Solid Specialty Fibre

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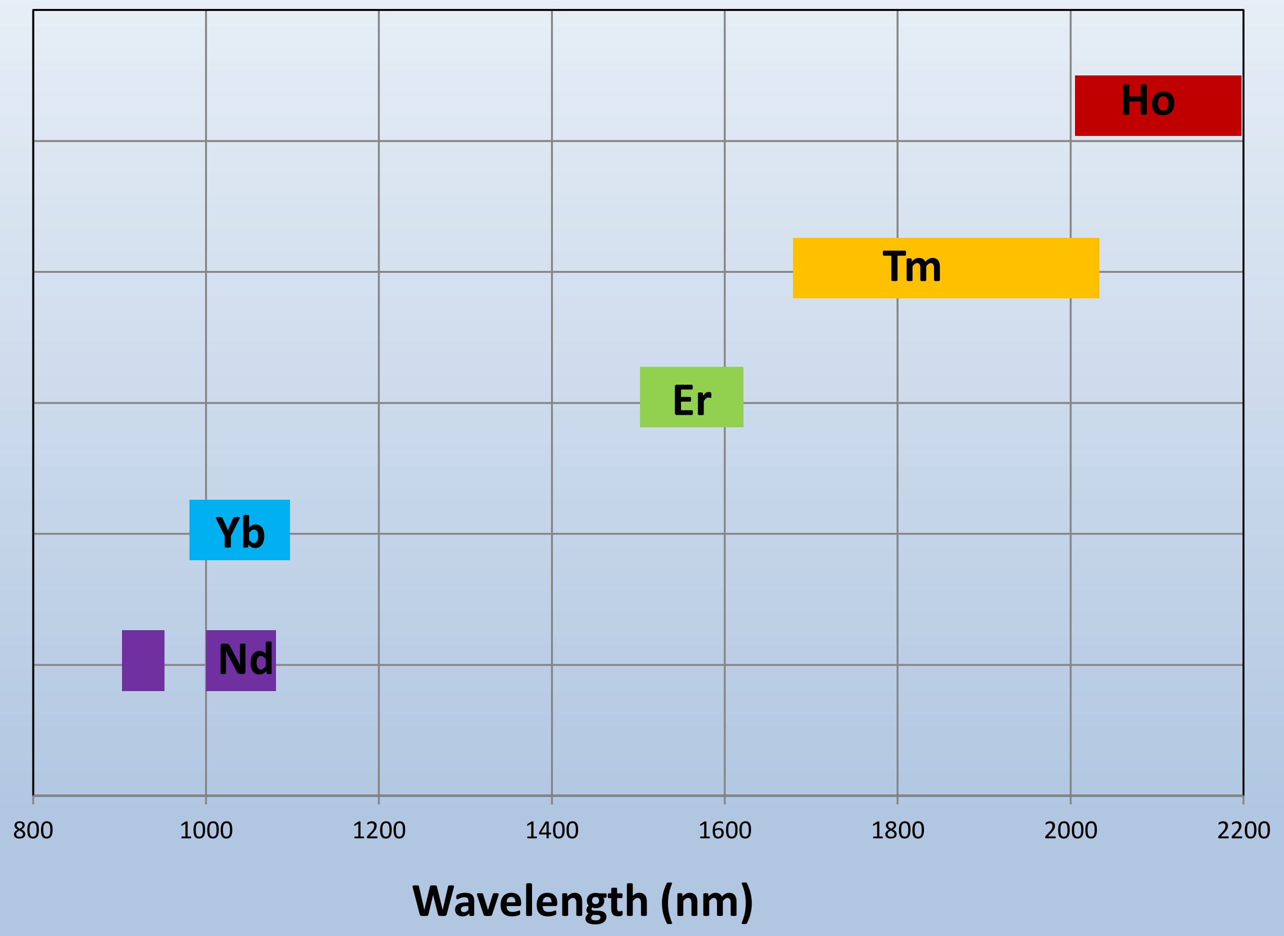
Outline

- Large mode area fibres for high power applications – current trends.
- Efficient Tm and Ho doped fibre development for operation at 2 μm.
- Bismuth (Bi) doped fibre lasers and amplifiers in the wavelength band 1150 – 1500nm
- 100% GeO2 core/silica cladding fibre using OVD technique

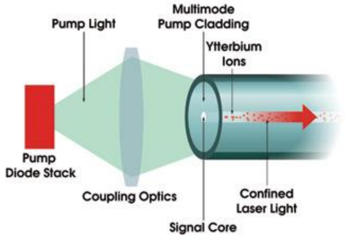
Wavelength span covered by rare-earth doped silica fibres in the high power regime



up to 20kW single-fibre, SM output power from Yb-doped fibre demonstarated

- direct diode pumping ~ 3kW
- tandem pumping >3kW

Challenges for power scaling:



►**Scaling core area whilst preserving single-spatial-mode output**

- Suppression of non-linear processes (such as SRS, SBS)

- Increase damage threshold (~ 2GW/cm^2 for silica)

$$P_{pth}^{SBS,SRS} \propto \frac{A_{eff}}{\mathrm{L}_{\mathrm{eff}}}$$

► **Reduce fibre length**

► **Reduce thermal load**

► **Increase brightness of pump didoes**

Solution:

Large mode area (LMA) fibres (low NA and large core), but often multimode in nature.

Effective Single Mode (ESM) operation:

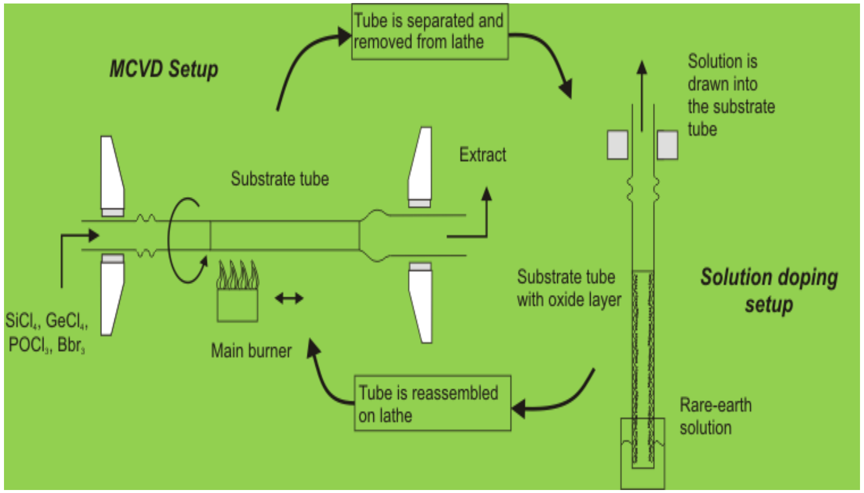
Desirable properties for ESM operation: Losses (or power delocalization) of HOMs and FM fulfilled over a range of fibre bend radius while offering a large $\mathbf{A_{eff}}$ for the FM.

SINGLE MODE CRITERIA:

Fundamental Mode Losses ≤0.1 dB/m

Higher Order Mode Losses ≥10dB/m

- Also, LMA fibre design is suitable for low-cost and mass manufacturing which requires fabrication techniques such as MCVD, OVD ……
- Easy post processing of fibre (splicing and cleaving..)



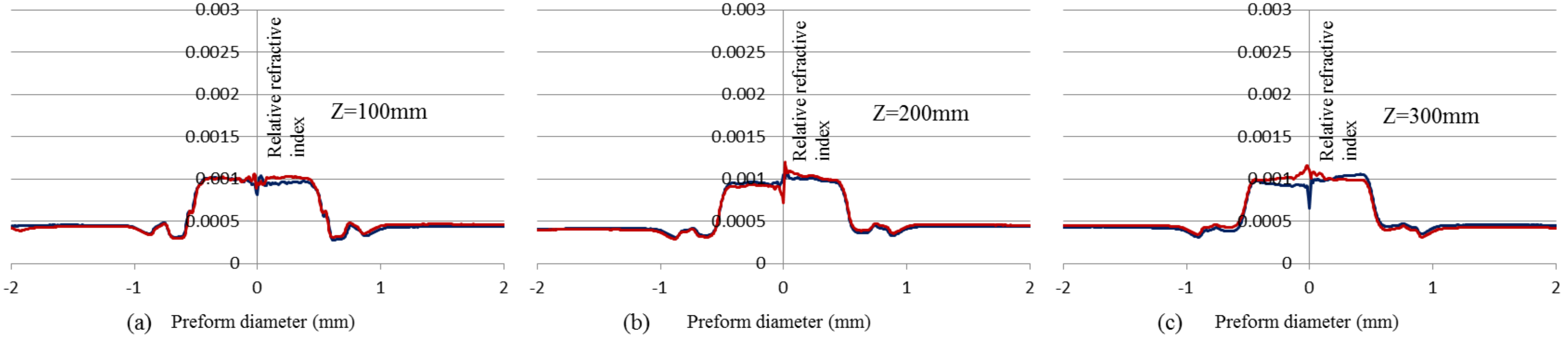
MCVD and solution doping for specialty fibre manufacturing

Analysis of mode area scaling for different core NAs in step index fibre (SIF)

Low NA	Effective area μm^2 (taking into account bend induced distortion)	Bend diameter (cm)	core diameter (μm)
0.048	~450	~15.5	~29
0.038	~700	~32	~35

Significant improvement
in effective area

Fabrication of ultra-low NA (~ 0.038) rare-earth doped step index fibre (SIF) using MCVD-solution doping



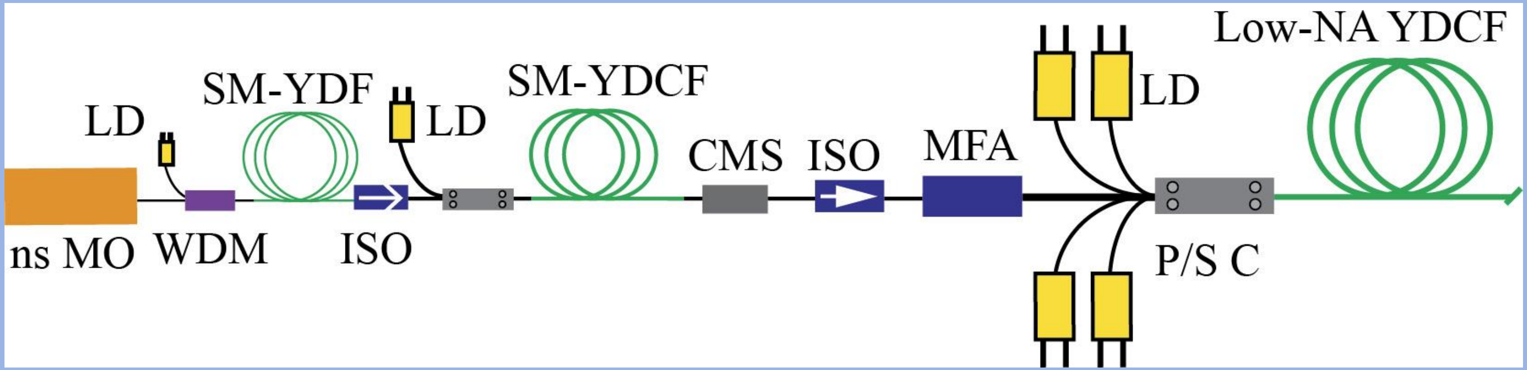
- ***Yb-doped SIF with 0.038 NA ($\Delta n = 5\text{x}10^{-4}$) demonstrated with a flat index profile.***

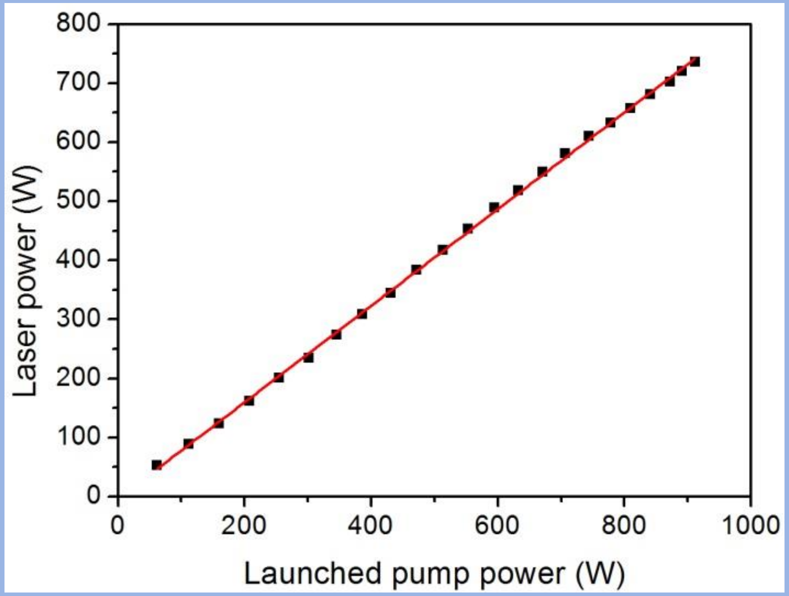
- ***Good manufacturing yield: 300mm long uniform preform from a starting tube length of ~400 mm long.***

- **Good laser efficiency and output beam (M2 < 1.1) from a 35 micron fibre.**

D. Jain et. al. "Demonstration of ultra-low NA step index fibre for high power fibre laser applications," Opt. Exp., **23 (6)**, 7407 - 7415 (2015).

High power demonstration of 35μm core ultra-low NA SIF in all fibre ns-pulsed MOPA

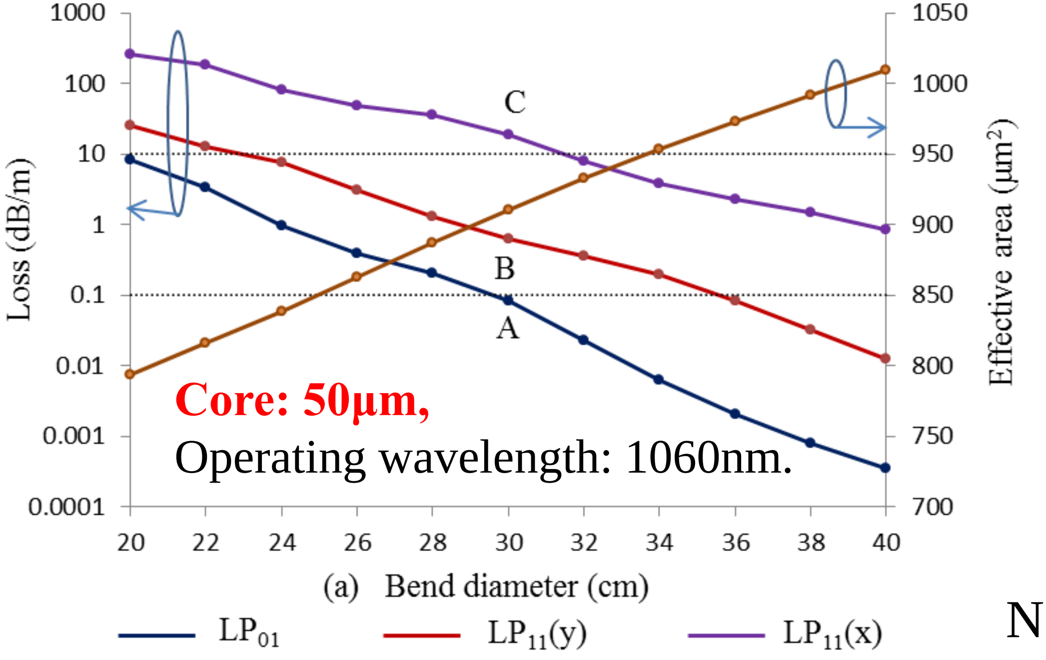


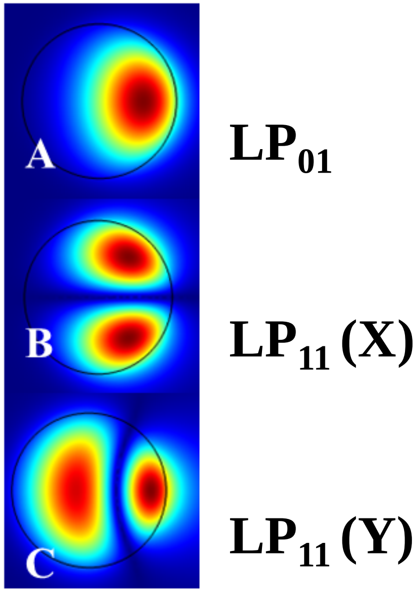


Average power: 736W
Pulse energy:0.39mJ
Peak Power: 64KW
Pulse duration: 6.47ns
Rep rate: 1.9MHz

In collaboration with College of Optoelectronic Science and Engineering, National University of Defence Technology, China

SIF with NA 0.038 and core diameter over 40 micron does not fulfil the ESM operation





Normalized electric field

At 30 cm bend diameter:

► LP_{01} loss is < 0.1dB/m

► LP_{11}(x) loss is > 10dB/m.

► but the LP_{11}(y) loss is < 10 dB/m (even below 1dB/m) that does not fulfil ESM.

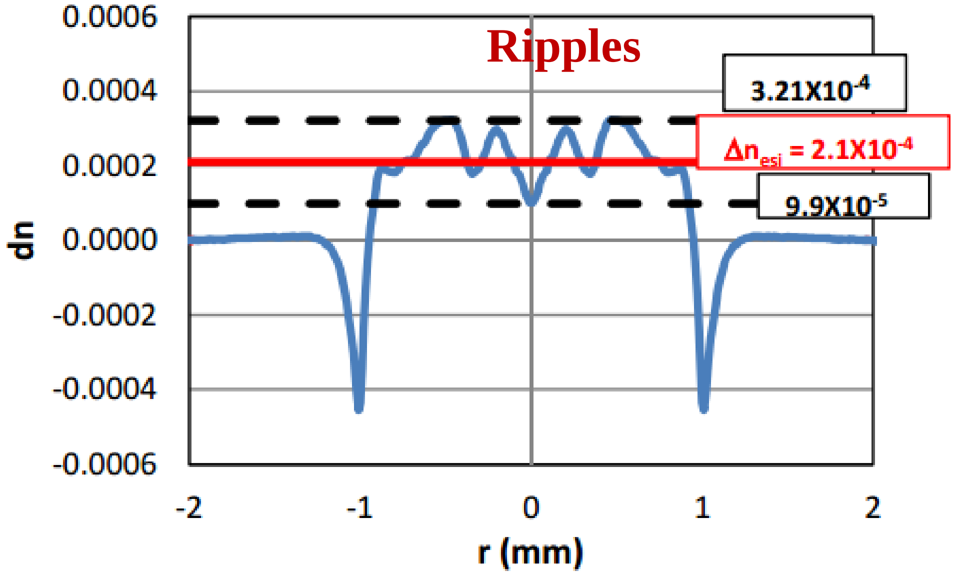
► Effective area of LP_{01} is ~900 μm^2

Obvious next step is to reduce the core NA < 0.038

Extremely low NA Yb doped preforms (<0.03) fabricated by MCVD

Vincent Petit [1], Richard P. Tumminelli [1], John D. Minelly [2], Victor Khitrov [2]
[1] Coherent Inc., 32 Hampshire Road, Salem NH 03079, USA
[2] Coherent Inc, 5100 Patrick Henry Drive, Santa Clara, CA 95054, USA

Photonics West 2016



- 50um core diameter with claimed NA of 0.025.
- Required large bend diameter of 60cm for a stable operation.
- **1dB/m calculated bend loss at 45cm bend diameter –** this will signficantly reduce the HOM loss.

Petit et al., “Extremely low NA Yb doped preforms (<0.03) fabricated by MCVD” presented at Photonics West 2016 © SPIE

CLEO, 2016

Large-mode-area fibers operating near single-mode regime

Fanting Kong,* **Christopher Dunn, Joshua Parsons, Monica T. Kalichevsky-Dong, Thomas W. Hawkins, Maxwell Jones, and Liang Dong**
ECE/COMSET, Clemson University, AMRL Building, 91 Technology Drive, Anderson, South Carolina 29625, USA
**FANTINK@clemson.edu*

Piexlated core structure

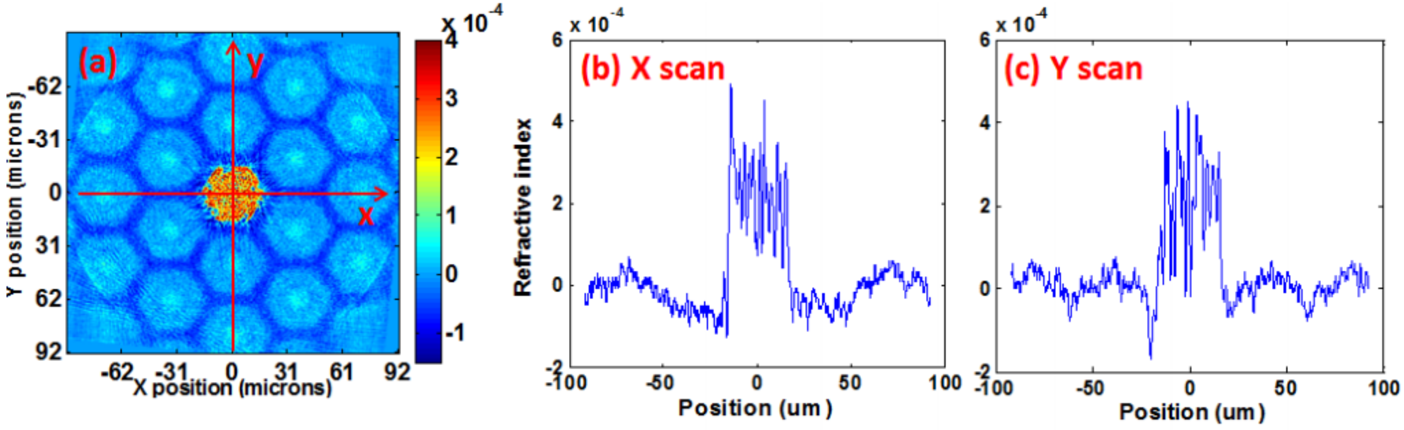


Fig. 2. (a) 2D refractive index of the 30/400 fiber, (b) refractive index scan along X axis and (c) Y axis.

- 30/400 and 40/400 core/cladding diameter fibre
- **NA: 0.028**
- Yb-doped phosphosilicate glass is used with additional boron doping
- ~3dB/m and ~4.5dB/m cladding pump absorption at 976nm for 30µm and 40µm core diameter fibres.
- **A large (> 100cm) operational bend diameter is required**,

F. Kong et al, "Large-mode-area fibres operating near singlemode regime" , presented at CLEO-2016 © OSA, and Optics Express, Vol 24, pp 10295 – 10301 (2016)

MCVD Based Fabrication of Low-NA Fibers for High Power Fiber Laser Application

ASSL, 2015

Christian Hupel[1], Stefan Kuhn[1], Sigrun Hein[1], Nicoletta Haarlammert[1], Johannes Nold[1], Franz Beier[1,2],
Bettina Sattler[1], Thomas Schreiber[1], Ramona Eberhardt[1], Andreas Tünnermann[1,2]
[1]Fraunhofer Institute for Applied Optics and Precision Engineering (IOF), Albert-Einstein-Str. 7, 07745 Jena,
[2]Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany
Author e-mail address: Christian.Hupel@iof.fraunhofer.de

Host glass: SiO_2+P_2O_5+Al_2O_3 (P : Al ⇒1:1)

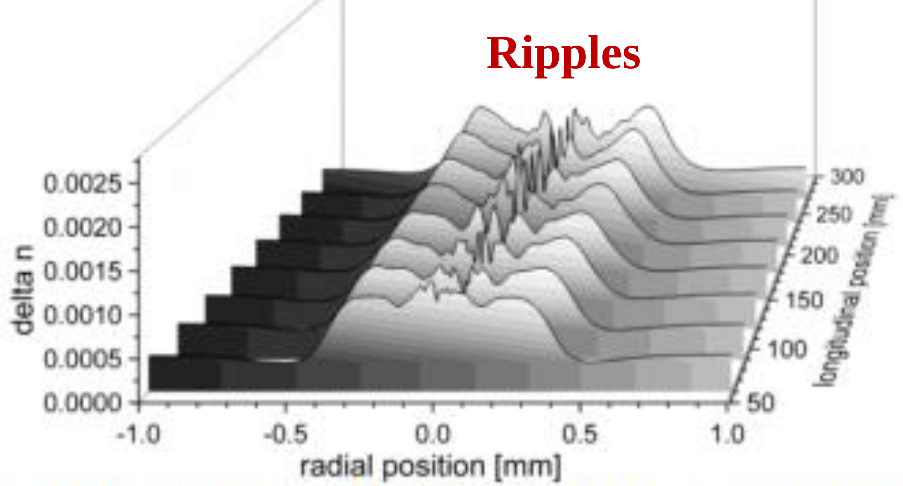


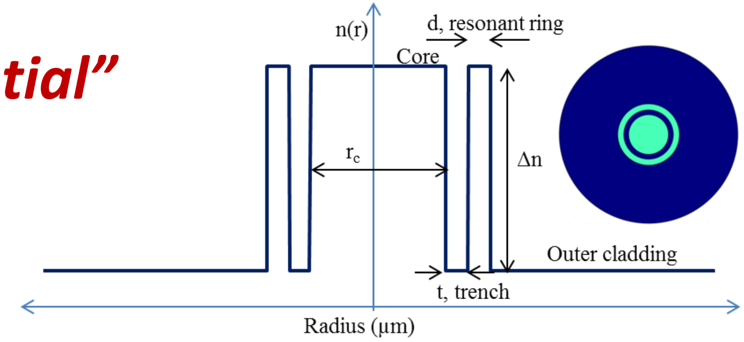
Figure 1: refractive index profile along the perform under test at drawn positions

- **MCVD + solution doping**
- **NA : 0.04**
- **Core/clad diameter: 22.5 (or 24.5)/450 µm**

F. Beier et al., " Narrow linewidth, single mode 3 kW average power from a directly diode pumped ytterbium doped low NA fibre amplifier," Opt. Express 24 (6), 6011 – 6020 (2016)

Our approach for mode-area scaling in LMA fibre: Single Trench fibre (STF)

STF: "Simple design, Great Potential"



Salient features:

1. Cylindrical symmetry
2. Cladding
   - -1 trench of same refractive index to cladding
   - -1 resonant ring of same refractive index to core
3. Low-index contrast < 0.001
   - - realizable by conventional fabrication techniques like MCVD in conjunction with solution doping technique.

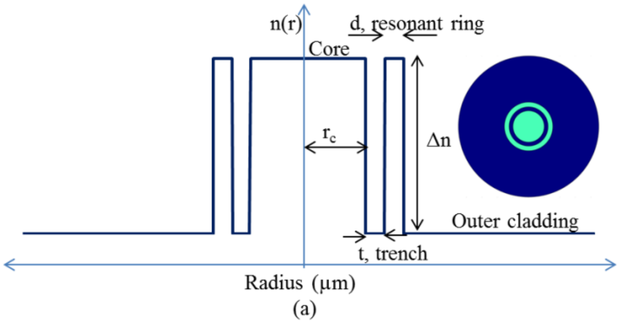
LMA fibre operating at 1.06 μm	Maximum A_{eff} (FM 0.1dB/m & HOM >10dB/m)	All-solid	Cylindrical symmetry	Core index higher than cladding
STF	**~1,200μm²**	**Yes**	**Yes**	**Yes**

D. Jain et. al. "First demonstration of single trench fibre for delocalization of higher order modes," Invited, CLEO 2014.

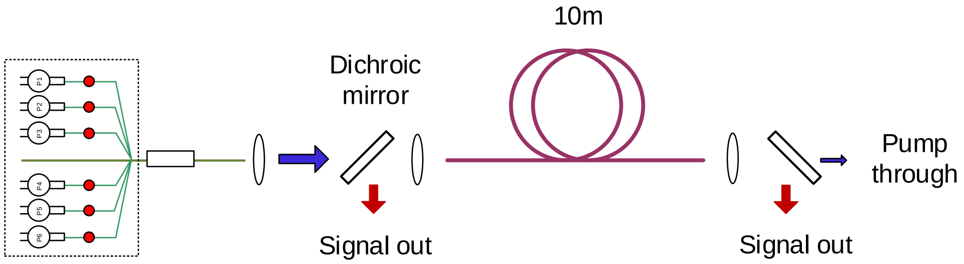
D. Jain et. al., "Large Mode Area Multi-Trench fibre With Delocalization of Higher Order Modes," IEEE JSTQE, 2014.

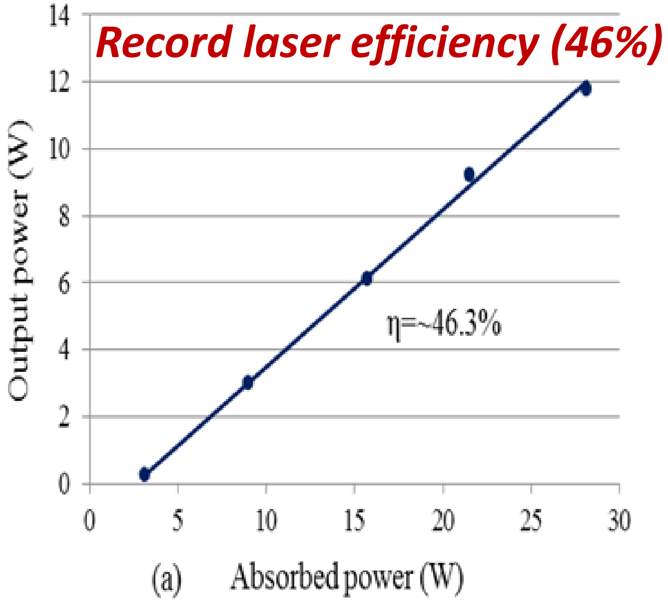
Er-doped STF for 1550nm Eye-safe Wavelength

A 60µm core fibre with FM effective area of ~ 1900 µm^2 can ensure SM operation



Experimental setup





Record laser efficiency (46%)

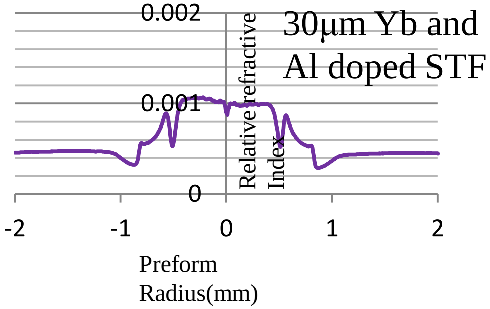
Fibre is suitable for high-energy pulse generation at 1550nm

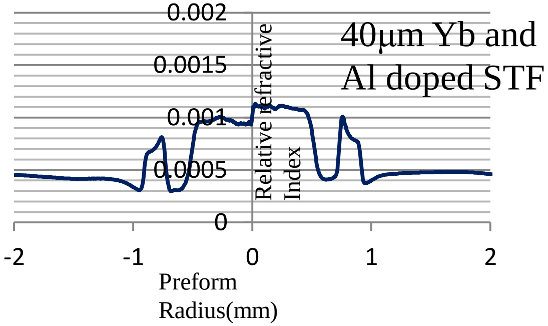
D. Jain et. al. "Highly efficient Yb free Er-La-Al doped ultra-low NA large mode area single –trench fibre laser," Opt. Exp., 23, 28282-28287 (2015).

Summary of STF operating at different wavelengths

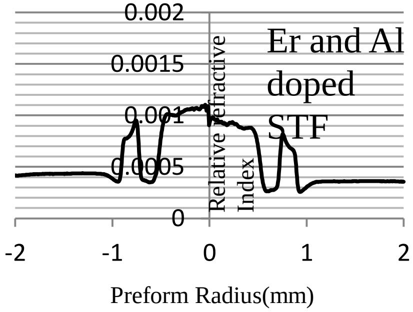
Wavelength of operation	Core diameter, NA	Bend diameter	Maximum achievable A_{eff} ensuring SM operation (considering bend induced mode distortion)
1.06 µm (Yb-band)	20 µm, 0.054	14cm	~ 375 µm^2
	40 µm, 0.038	40 cm	1000 – 1200 µm^2
1.55 µm (Er-band)	60 µm, 0.038	50 cm	1850 – 1950 µm^2
2 µm (Tm and Ho band)	60 µm, 0.054	60 cm	2200 – 2600 µm^2
	80 µm, 0.038	60 cm	3800 – 4700 µm^2
	80 µm, 0.038	80 cm	3600 – 4000 µm^2

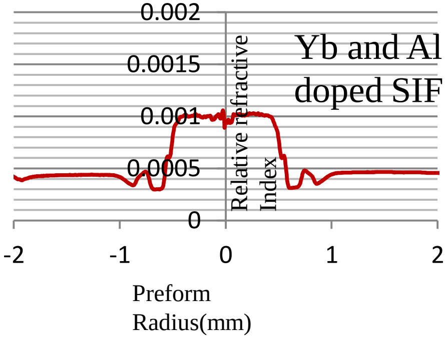
Good **yield** and **reproducibility** of rare-earth doped ultra-low NA (~0.038) and single-trench fibres demonstrated at ORC





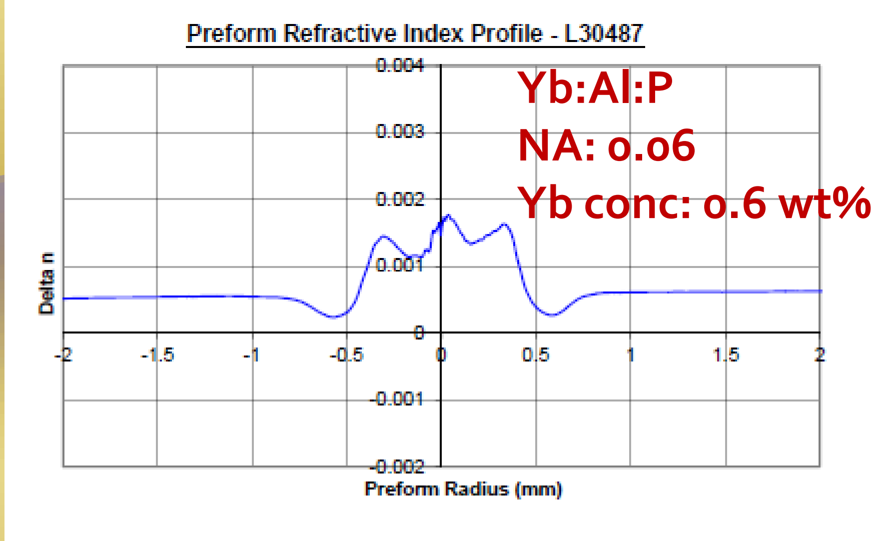
Different preforms, different geometry, and different dopants





D. Jain et. al. “Demonstration of ultra-low NA step index fibre for high power fibre laser applications,” Submitted, Opt. Exp., 2014.

Towards isomorphic Al:P (1:1) low-NA rare-earth doped preform fabrication using MCVD-solution doping

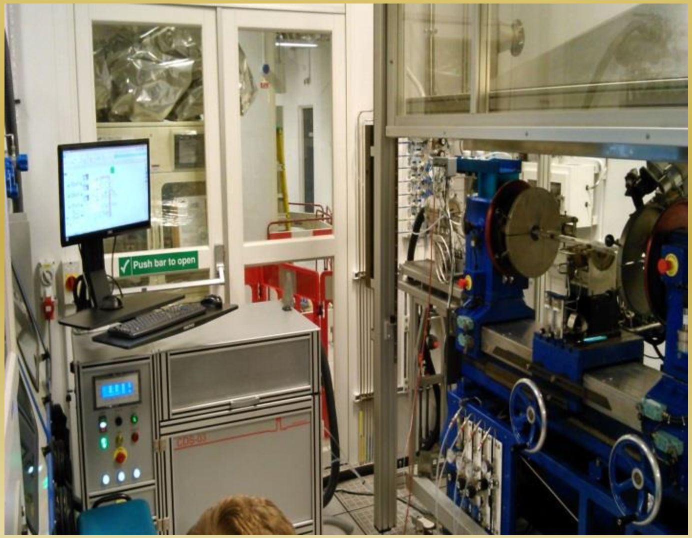


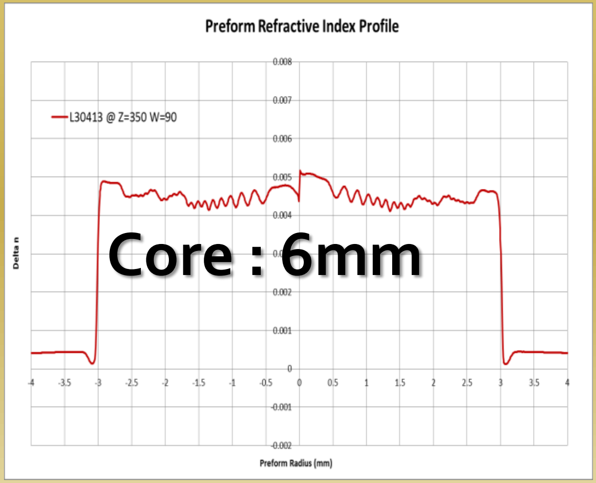
Yb:Al:P

NA: 0.06

Yb conc: 0.6 wt%

Ultra-large core rare-earth doped preform fabrication using gas phase technique



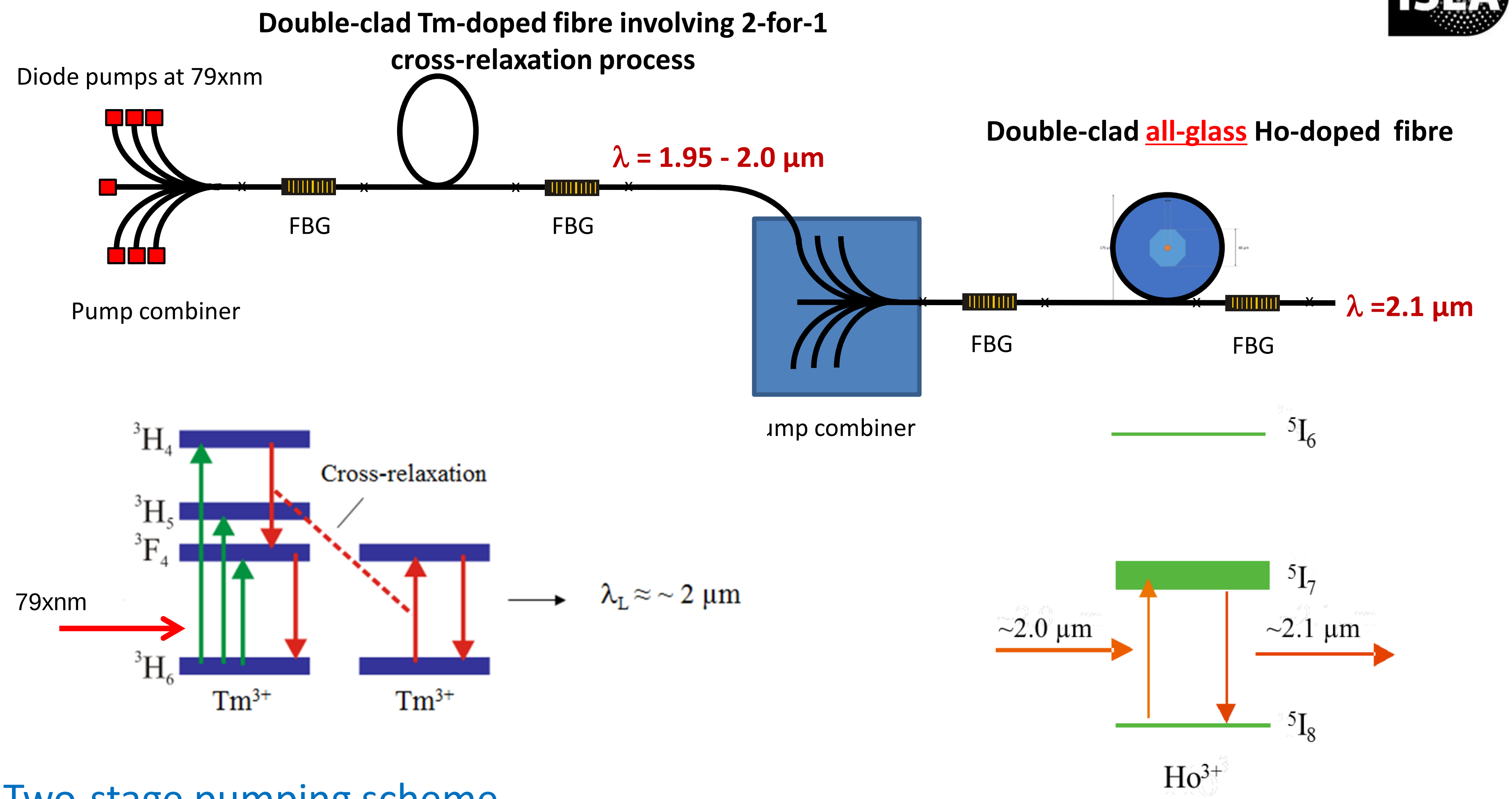


Core : 6mm

50/125 µm core/clad YDF

Optimised Tm and Ho doped silica fibres for high power 2µm sources

Courtesy of Prof Andy Clarkson and Dr Peter Shardlow



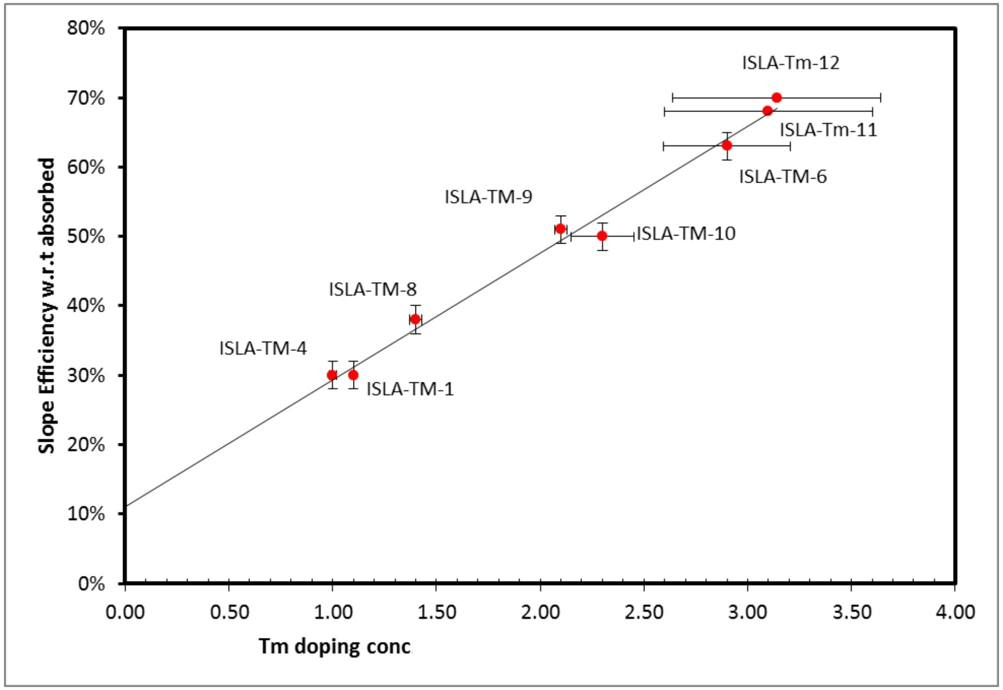
- Two-stage pumping scheme
- Exploits 2-for-1 cross-relaxation process in Tm fibre
  - requires high Tm concentration
  - **reached Tm-fibre laser efficiency ~ 70%**
- High efficiency low-quantum-defect at Ho fibre stage
  - our current double-clad Ho fibre laser efficiency ~ 68% at ~ 2100nm

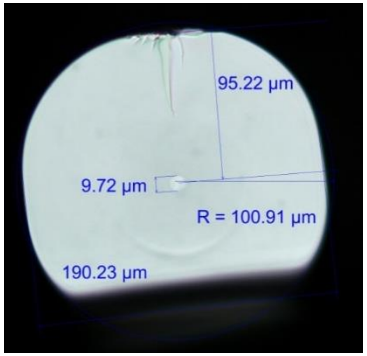
Development of efficient Tm-doped fibre

- **For efficient Tm-laser operation requires;**

▸ fibre with a low OH contamination – obtained OH (0.1 – 0.3 ppm) with our optimised process.

▸ optimisation of Tm/Al concentration to enhance cross-relaxation efficiency without significantly increasing the detrimental impact of ETU

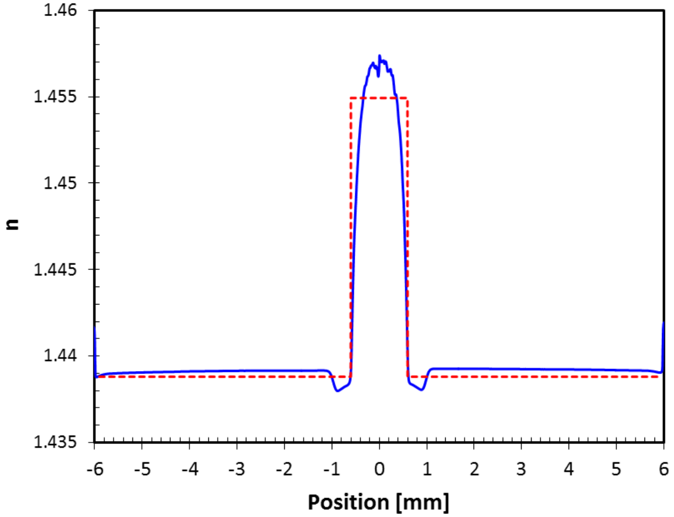




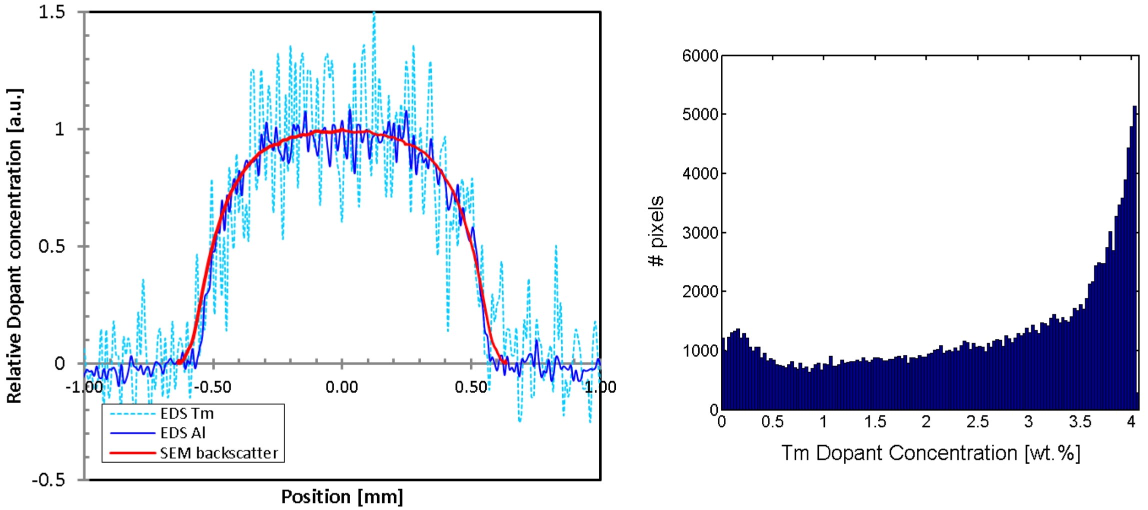
Double clad TDF:
Pump absorption at 793nm ~ 2.6 dB/m

- **Demonstrated output power of >100W with 68 -70% laser efficiency in a SM output beam**

► In current fibres, Tm and Al dopant levels vary along the radial position and this is likely to influence the 2-for-1 cross-relaxation process



Refractive index profile



Dopant distribution of Tm and Al

Further optimization of Tm-doping profile is required to improvement the laser performance close to the theoretical limit.

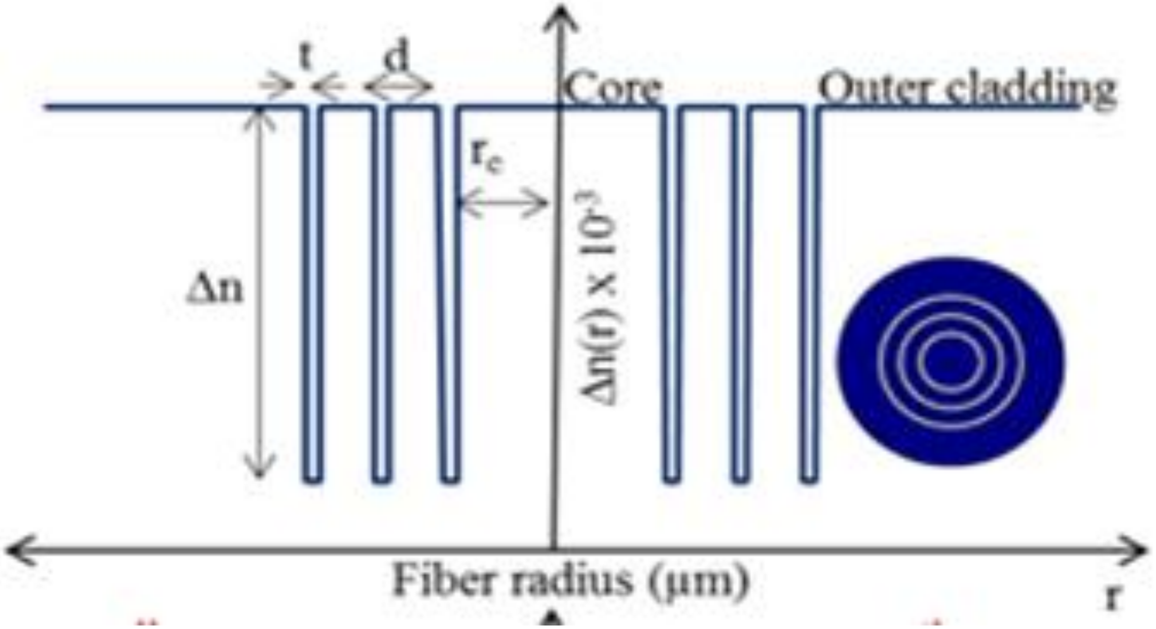
Courtesy of Prof Andy Clarkson

Multi Trench fibre (MTF) for high power beam delivery

Advantages:

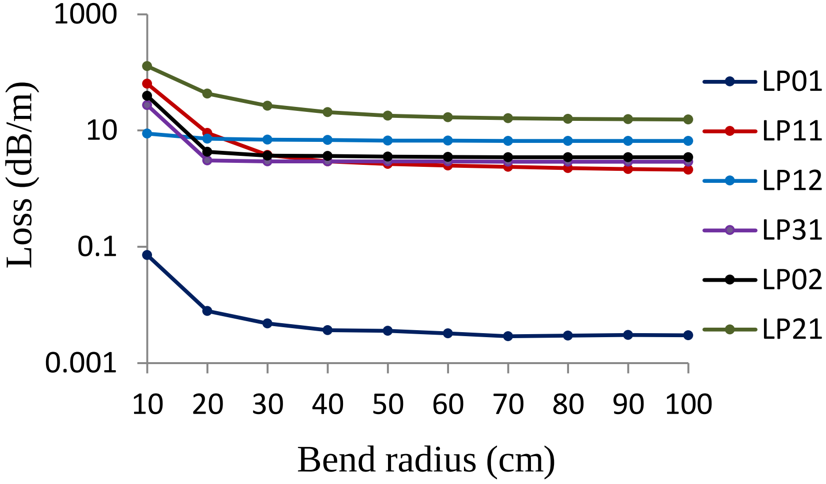
♦ All solid structure

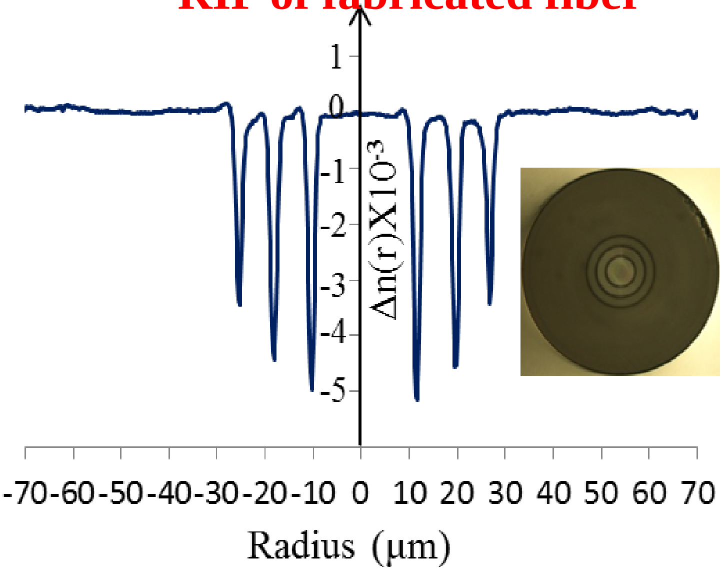
♦ Suitable for high-power beam delivery in the visible and UV wavelengths.

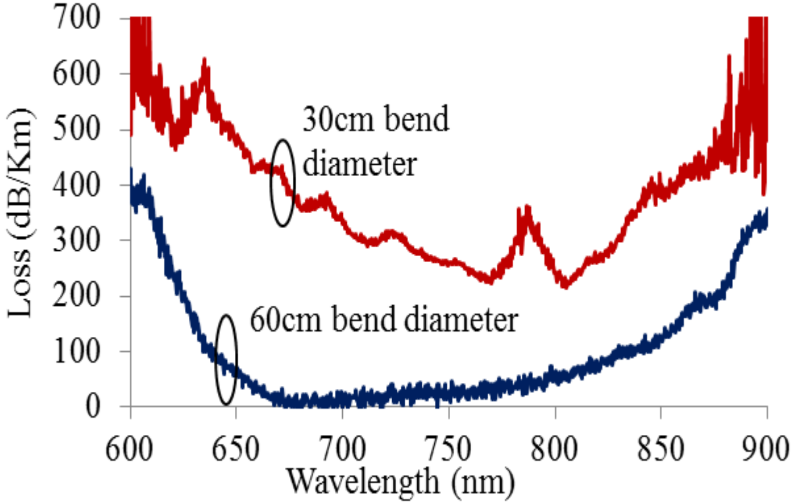


► **20μm and 10 μm core MTF** can offer SM operation at wavelength **632nm and 300 nm** respectively over a wide range of bend radii.

20μm core MTF for single mode operation at 632nm


Numerical simulation


RIP of fabricated fiber



Measured loss in a 20μm STF

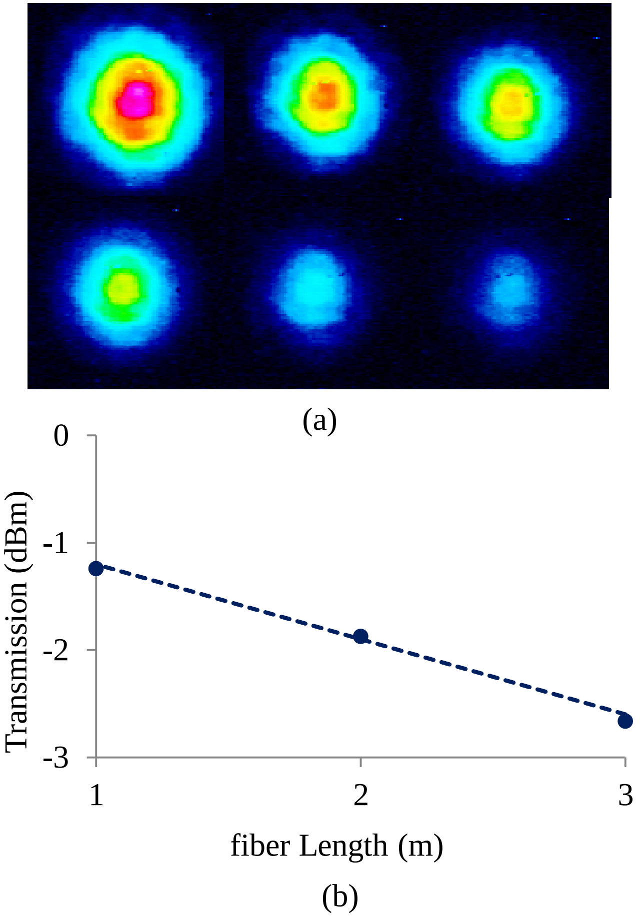
♦ The loss remains below 0.2dB/m and 0.5dB/m at ~30cm and ~15cm bend radius respectively.

♦ Loss can be improved with further refinement in fabrication.

MTF for UV wavelength

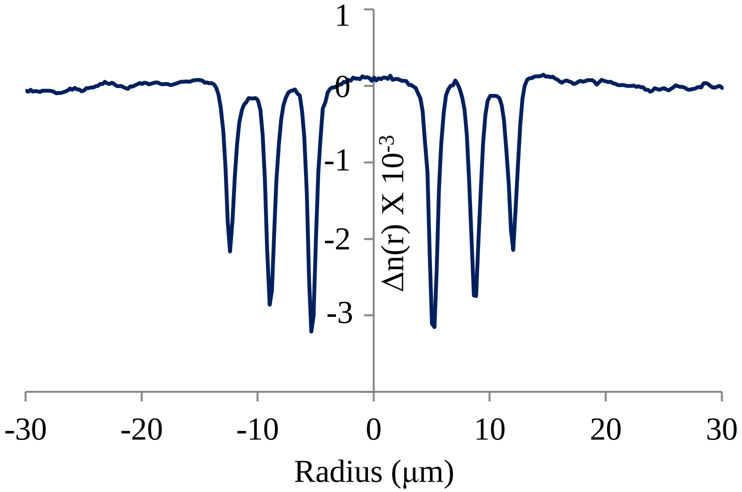
Measurement was made using 405nm laser

Output of fibre remains Gaussian irrespective of launching condition.



(a)

(b)



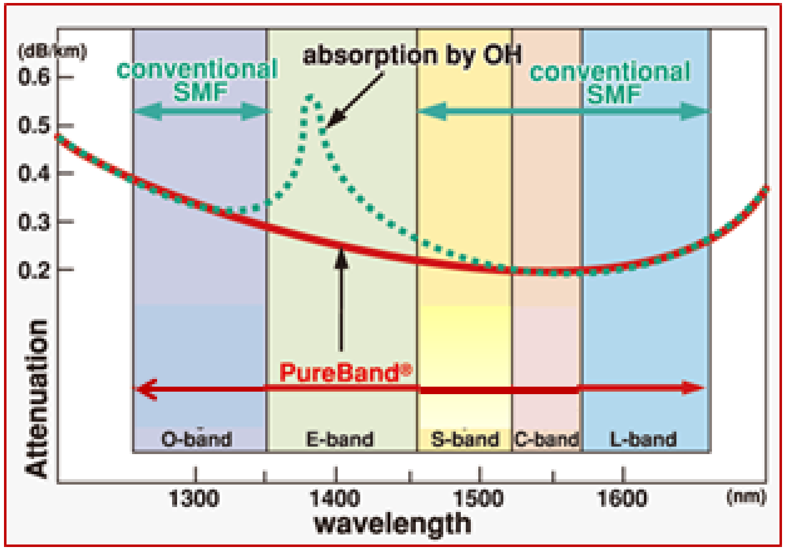
RIP of fabricated 10µm core MTF

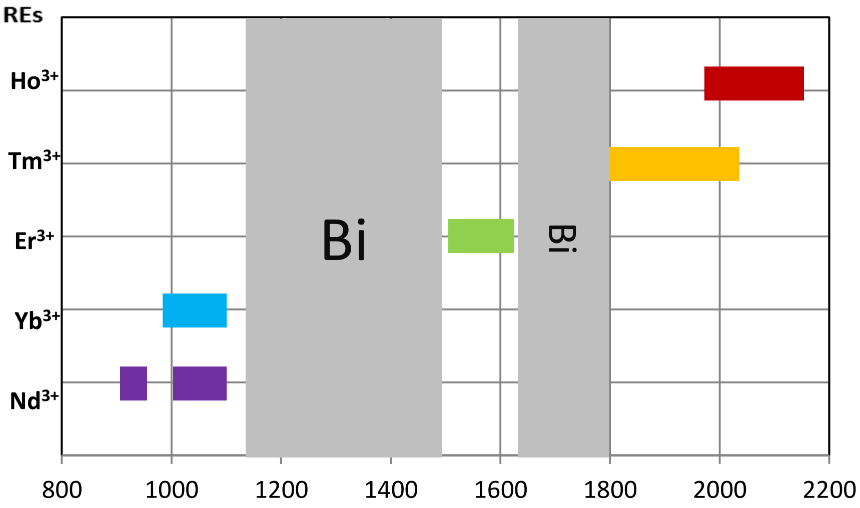
▶Measured loss ~0.7dB/m at ~405nm at ~30cm bend diameter.

▶ Loss can be improved with further refinement in fabrication.

Bismuth doped fibre lasers and amplifiers operating in the 1150 – 1500nm wavelength band

Why Bismuth?





Applications

Optical fibre communication

Medicine –Ophthalmology, Dermatology

Astronomy
-Laser guide star

- http://www.sumitomoelectric.ru/en
- I. A. Bufetov etc al., “Bi-doped optical fibres and fibre lasers,” IEEE J. Sel. Topics Quantum Electron. 20, 111-125 (2014)

Bi emission in different glss hosts

Bi-Al-Si (BAS) : 1140-1250nm

Bi-P-Si (BPS) : 1300-1400nm

Bi-Ge-Si (BGS) : 1400-1500nm

Bi-Ge(>50%)-Si : 1600-1750nm

❖ I. A. Bufetov etc al., “Bi-doped optical fibres and fibre lasers,” IEEE J. Sel. Topics Quantum Electron. 20, 111-125 (2014)
❖ S. Firstov, "Bismuth-doped optical fibres and fibre lasers for a spectral region of 1600–1800 nm," Opt. Lett. 39, 6927-6930 (2014)

What is holding us back from efficient operation of BDFL?

A) Origin of NIR emission in Bi-doped optical fibres: Bi^0,Bi^+,Bi^{2-},$Bi2^{2-}$,point defects and clusters of Bi ions and oxygen vacancies but not Bi ions themselves

► Origin of Bi NIR emission is still unclear- Need further investigations

B) **Bi concentration** – lasing has been observed in fibres with low Bi (<0.1 wt%) concentration. High concentration requires for power scaling through cladding-pumping.

Unwanted processes:

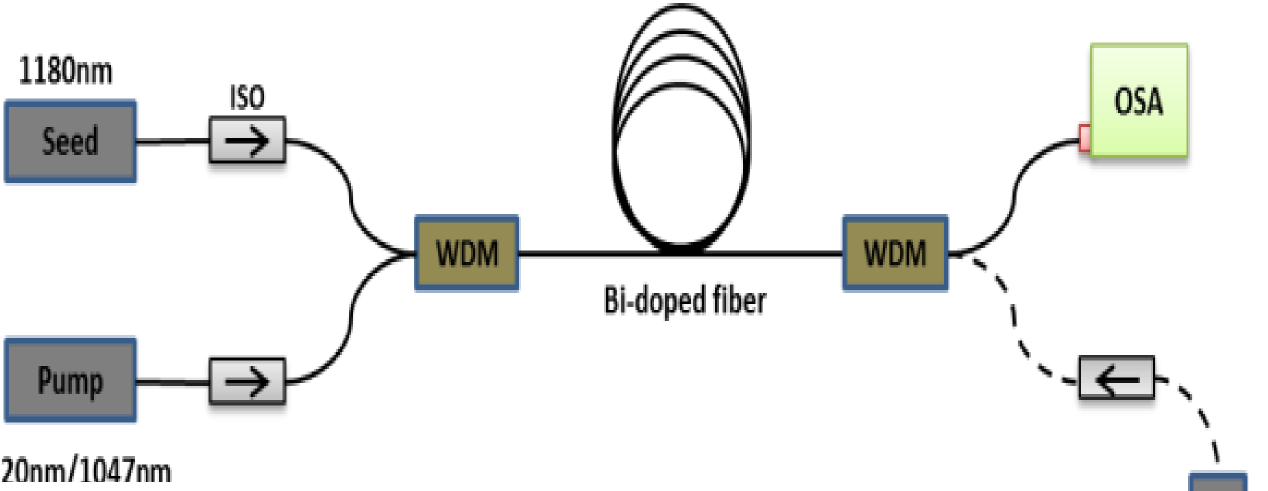
- Unsaturable losses
- Excited state absorption (ESA) – alumino-silicate host suffers mostly from ESA

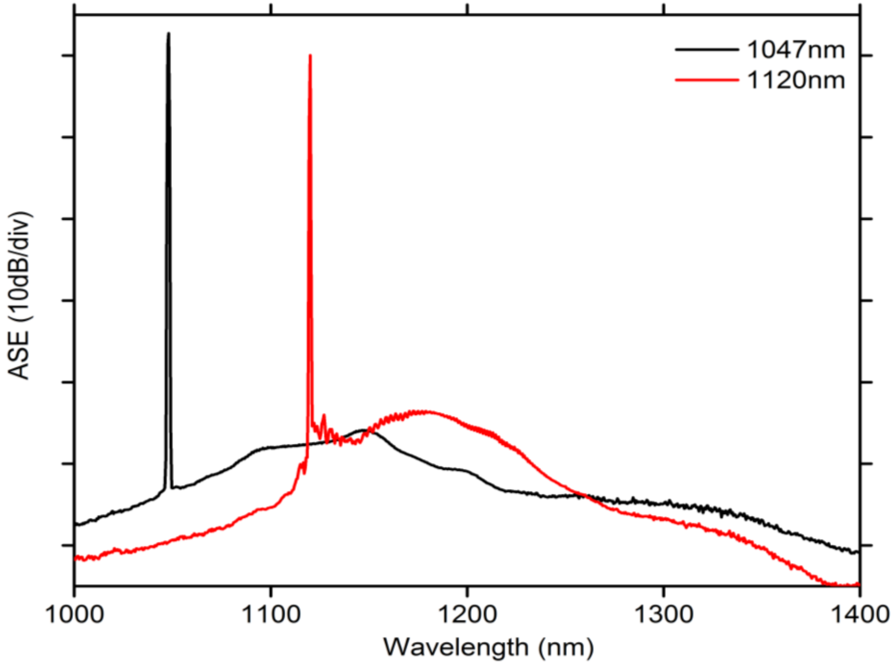
Both are contributing to lower BDFL efficiency.

- S. Firstov, "Bismuth-doped optical fibres and fibre lasers for a spectral region of 1600–1800 nm," Opt. Lett. 39, 6927-6930 (2014)
- I. A. Bufetov, "Bi-doped optical fibres and fibre lasers," IEEE J. Sel. Topics Quantum Electron. 20(5), 111-125 (2014).
- M. P. Kalita, "Bismuth doped fibre laser and study of unsaturable loss and pump induced absorption in laser performance," Opt. Express 16(25), 21032-21038 (2008).

1180nm operation of BDFA (Host glass: Bi/Al/Si)

Experimental schematic



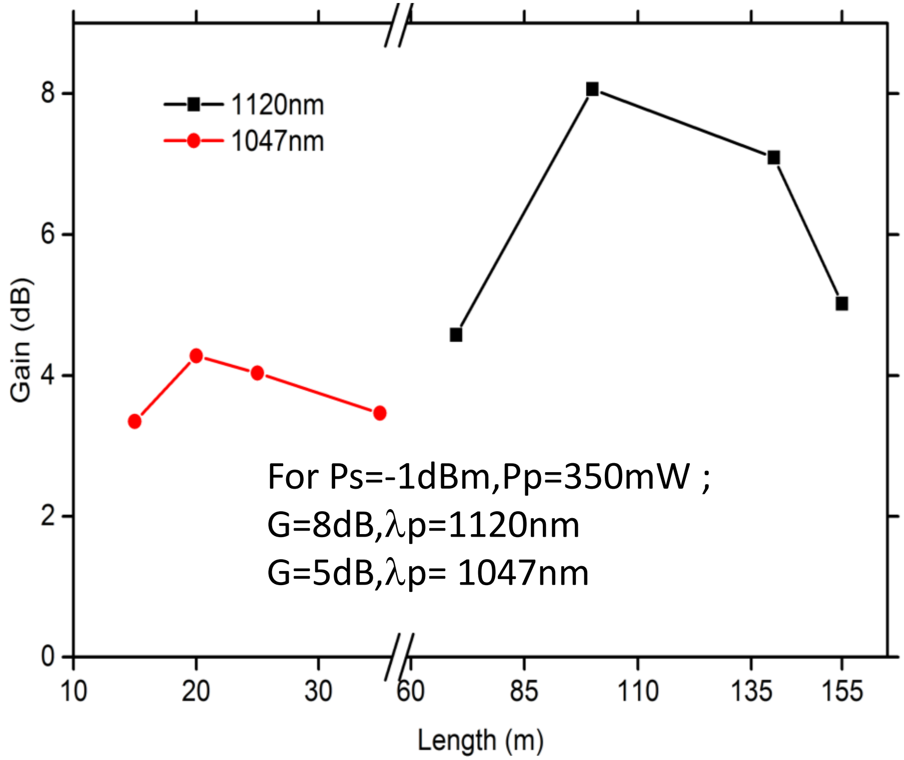


ASE spectra for 1047 nm and 1120 nm pump wavelengths (Pump power: 350 mW)

- **Commercially available LD was used for 1120nm pumping**
- **1120nm pump shifted ASE peak to 1180nm**
  - **An important wavelength for laser guide star application after frequency doubling**

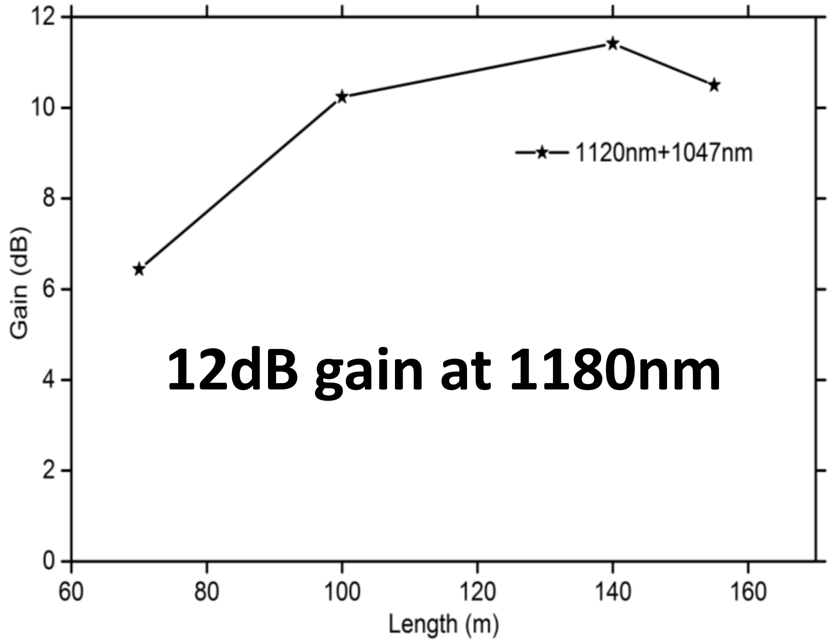
❖ N. K. Thipparapu, S. Jain, A. A. Umnikov, P. Barua, and J. K. Sahu, Opt. Lett. 40(10), 2441-2444 (2015).

BDFA gain at two pump wavelengths: 1047nm and 1120nm



For Ps=-1dBm,Pp=350mW ;
G=8dB,λp=1120nm
G=5dB,λp= 1047nm

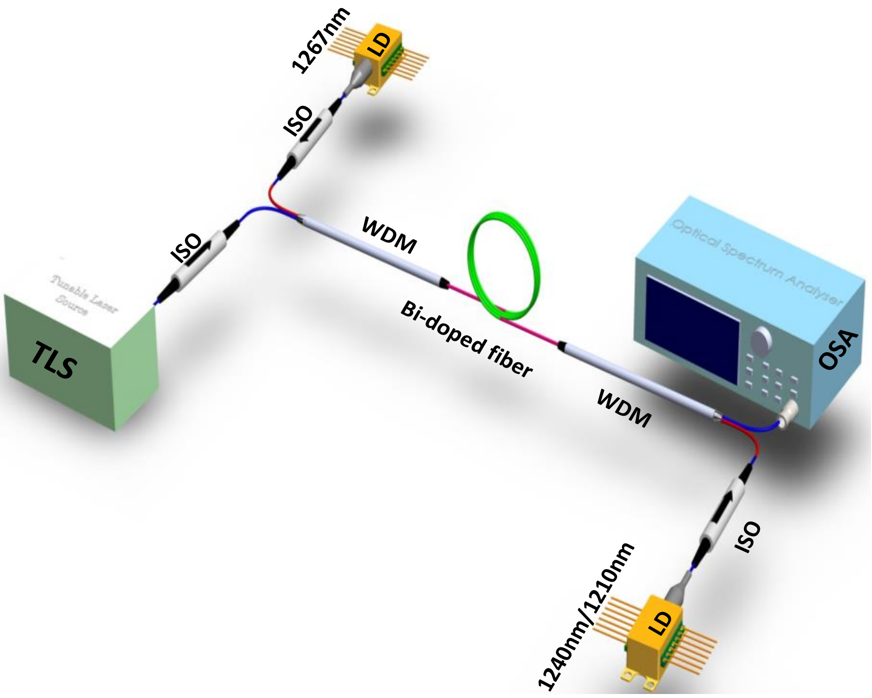
Length optimisation for λp = 1120nm + 1047nm, Pp=700mW

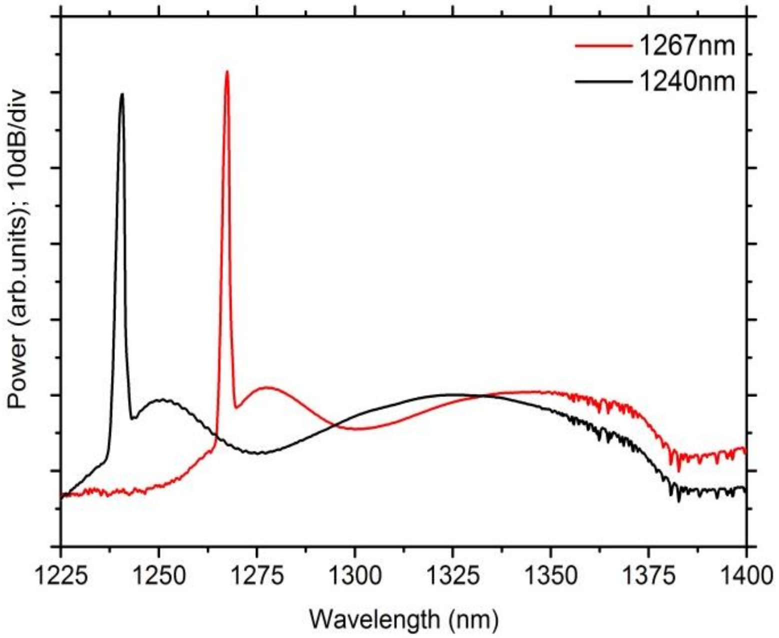


12dB gain at 1180nm

BDFA with a flat Gain of 25 ± 1 dB operating in the wavelength band 1320-1360nm

Experimental Set

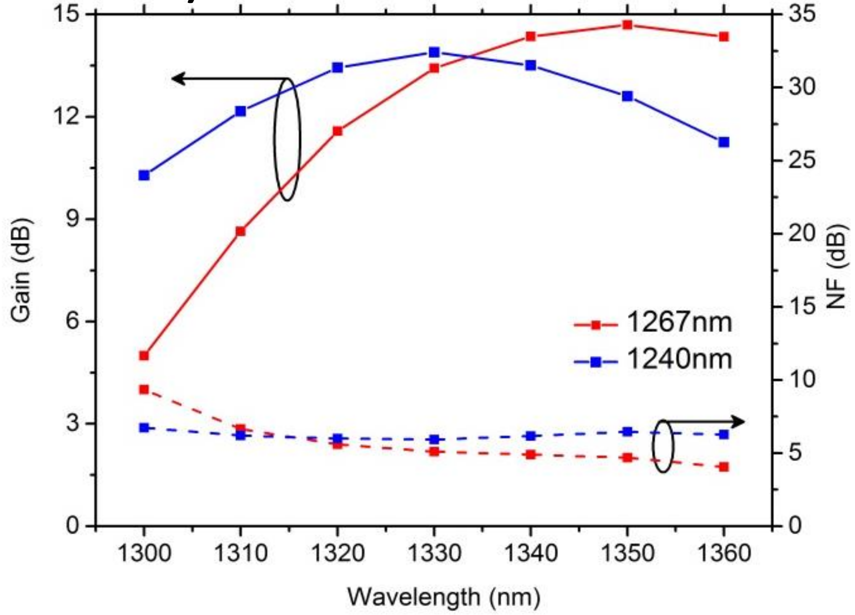




ASE for λp=1267nm (360mW) or λp=1240nm (400mW), L=100m.

❖ N. K. Thipparapu,etc.al, "Bi-doped fibre amplifier with a flat gain of 25 dB operating in the wavelength band 1320–1360 nm," Opt. Lett. 41, 1518-1521 (2016).

Gain & NF for Lop=100m @ λp=1267nm (360mW) and Lop=75m @ λp=1240nm (400mW) , (Ps= -10dBm)



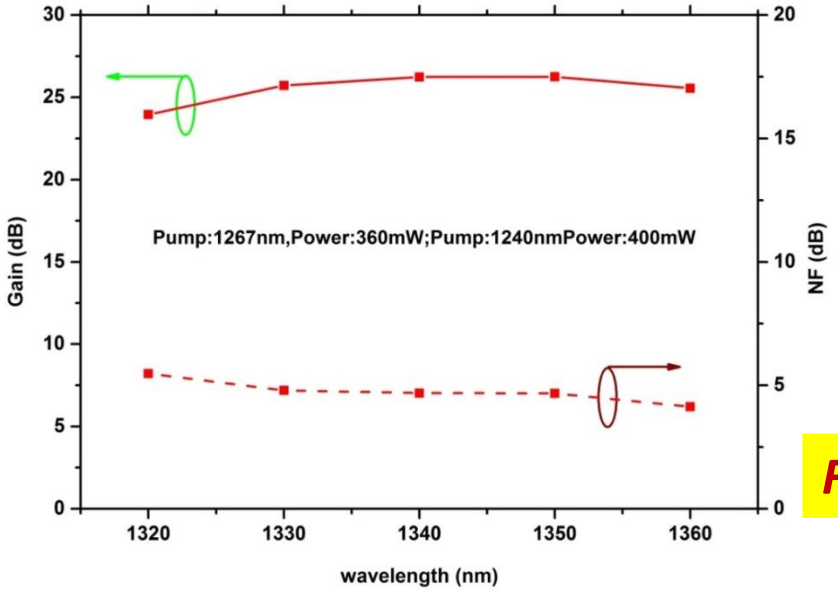
For λp=1267nm (360mW)

G=15dB,NF=5dB @1350nm; G=5dB@1300nm

For λp=1240nm (400mW)

G=14dB,NF=6dB @1330nm; G=10dB@1300nm

Bi-directional pumping using single mode LDs at 1267nm and 1240nm



- *L=150m*
- *P_{tot}=760mW*
- *P_{sig} =-10dBm*
- *NF <5dB*
- *Gain from 1310-1360nm>20dB*
- *OSNR>30dB*

Flat gain, 25±1dB, from 1320-1360nm

❖ N. K. Thipparapu,etc.al, "Bi-doped fibre amplifier with a flat gain of 25 dB operating in the wavelength band 1320–1360 nm," Opt. Lett. 41, 1518-1521 (2016).

OVD: New glass for new challenges

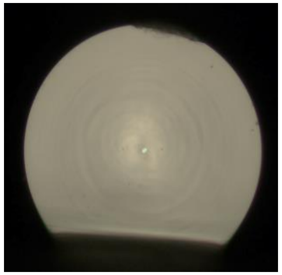
Realised transparent and bubble free OVD preforms/fibres in a wide range of glass compositions.

100% GeO2 fibre by OVD

Theoretical loss value for a GeO2 fibre is <0.2 dB/km at ~ 2 µm

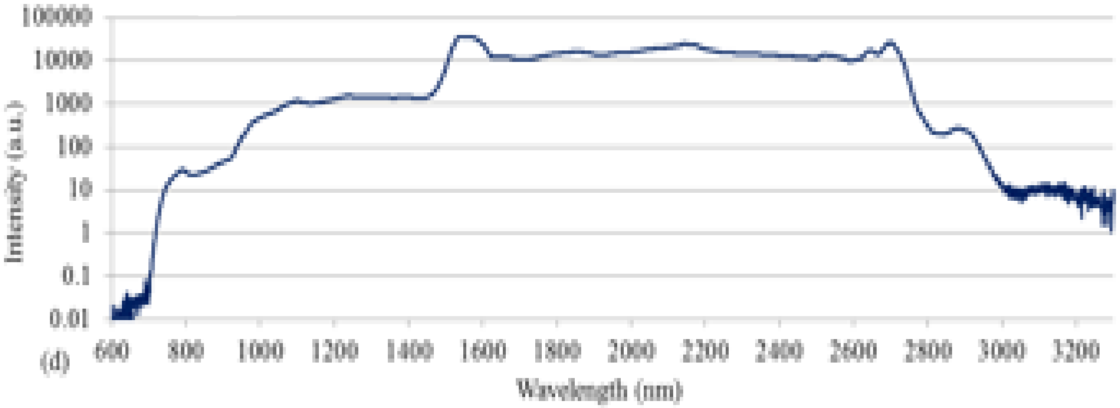
100% GeO_2 Core – silica cladding

- ❖Preform drawn in a standard silica draw tower
- ❖OD: 200µm, Core: 3 µm



Fibre is suitable for SC generation up to 3.2 µm

Example of SC generation in a 55 mol % GeO2-doped silica fibre



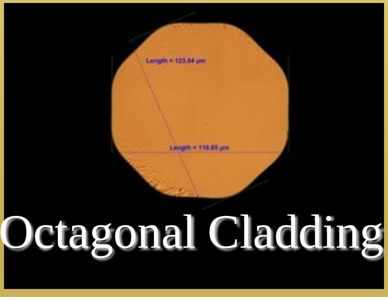
Acknowledgement: Dr Deepak Jain, DTU Fotonik, Denmark

Our aim is to develop new types of fibre and fabrication techniques with unique properties and new functionality in fibre as well as increased fabrication yield, using state-of-the-art custom-designed fibre fabrication facility, suitable for novel applications and devices……

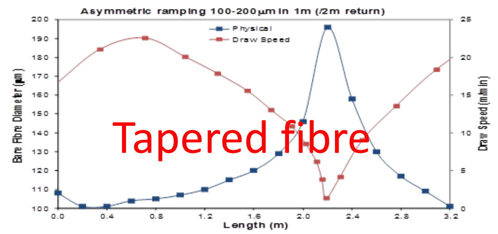
Examples of novel geometry fibres made at ORC

Flat-fibre

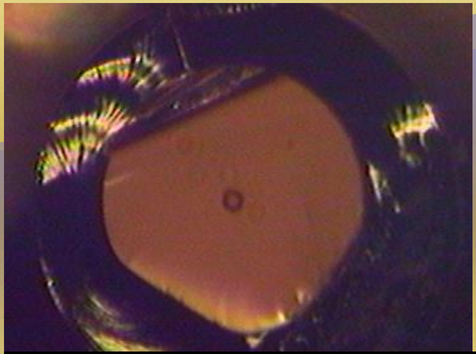
Integrated optics in fibre platform



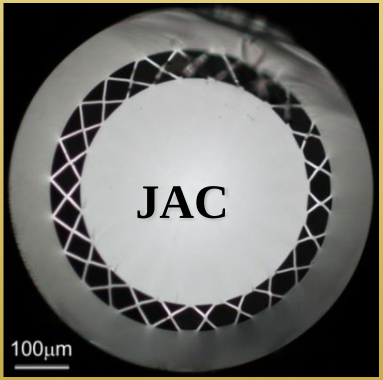
Octagonal Cladding

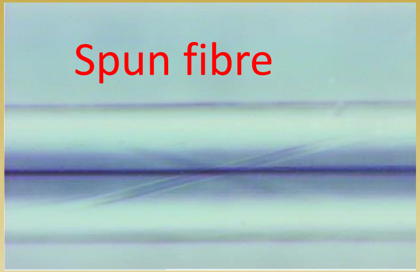


Tapered fibre

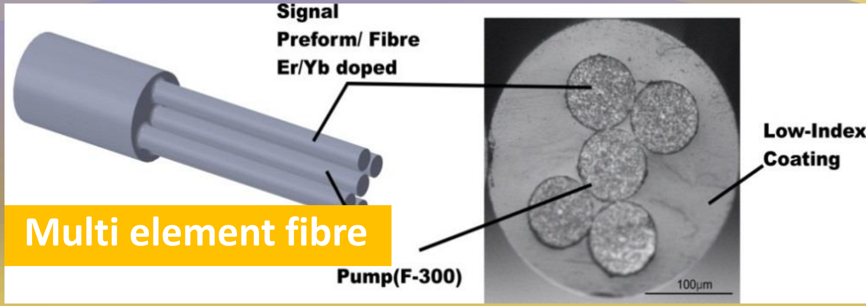


Large core (10s of µm) for high power applications

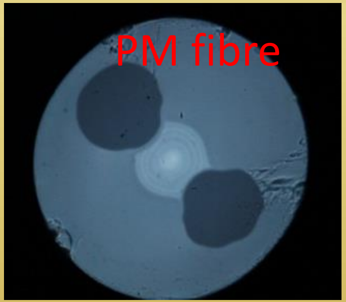




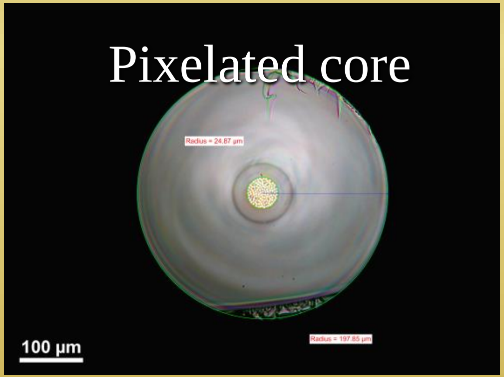
Spun fibre



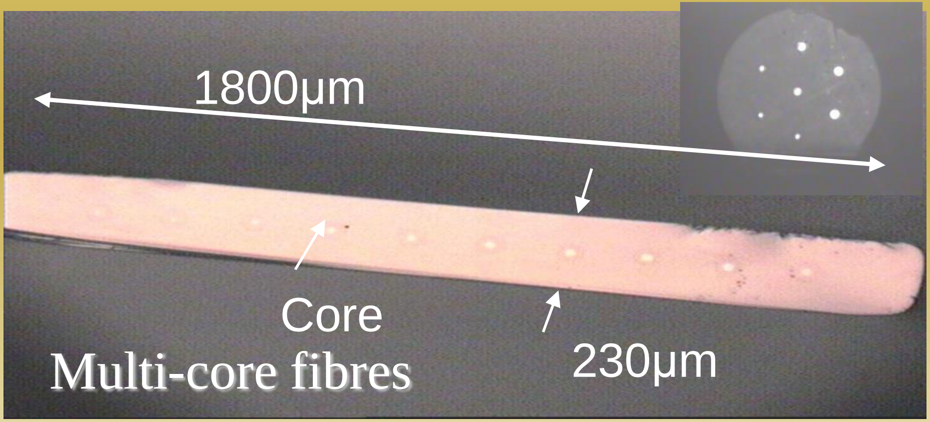
Multi element fibre



PM fibre



Pixelated core



Multi-core fibres

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Mr Nikita Simakov

EXCELLENCE IN SCIENCE
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Defence Science and Technology Group

THANK YOU