Emerging Fibers and Amplifiers for Next Generation Communications and Laser Applications

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Light

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Shaiful Alam
Alexander Heidt
John Hayes
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Yongmin Jung
Qionqyue Kang
Eelong Lim
Zhihong Li
Eric Numkam
Marco Petrovich
Periklis Petropoulos
Francesco Poletti
Victor Rancano
Jayanta Sahu
Radan Slavik
David Payne
Natalie Wheeler
John Wooler +………..

Lars Gruner-Nielsen
Bera Palsdottir
Brian Mangan

Dean Giles
Ian Giles

Beril Inan
Maxim Kuschnerov
Vincent Sleiffer
+….

Haoshou Chen
Ton Koonen
Chigo Okonkwo
Roy van Uden
Huug de Waardt

Brian Corbett
Andrew Ellis
Fatima Gunning
Peter O'Brien
Naoise MacSuibhne
Richard Winfield
+…

Brian Kelly
John O'Carroll
Richard Phelan
+…

Acknowledgements (Funders)

MODE GAP

eblanaphotonics

Phoenix Photonics

ofs A Furukawa Company

TU/e Technische Universiteit Eindhoven University of Technology

UCC

University of Southampton

ESPCI ParisTech

THE ROYAL SOCIETY

UCL

COMIMO

University of Oxford

University of Southampton

EPSRC Pioneering research and skills

University of Cambridge

Transforming the Internet Infrastructure:
The Photonics Hyperhighway

University of Southampton

EPSRC Pioneering research and skills

University of Bristol

Routes to Higher Capacity

Overall Fibre Capacity =

New amplifiers
Extended low loss

Available Bandwidth

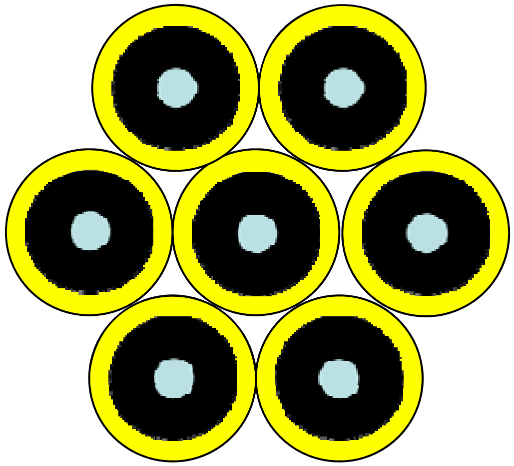
Exploit electronics…
Low nonlinearity
Ultralow loss

x Spectral Efficiency

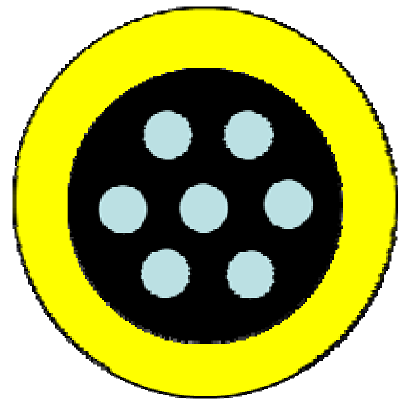
Multi core fibre
MM fibre

x Number of Information Channels

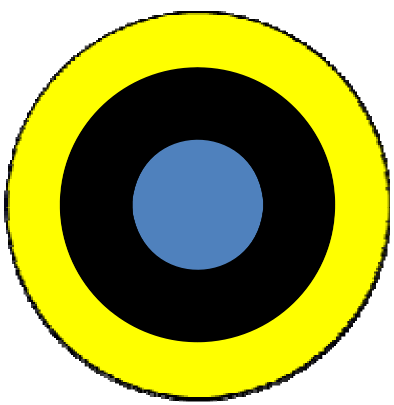
Contender Fiber Solutions



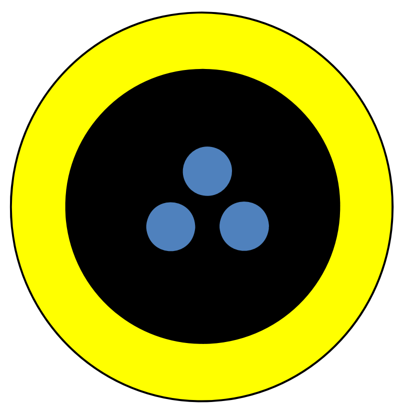
Fiber Bundle



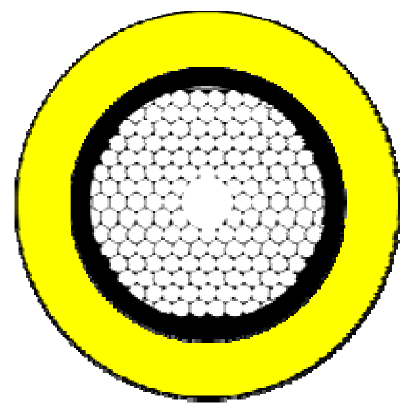
Multi Core Fiber (MCF)



Few Mode Fiber (FMF)



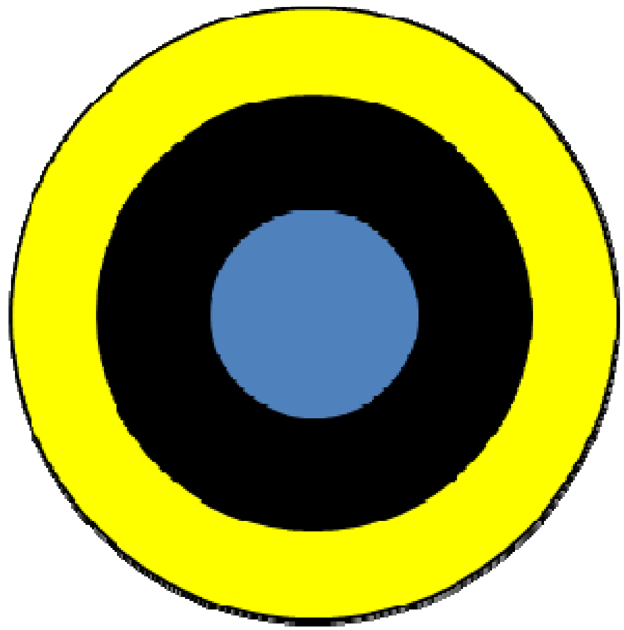
Coupled Core (CC)



Photonic Band Gap Fiber (PBGF)

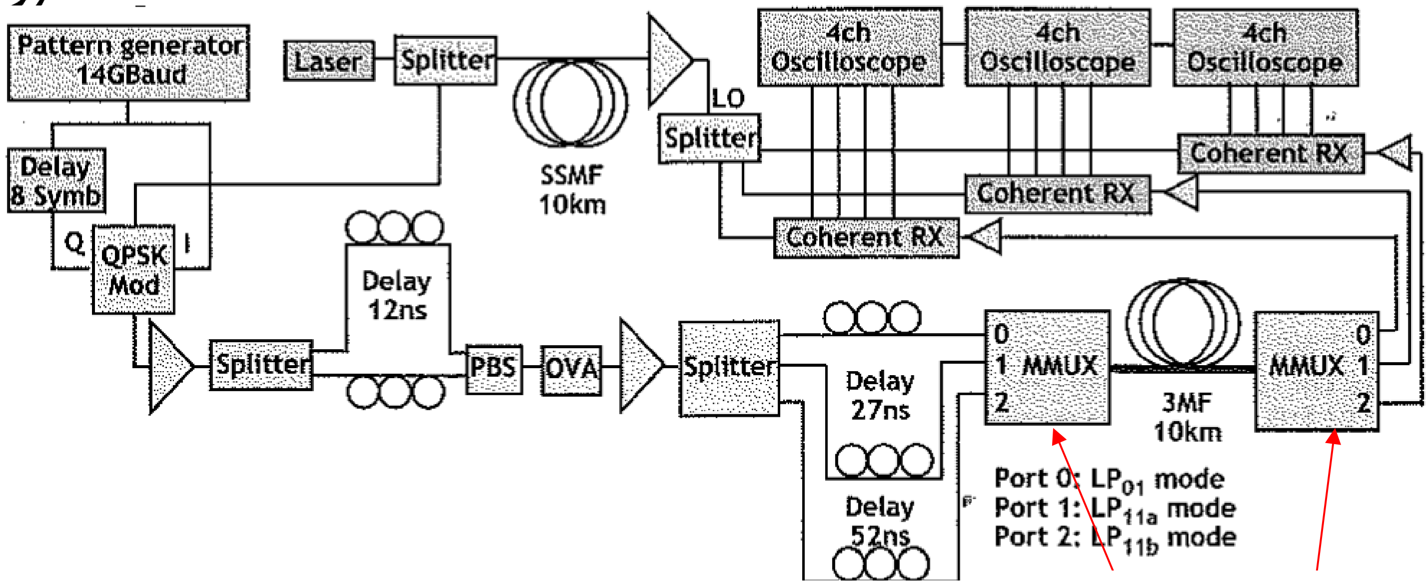
D.J. Richardson, J.M. Fini and L.E. Nelson, Nature Photonics, 7,354–362, (2013)

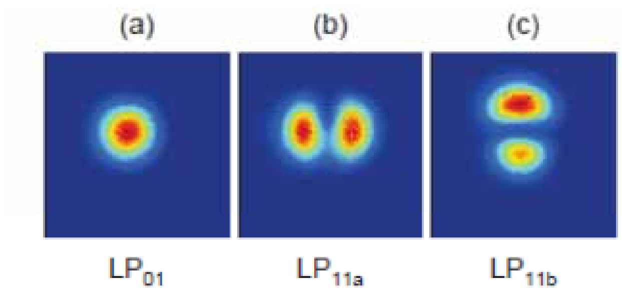
Light

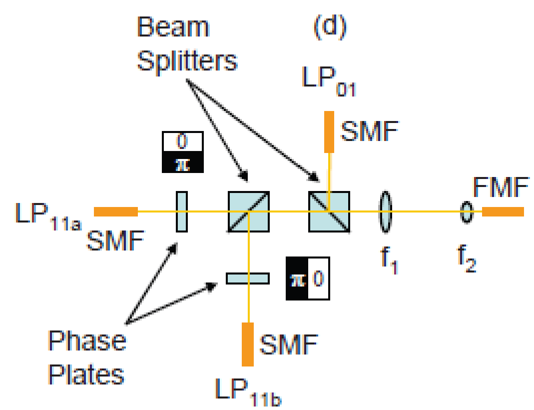


Few Mode Fiber

MDM over 10km TMF with MIMO DSP





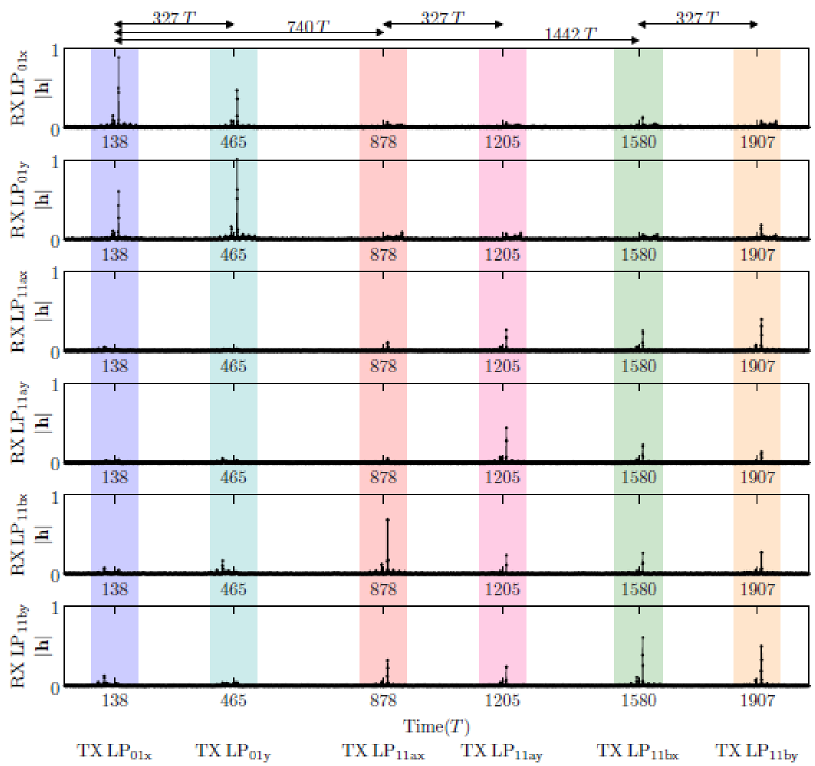


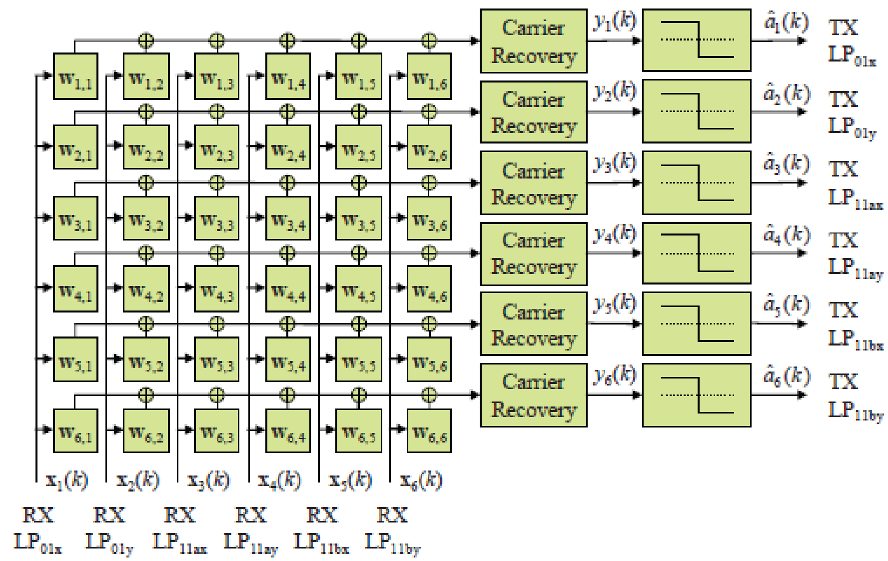
- 6-channel MDM over 10 km three mode fiber (3 modes/2 polarisations)
- Phase plate/bulk optic excitation
- MIMO correction of mode coupling effects
- Offline processing (computationally intensive)

R Ryf et al., OFC 2011 PDPB10

(A. Li et al., OFC 2011, PDPB8)

MIMO Processing

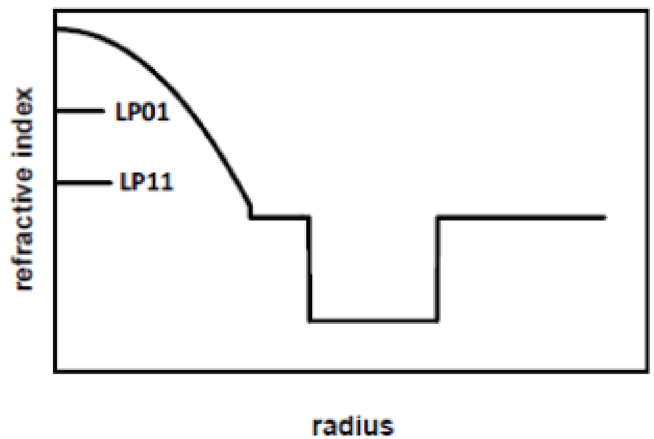




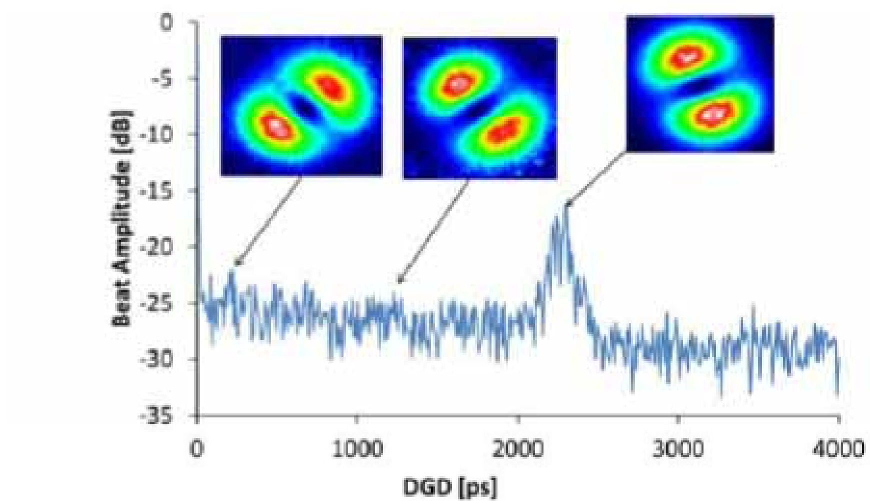
- Linear properties of system characterised by 6x6 impulse response matrix
- Need to use an N-tap DSP filter to retrieve data where N determined by the impulse response spread.
- Need to reduce fiber DGD to reduce N and complexity of processing.
- MDL/MDG ideally also needs to be small

S. Randel et al., OE,19,16697-16707, (2011)

Low DGD 3-Mode Fibre



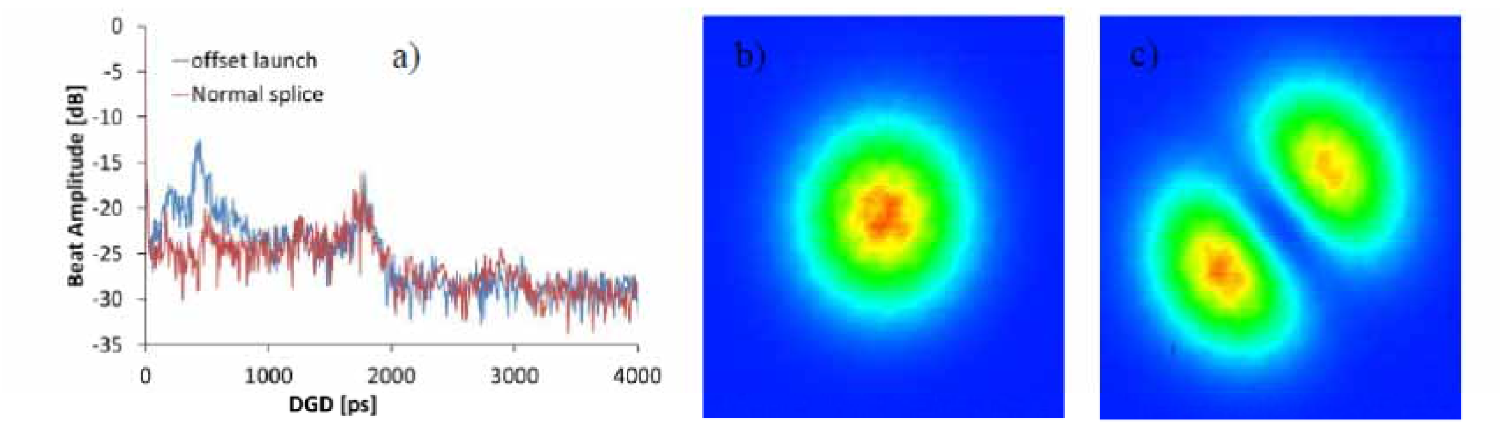
Property	Unit	Value
Spool length	m	30000
Distributed mode coupling LP_{01} to LP_{11}	dB	-25
DGD between LP_{11} and LP_{01}	ps/m	-0.076/*-0.081*
Dispersion LP_{01}	ps/(nm·km)	20.0/*19.8*
Dispersion slope LP_{01}	ps/(nm^2·km)	0.065/*0.067*
Effective area LP_{01}	µm^2	97/*95*
Dispersion LP_{11}	ps/(nm·km)	*20.0*
Dispersion slope LP_{11}	ps/(nm^2·km)	*0.065*
Effective area LP_{11}	µm^2	*96*
Attenuation OTDR LP_{01}	dB/km	0.198
Attenuation OTDR LP_{11}	dB/km	0.191
PMD LP_{01}	$ps/\sqrt{km}$	0.022



- Parabolic profile to minimise DGD
- Excellent fibre uniformity
- Low loss
- Very low intrinsic mode coupling
- Low DGD obtained (of both signs)
- Low DGD 6-mode fibre now developed

L. Gruner-Nielsen et al., OFC2012, PPD 5A.1

DGD Compensation



Length	M	30000	10000	30000
Distributed mode coupling	dB	-26		-26
DGD LP_{11} - LP_{01}	ps	1800	44	-1400

By concatenating lengths of fiber of different signs of DGD significant further levels of DGD reduction can be obtained as determined by S2 measurements (and ultimately systems experiments).

L. Gruner-Nielsen et al., OFC2012, PPD 5A.1

FM-EDFA Gain Control through Pumping

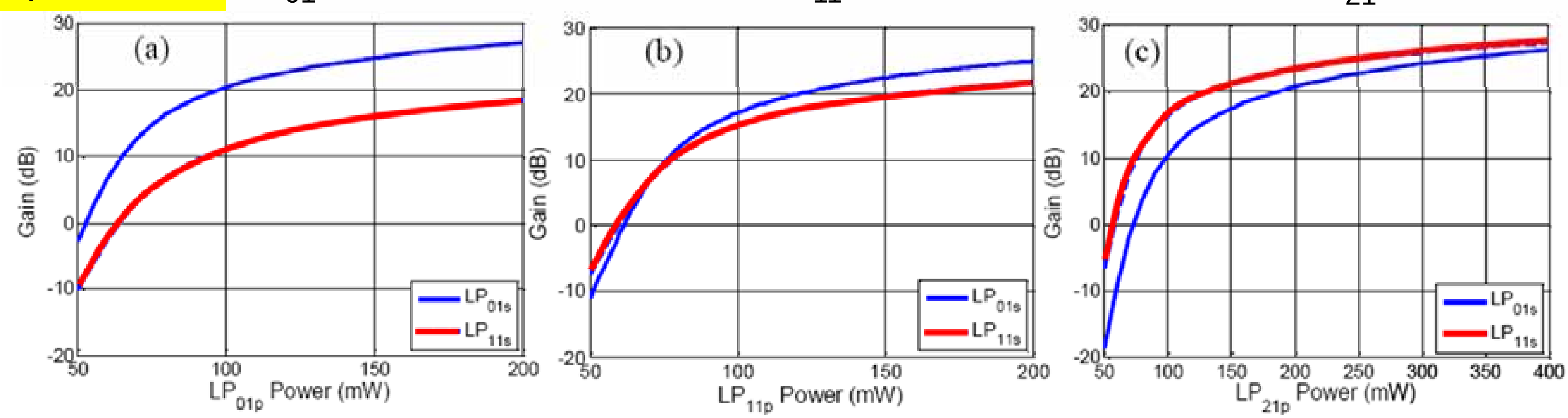
The overlap integral between the signal and pump intensity plays a critical role in defining the modal gain

$$\eta_{pj,si} = \int_0^{2\pi}\int_0^{a} r\,dr\,d\varphi\,\Gamma_{p,j}(r,\varphi)\Gamma_{s,i}(r,\varphi)$$

$$\frac{dn_2(r,\phi,z)}{dt} = \sum_{i=1}^{k}\frac{P_k(z)i_k(r,\phi)\sigma_{ak}}{h\nu_k}n_1(r,\phi,z) - \sum_{i=1}^{k}\frac{P_k(z)i_k(r,\phi)\sigma_{ek}}{h\nu_k}n_1(r,\phi,z) - \frac{n_2(r,\phi,z)}{\tau}$$

$$\frac{dP_k(z)}{dz} = u_k\sigma_{ek}[P_k(z)+2h\nu_k\Delta\nu_k]\int_0^{2\pi}\int_0^{a} i_k(r,\phi)n_2(r,\phi,z)\,r\,dr\,d\phi - u_k\sigma_{ak}P_k(z)\int_0^{2\pi}\int_0^{a} i_k(r,\phi)n_1(r,\phi,z)\,r\,dr\,d\phi - u_k\alpha P_k(z)$$

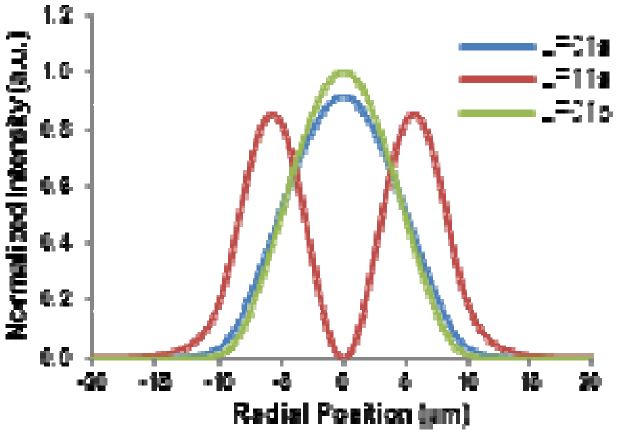
Pump in → LP_{01} LP_{11} LP_{21}

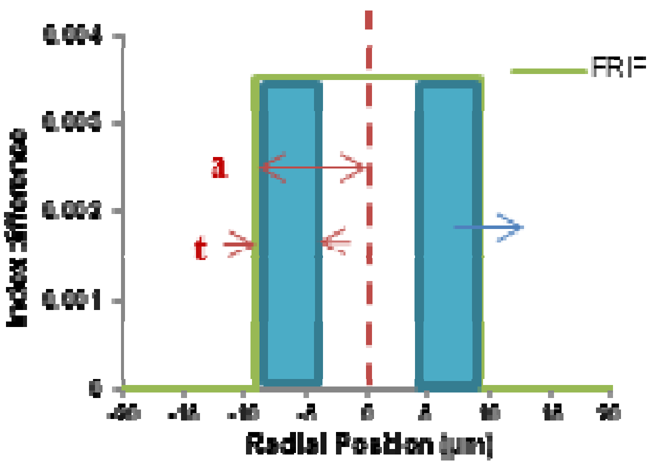


- Higher gain observed for LP_{01} when $LP_{01,p}$ pump mode is used.
- Pumping in $LP_{21,p}$ gives higher gain for $LP_{11,s}$

N. Bai et al. OE, 19, pp 16602-16611, (2011)

FM-EDFA Gain Control by Fiber Design





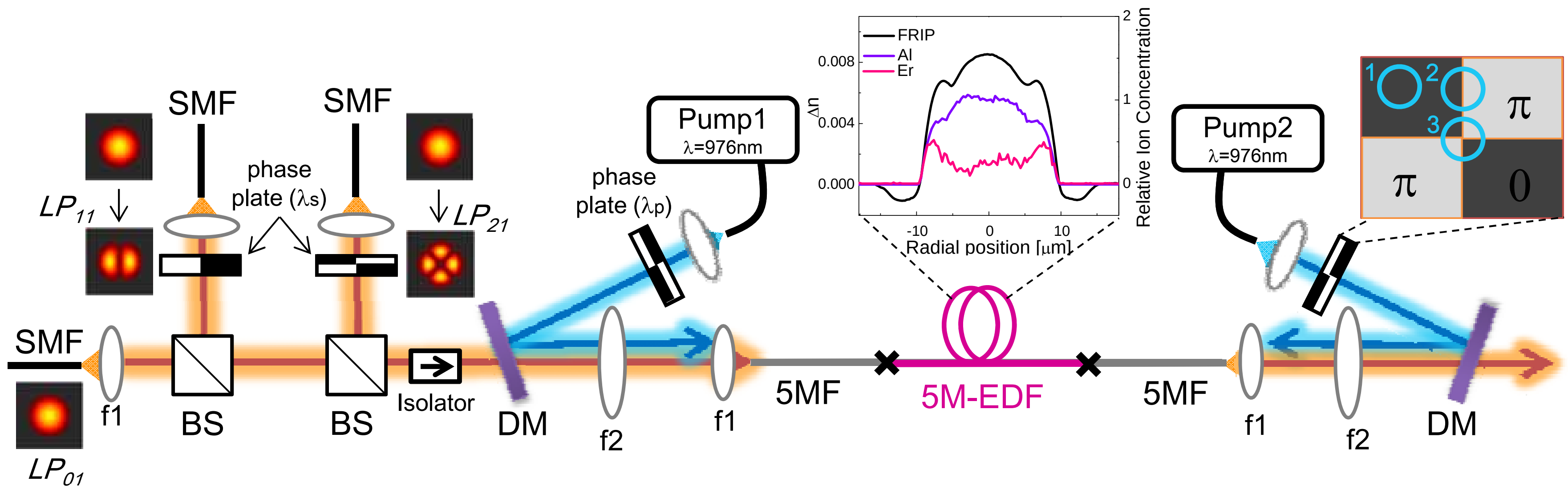
Q. Kang et al. Optics Express, 20, pp.20835-20843 (2012)

Pumping with centrally distributed fields – preferentially amplifies LP_{01} mode

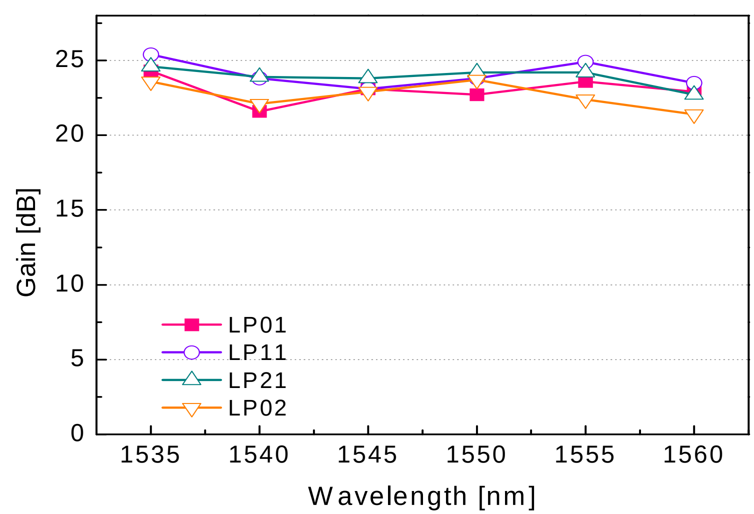
LP_{11} mode has the maximum overlap with the doped region. The thickness of the doped strip essentially determines the relative gain between the guided modes

Simplified amplifier design since just LP_{01} pump required for optimum ring design

Gain Equalised 6-Mode EDFA

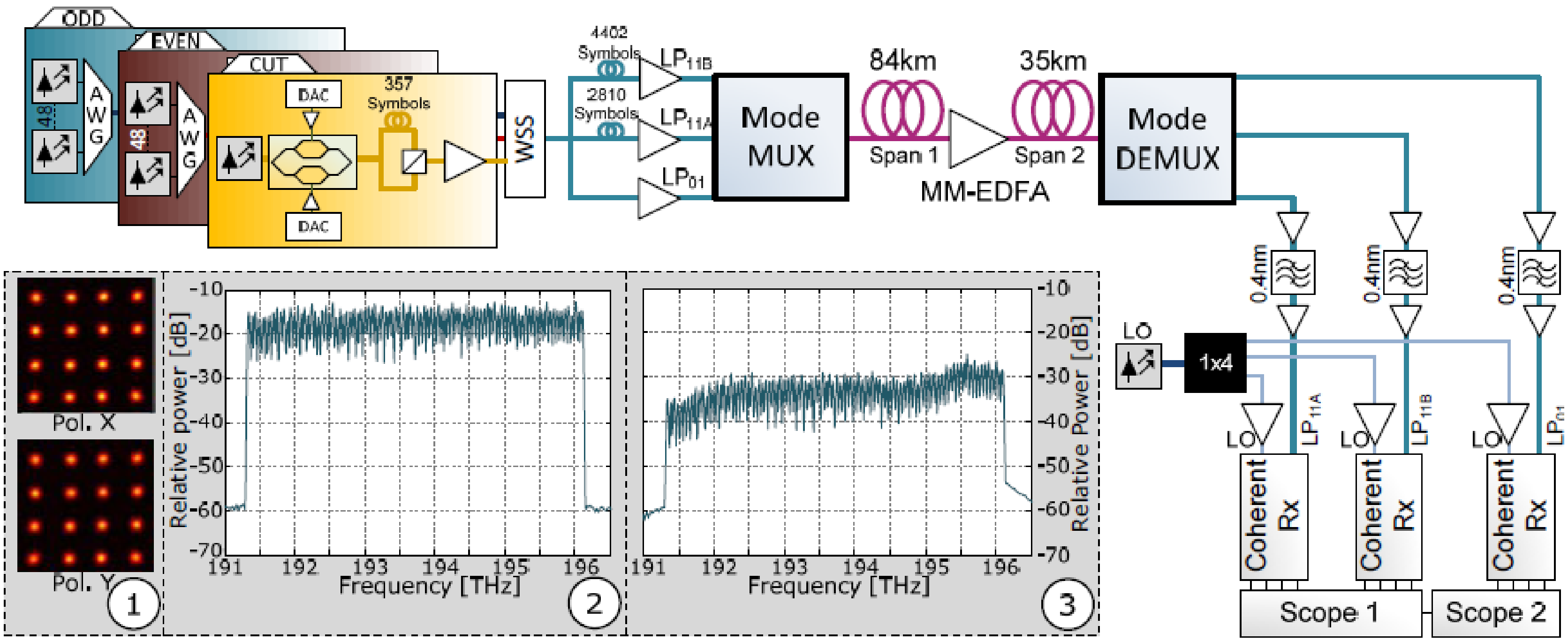


- Ring-doped fiber
- Bidirectional 980nm pumping
- Pump mode control through phase plate launch
- Gain flatness of <2.5dB across the C-band



Y. Jung et al. ECOC 2013

73.7 Tbit/s amplified FMF system

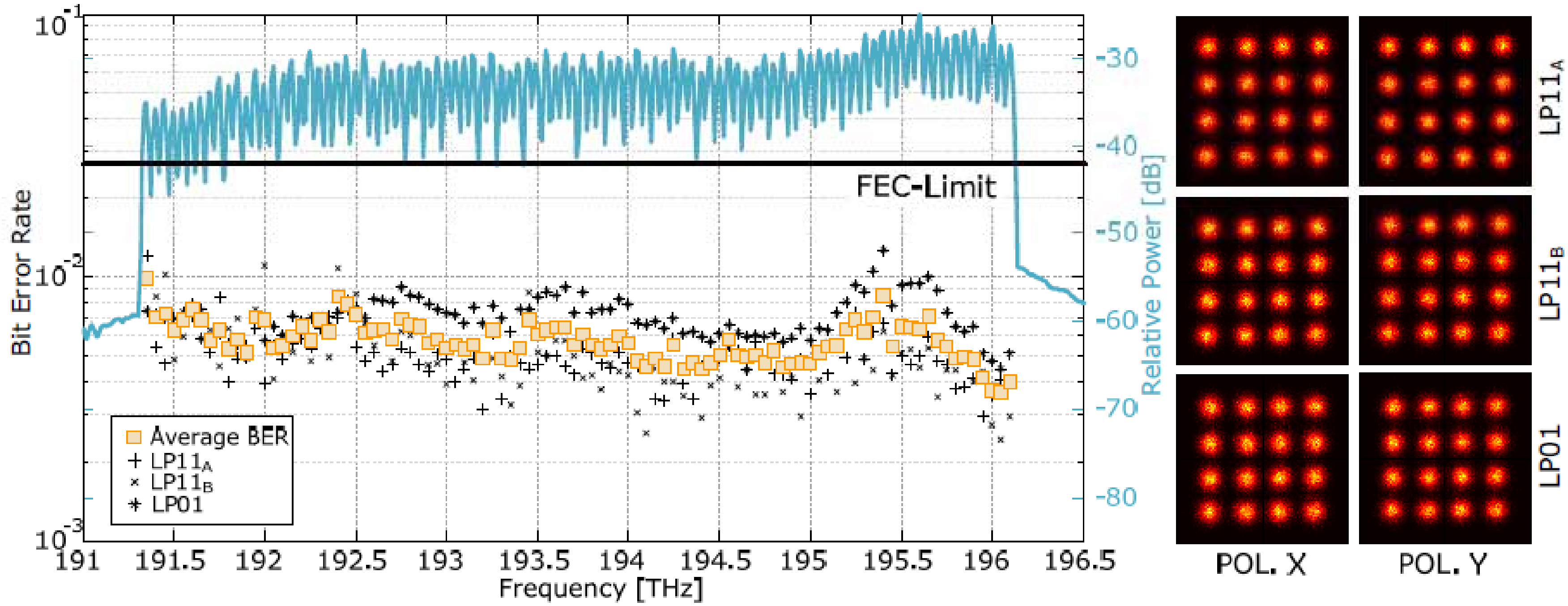


- 96 (WDM) x 3 (SDM) x 256Gbit/s (PDM-16QAM)
- Inline FMF-EDFA, 119km
- Low DGD fiber + partial DGD compensation
- Phase plate based Mux-DeMux

V. Sleiffer et al. ECOC 2012, paper TH3.C.4

Nokia Siemens Networks

73.7 Tbit/s amplified FMF system



- TS-based DSP
- 20% FEC overhead – total transmission rate = 55.7 Tbit/s
- Total distance 119 km (84km+35 km)
- Distance limited by ~10 dB Mux/De-Mux loss

V. Sleiffer et al. ECOC 2012, paper TH3.C.4

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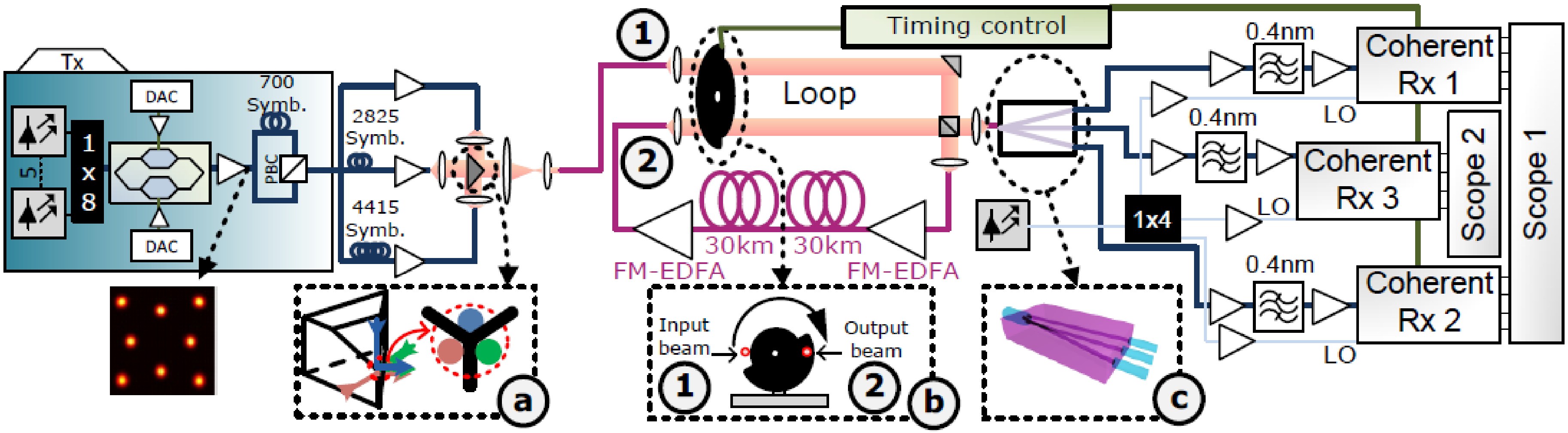
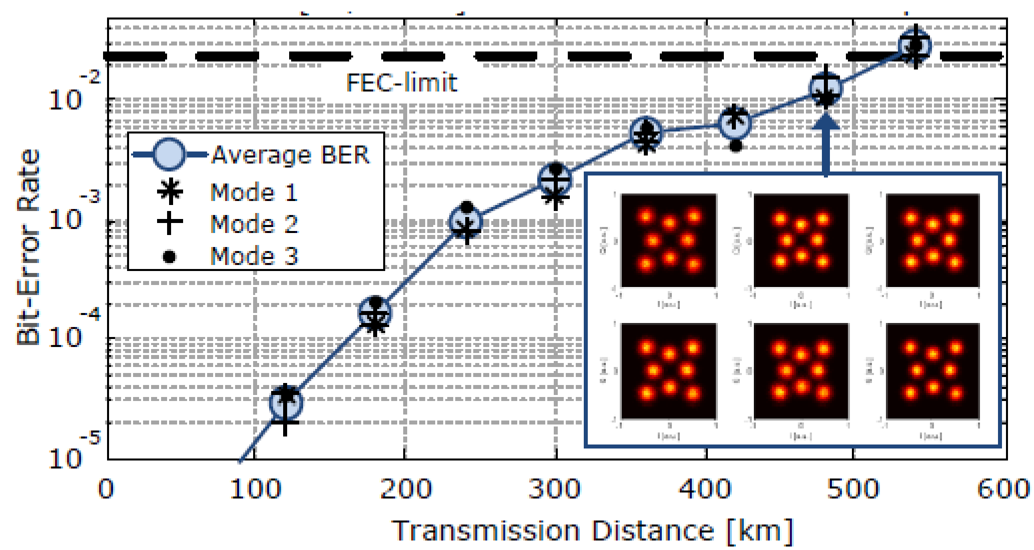
480 km MDM 576-Gb/s 8QAM Transmission

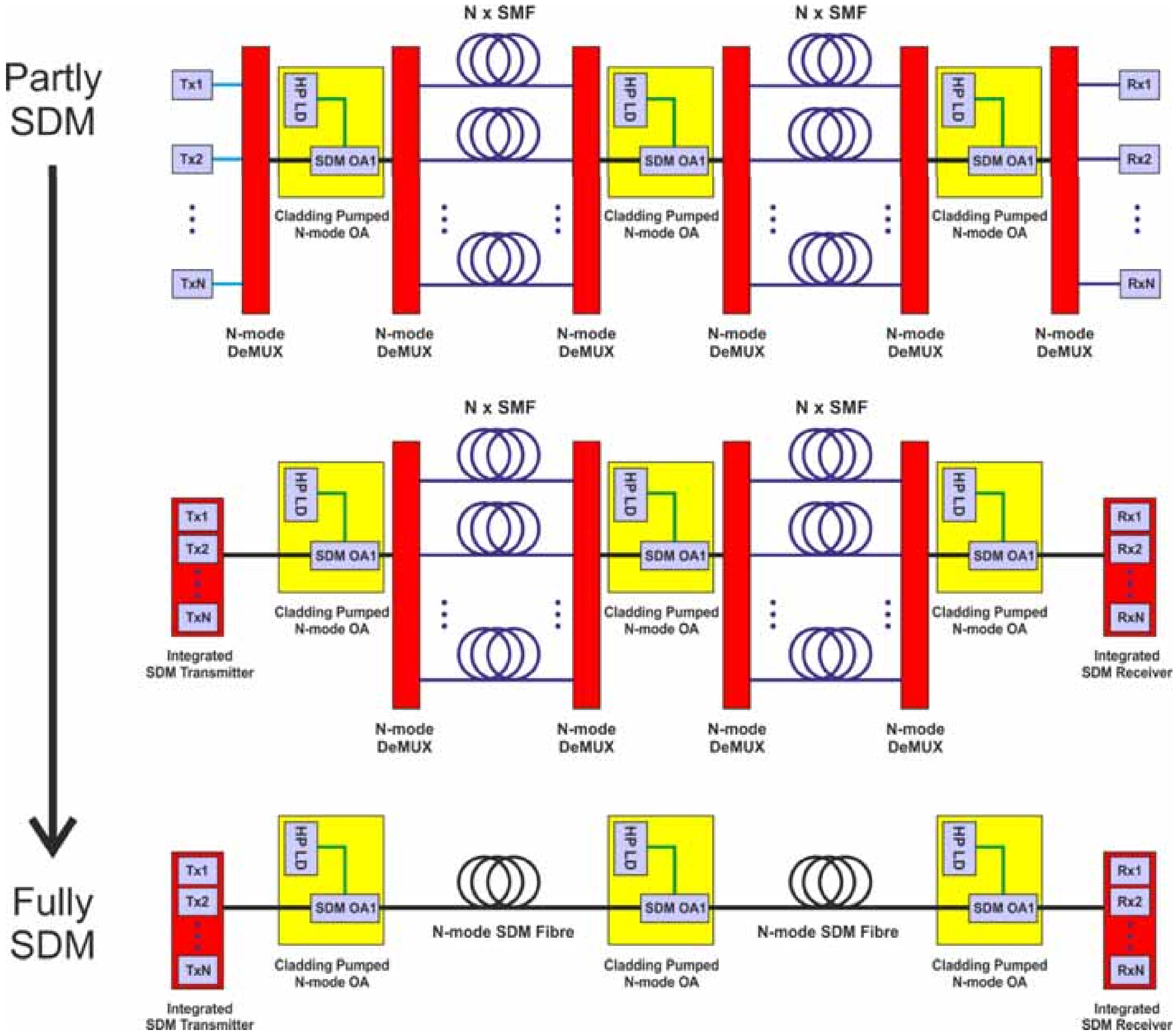


- 192 X3 Modes x 5WDM
- 32 Gbaud PDM-8PSK
- Low DGD fiber
- Ring doped EDFA
- ~480 km Error free with FEC
- >1000km with QPSK

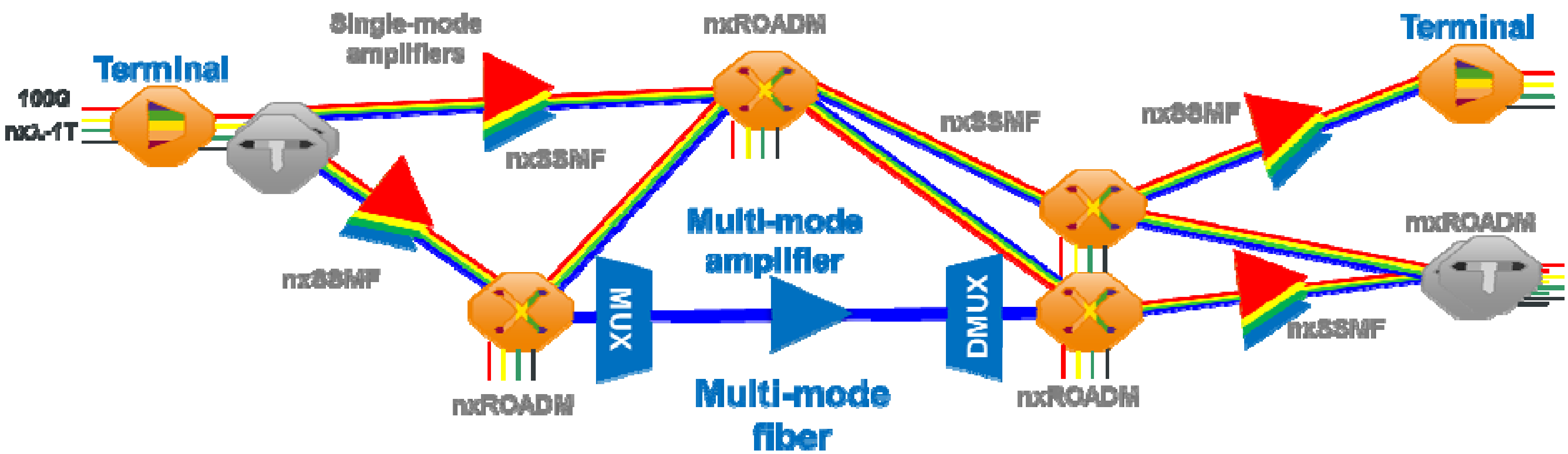


V. Sleiffer et al. PDP 6 IPC (2013).

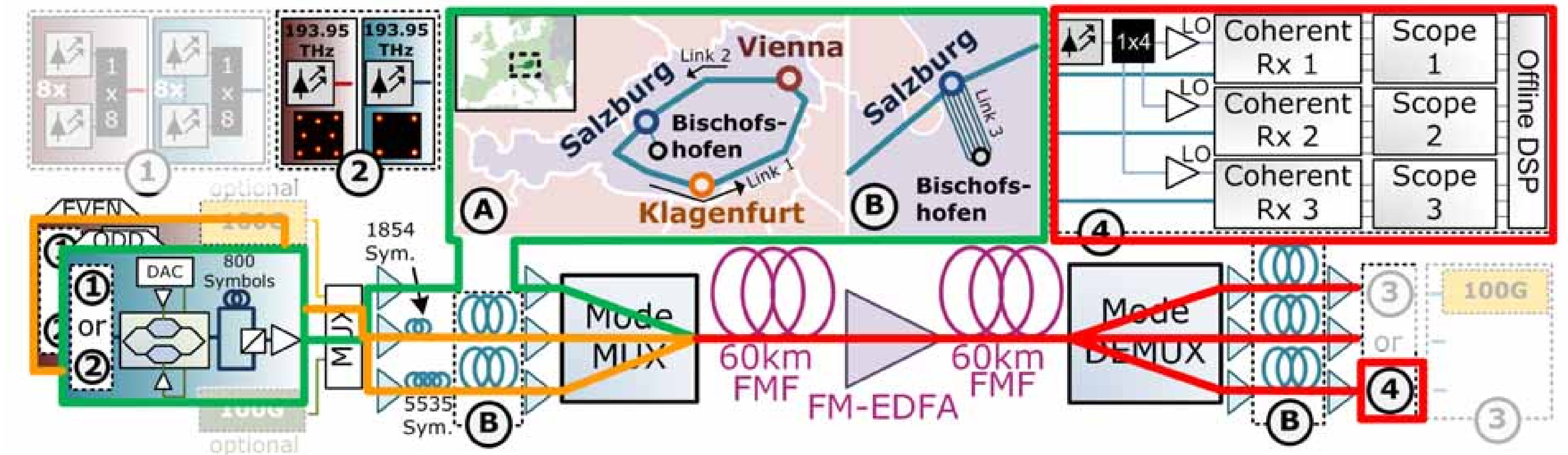
Possible Upgrade Scenarios



First MDM Field Experiment



First MDM Field Experiment



- 1 x 112 Gb/s DP-QPSK, 2 x 192 Gb/s DP-8QAM, different transmitters (lasers) running at the same wavelength
- Hybrid transmission in operation with live network
- 112-Gb/s DP-QPSK over 1,245 km, 192-Gb/s DP-8QAM over 220 km

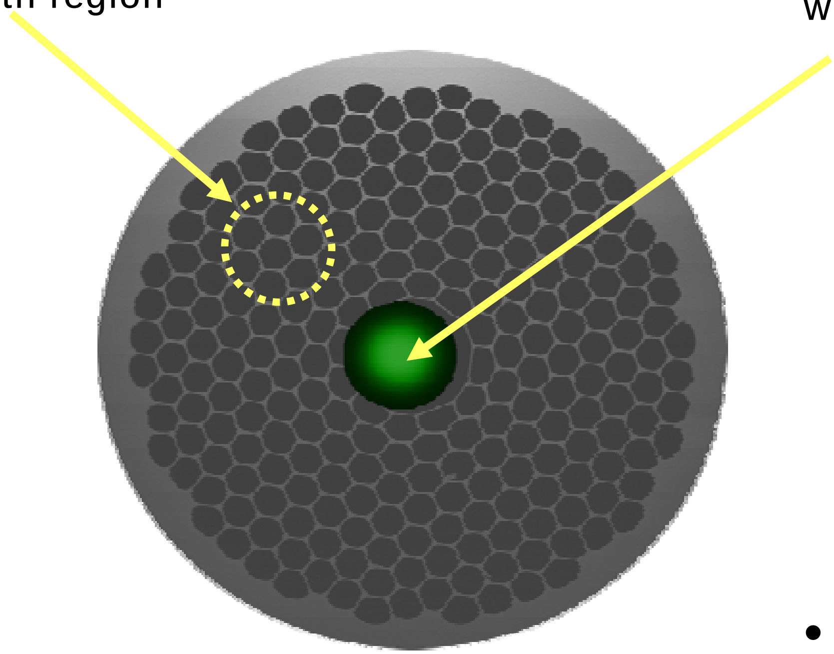
Even More Radical Solutions: Hollow Core PBGFs

Periodic lattice of holes

Optical bandgap covering a well defined wavelength region

Hollow core

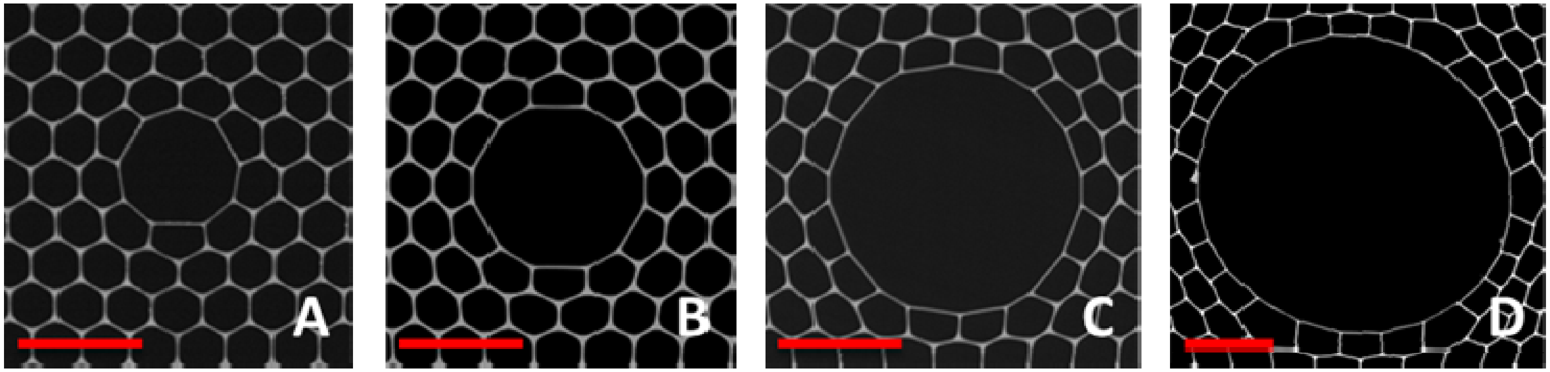
Modes in a low-index core are supported at frequencies within the bandgap

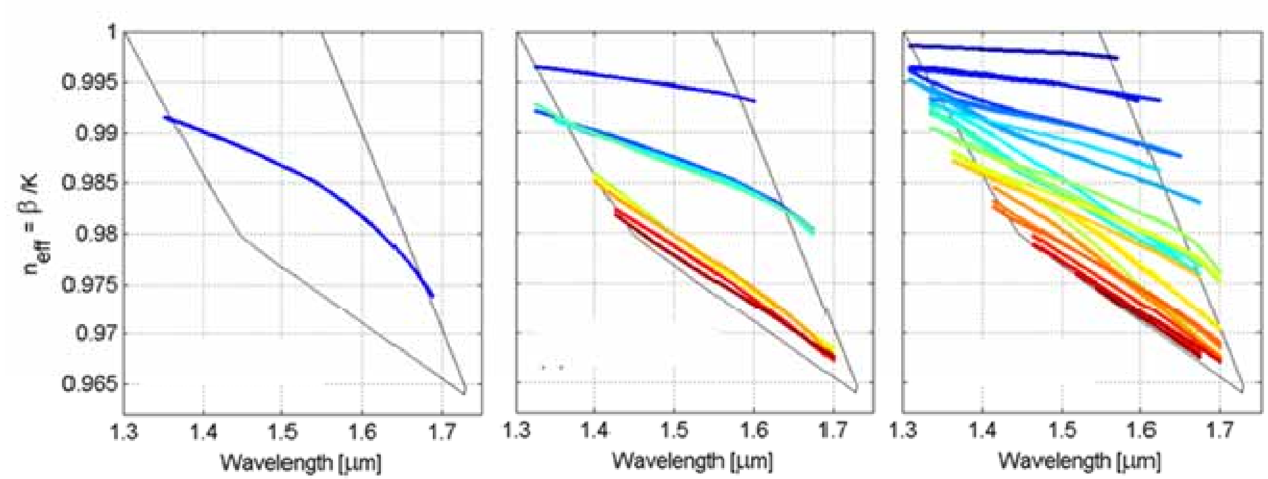


Key Attractions

- Ultralow nonlinearity
- Potential for ultralow loss
- Minimum latency

Managing Mode Size and Modality





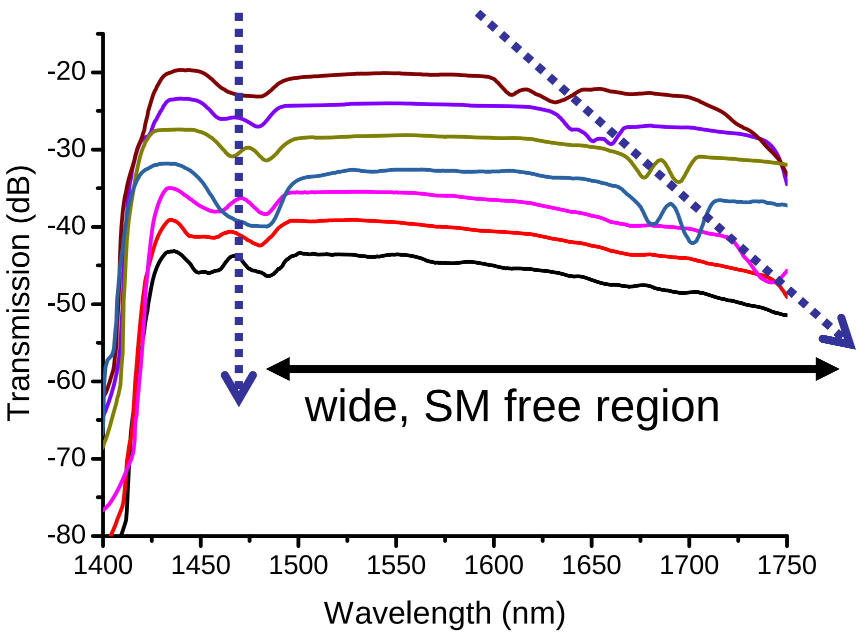
- Loss of FM decreases with increasing core size
- Number of supported modes though increases steadily
- Surface mode control more challenging for large cores

Petrovich et al., Optics Express, 16(6), 4337-4346, (2008)

Surface Mode Control

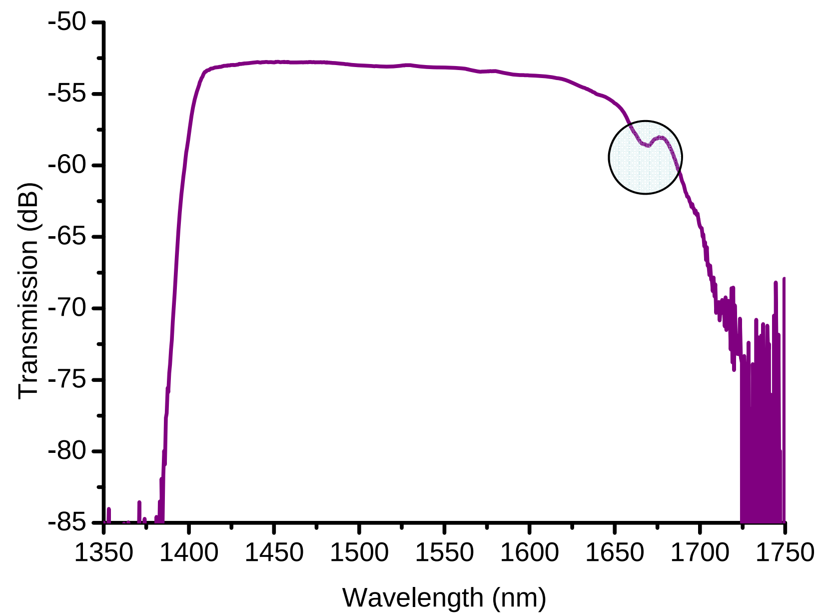
- SM control essential for low loss, wide bandwidth, “good” polarisation and dispersion properties
- We are progressing the work towards their complete elimination

Previous fibres (OFC12 PDP)



- 2 SM groups, 4+ SMs in total

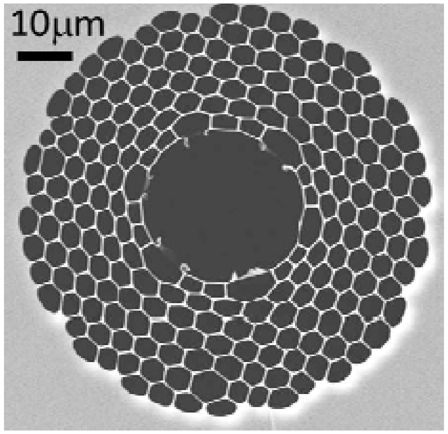
Latest fibre



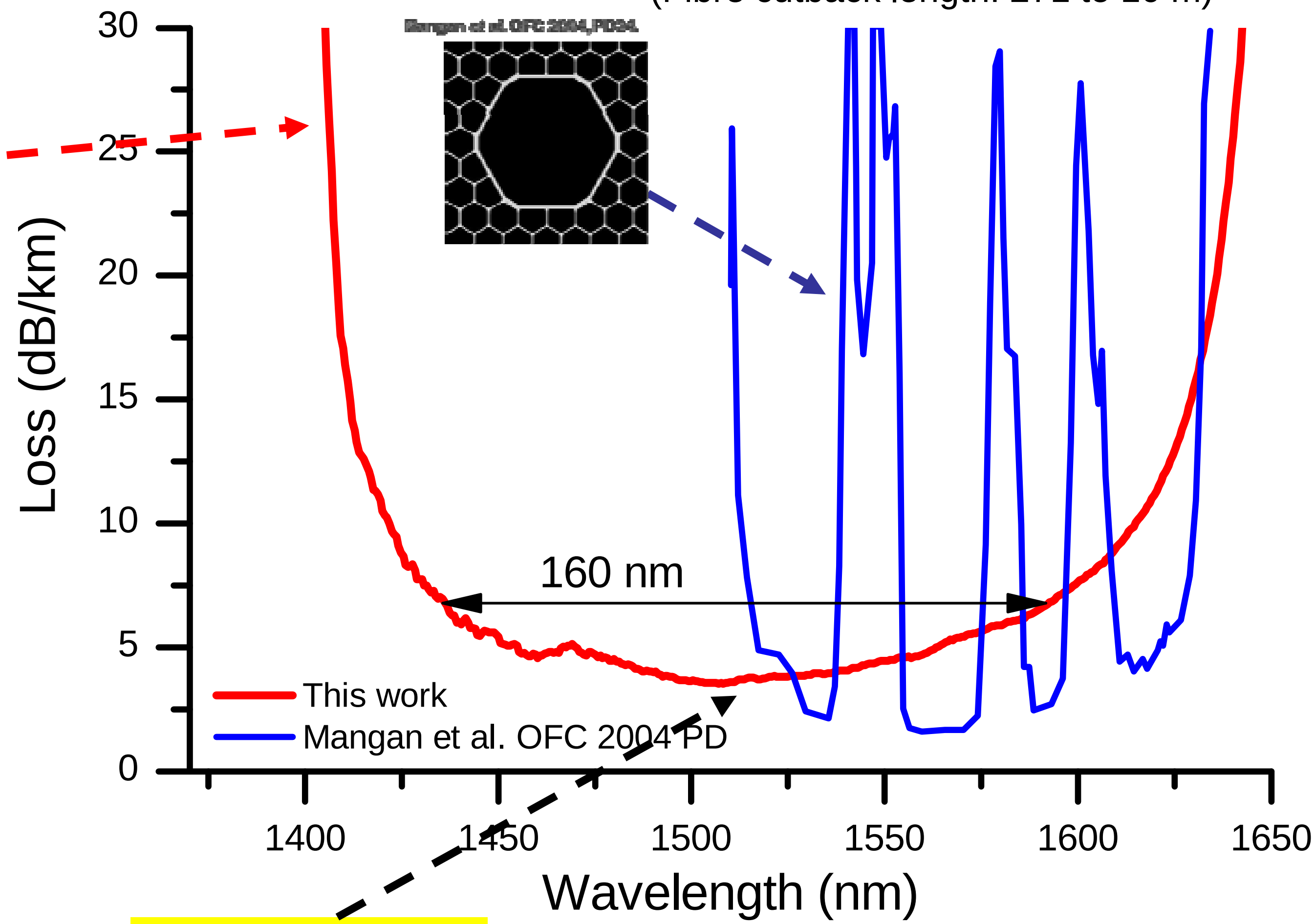
- Only 1 SM!
- Wider SM free bandwidth

N. Wheeler et al. OFC 2012, Los Angeles, PDP5A.2

Low loss wide BW 19-cell HC-PBGF



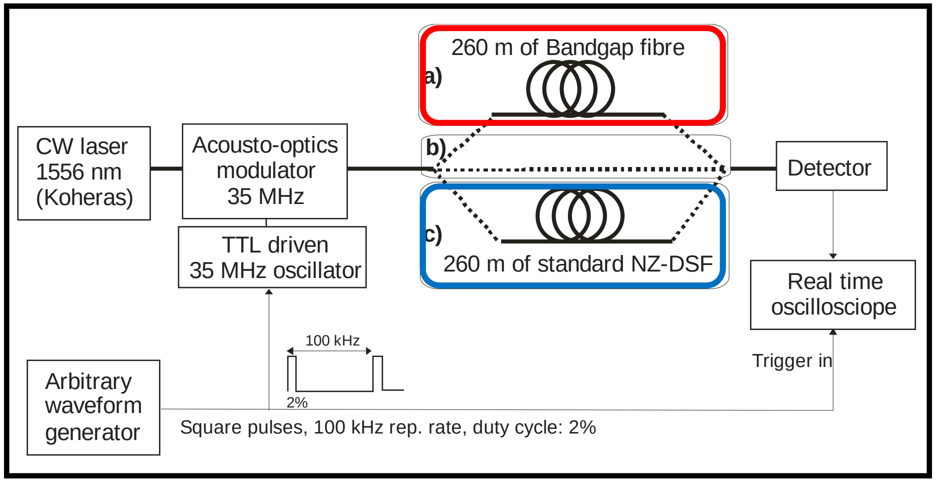
19c core
Λ ~ 4.4 μm
d/Λ~ 0.976
Core diam: 26 μm



Minimum loss: 3.5 dB/km

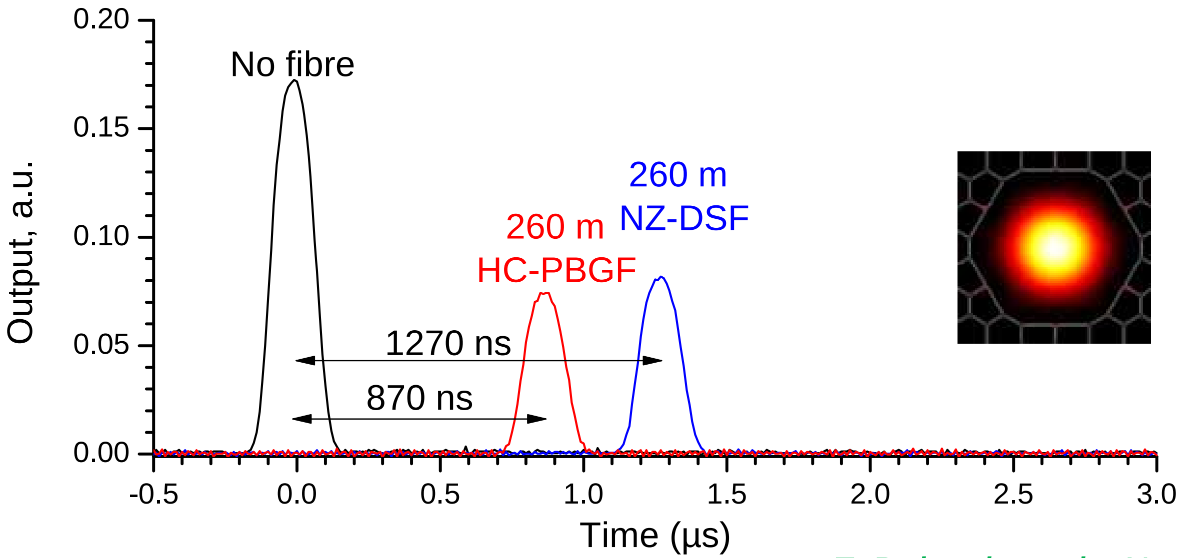
N. Wheeler et al. OFC 2012, Los Angeles, PDP5A.2

First Low Latency Measurements



Direct comparison with standard NZ-DSF

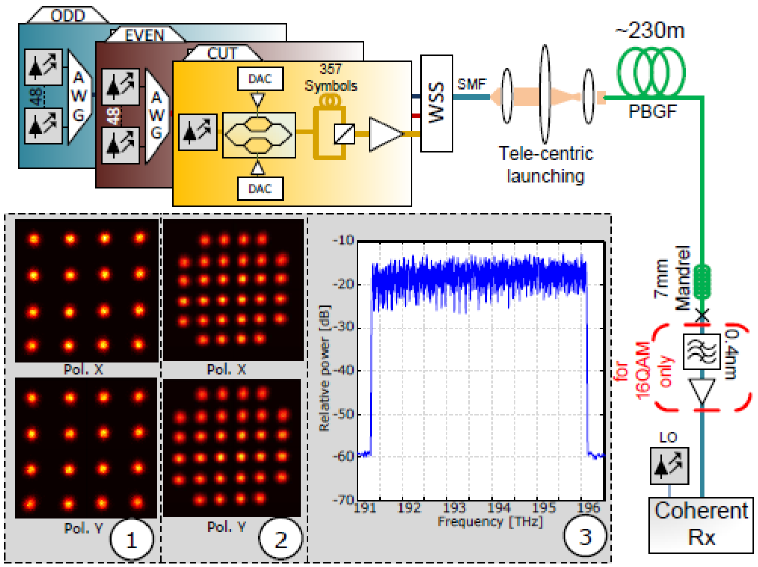
- n_G~1.003
- 1.46x faster propagation in PBGF than in SMF

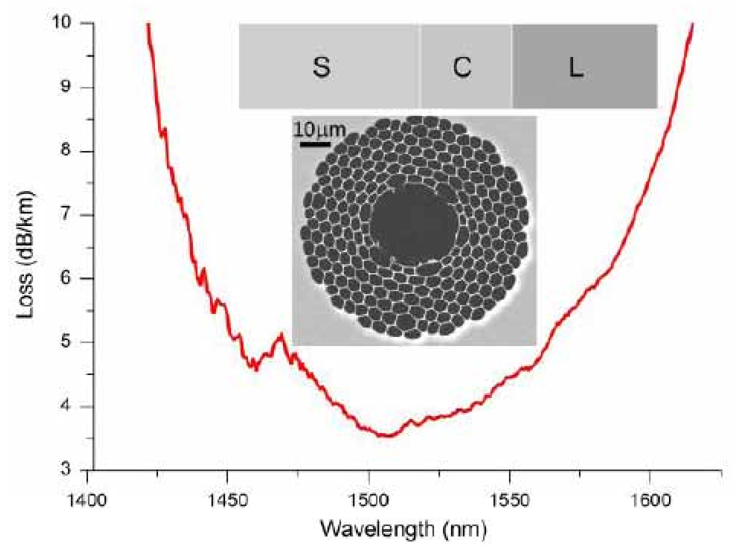


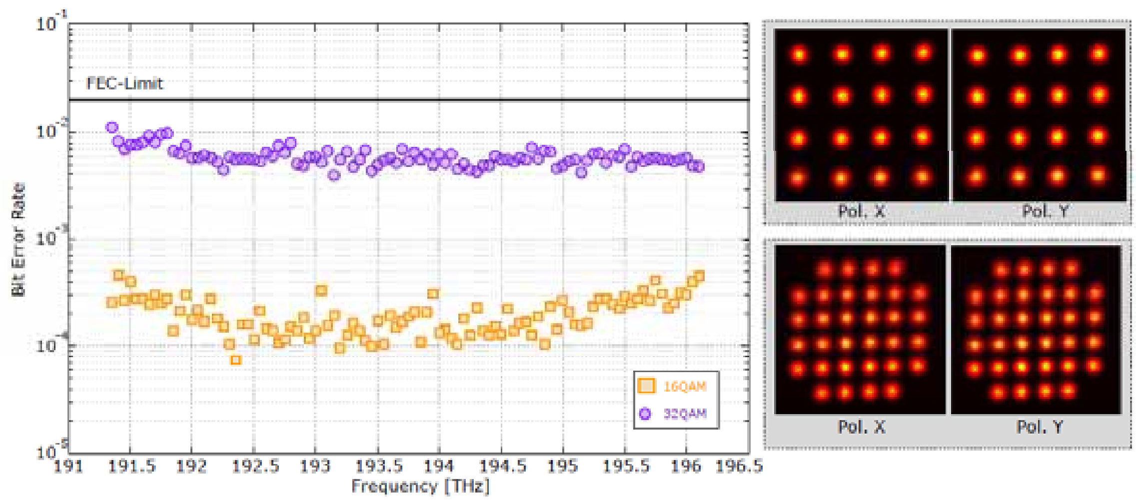
1.33 x faster propagation
1.54ms/km lower latency

F. Poletti et al. Nature Photonics, 7, pp279–284 (2013).

30 Tbit/s Low Latency Transmission in 250m HC-PBGF

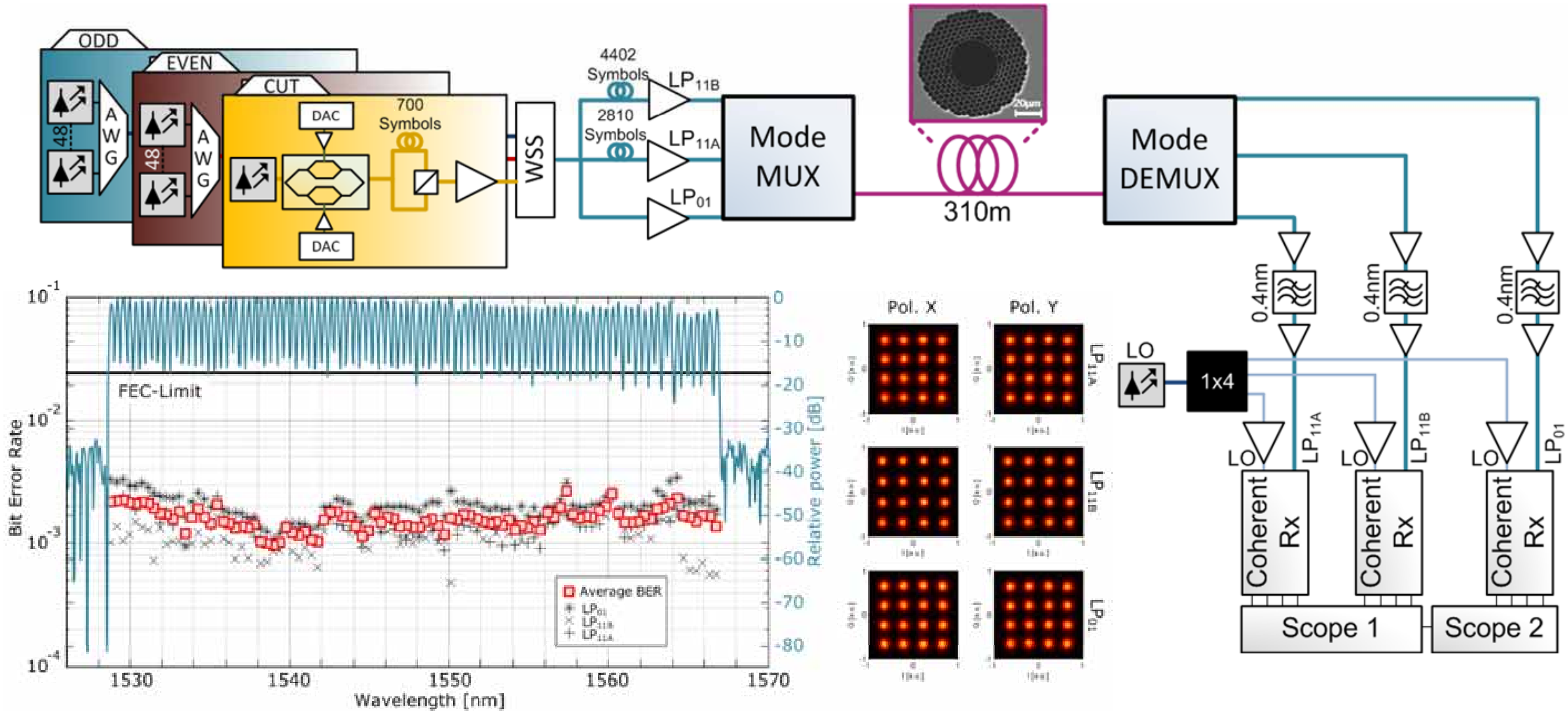






V. Sleiffer et al. OFC 2013

57.6 Tbit/s 96(WDM) x 6(MDM) in PBGF



- Feasibility of MDM in HC-PBGF demonstrated
- High DGD and MDL need to be accommodated

Y. Jung et al. OFC PDP 5A.3 2013.

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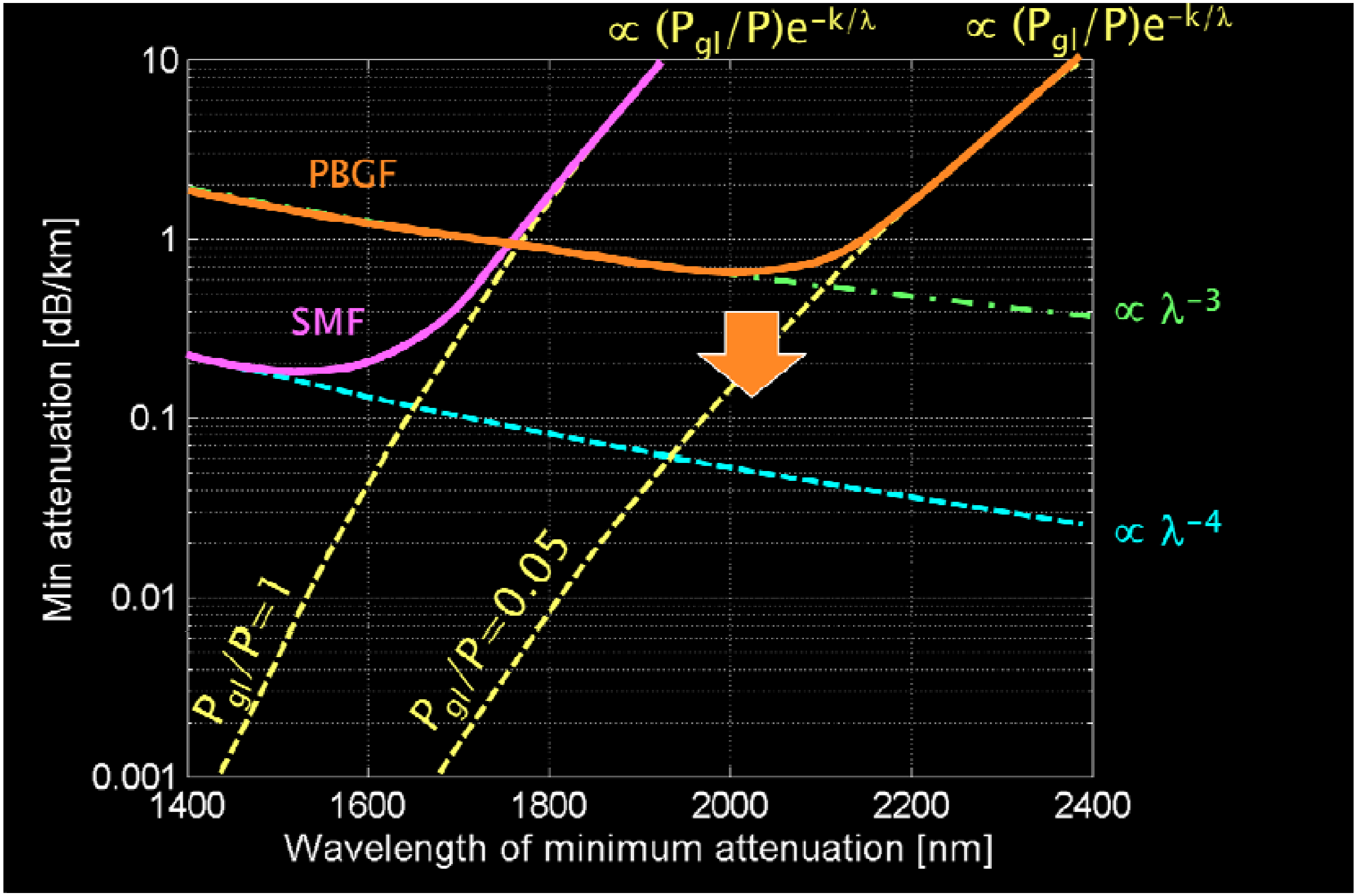
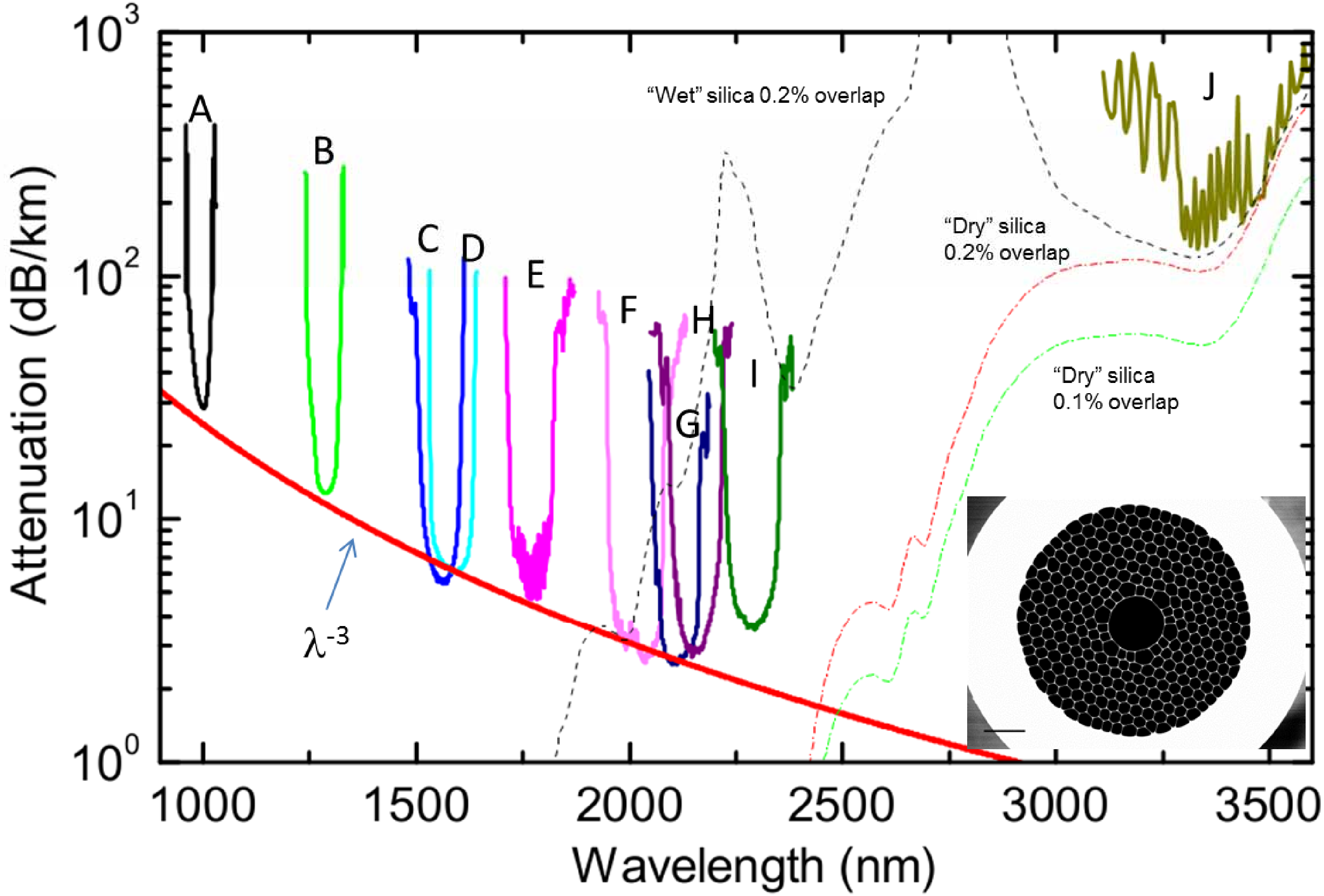
Loss Limits in PBGFs

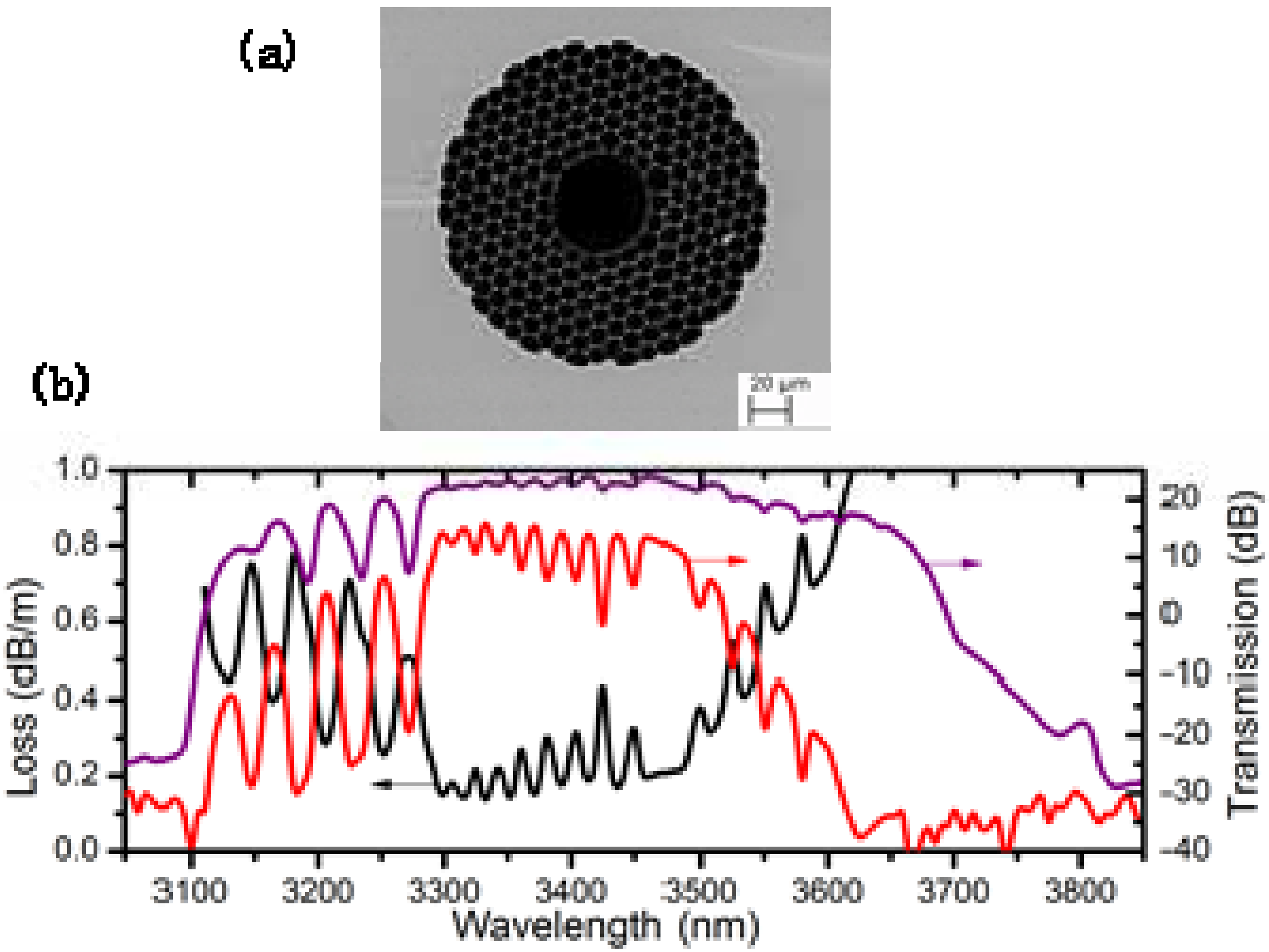


Roberts et al. Optics Express, 13(1), 236-244, (2005)

Confirming Origin of Loss in PBGF

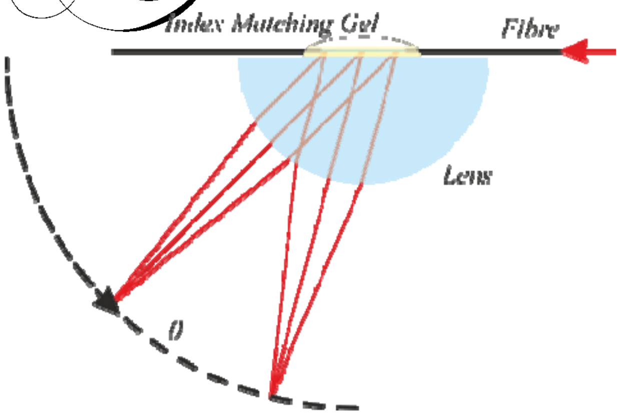


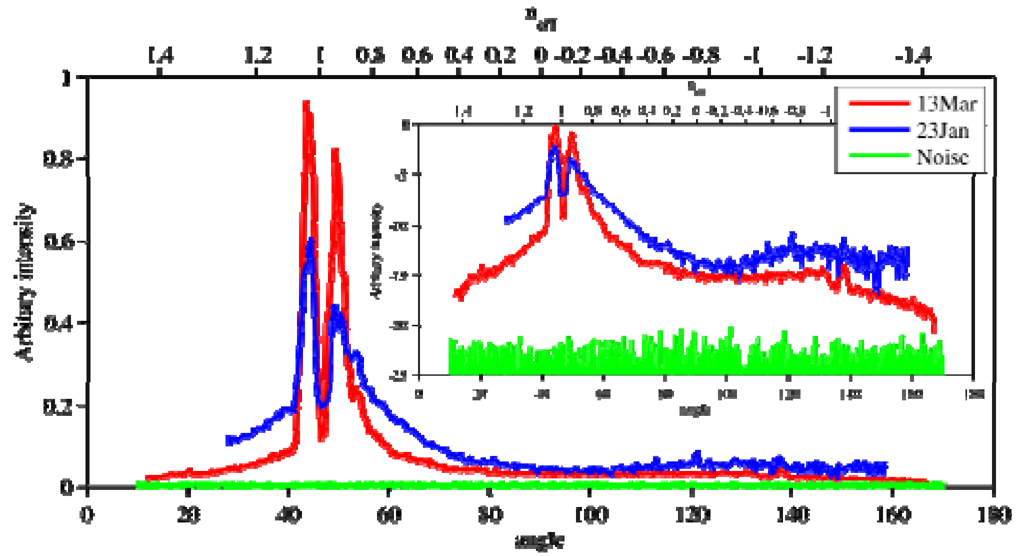
Low Loss mid-IR PBGF

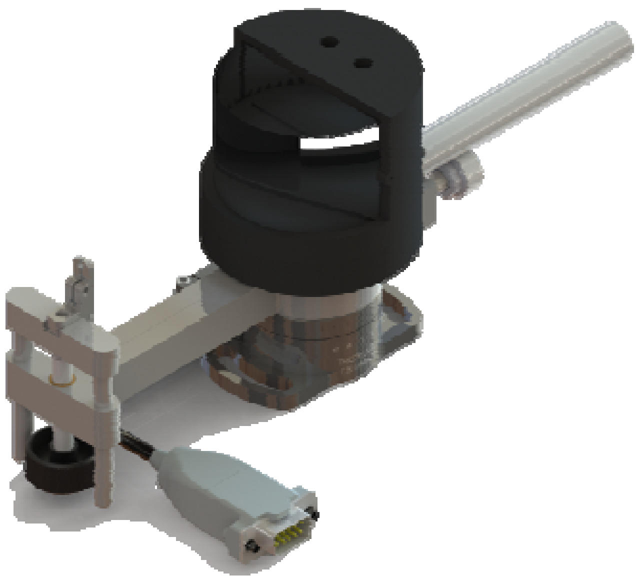


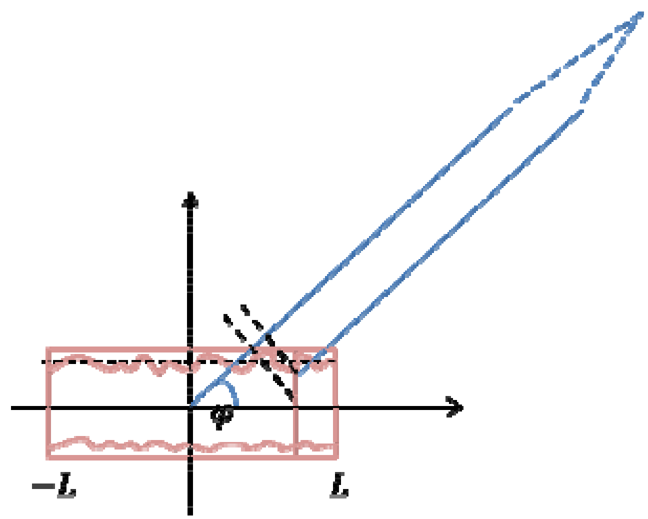
W. Wheeler et al. Specialty Optical Fibers, 2013.

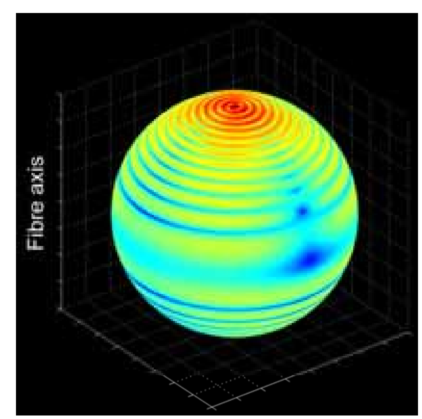
Surface Roughness Scattering







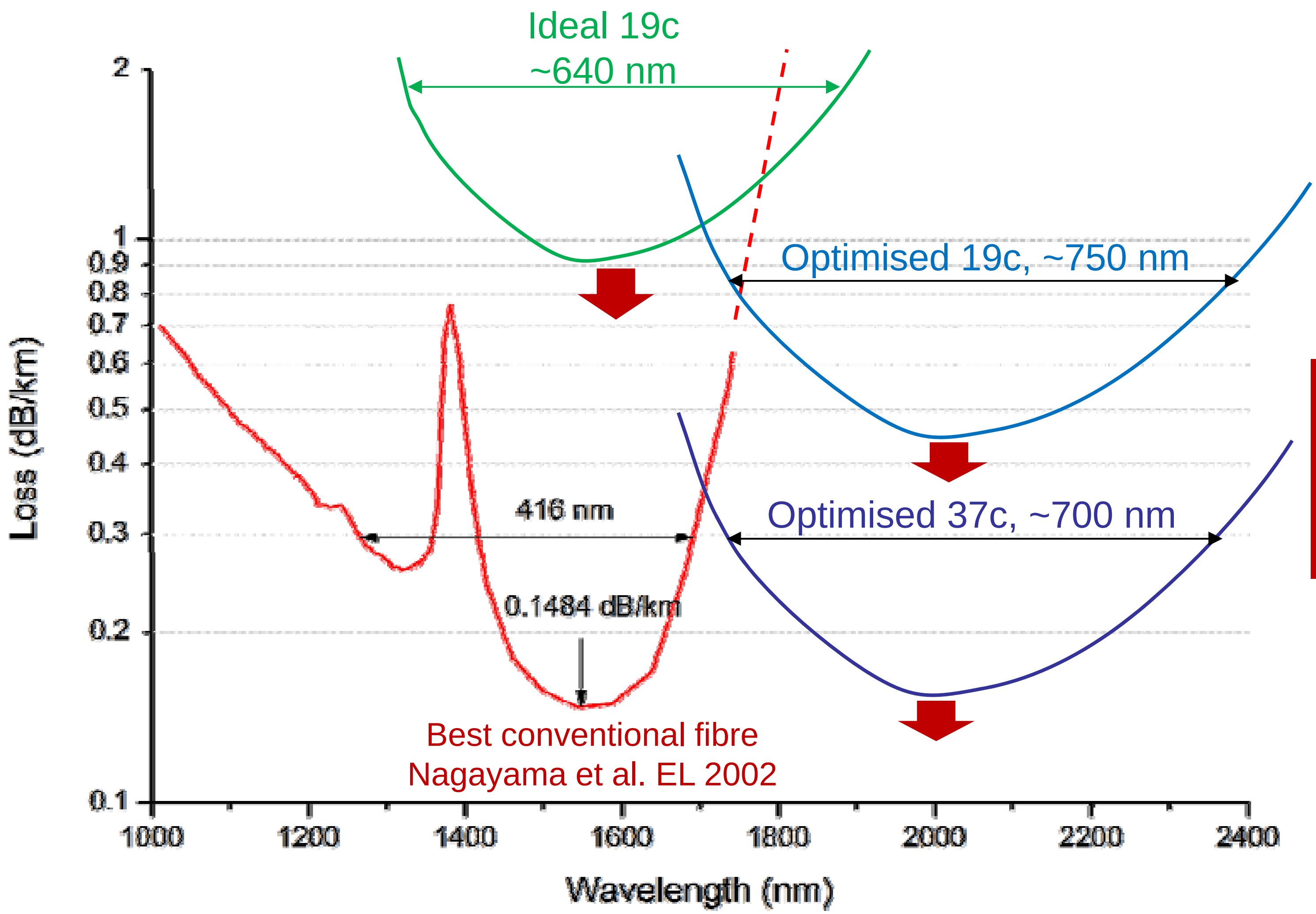




Fokoua et al. Optics Express, 20(19), 20980-20991, (2012)

Ultimate PBGF: Loss Prediction

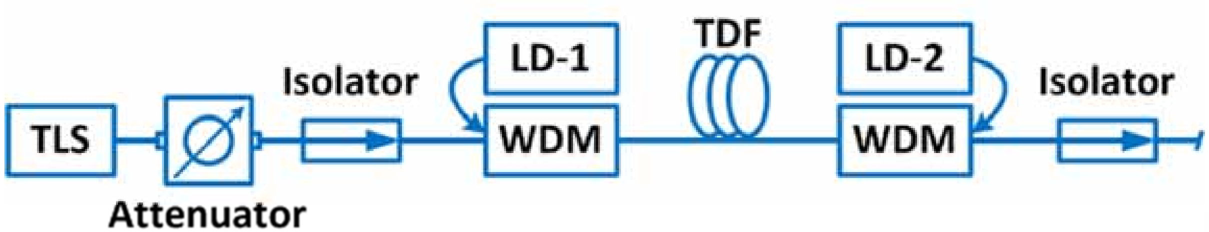
Predicted loss and bandwidth of realistic, optimised HC-PBGFs using the scattering loss model appropriately calibrated :

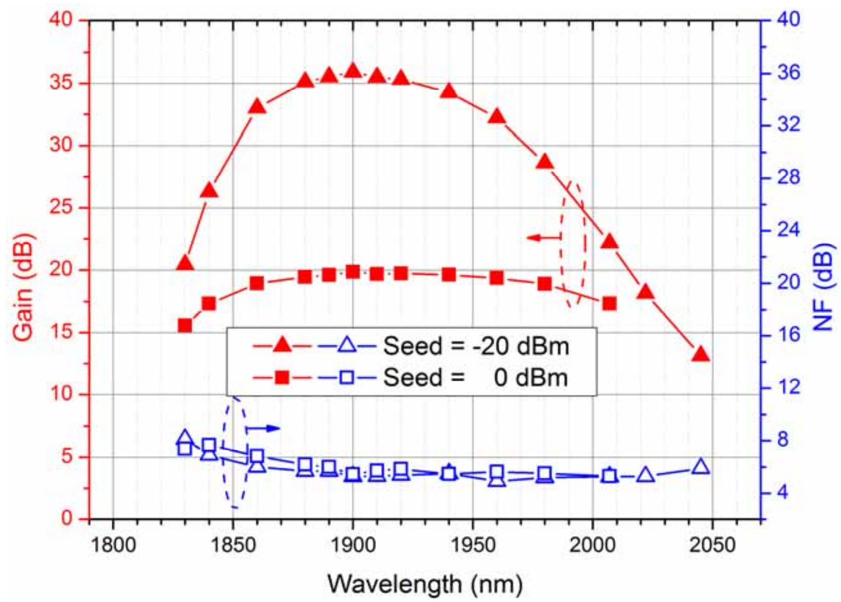


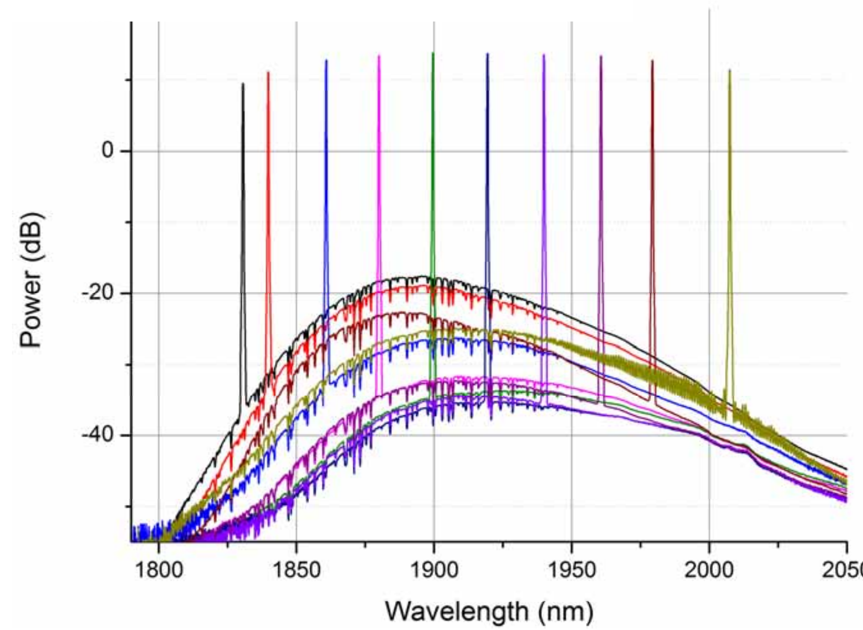
This assumes surface roughness as in current fibres

Any roughness reduction will further reduce these losses

The TDFA for Broadband Gain at 2µm



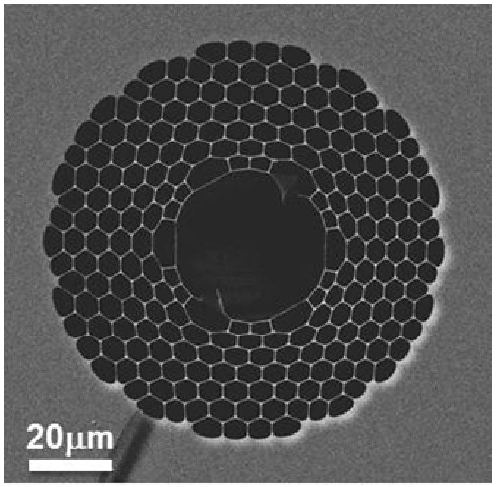


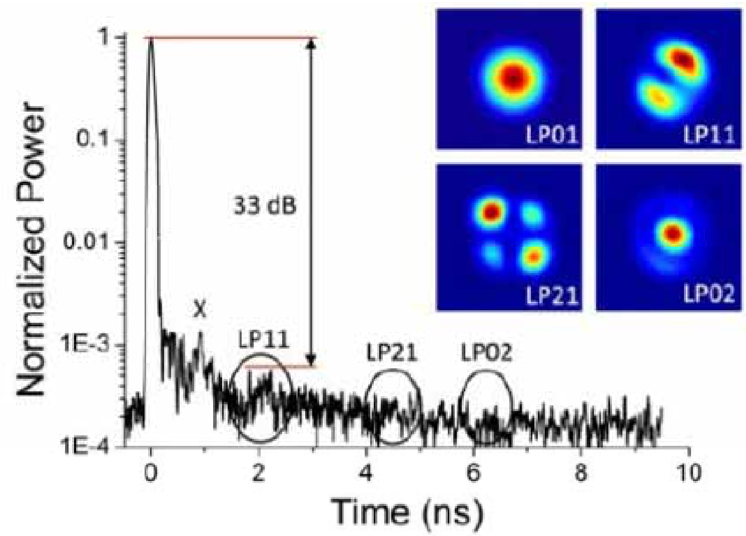


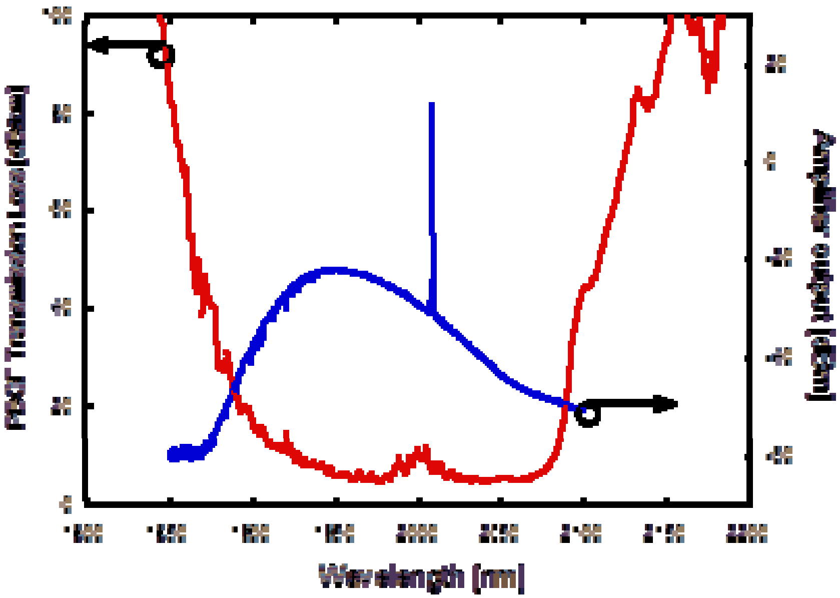
- 1560nm diode pumps
- More than 35dB small signal gain at the peak operating wavelength of 1900nm
- 100mW saturated output power, >40% conversion efficiency
- <5dB external
- >300nm BW now demonstrated (1730nm-2050nm)

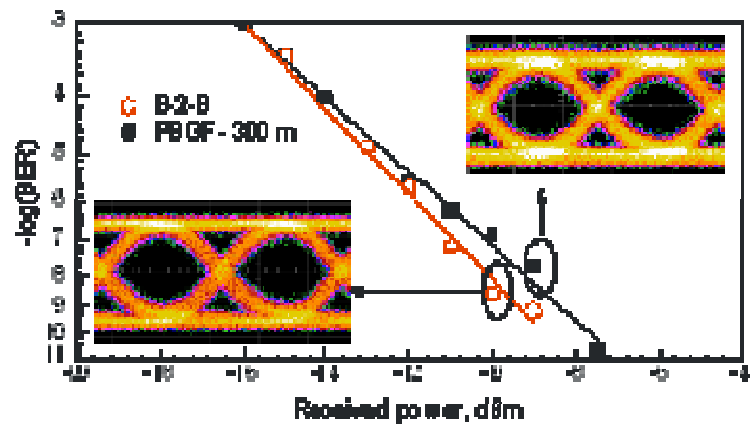
Z. Li et al. Optics Express 2013

First demonstration of 2000nm (amplified) transmission in a HC-PBGF



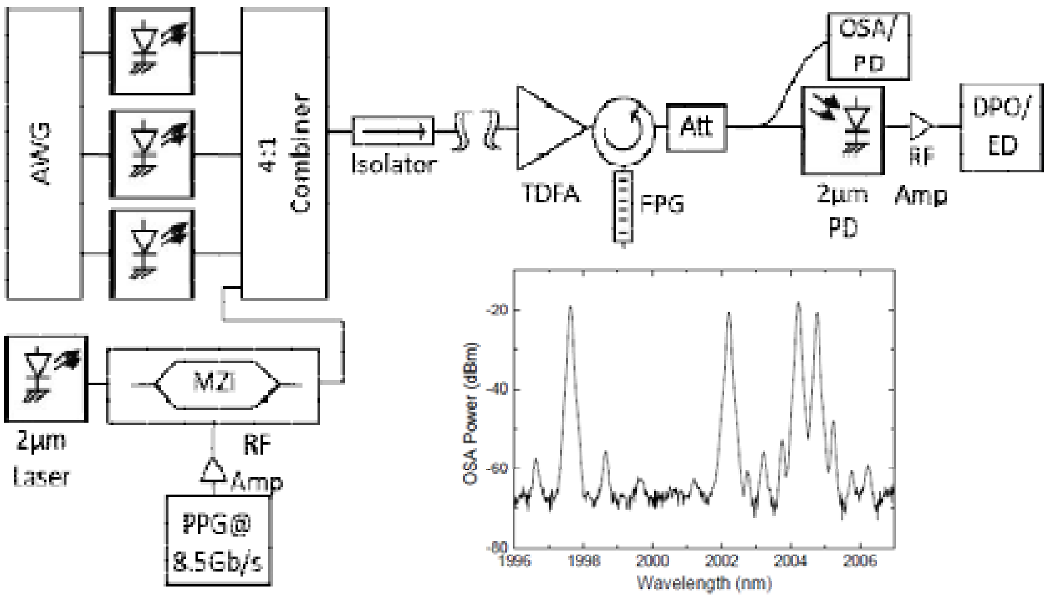


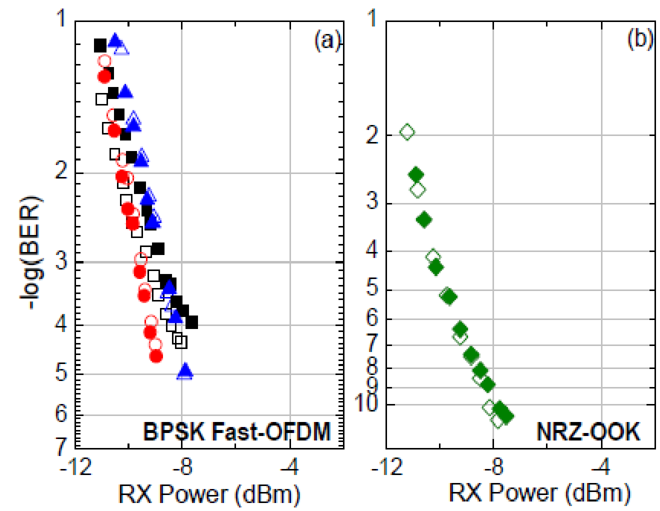




M. Petrovich et al: ECOC 2012 PDP Th3.A.5

First WDM Experiments at 2000nm

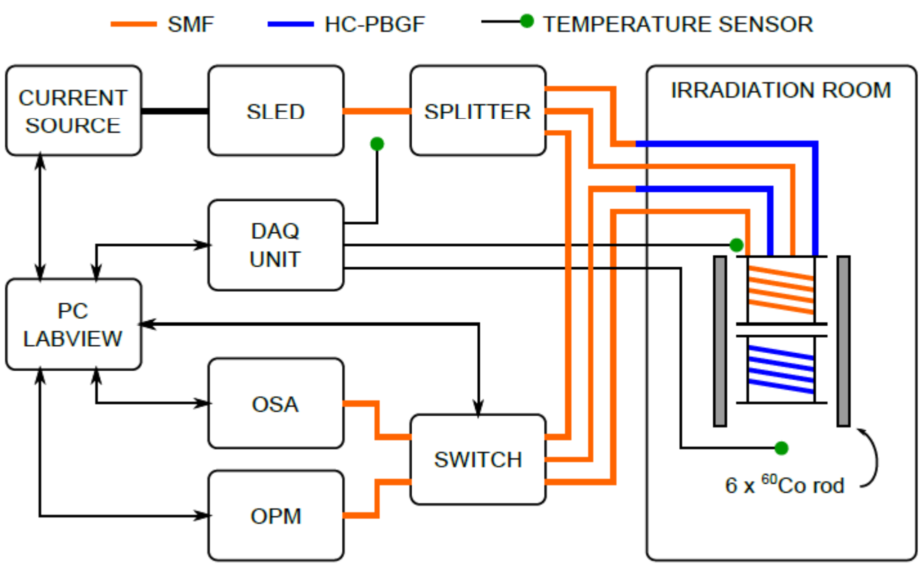


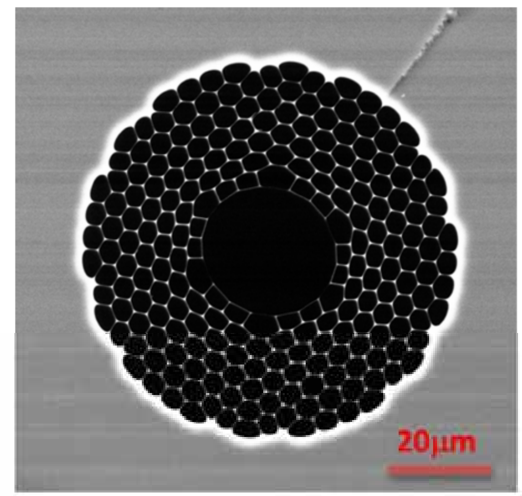


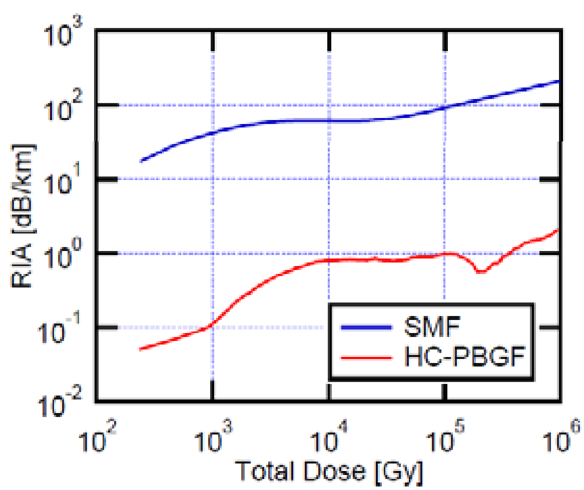
- **All component technologies required for 200nm transmission now exist**
- **First WDM experiments demonstrated, albeit over modest fiber lengths**
- **Prospects for low loss fibers around 2000nm?**

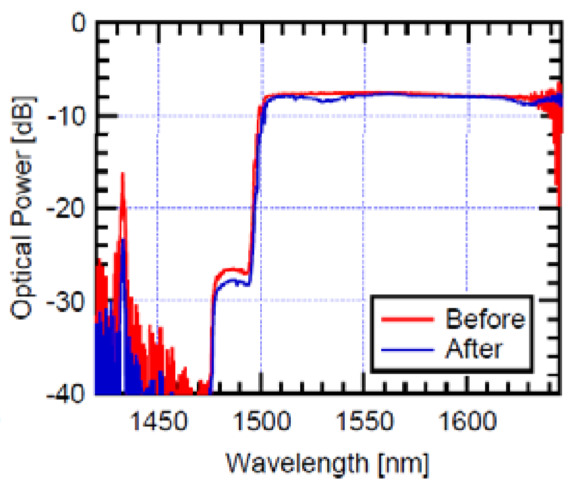
N. MacSuibhne et al. PDP Th.3.A.3 ECOC 2012.

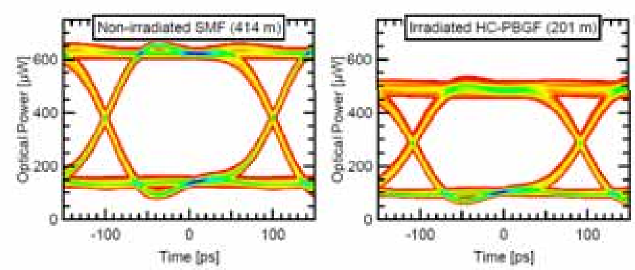
Radiation Hardness





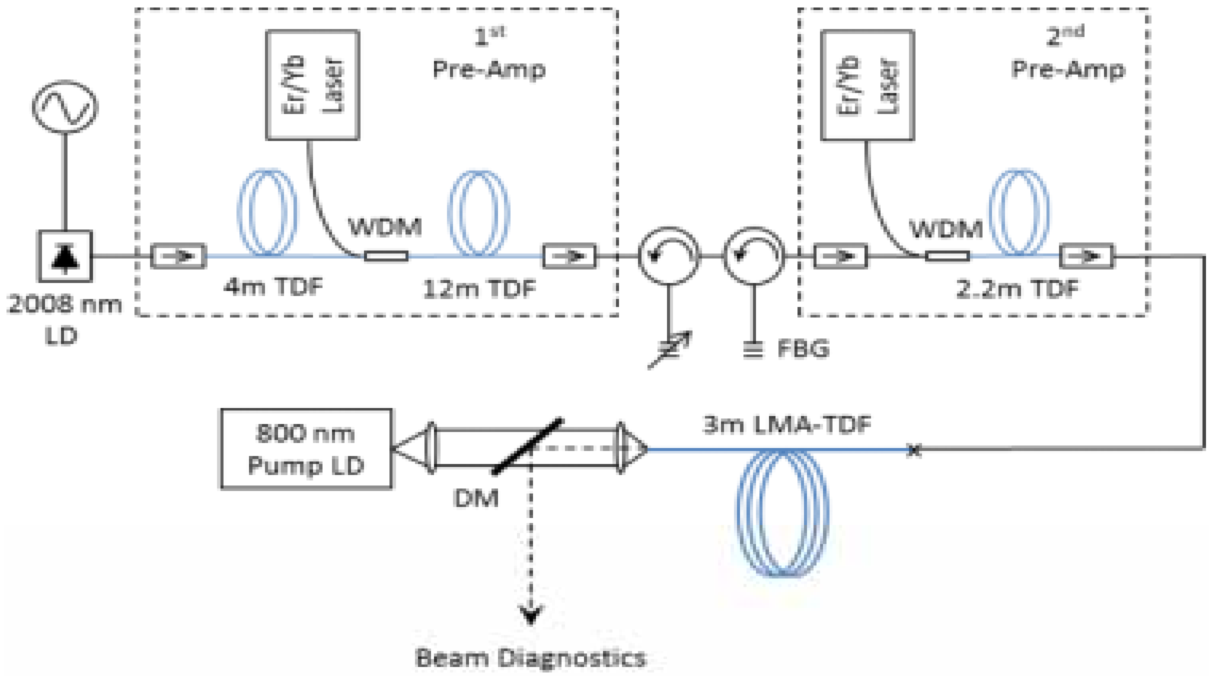


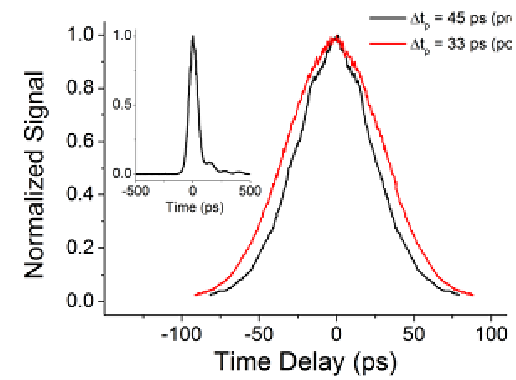


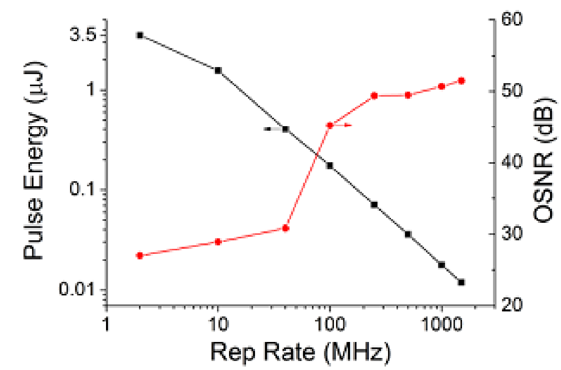


J. Olantera et al. TWEPP 2013.

High Power TDFLs



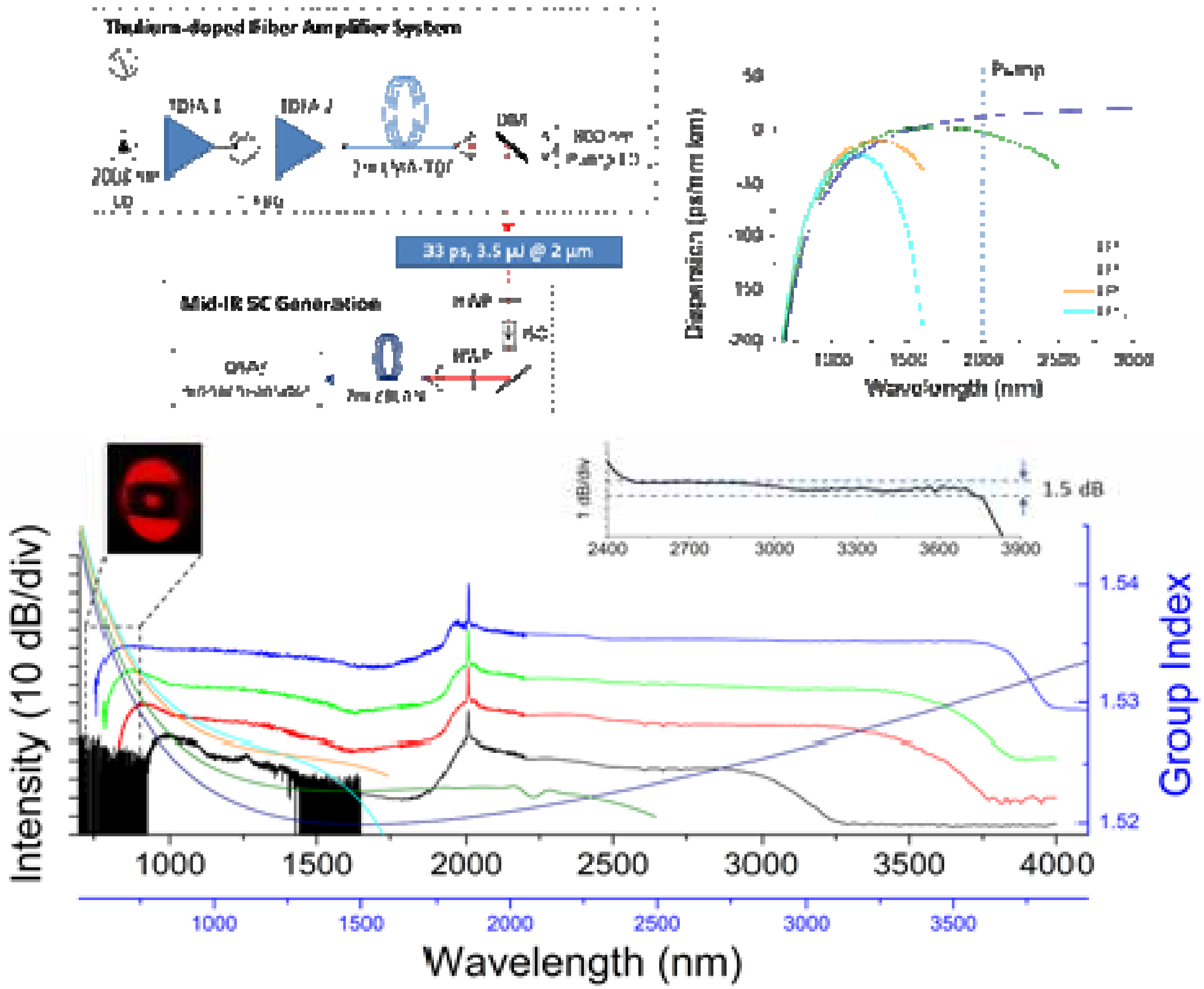




- Cladding pumped power amplifier
- More than 100kW peak power pulse at 2008nm
- >10 W Average power
- ns/ps/fs operation possible with different seeds
- Excellent source for conversion to mid-IR

A. Heidt et al. Optics Letters (2013).

2 micron pumped Mid-IR SC

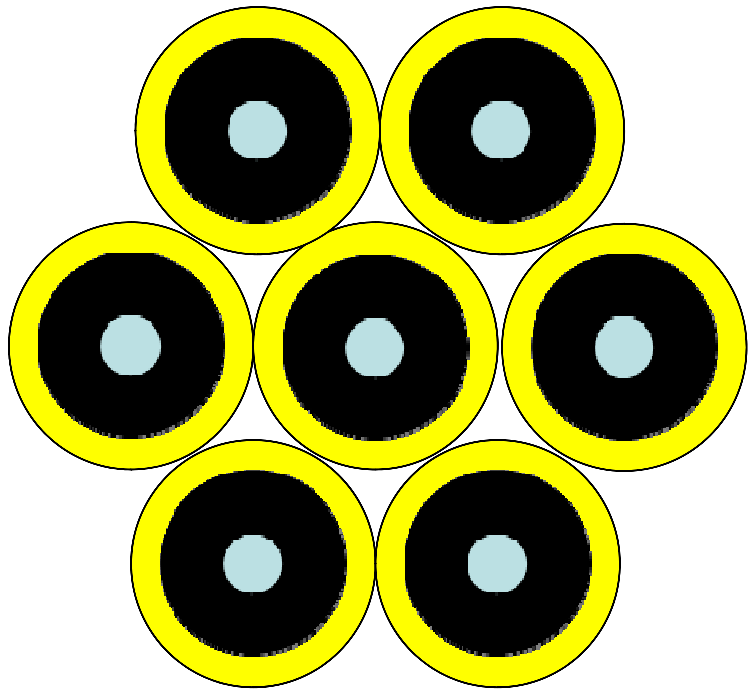


A. Heidt et al. Optics Express (2013).

Conclusions

- Tremendous technical progress in a very short period of time across all candidate approaches and all aspects of the increasing capacity per fibre problem. Much fundamental work still though required.
- The potential cost advantages and practicality of any SDM approach is yet to be proven (and much justified scepticism abounds).
- More critical assessment of prospects for real time DSP required.
- Early attempts at networking underway. More work on ROADMs and study of network opportunities/functionality benefits needed.
- More focussed adaptation for specific telecommunication requirements beyond long haul needed exploiting in particular the increased spatial channel packing densities achievable.
- Significant new components and measurement techniques developed. With broad applications in many other fields (and likely on much shorter timescales).

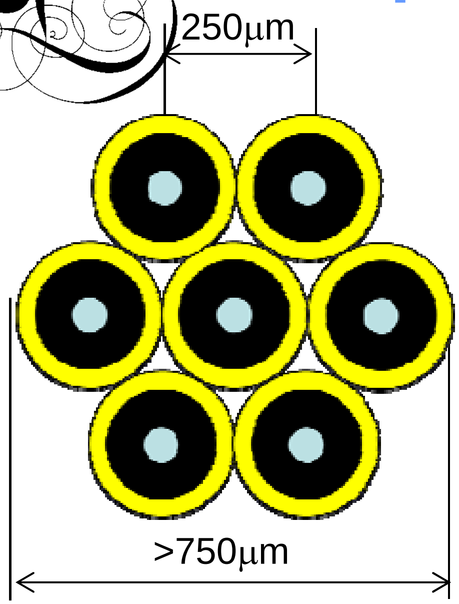
Light



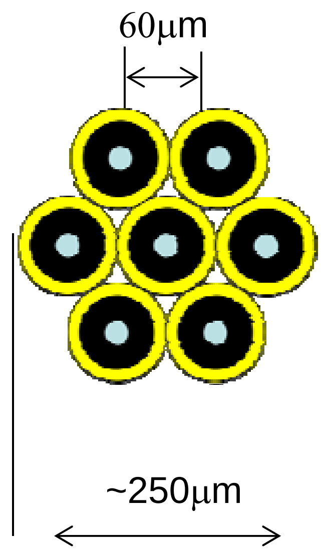
Fiber Bundles

Exploiting Space

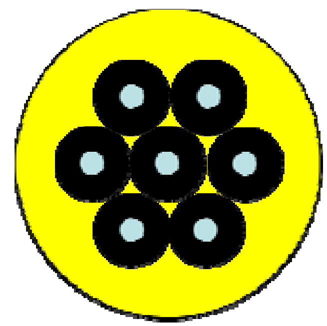
A question of reducing volume



SMF BUNDLE



BUNDLE OF THINNER FIBRES



MULTI-ELEMENT FIBRES

Cost similar to that of laying many fibre cables

Excessive volume

Significant saving in volume/increased spatial density

Microbending of the thinner fibres an issue

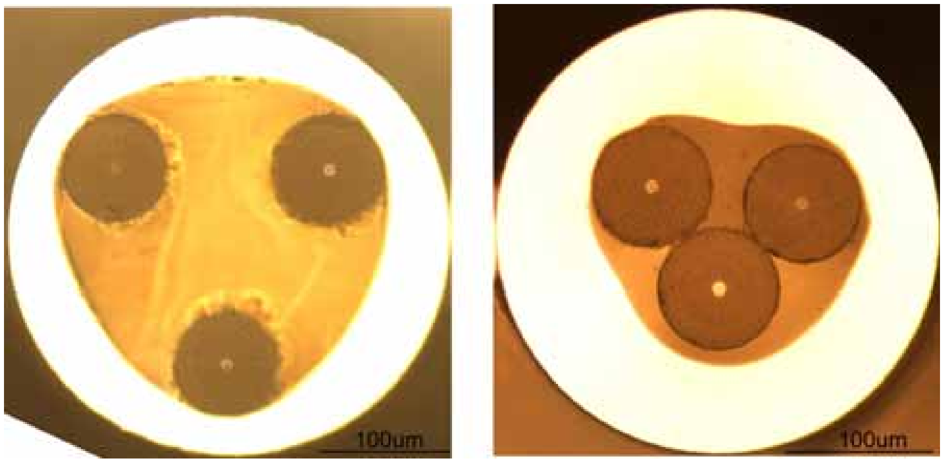
Rigidity/strength increased by including a common jacket

Reduced Microbending

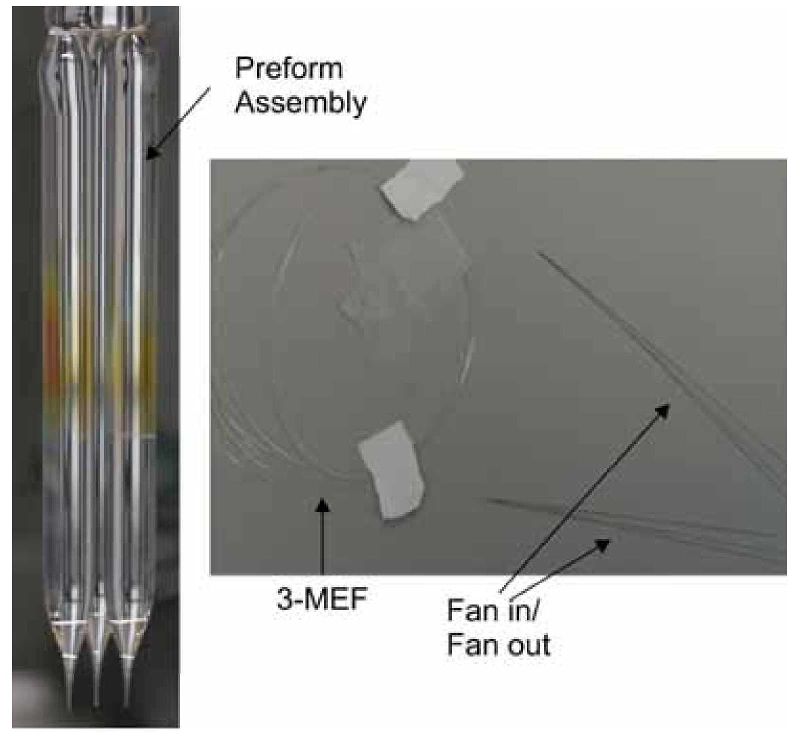
No restrictions on the outer diameter

No specialised interfacing components

Multi Element Fiber (MEF)



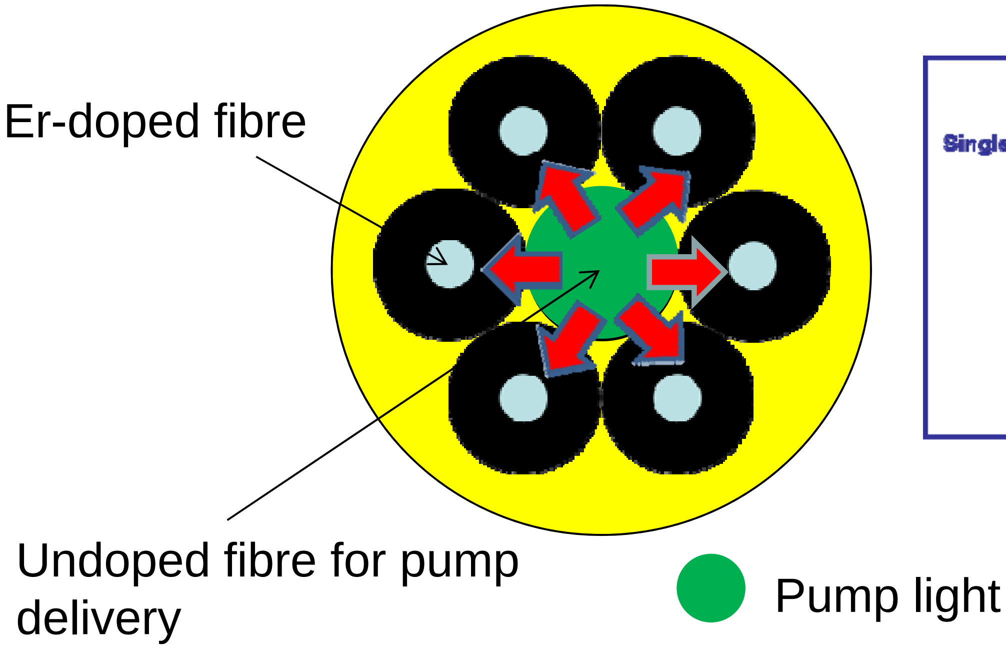
Non-compact and Compact 3-MEF

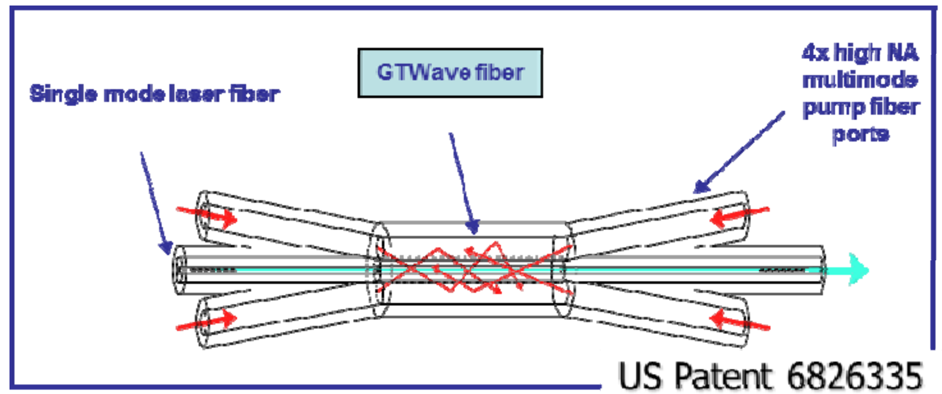


- MEFs drawn in up to 10km lengths with negligible additional loss as opposed to single core preform
- First transmission experiments successfully undertaken

S Jain et al. to be presented ECOC, 2013

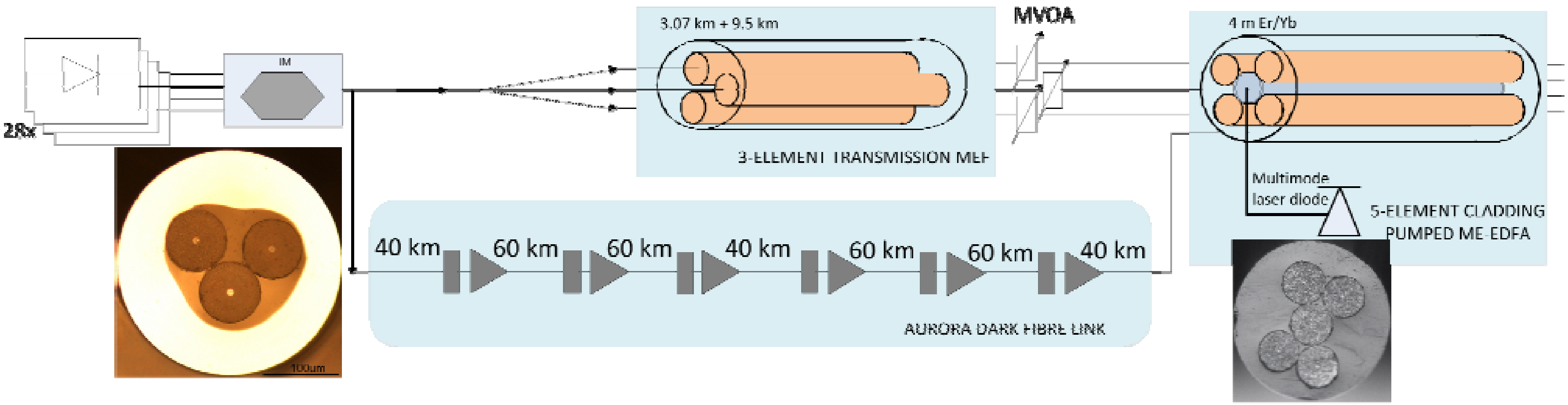
Exploiting Space
A route to lower cost amplification

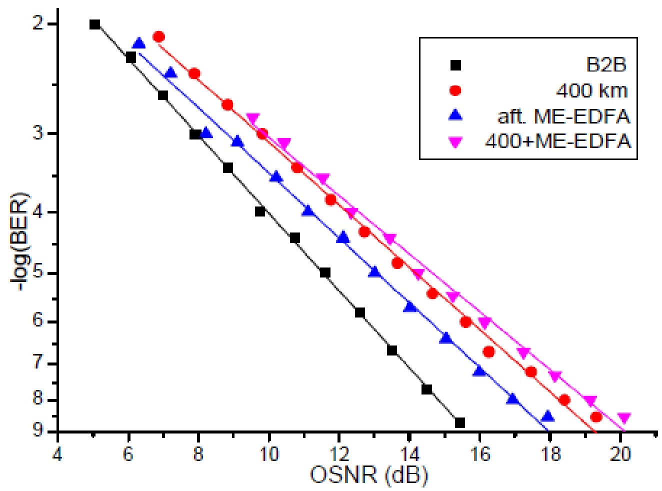


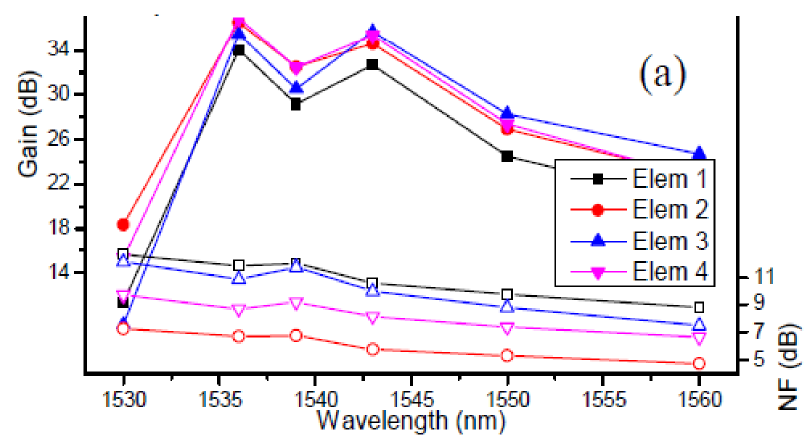


- Active fibre elements cladding-pumped, providing gain in each doped core
- Pump delivery through one fibre element
- Pump coupler effectively produced in the fibre draw
- Allows use of low cost, broad-stripe pump diodes
- Previously commercialised in context of high power fibre lasers (SPI Lasers Ltd)

Amplified MEF Transmission Line



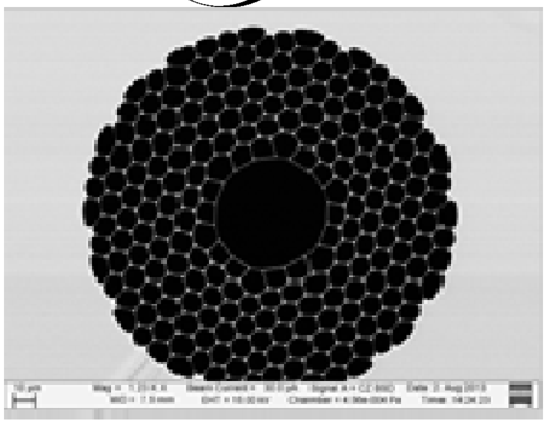


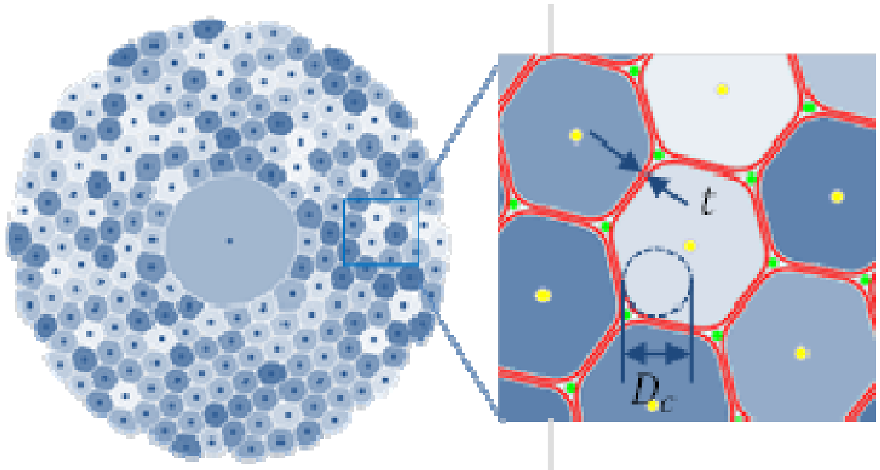


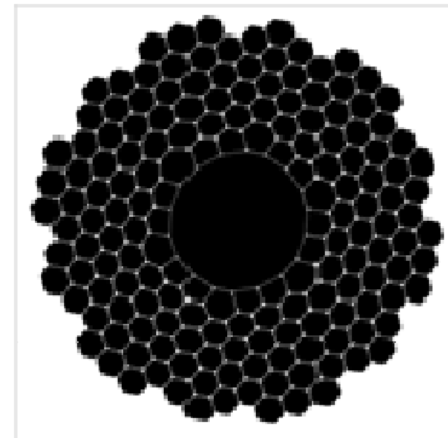
- Transmission fibre and amplifier concepts validated
- Compatibility with installed fibers shown
- Both 3 & 7 element components fabricated

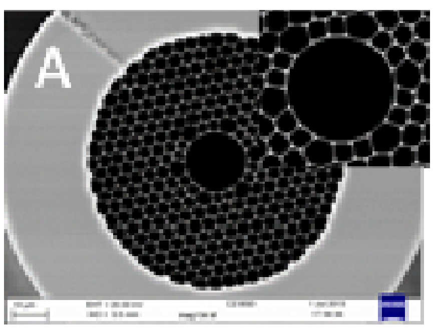
V. F. Rancano ECOC PDA1.C.2 (2013)

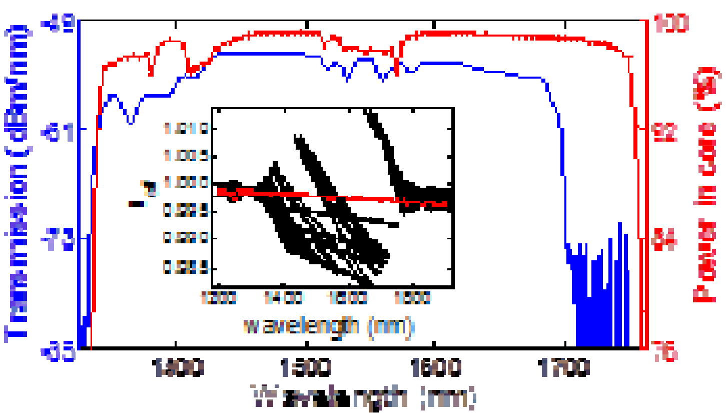
New Modelling Capabilities

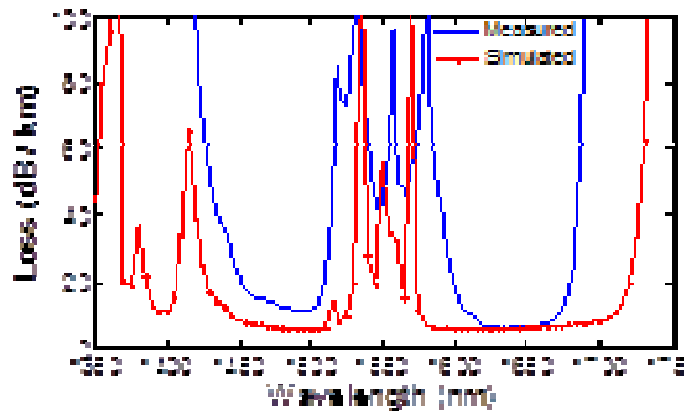






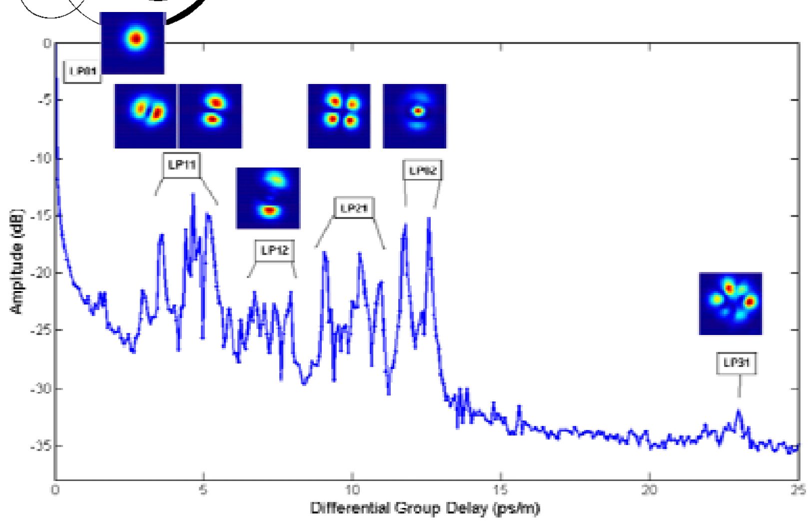


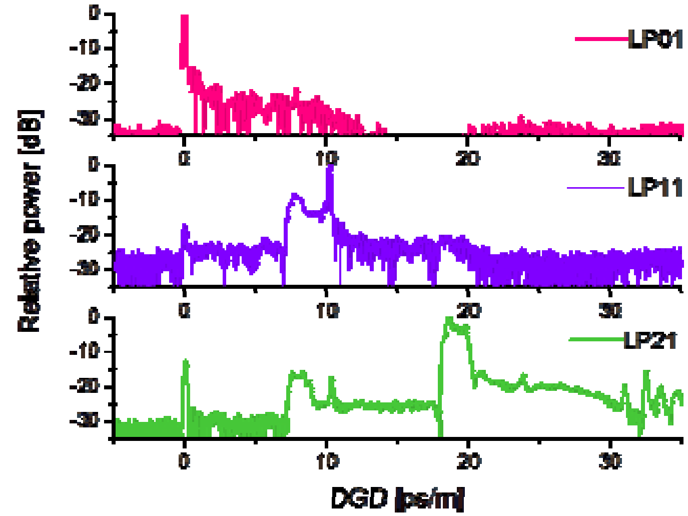


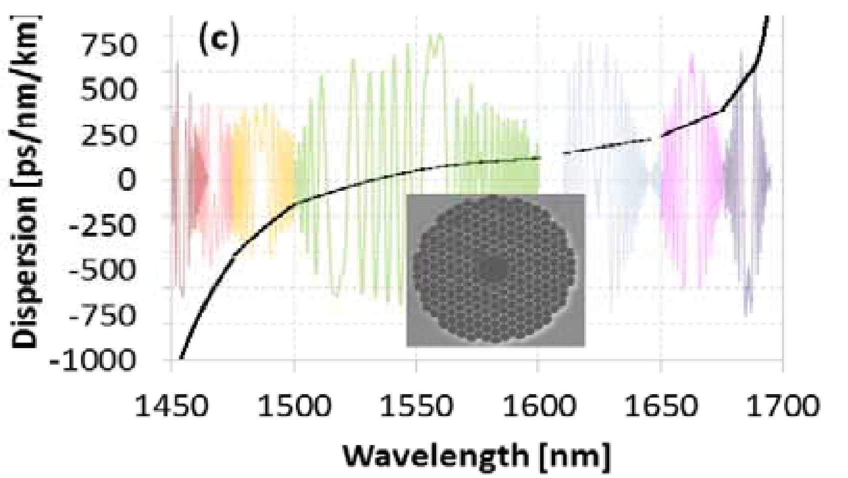


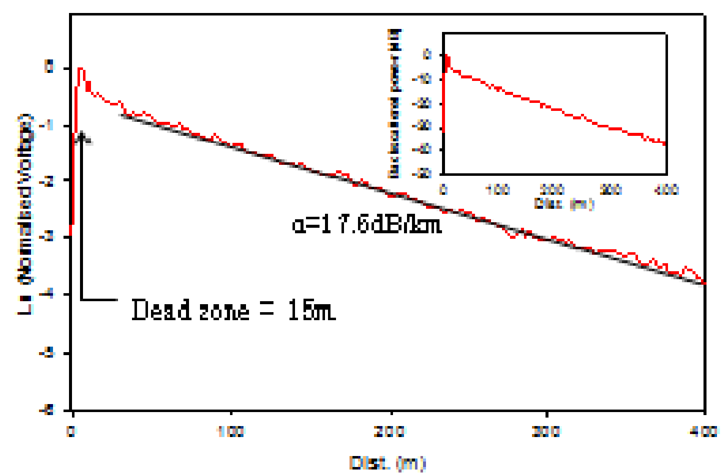
Fokoua et al. Opt. Lett., 38(9), 1382-1384

New Characterisation Tools

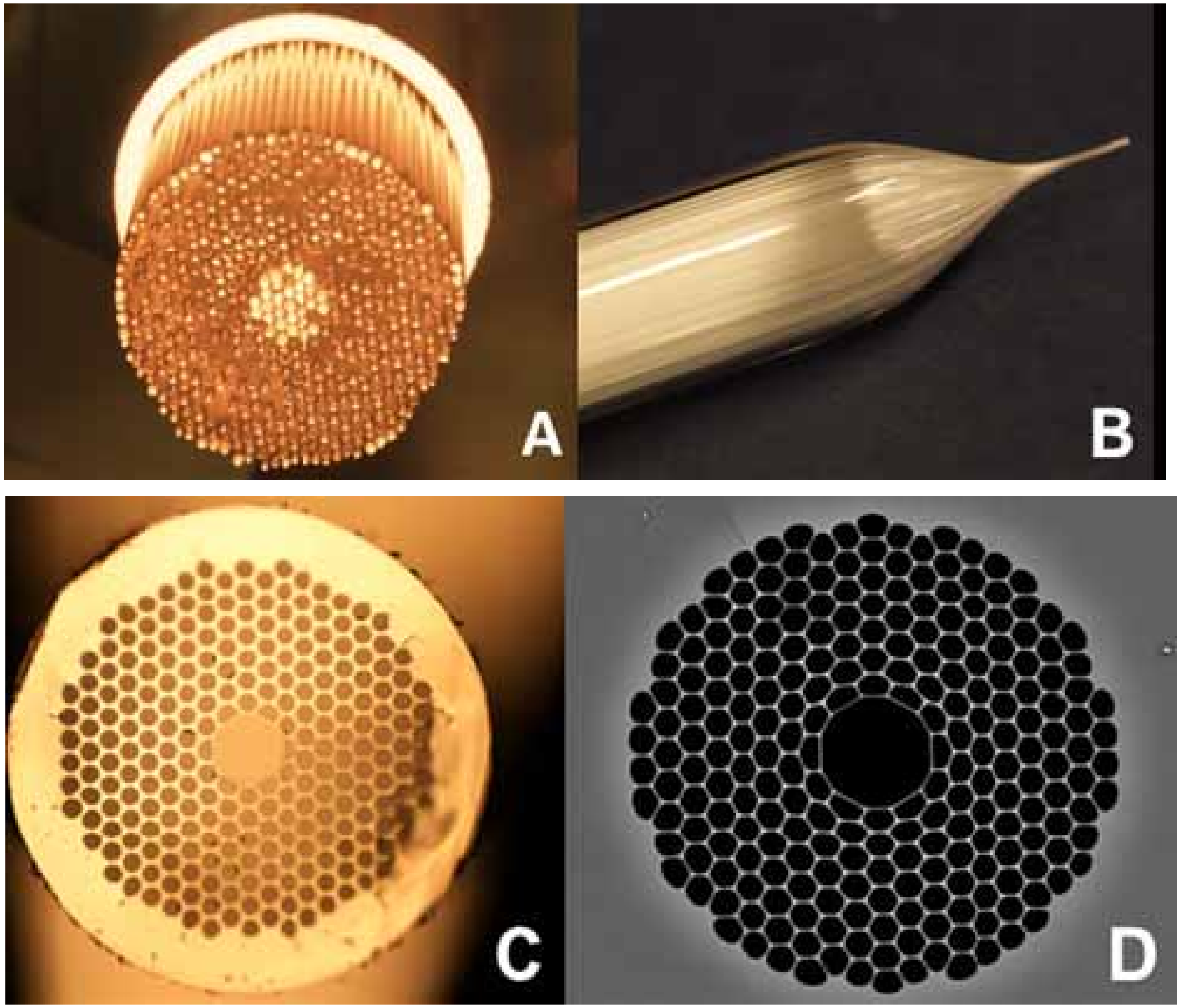




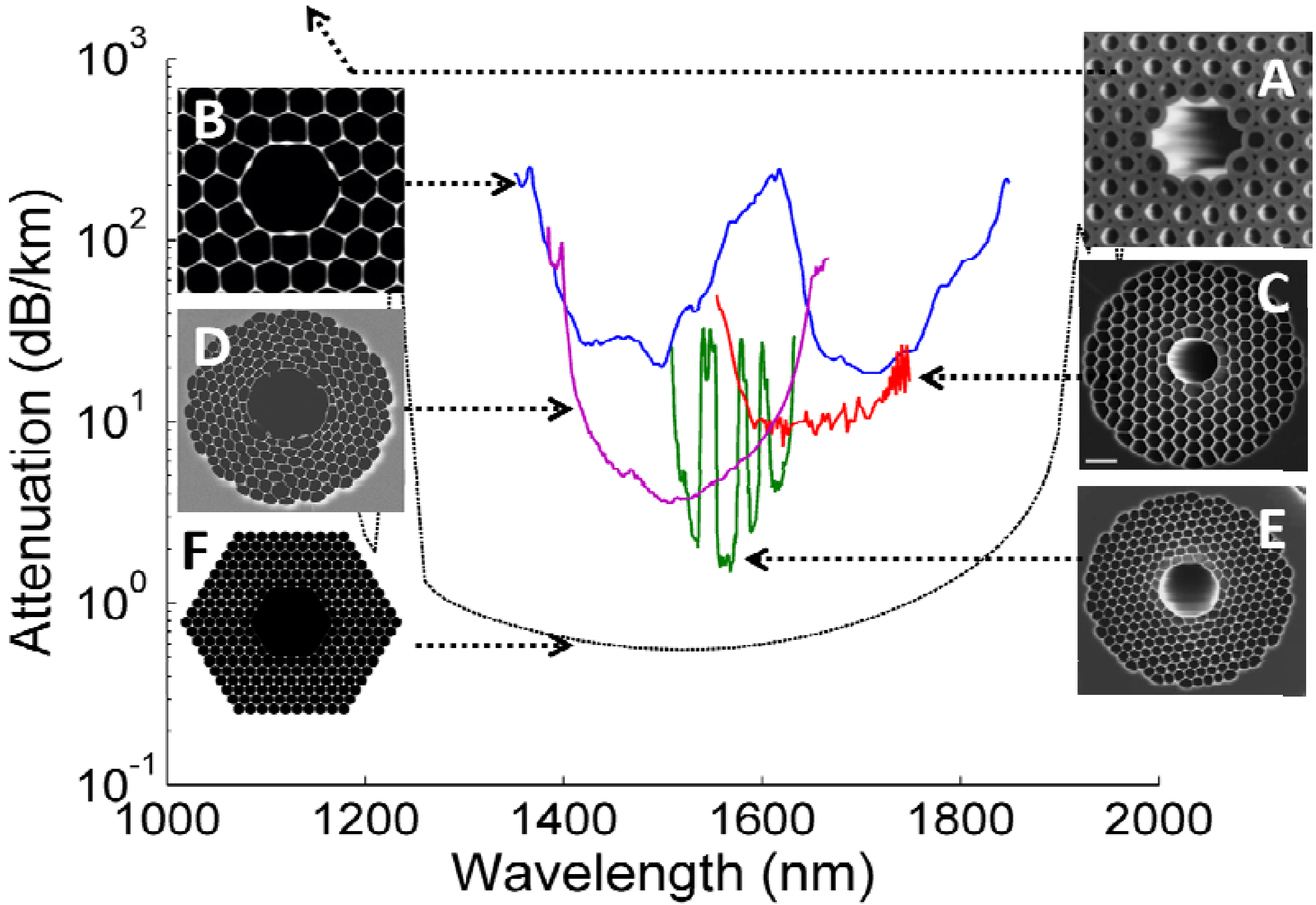




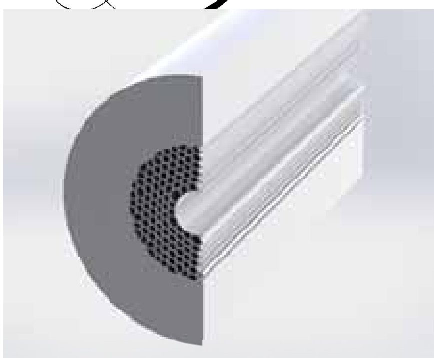
Fabricating PBGF

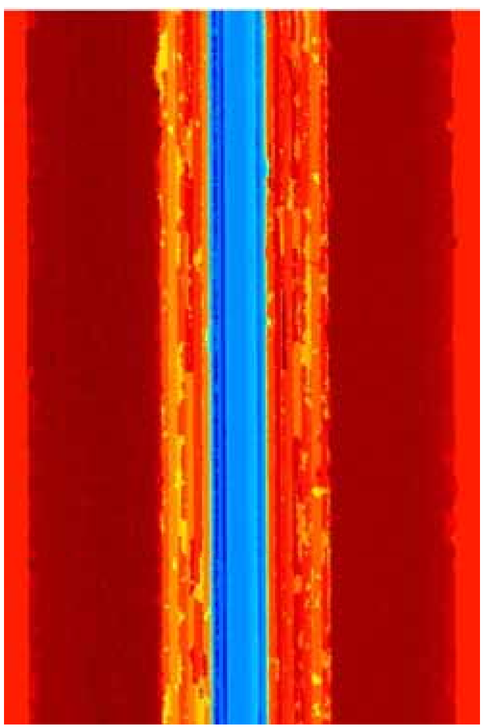


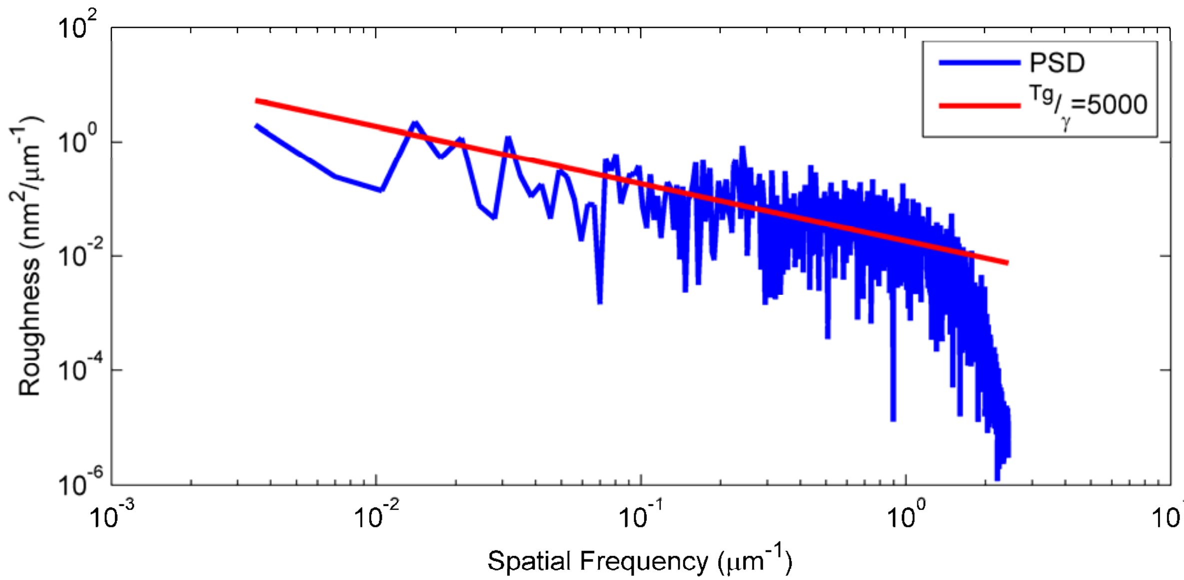
Loss Reduction in PBGFs



Measuring Surface Roughness

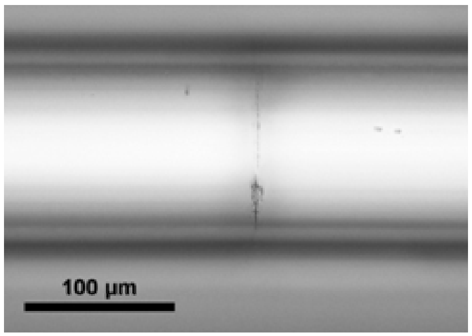


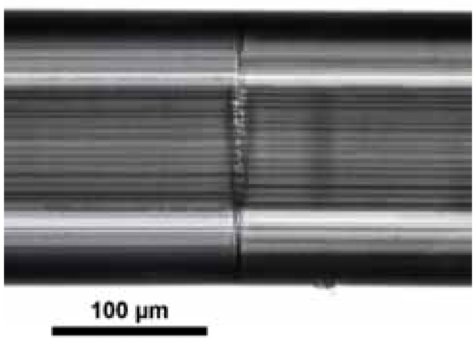


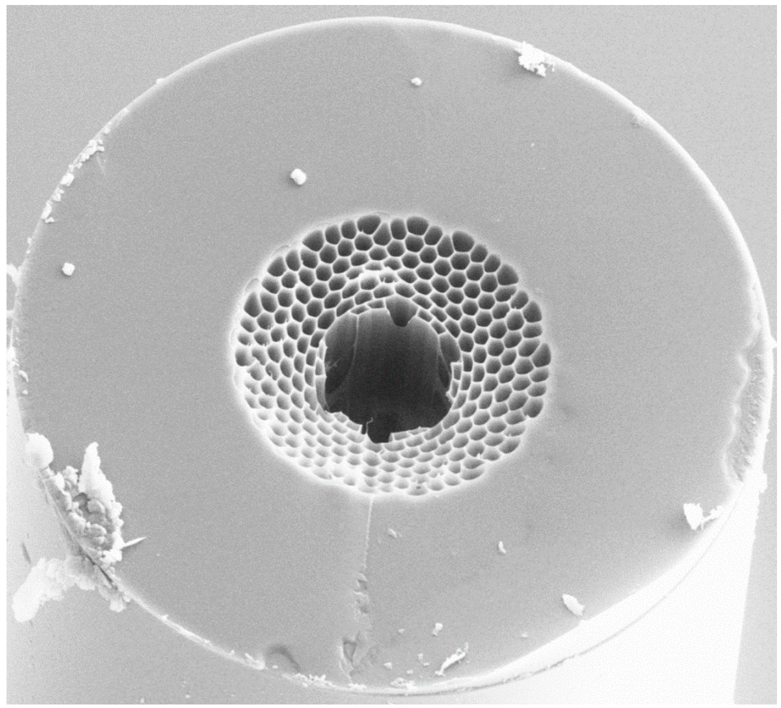


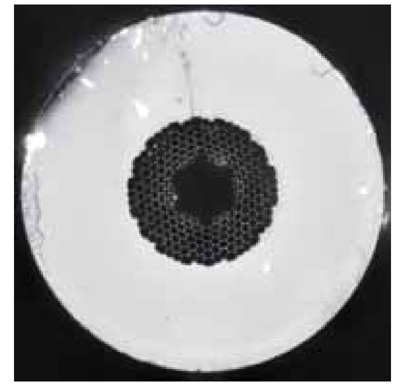
- Sample was analysed using a commercial optical surface profiler
- PSD along the axis of fibre on a line on surface of core was computed

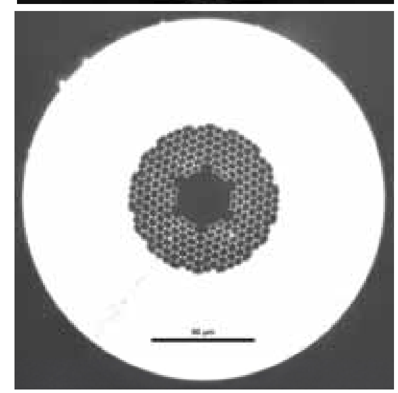
Splicing PBGF- PBGF







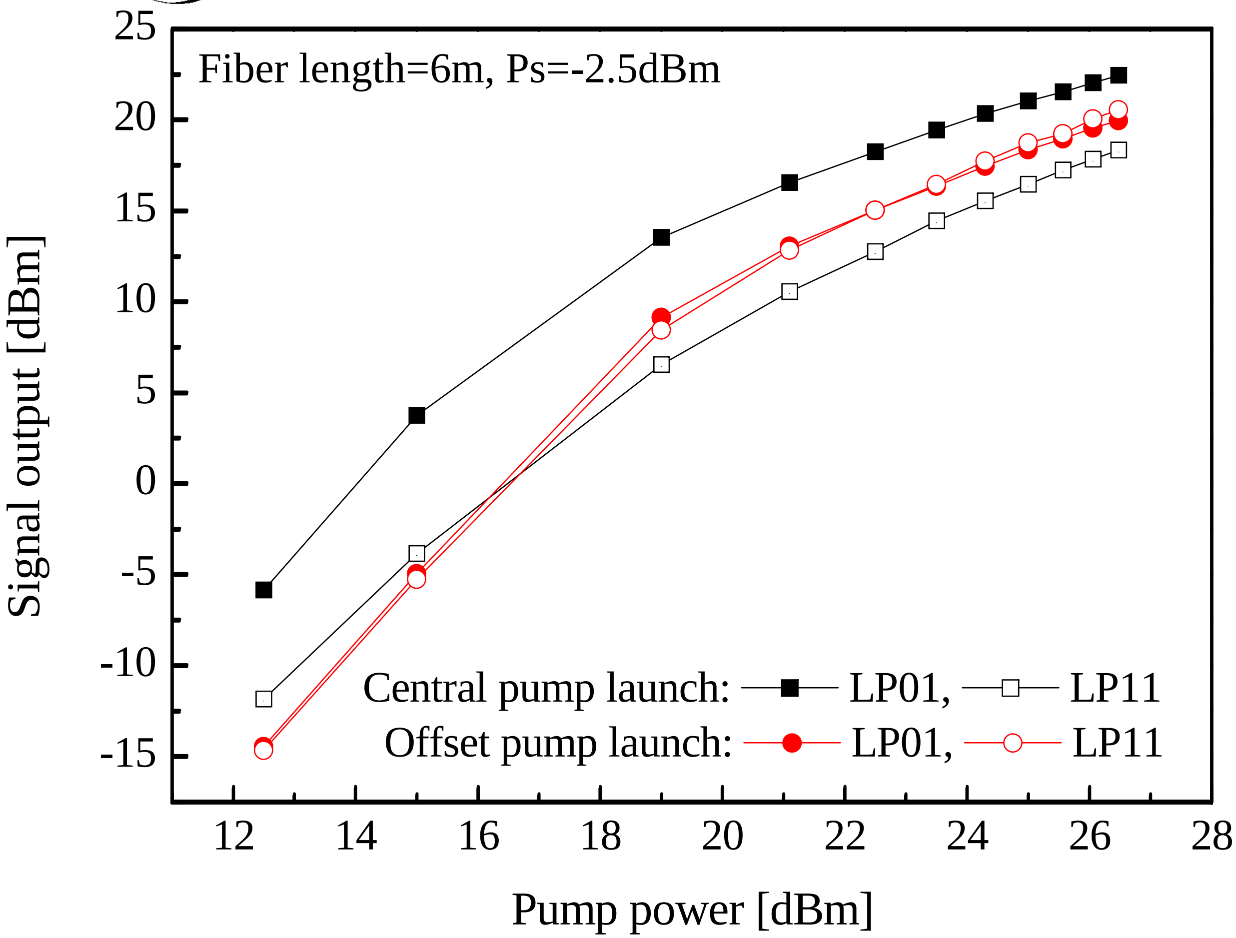


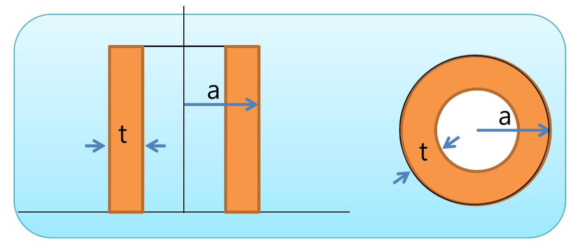


- Strong Mechanical bonding
- Loss <0.15 dB
- Low deformation - (Cave-in depth <5µm)
- Further Loss and deformation optimization in process

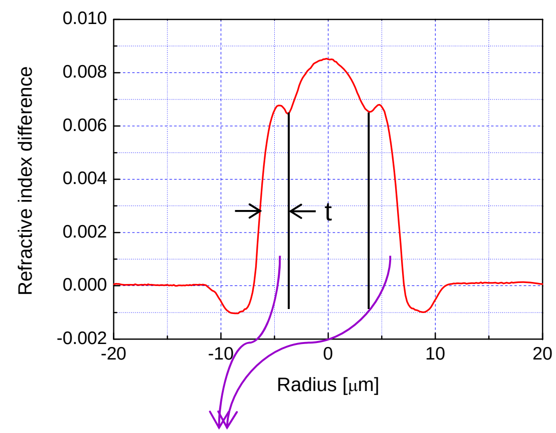
Wooler, OFC, paper OM3I.5, (2013)

Reducing DMG in a 3-Mode EDFA



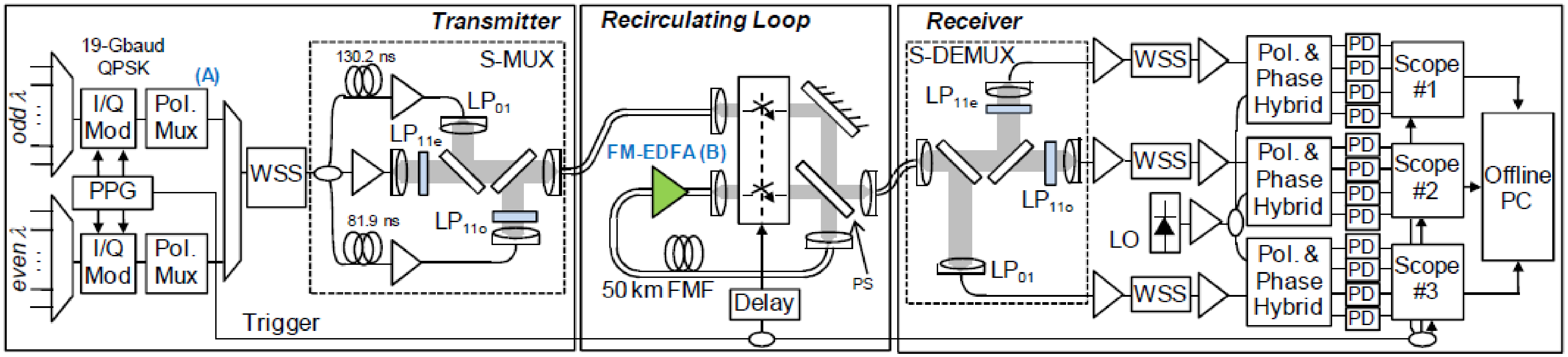


(Designed parameter: a= 6μm, t/a=0.4, NA=0.12)

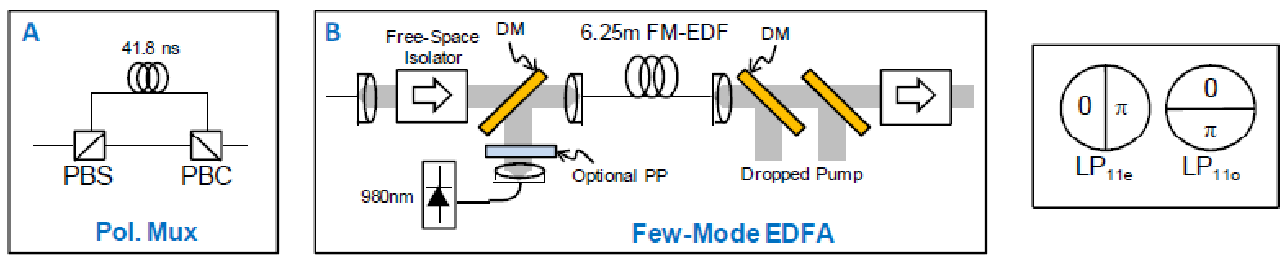


For offset pump launch conditions almost equal gain between the LP_{01} and LP_{11} modes is observed

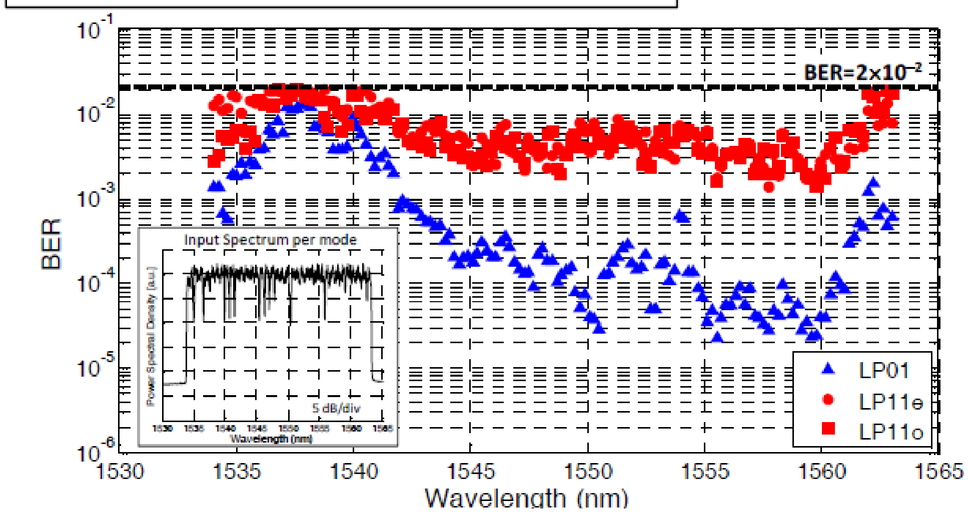
146(WDM) x 3(MDM) over 10x50km



DM = Dichroic Mirror
FMF = Few-Mode Fiber
I/Q Mod= IQ Modulator
LO = Local Oscillator
PD = Photodiode
PP = Phase Plate
PS = Plate Splitter
Pol. Mux = Polarization Multiplexer
Tx = Transmitter
WSS = Wavelength Selective Switch



- 19 Gbaud QPSK
- Low DGD fiber
- Ring doped EDFA
- ~1000 km with 16 WDM



E. Ip et al. OFC PDP5A.2 (2013).

Conclusions

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