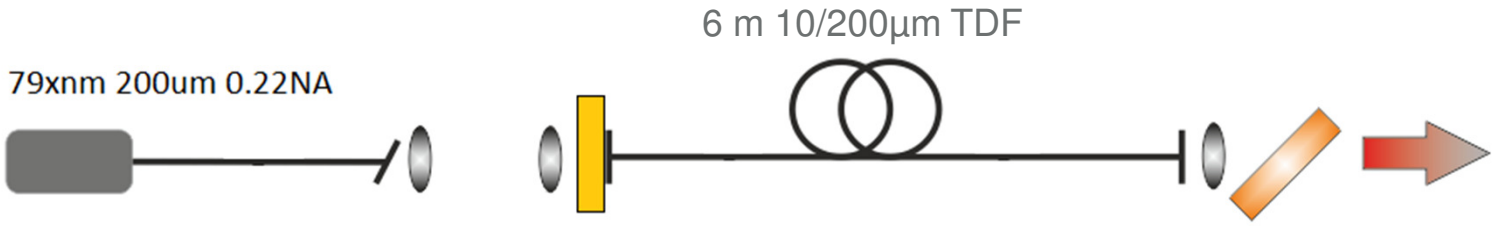
- core to cladding area ratio ~ 100:1
- ~10dB/m cladding attenuation @ 790nm
- Too high for high power operation

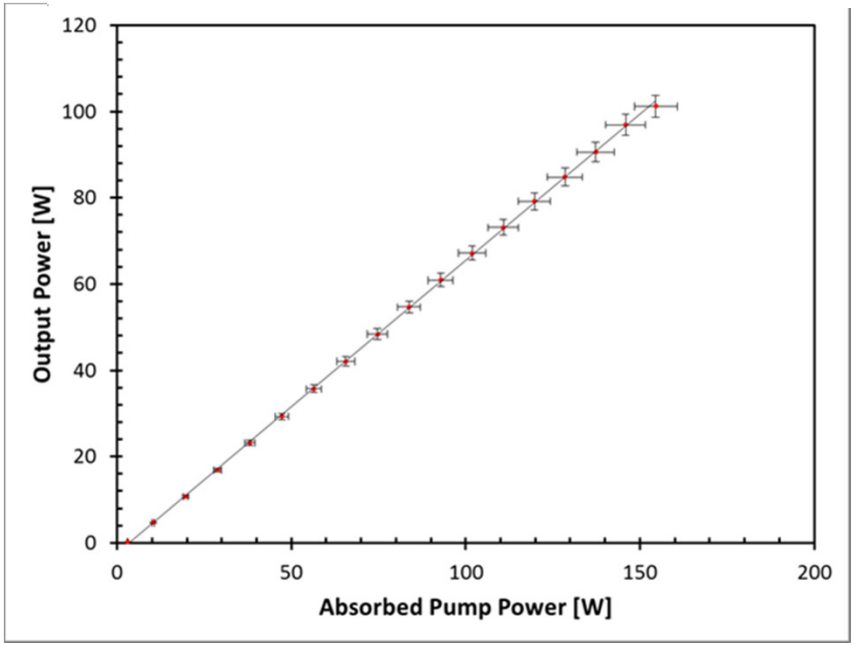


Reducing Pump Attenuation

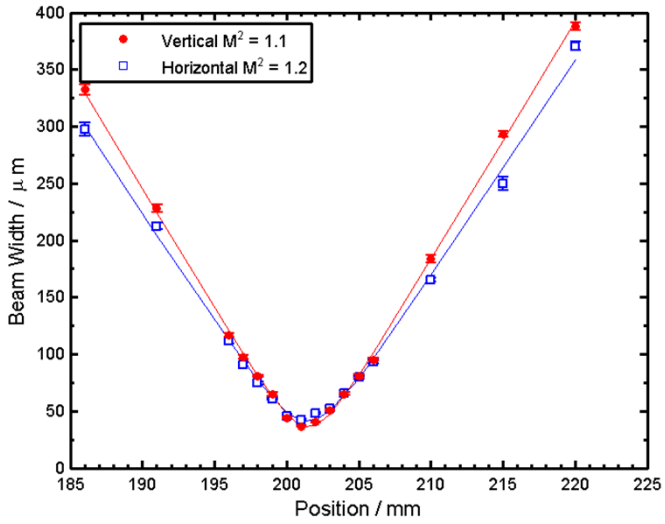
- Preform sleeved to target 2.5dB/m attenuation
- Machined to Quasi Octagon
- 2.6+-0.1dB/m attenuation at 79xnm
- 10µm core diameter
- 205µm circular to circular cladding diameter (190µm flat to flat)

PERFORMANCE





- 100W output
- 68% slope w.r.t. absorbed pump power
- Free running wavelength 2020nm

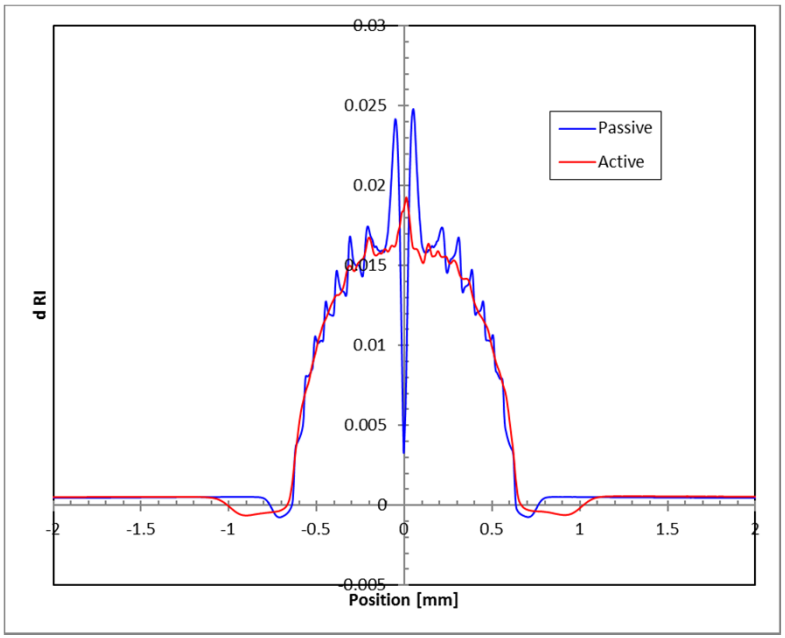


Photosensitive passive fibre

Active and passive fibre index profiles matched

Highly doped Al:Tm doped active fibre

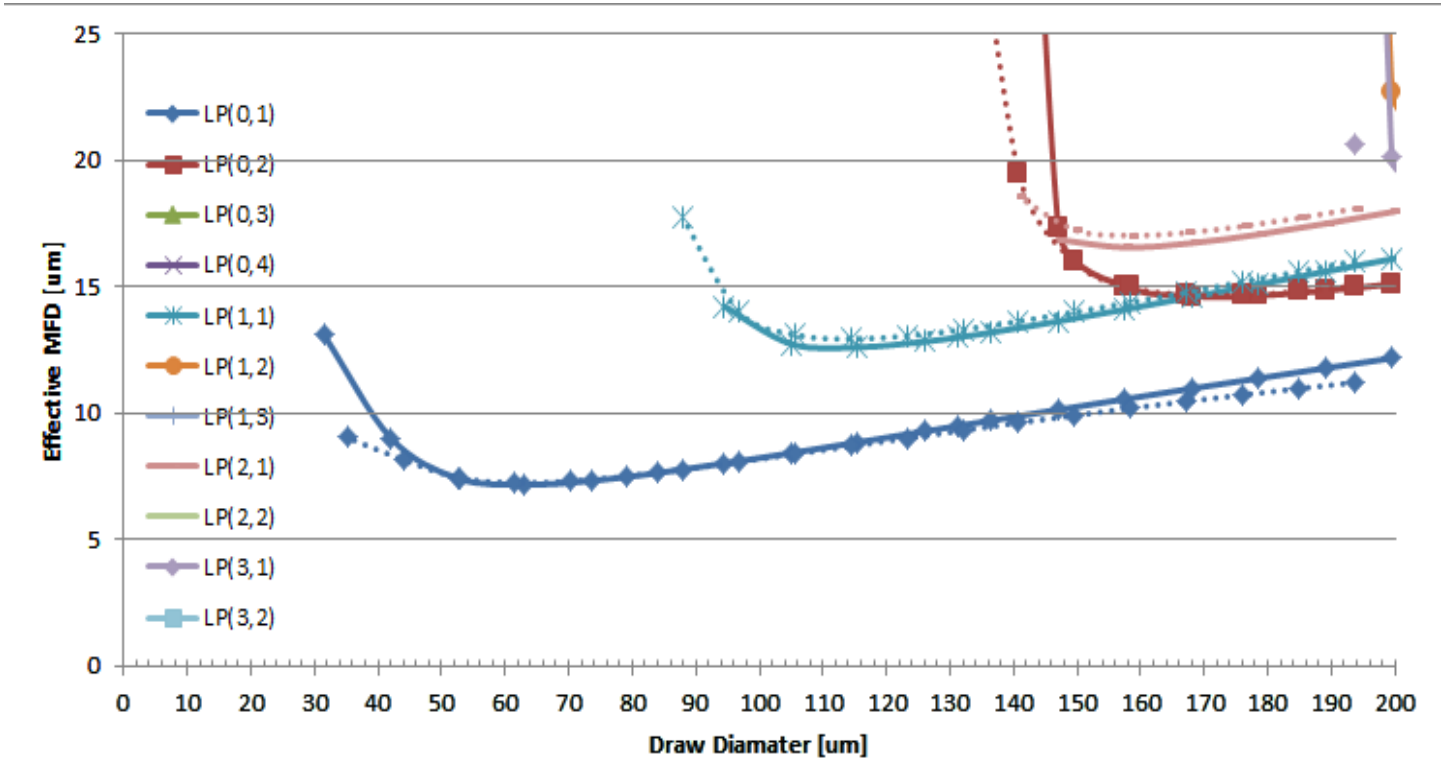
7 layer passive germano-silicate core



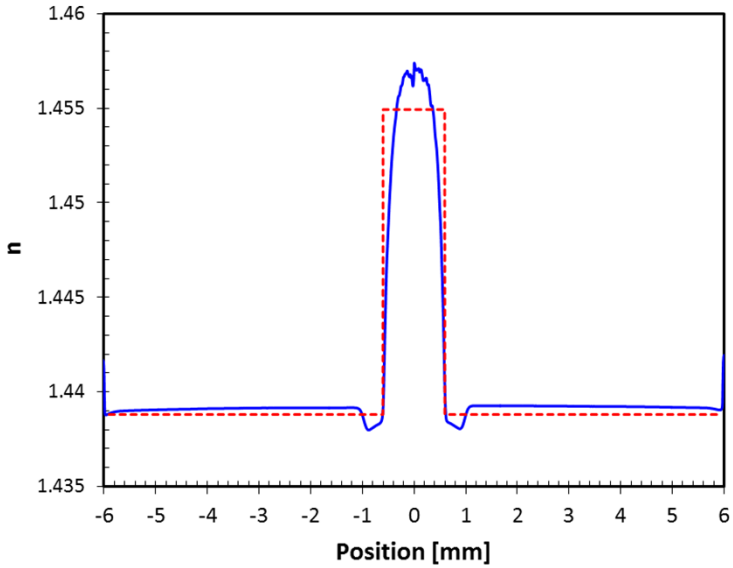
Photosensitive passive fibre

Mode field diameters of >4 modes match well

- Freedom in fibre diameters
- Freedom in wavelength
- Should reduce splice loss and increase laser stability and reliability



POSSIBLE?

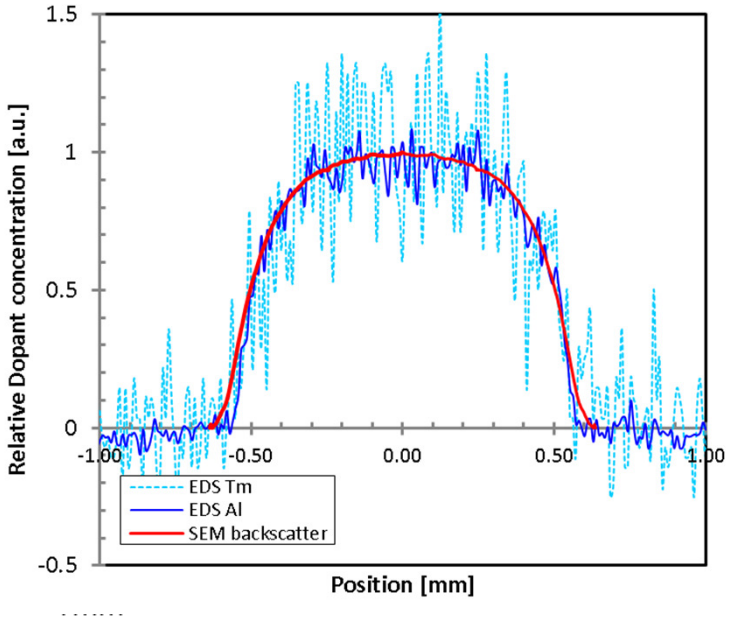


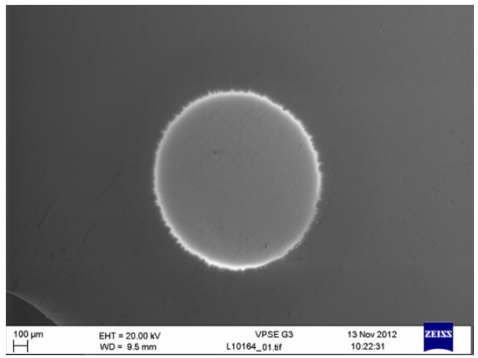
- Dopant distribution not flat topped
  - Likely due to variations in soot porosity prior to solution doping
- Refractive index indicative of variation in the dopant distribution over the core
  - If dopant distribution not uniform will lead to variation in 2-for-1 efficiency
- Index changes via Preform Refractive Index Profile (PRIP) not clear whether variation is Al/Tm

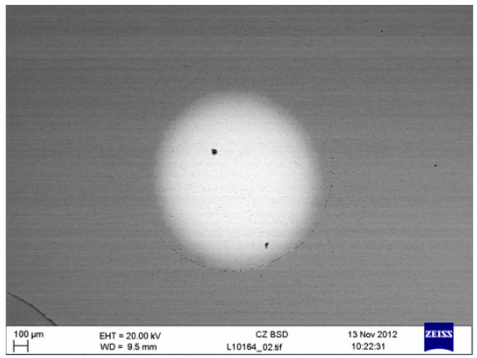
SPECTROSCOPY

- Energy Dispersive X-ray Spectroscopy
  - Tm : 4.07±0.18 wt.%
  - Al : 3.96±0.13 wt.%

- SEM Backscatter signal gives higher resolution map of the Tm distribution
  - Al variations not mapped as Si and Al similar in atomic number.



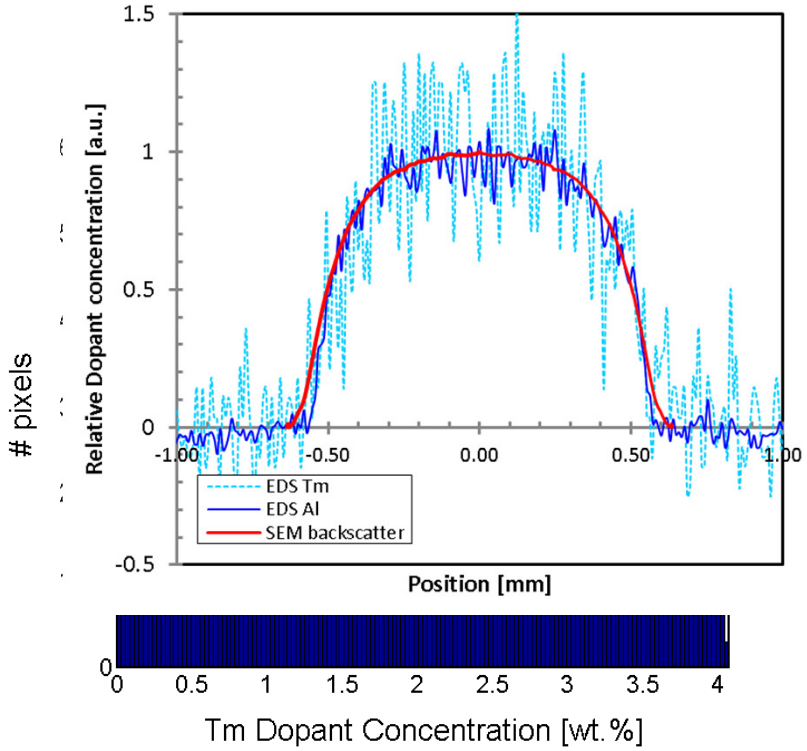




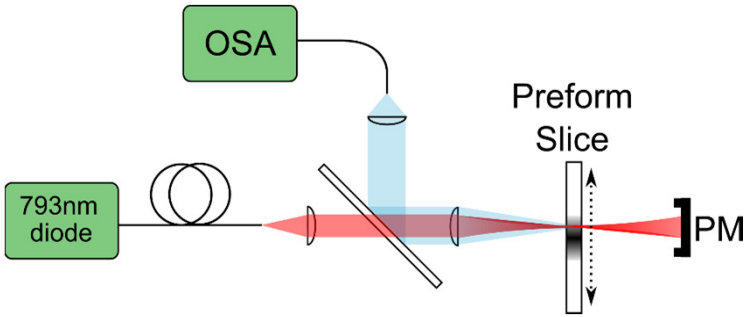
DISTRIBUTIONS

- Peak has high Tm concentration
- Large distribution in dopant concentrations across core
- Overall efficiency is limited as not all of core is not uniformly optimised for 2-for-1 cross relaxation

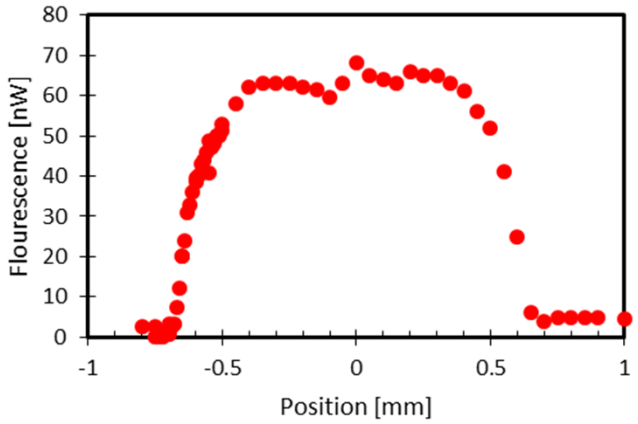
Pixel effective weight % histogram

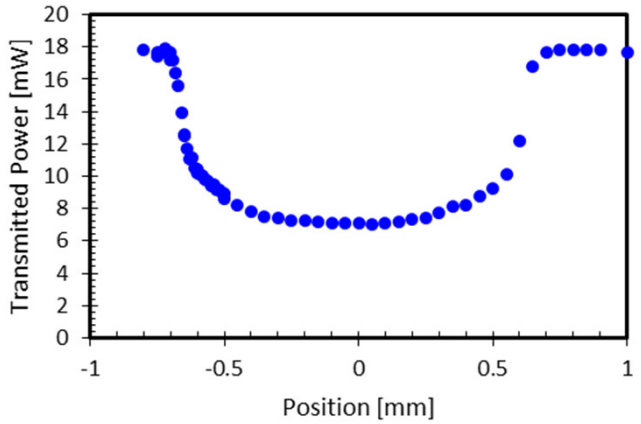


SPATIAL FLUORESCENCE MEASUREMENT

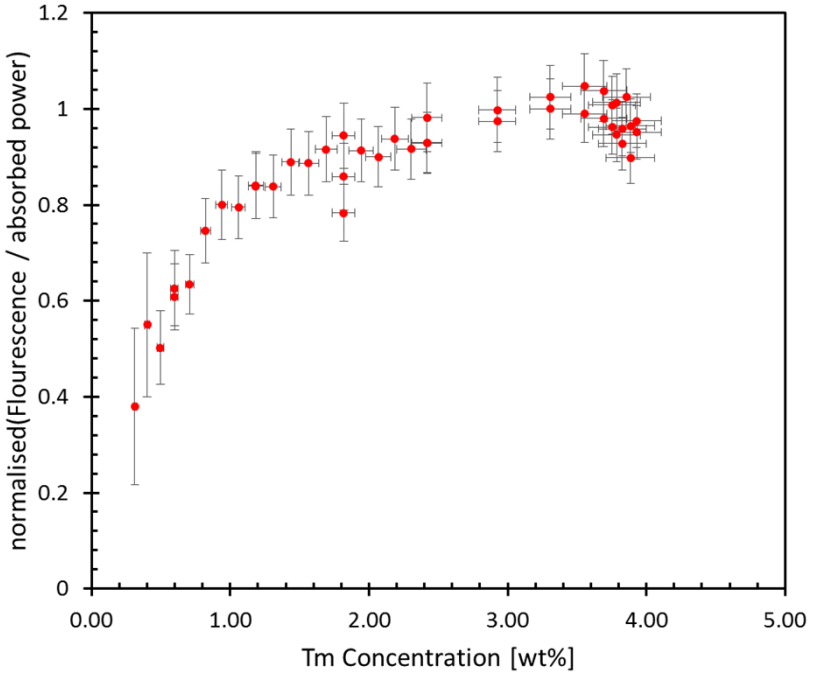


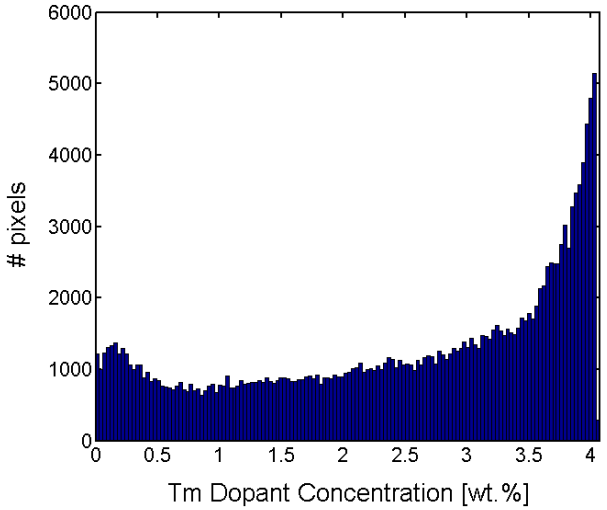
- Slice polished from preforms
- 1mm core diameter
- Spatially resolved fluorescence measurement 1900nm-2200nm





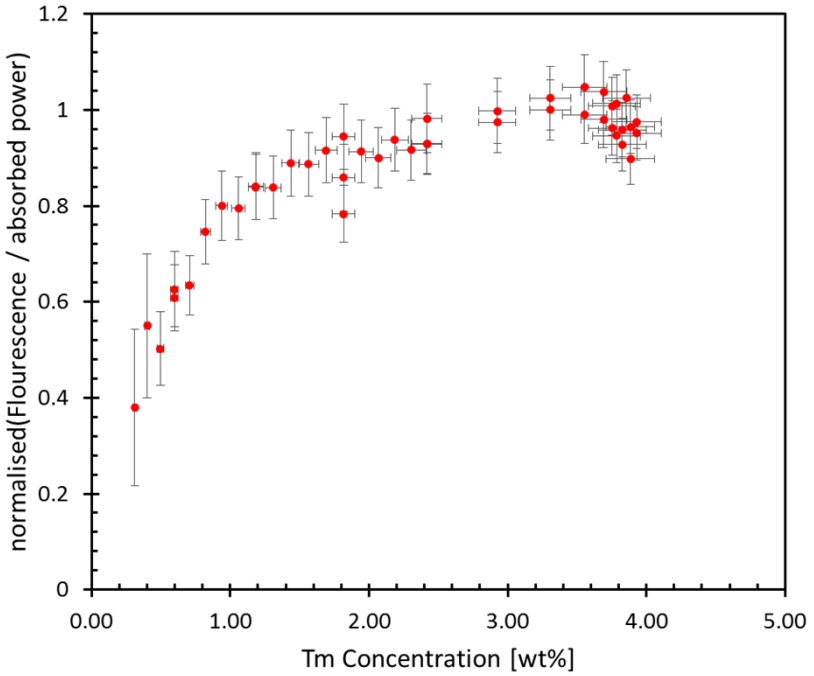
PREDICTING THE PREFORM EFFICIENCY





Wavelength [nm]	Predicted Efficiency
1900	70%
1950	68%
2000	67%
2050	65%
2100	63%

CONCENTRATION



- Fluorescence shows plateau for > 3wt% Tm concentrations
- Doping to >4 wt% is only beneficial as it creates more of the core above 3 wt%.
  - Higher reabsorption loss
  - Upconversion
- Further increases in efficiency should focus on making dopant distribution more 'top hat'

CONCLUSION

- High efficiency fibers developed
  - Tm
    - Composition optimised
    - Route to further improvements identified
  - Ho
    - Composition optimised
    - Triple clad design developed
  - Passive fibers
    - Matched photosensitive fibers developed

- 100W 2µm fibre lasers demonstrated
  - Pump blocks for Ho final stage under construction