The World Wide Web of Glass

The Past, Present and Future of Fiber Optics

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Light

Early Days of Optical Communications

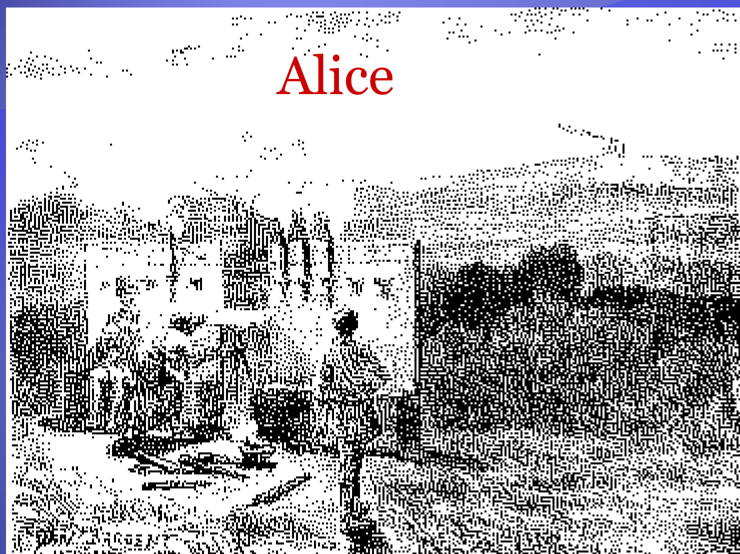
written by Aeschylous 458BC

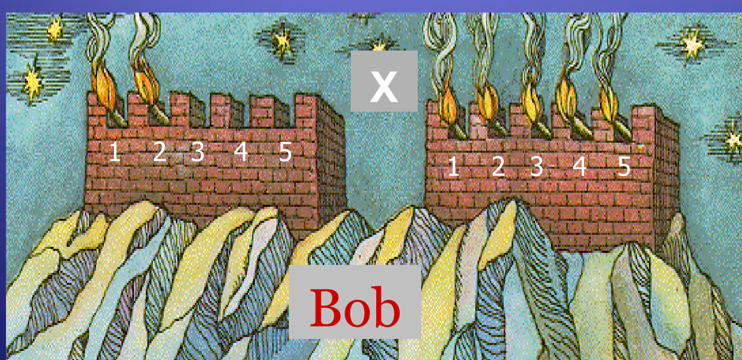
SECOND CHORISTER
What time of day was it when Troy was destroyed?
CLYTEMNESTRA
Not day, but at night. Last night, in fact.
FIRST CHORISTER
And the news has arrived already? How
CLYTEMNESTRA
At the speed of light. Hephaestus' sacred fire blazed from beacon tower to beacon tower, from Ida's top to Lemnos, and from there to Athos, that island sacred to Zeus, where they set the blaze they had kept prepared so long, and the tongues of flame leaped up in the dark ...nd of chorus singing the ... in splendid crescendo. ....

- First free-space optical link transmission ~600km
- Longest span 150km
- 1 bit/night
- 5-10m wood-pile fire (tens of MegaWatts)
- Too bad if it rained!

Early Optical Encoding Schemes

Pyrsia or Telegraph of Polybius (ca 150 BC)





- building on ideas of Cleoxenus and Democleitus
- designed an alphabetic code based on a "code-tablet" concept.

	1	2	3	4	5
1	Α	Β	Γ	Δ	Ε
2	Ζ	Η	Θ	Ι	Κ
3	Λ	Μ	Ν	Ξ	Ο
4	Π	Ρ	Σ	Τ	Υ
5	Φ	Χ	Ψ	Ω	

Α = (1,1)

Γ = (3,1)

Ω = (4,5)

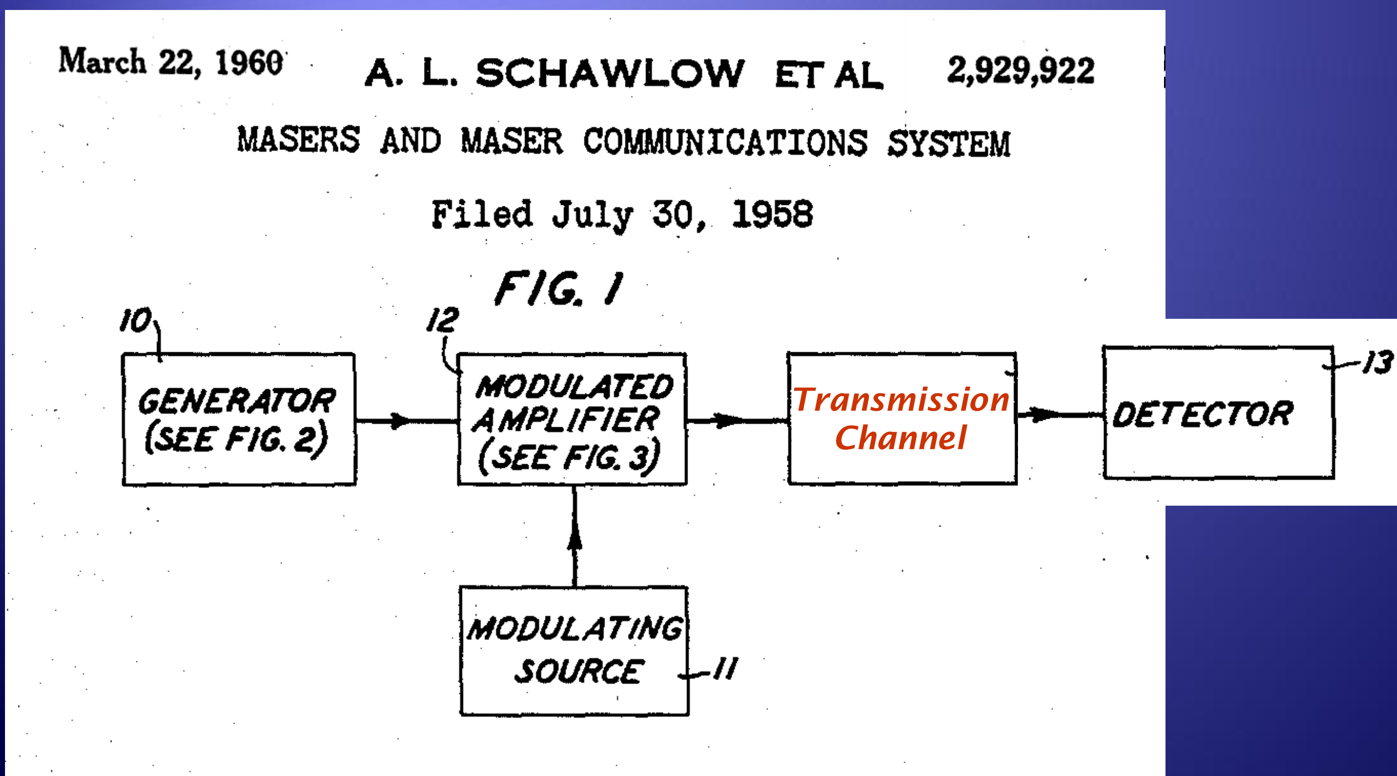
"Pyrsia": instrument using fire lights to communicate information

Modern Optical Communications

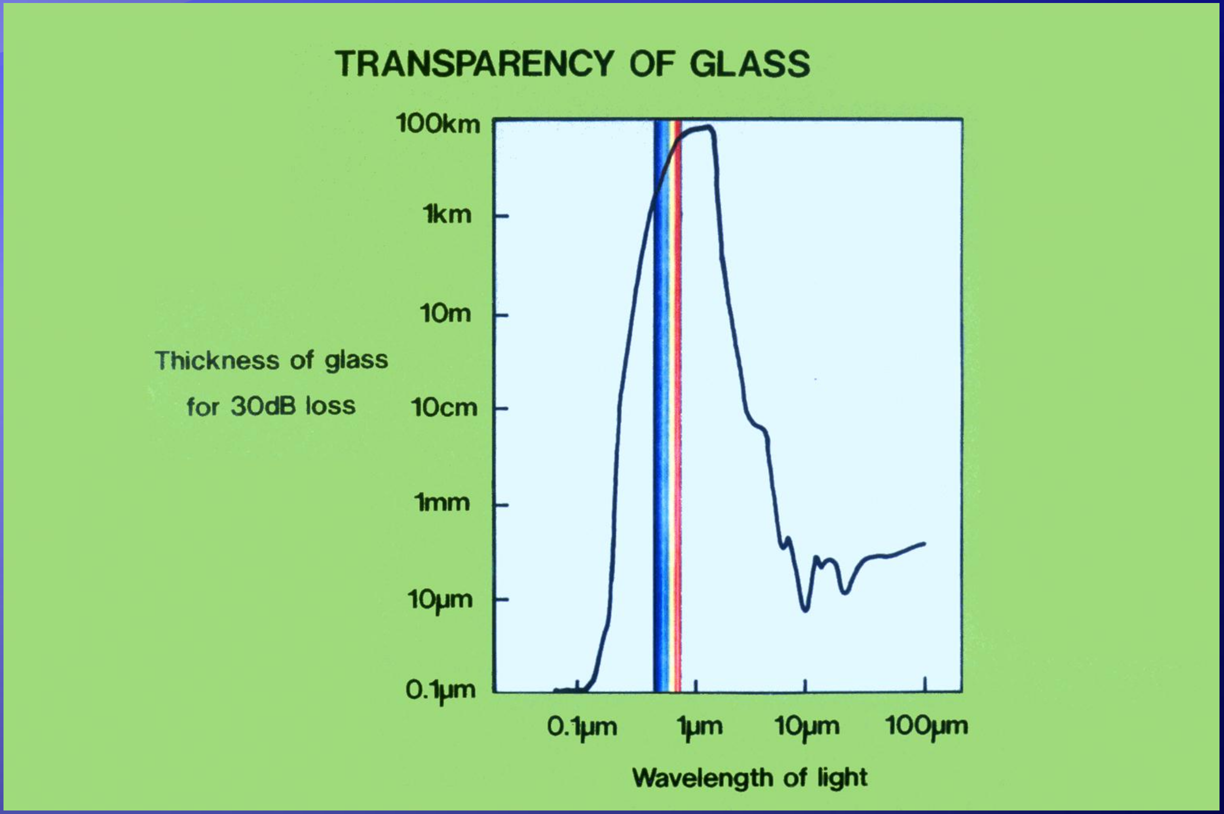
What is claimed is:

1. A communications system for operation in the infrared, visible, or ultraviolet regions of the electromagnetic wave spectrum comprising a monochromatic maser generator, a coherent modulated maser amplifier, a modulating source, and a detector;

- A transmitter source
- A modulator
- A detector
- A transmission channel



Nature has been kind! But it took the genius of Kao to realise it!

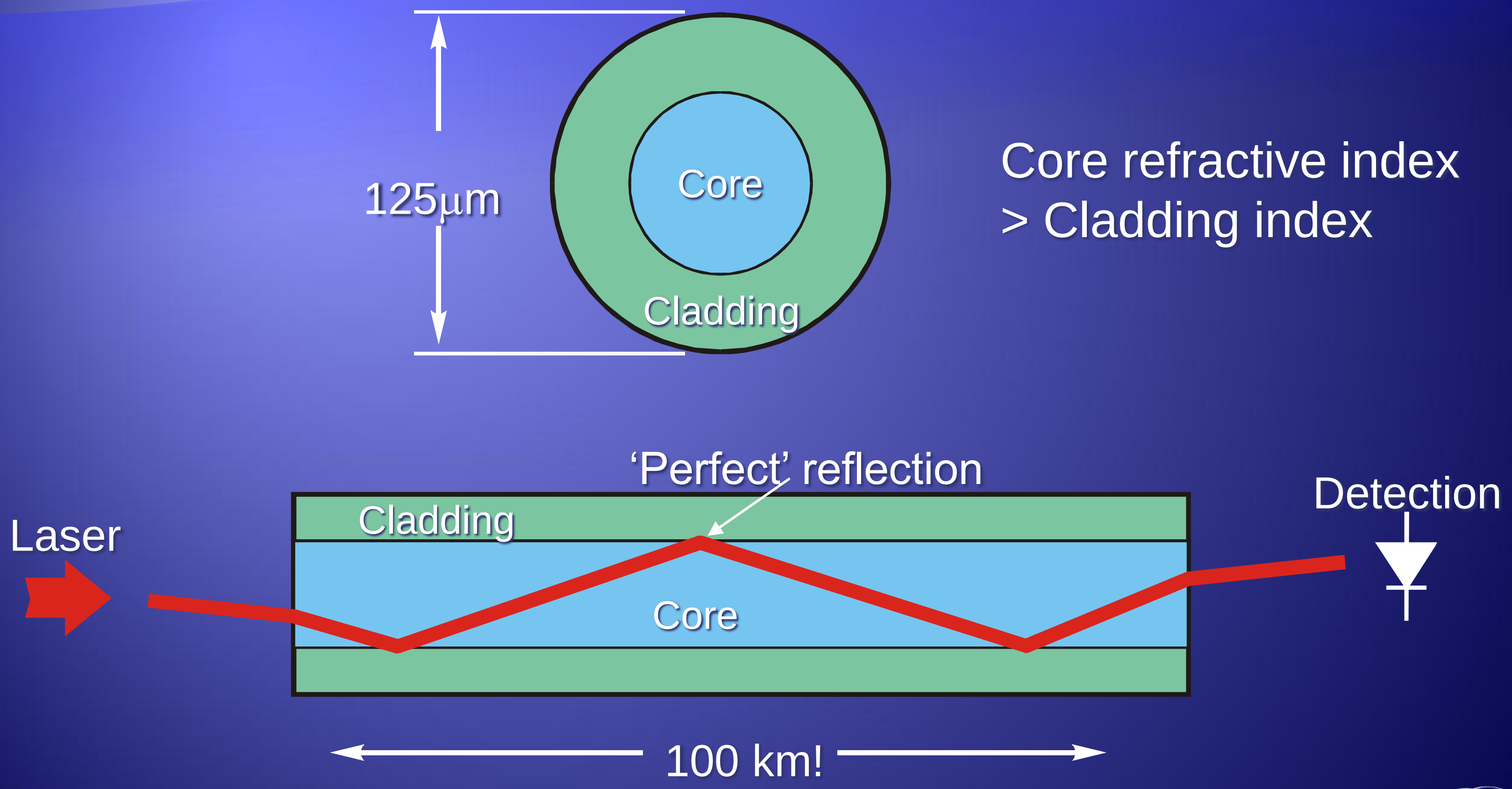


Kao and Hockham
'Dielectric-fibre surface waveguides for optical frequencies'
IEE Proceedings 1966

"a fibre of glassy material..... represents a possible practical optical waveguide with important potential as a new form of communication medium"

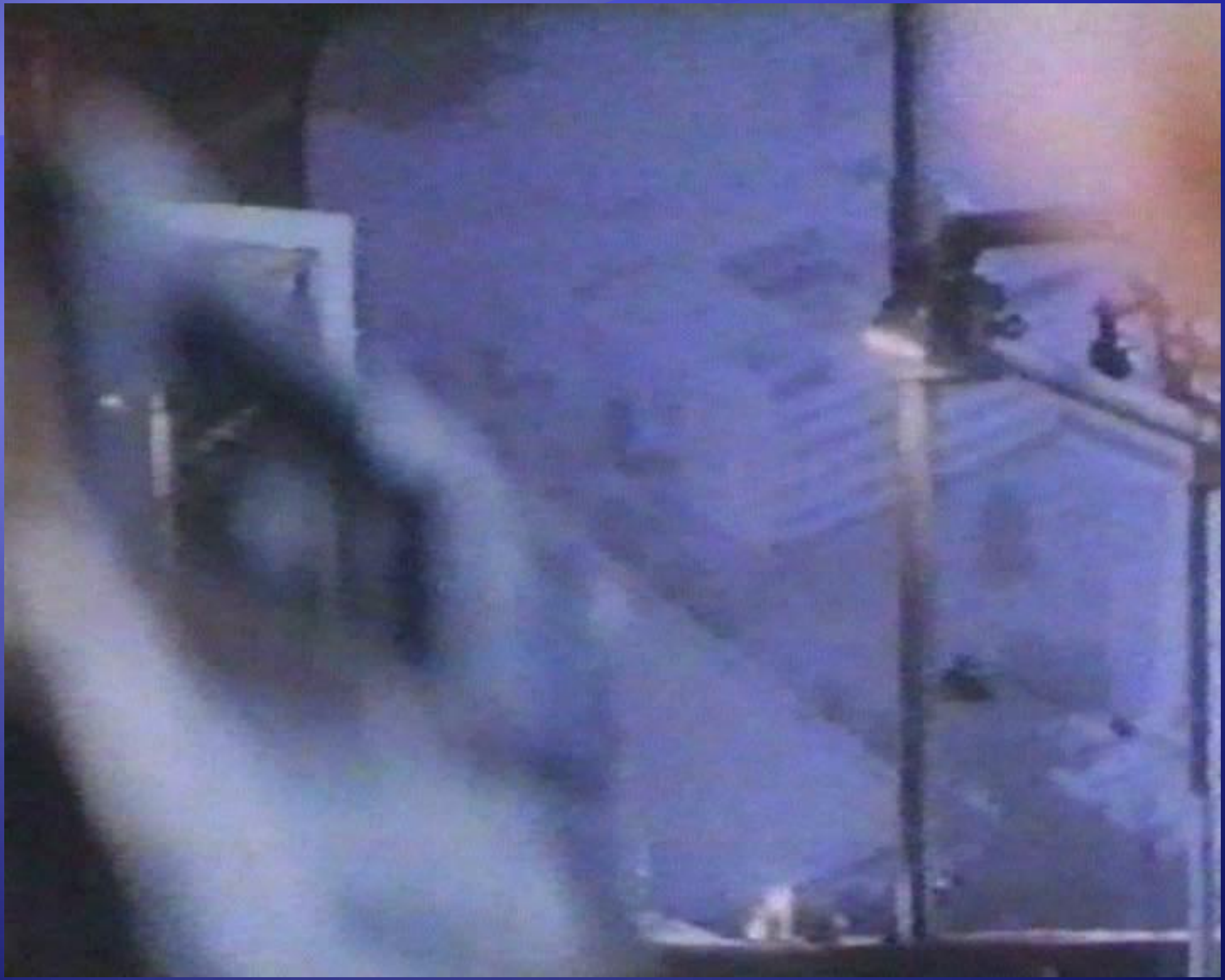
Light

How does fibre work?



Core refractive index
> Cladding index

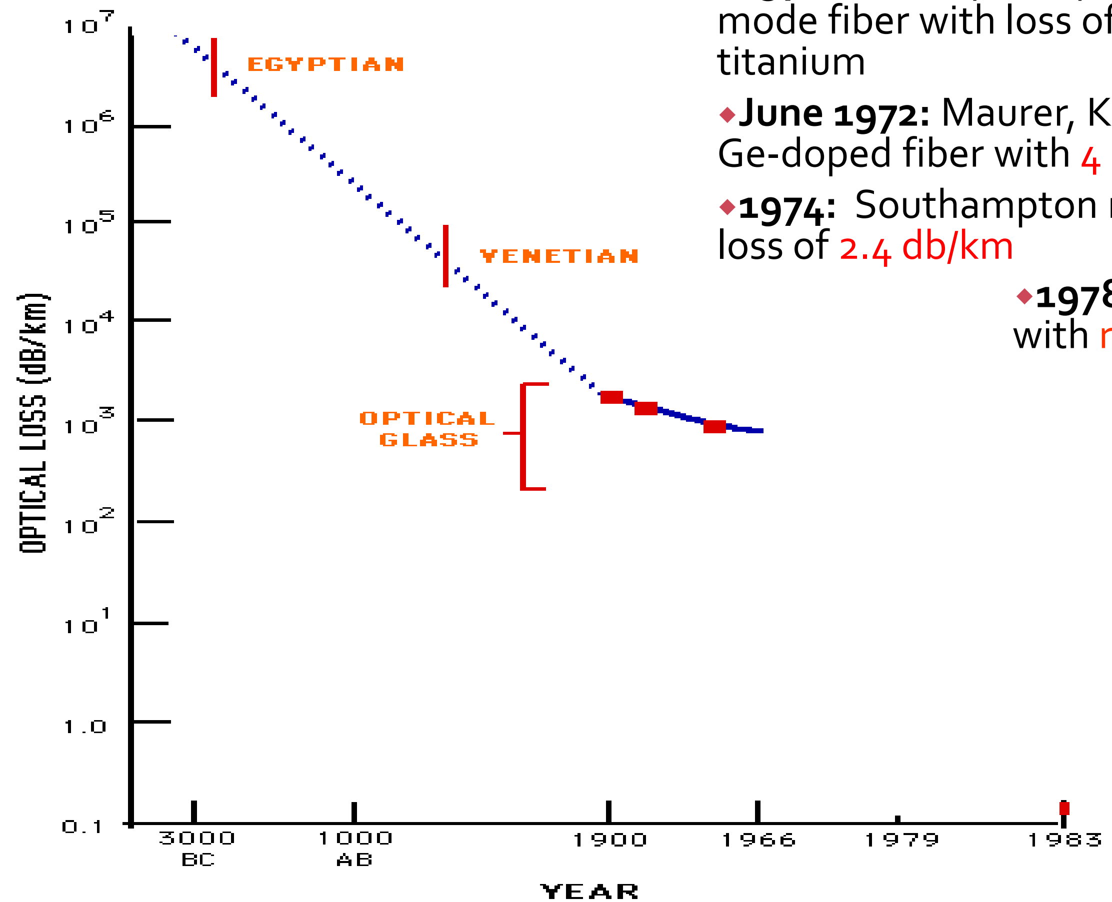
The early days in Harlow - 1966



Charlie Kao

Optical Attenuation in Silica

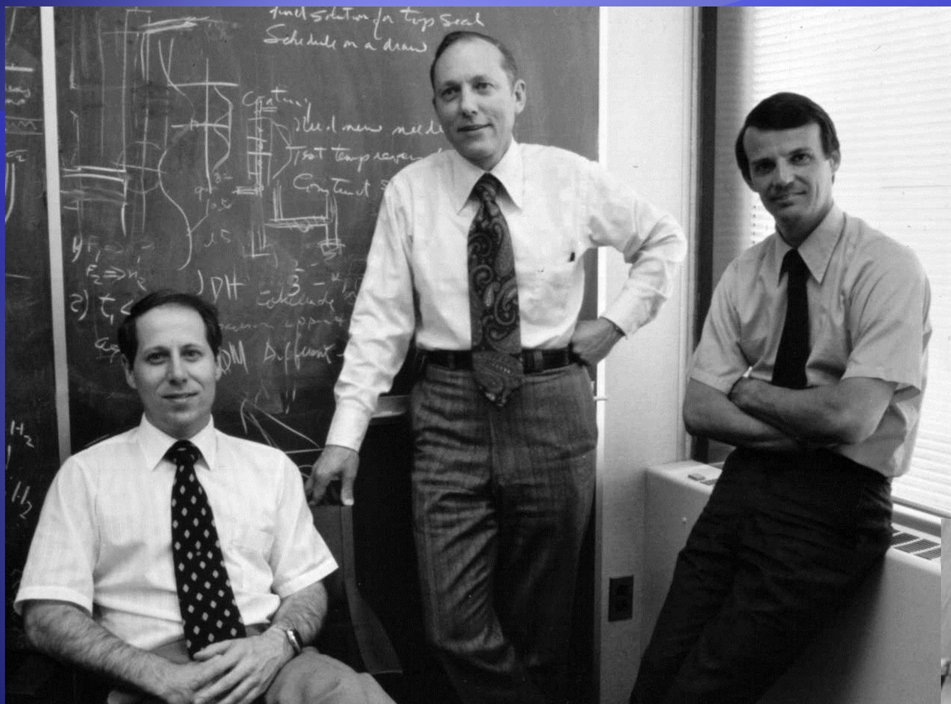
Source: S. Nagel



- **1966**: Kao and Hockham publish paper in Proc IEE
- **1968:** Kao and Jones measure intrinsic loss of bulk silica at 4 dB/km.
- **1970:** Maurer, Keck, Schultz at Corning report a single-mode fiber with loss of 17 dB/km by doping with titanium
- **June 1972:** Maurer, Keck and Schultz make multimode Ge-doped fiber with 4 dB/km loss
- **1974:** Southampton reports phosphosilicate fibre with loss of 2.4 db/km
- **1978:** NTT makes single-mode fiber with record 0.2 dB/km loss at 1.55 um

Source:
Jeff Hecht – City of Light

1970: 20 dB/km fiber breakthrough at Corning



Keck, Maurer and Schultz

OVD Soot preform-making

Source: Pete Schultz

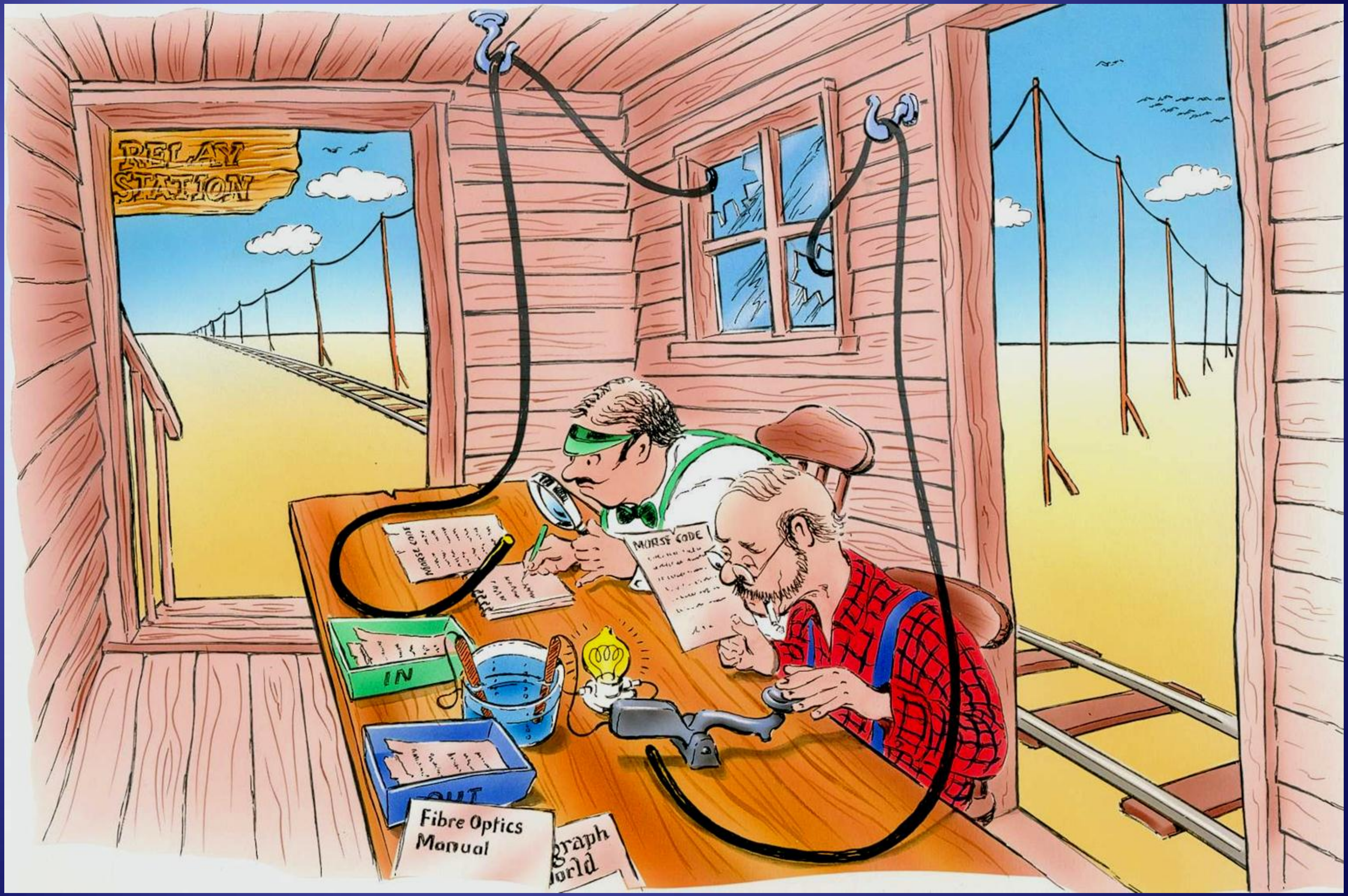
Early Fibers at Southampton

Vintage Payne
1969

2005

The historic drawing machine
lost forever

There was just one further problem

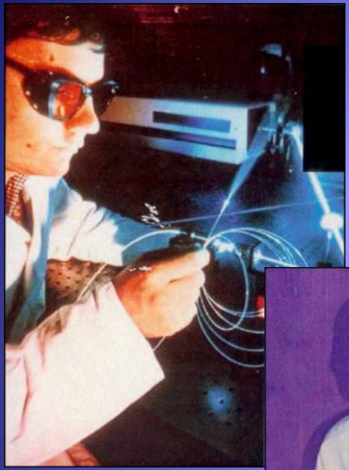


No amplifier!

Who needs an amplifier….?

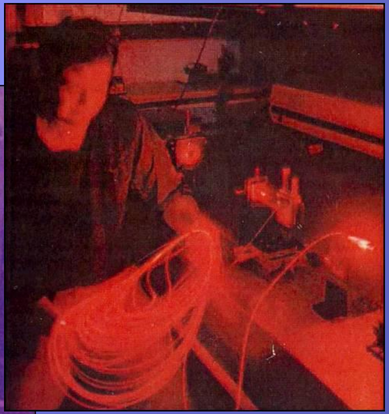
The Erbium-doped fibre amplifier

Southampton 1986

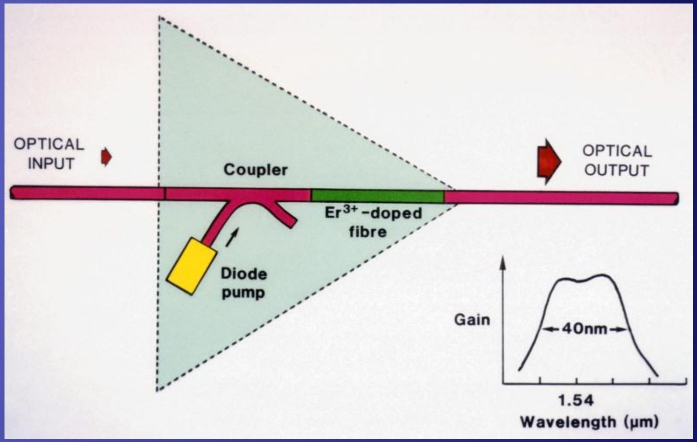


Reekie

Poole



Mears

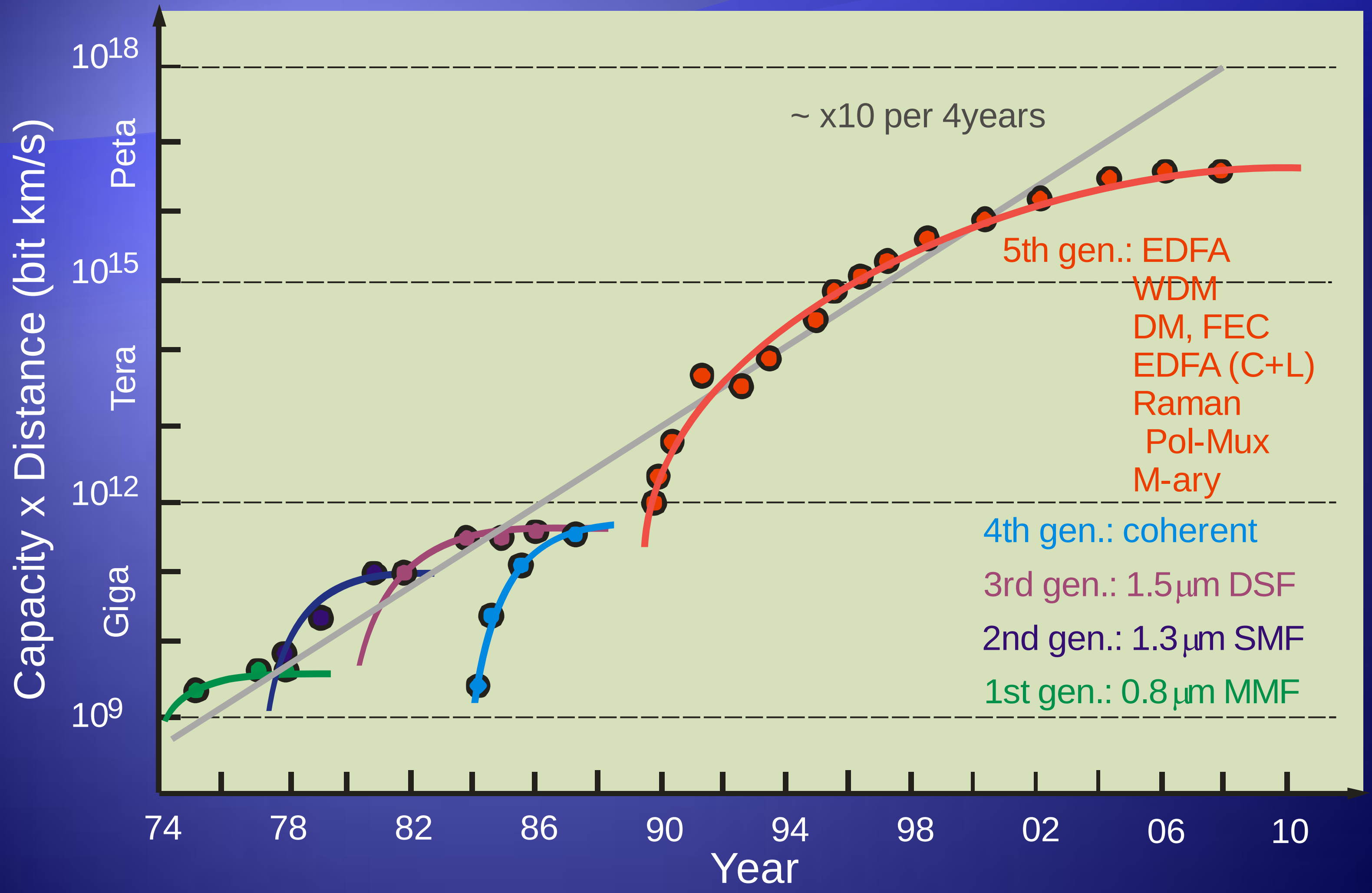


"The broad fluorescence linewidth of rare-earth ions in glass allows the construction of broadband amplifiers for use in wavelength-division multiplexing. It should be possible to use distributed amplification as a means of overcoming losses in soliton propagation"

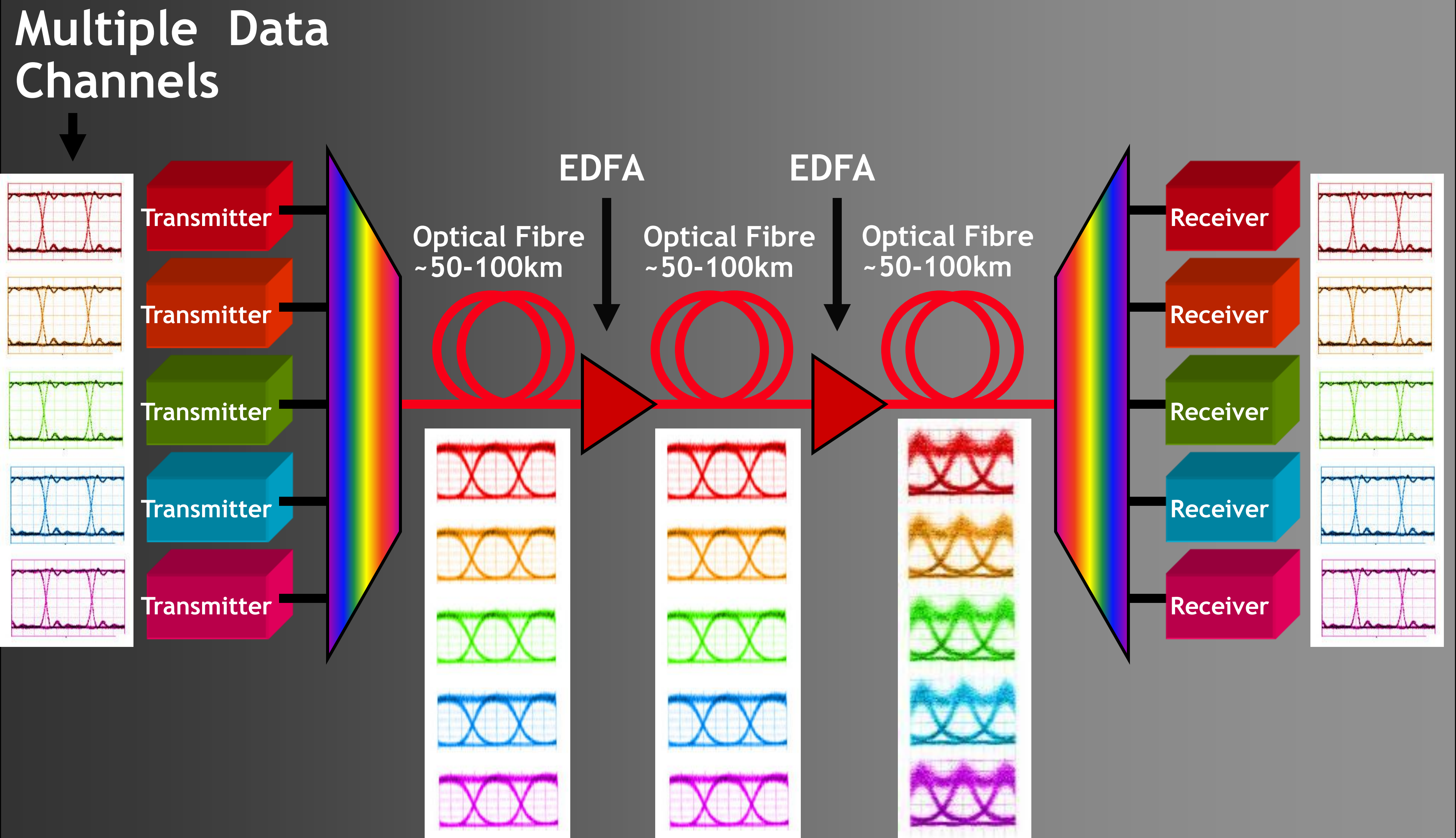
ECOC 1985, Venice

Capacity x Distance Growth

(over single fibre)

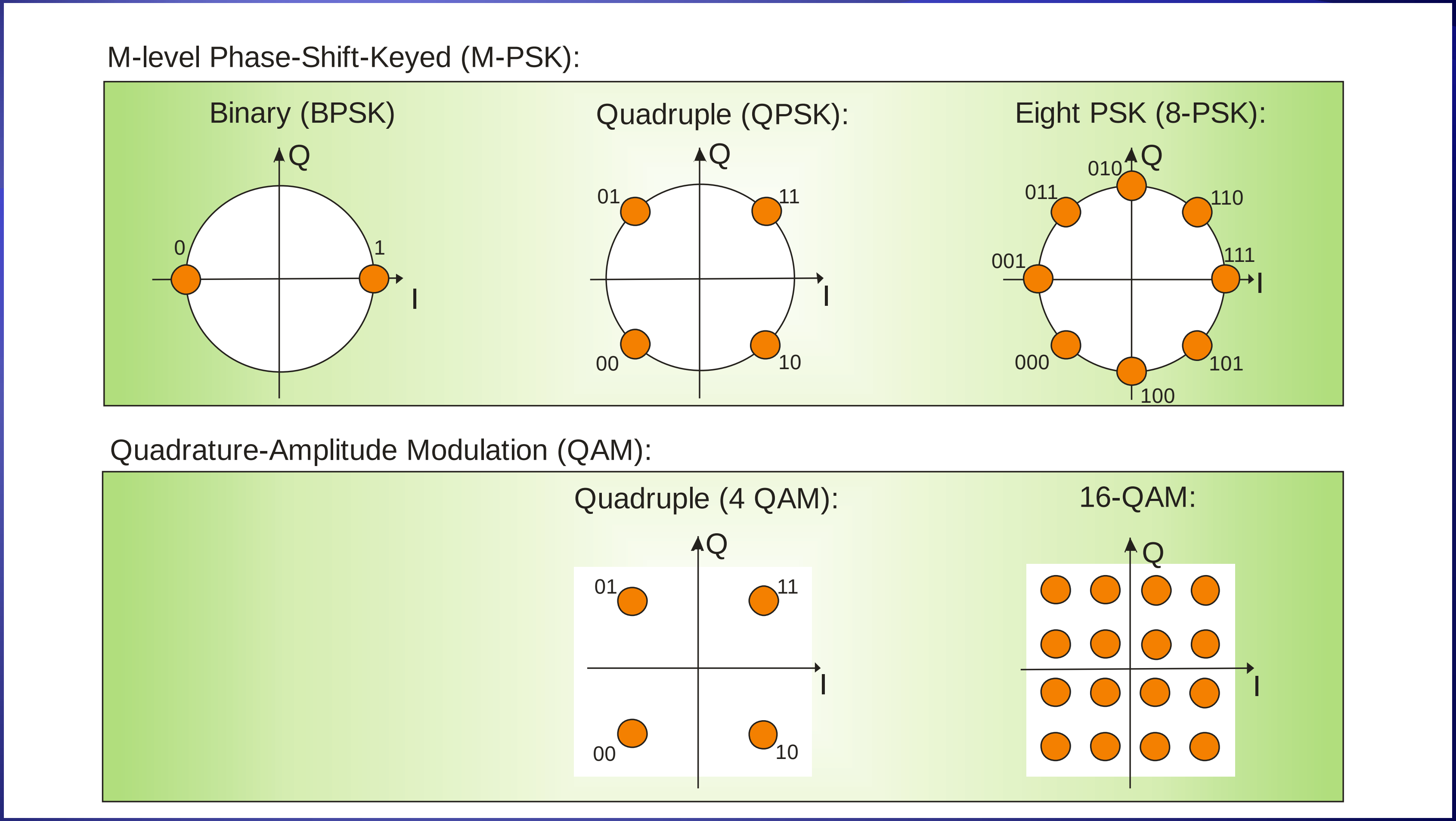


Optically-Amplified Transmission of Wavelength Division Multiplexed Signals



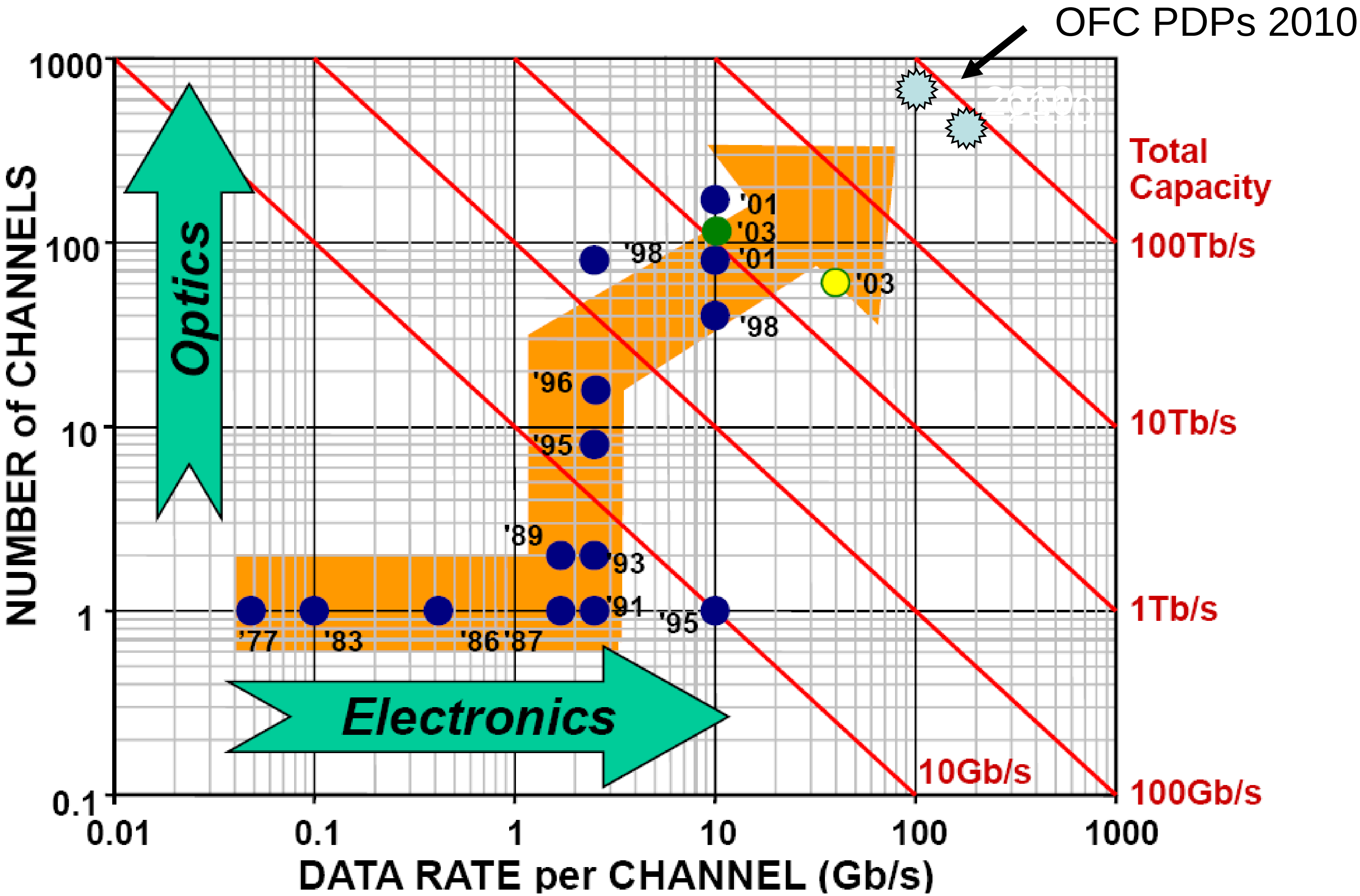
10s to 100s of WDM channels in a single optical fibre

Advanced Modulation Format Signalling



- Exploit phase and amplitude of electric field
- Use electronic DSP to make practical
- Higher spectral efficiency, increased tolerance to transmission impairments
- Better receiver sensitivity

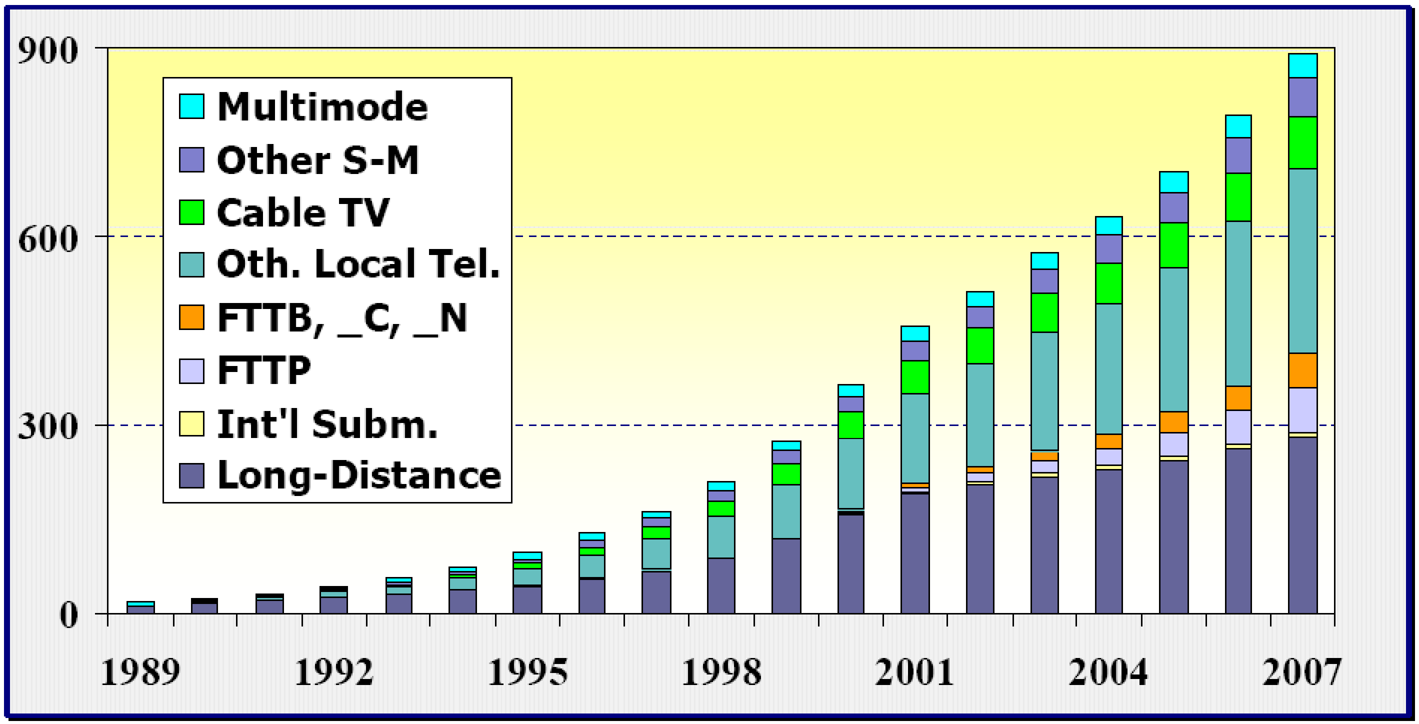
Commercial System Capacities



Ultimately Constrained by Amplifier BW

Ultimately Constrained by Nonlinearity

Global Fibre Deployment (Mkm)



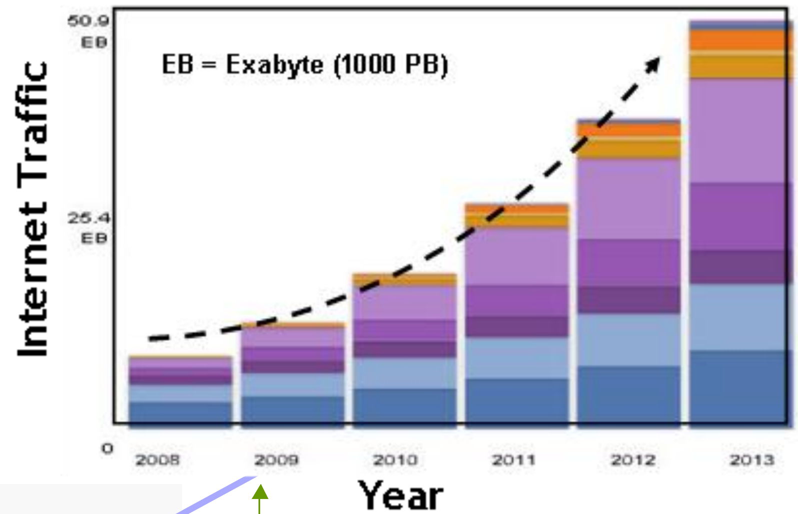
Other S-M = utility, railway, highway, government, military, premises, etc.

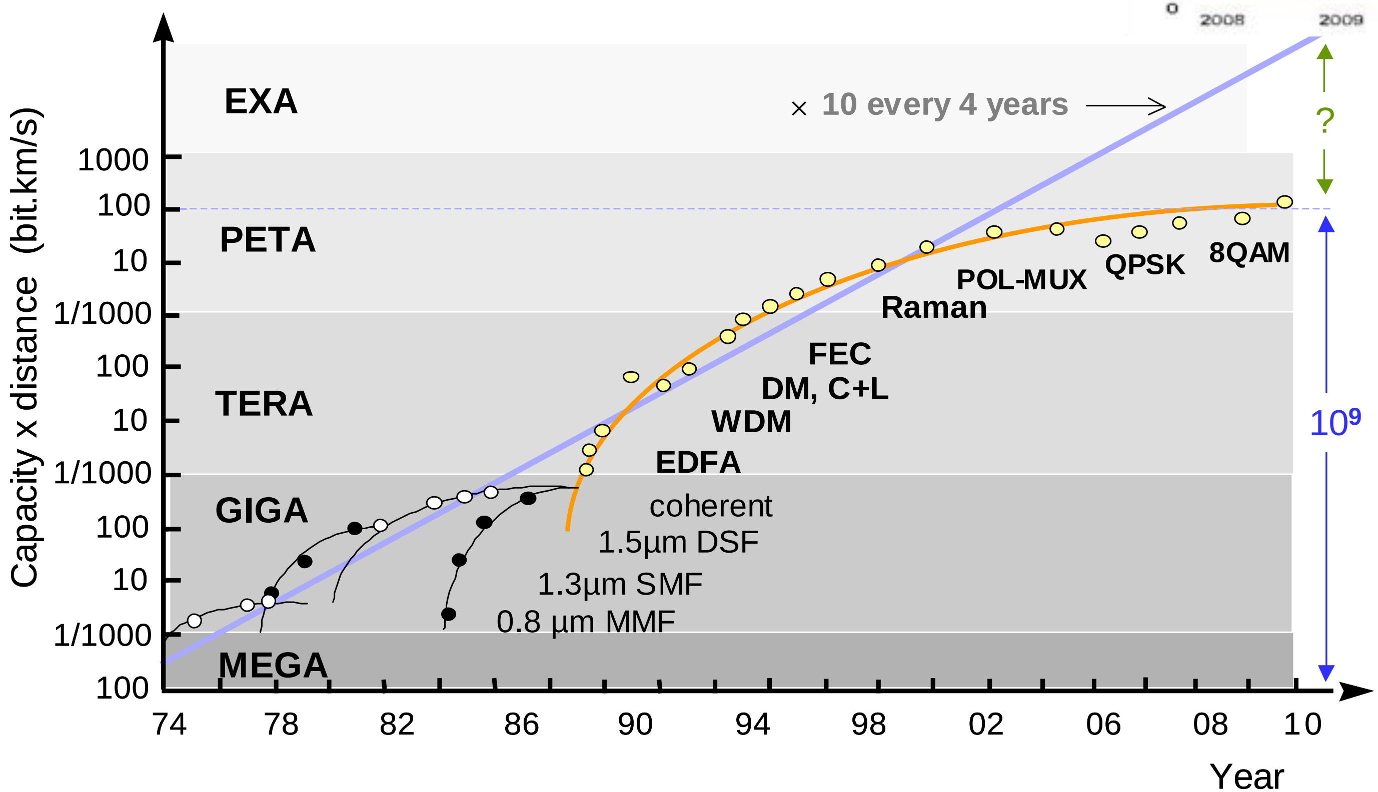
Other local tel. =CO trunks, metro rings, business/office parks, CLEC, etc.

- Total deployment approaching 1 Billion km!
- Growth in all sectors
- Greatest in the Metro/Access
- Most rapid growth in FTT-P

Growth in Capacity and Demand

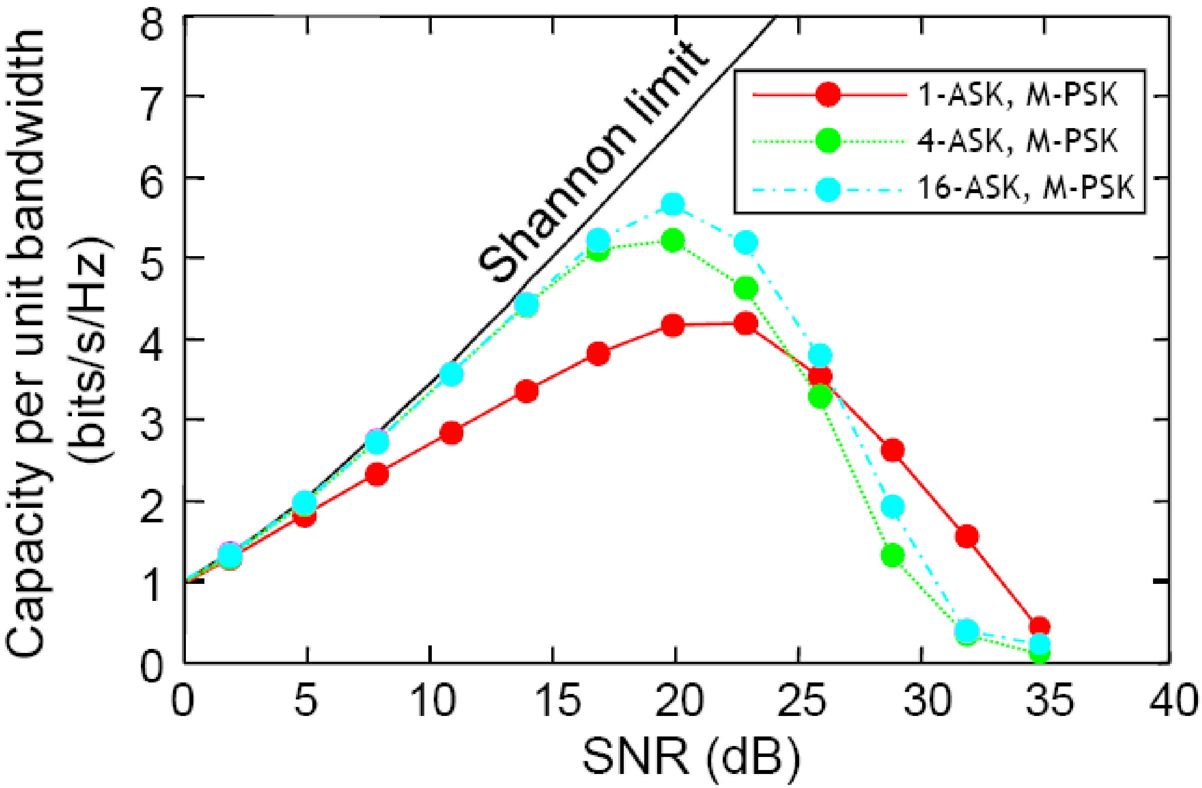
Unrelenting demands for increasing internet data traffic (40-50% p.a.)

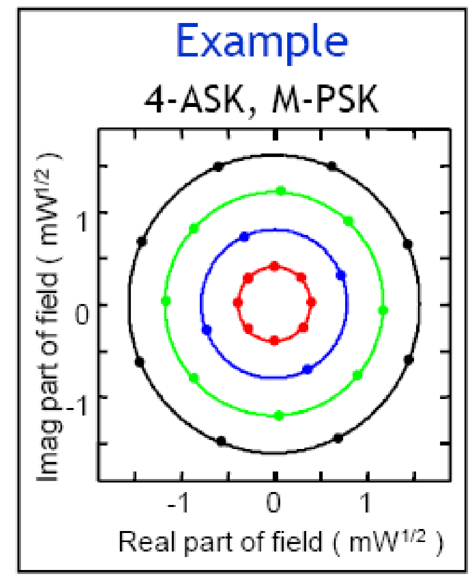




Saturation in single fibre transmission capacity looming

The Ultimate Capacity Limits

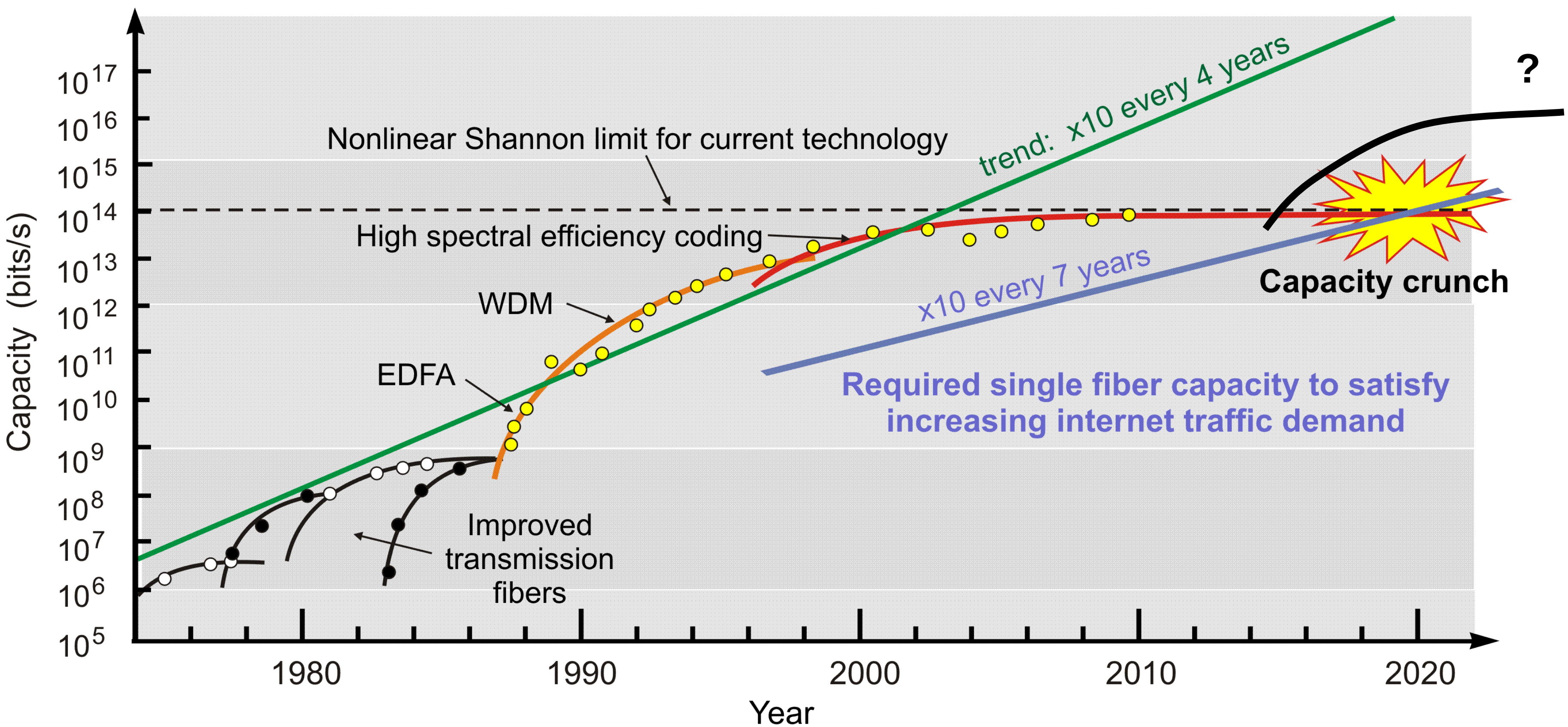




- Maximum information spectral density (ISD) limited by fiber nonlinearity
- Up to 5.5 bits/Hz possible per polarisation (@2000km)
- 8bits/Hz SE over 320km achieved recently 32QAM + 2 polarisations
- ~ 100 Tbit/s accepted limit of current SM technology

R.J. Essiambre et al., PRL, 101, 163901, (2008).

The Telecomms Challenge



- Potential crunches ahead in both Capacity and Energy!

Routes to Higher Capacity

Overall Fibre Capacity =

New amplifiers
Extended low loss

Available Bandwidth

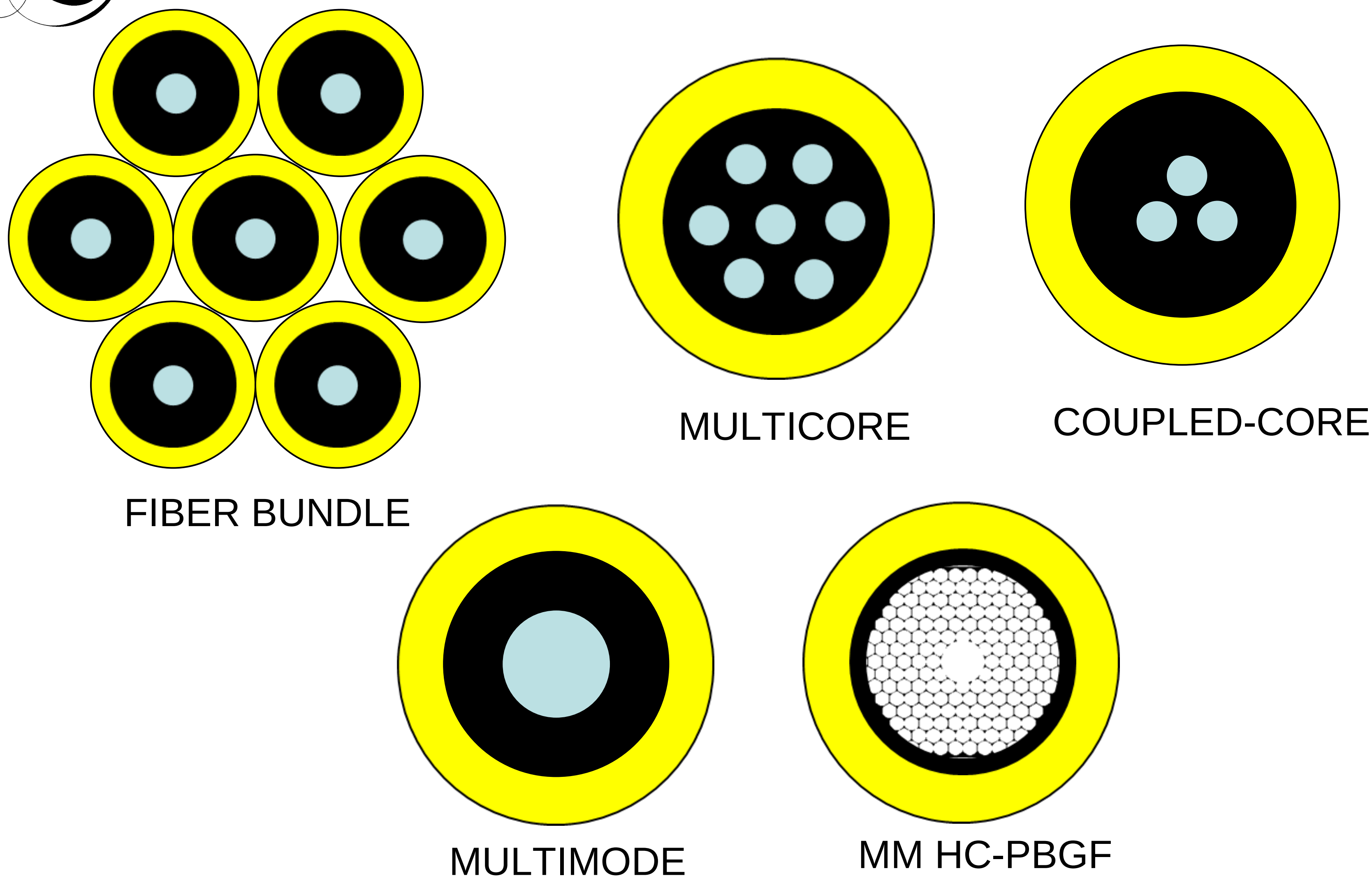
Exploit electronics…
Low nonlinearity
Ultralow loss

x Spectral Efficiency

Multi core fibre
MM fibre

x Number of Information Channels

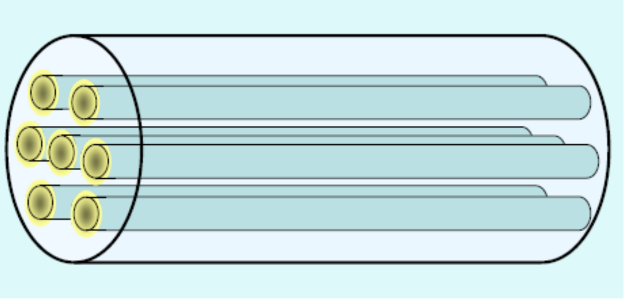
Exploiting Space



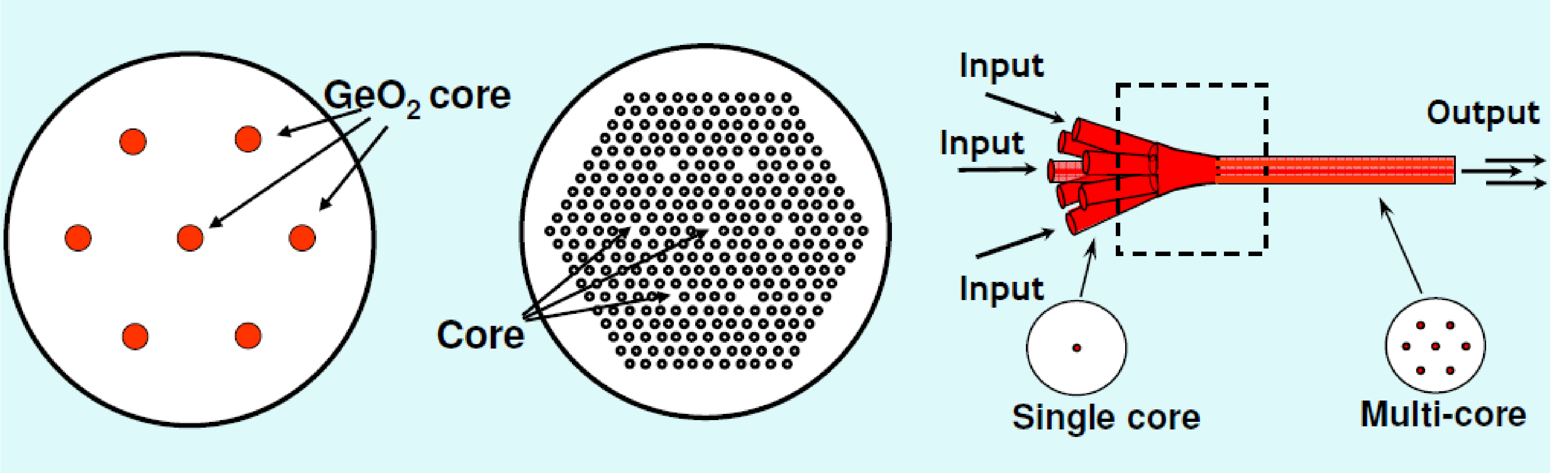
Multicore Fibres for SDM

- **Passive and active (Er-doped) multi core fibre (MCF) demonstrated by several groups (***Furukawa Electric co., OFS …..***)**

MCF preform assembly



- Crosstalk between cores is a critical issue for MCF



(a) MCF with multiple GeO_2 cores in a uniform cladding

(b) MCF with multiple silica cores in an air-hole cladding

(c) Multi-core coupler

- M. Koshiba et al., IEICE Electron. Express, vol. 6, pp 98 (2009)
- B. Zhu et al., Optics Express, 18, pp. 11117 (2010)
- K. S. Abedin et al., Optics Express, 19, pp.16715 (2011)

Recent Low Crosstalk 7-core Fibers

Furukawa

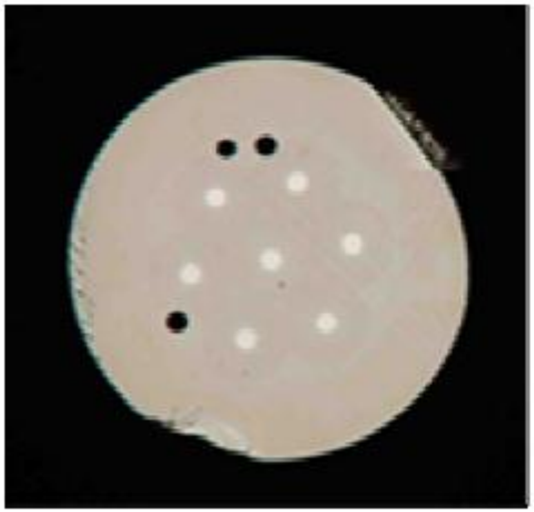
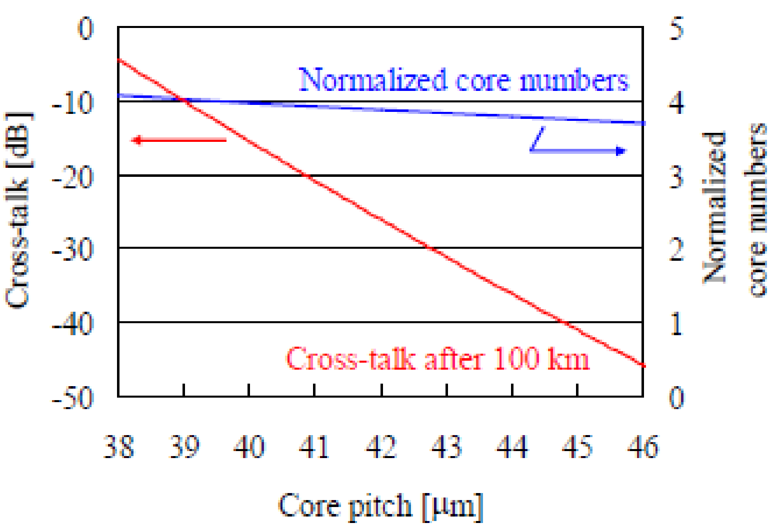


Fig. 5 A cross section of a solid MCF



Sumitomo

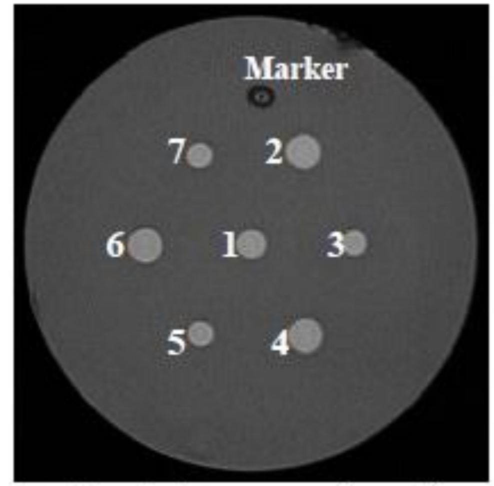


Fig. 1. A cross section of the fabricated fiber.

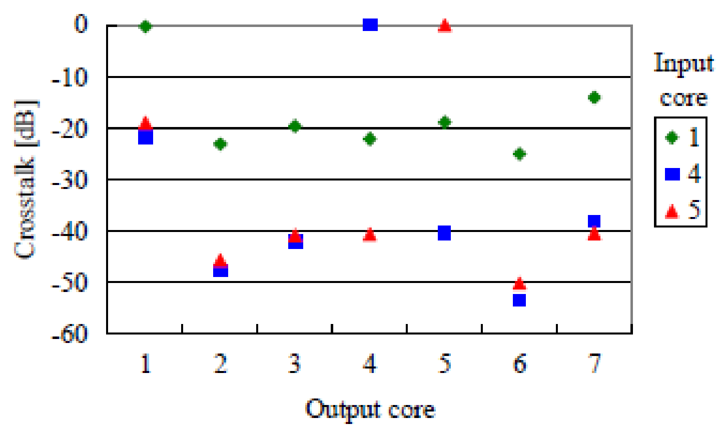
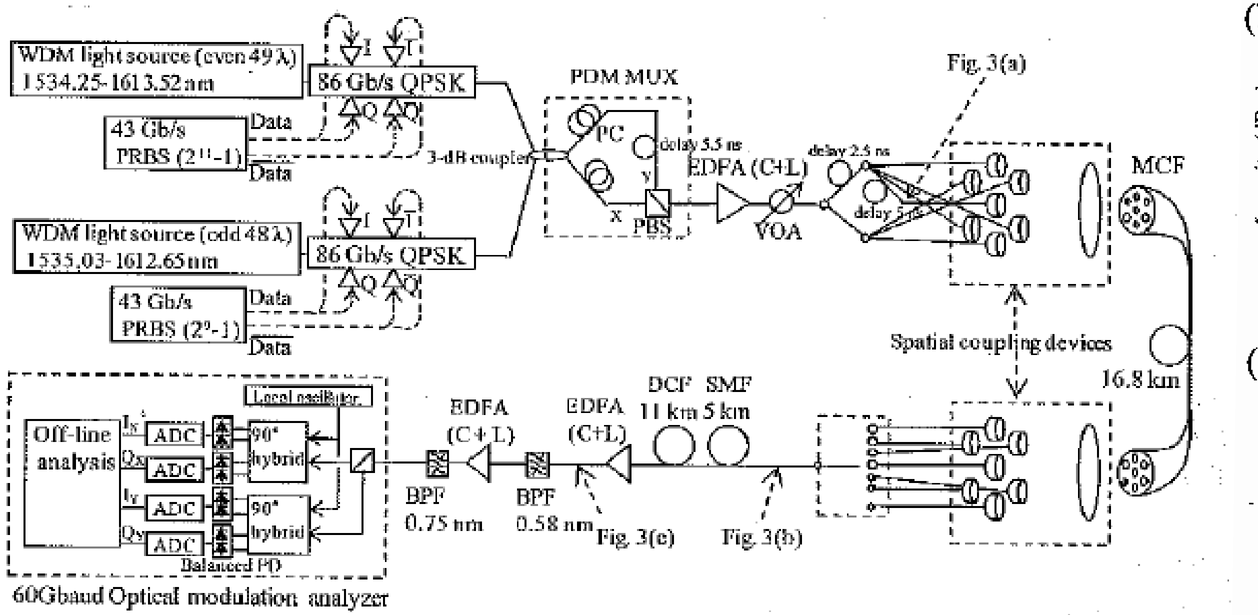
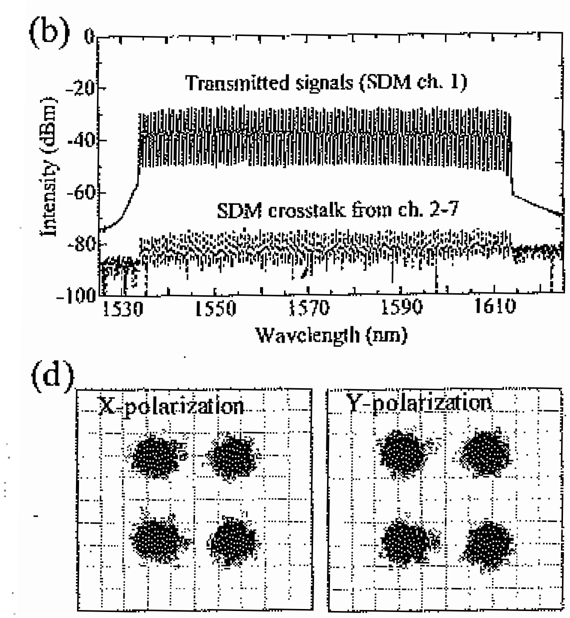


Fig. 2. Measured crosstalk after 5-km propagation.

109 Tbit/s Transmission Experiments





109-Tb/s (7x97x172-Gb/s SDM/WDM/PDM) QPSK transmission through 16.8-km homogeneous multi-core fiber

Jun Sakaguchi[1], Yoshinari Awaji[1], Naoya Wada[1], Atsushi Kanno[1], Tetsuya Kawanishi[1], Tetsuya Hayashi[2], Toshiki Taru[2], Tetsuya Kobayashi[3], Masayuki Watanabe[3]

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[2]*Optical Communications R&D Laboratories, Sumitomo Electric industries, Ltd., 1, Taya-cho, Sakae-ku, Yokohama, 244-8588, Japan*
[3]*OPTOQUEST Co., Ltd., 1335 Haraichi, Ageo, Saitama 362-0021, Japan*
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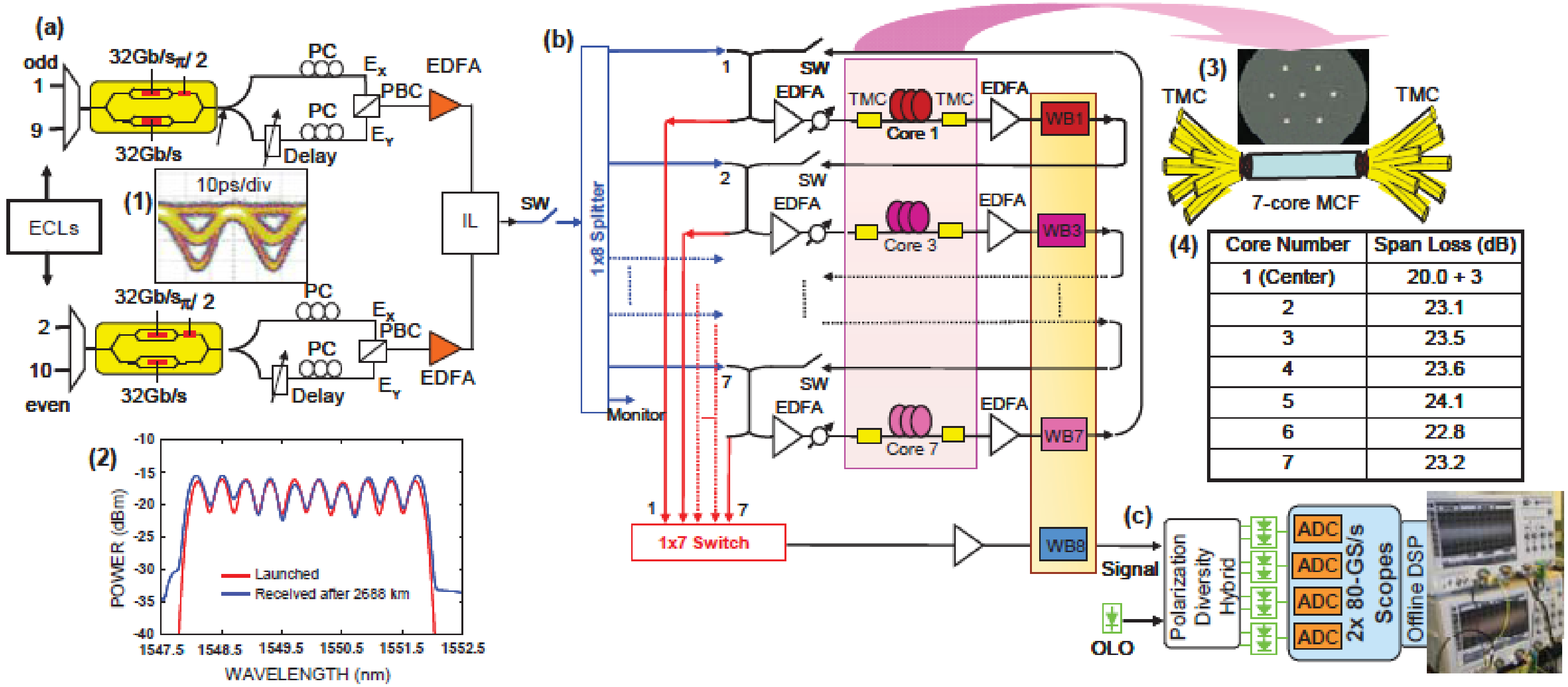
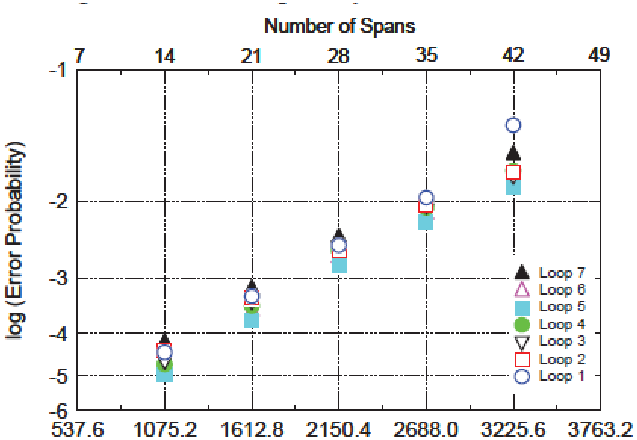
Amplified 7-core Transmission Experiment over 2688km



Core Number	Span Loss (dB)
1 (Center)	20.0 + 3
2	23.1
3	23.5
4	23.6
5	24.1
6	22.8
7	23.2



WDM/SDM Transmission of 10 x 128-Gb/s PDM-QPSK over 2688-km 7-Core Fiber with a per-Fiber Net Aggregate Spectral-Efficiency Distance Product of 40,320 km·b/s/Hz

S. Chandrasekhar[1], A. H. Gnauck[1], Xiang Liu[1], P. J. Winzer[1], Y. Pan[1], E. C. Burrows[1],
B. Zhu[2], T.F. Taunay[2], M. Fishteyn[2], M. F. Yan[2], J. M. Fini[2], E.M. Monberg[2], F.V. Dimarcello[2]
1: Bell Labs, Alcatel-Lucent, 791 Holmdel-Keyport Road, Holmdel, NJ 07733, USA
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e-mail: Chandra.Sethumadhavan@alcatel-lucent.com

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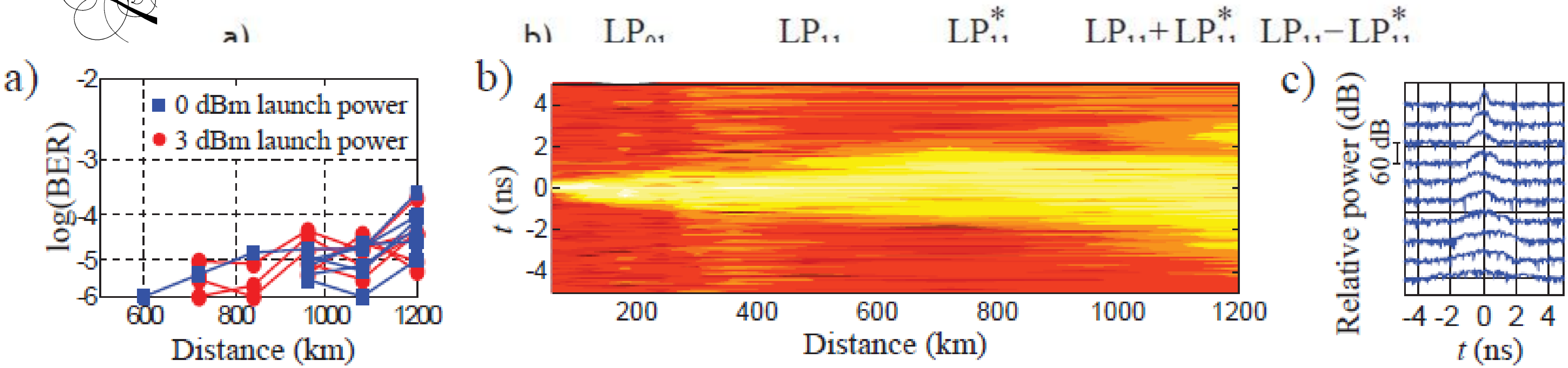
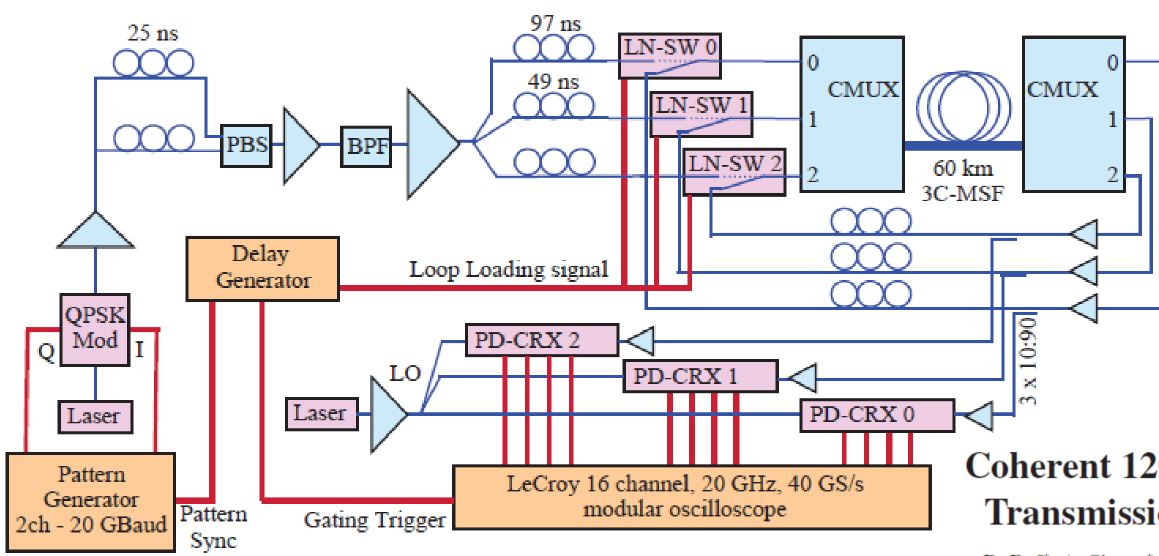
Amplified 3-core Super Mode Transmission Experiment over 1200km





Coherent 1200-km 6 x 6 MIMO Mode-Multiplexed Transmission over 3-core Microstructured Fiber

R. Ryf*, A. Sierra*, R.-J. Essiambre*, A. H. Gnauck*, S. Randel*, M. Esmaeelpour*, S. Mumtaz*, P. J. Winzer*, R. Delbue†, P. Pupalaikis†, A. Sureka†, T. Hayashi‡, T. Taru‡, and T. Sasaki‡

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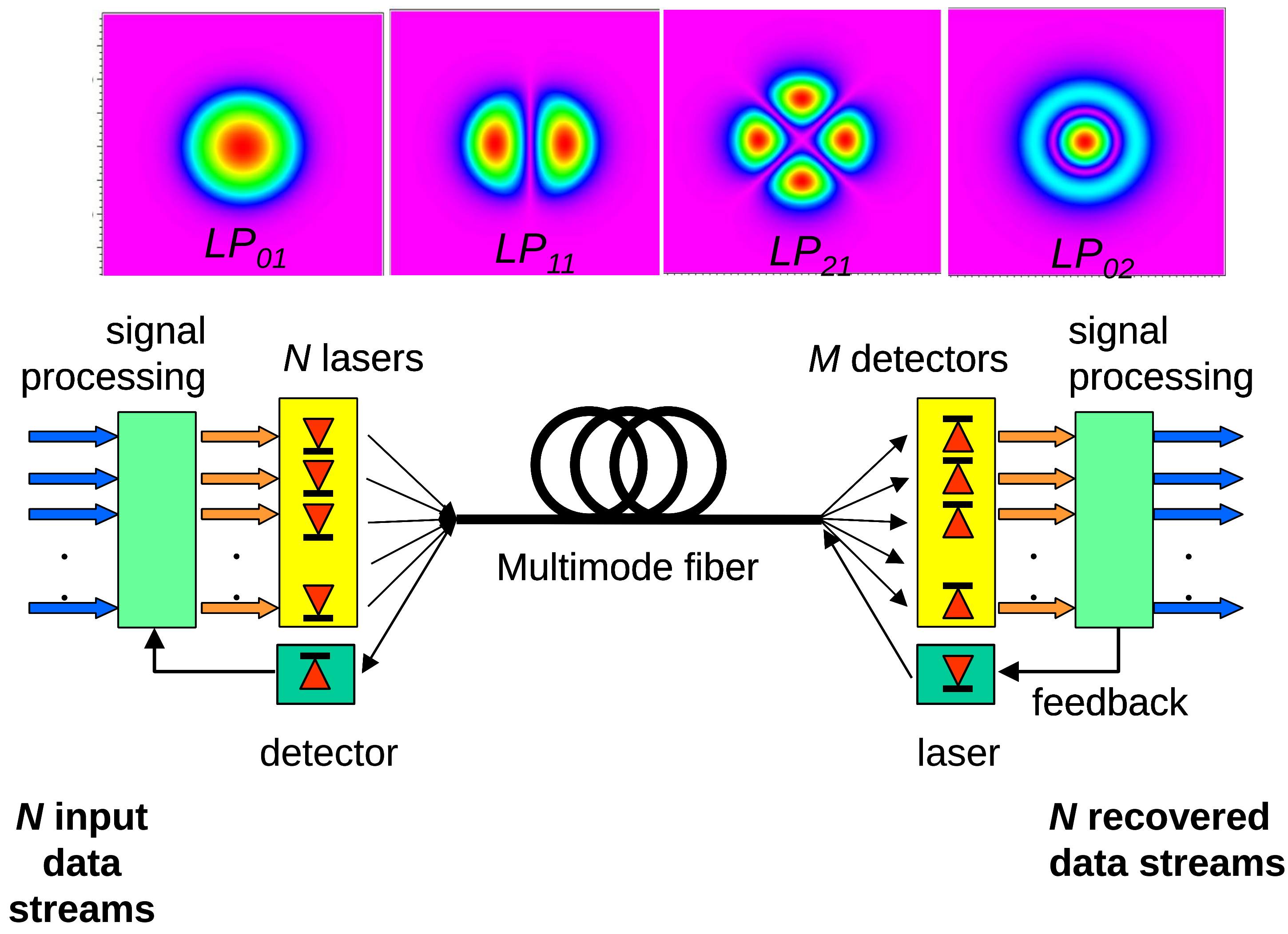
Multiple Input Multiple Output



Transmission in Few Mode Fiber

Demonstration of mode-division multiplexing transmission over 10 km two-mode fiber with mode coupler

Nobutomo Hanzawa[1], Kunimasa Saitoh[2], Taiji Sakamoto[1], Takashi Matsui[1], Shigeru Tomita[1], and Masanori Koshiba[2]

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Abstract: We realized mode-division multiplexing(MDM) transmission by using orthogonal LP modes with negligible modal crosstalk, for the first time. A 2x10Gbps MDM transmission was achieved over a 10km two-mode fiber with sufficiently low power penalty.

OCIS codes: (060.2270) Fiber characterization; (060.2330) Fiber optics communications

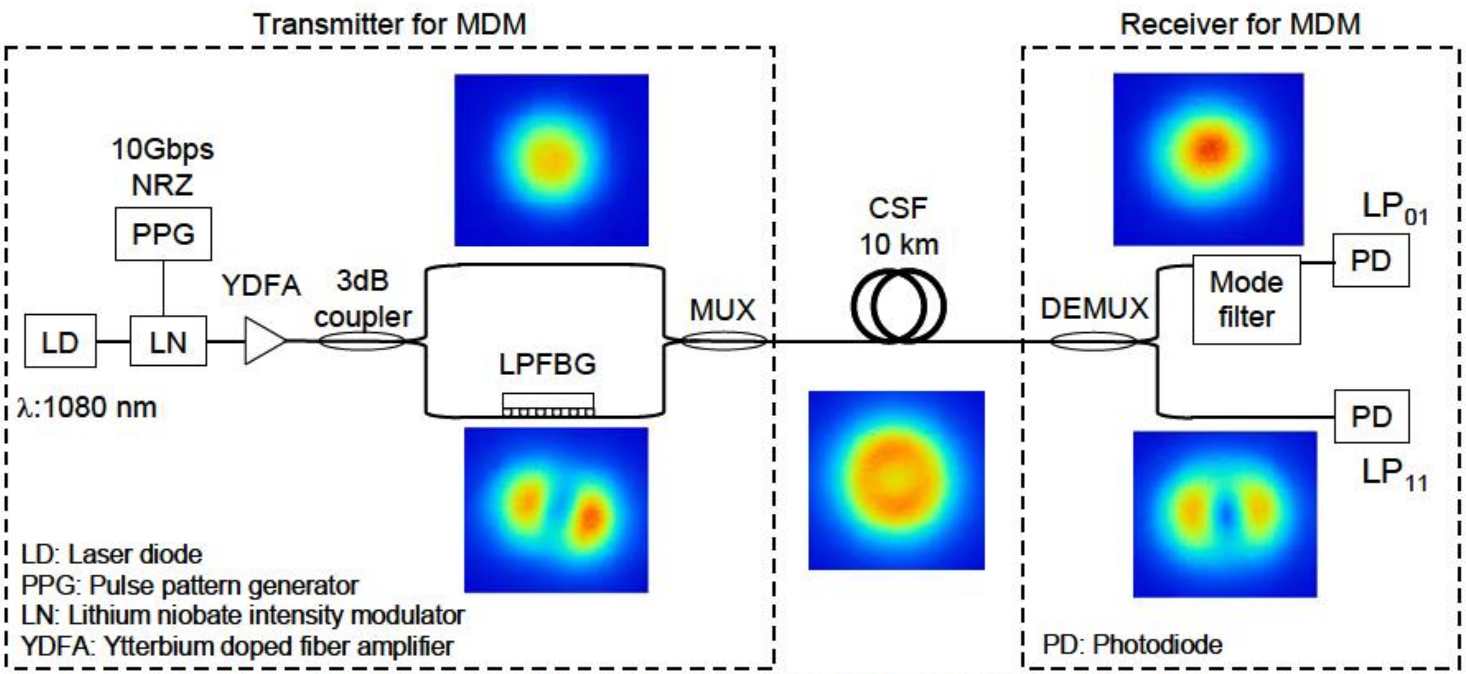


Fig. 2. Experimental setup for mode division multiplexing transmission

System Results

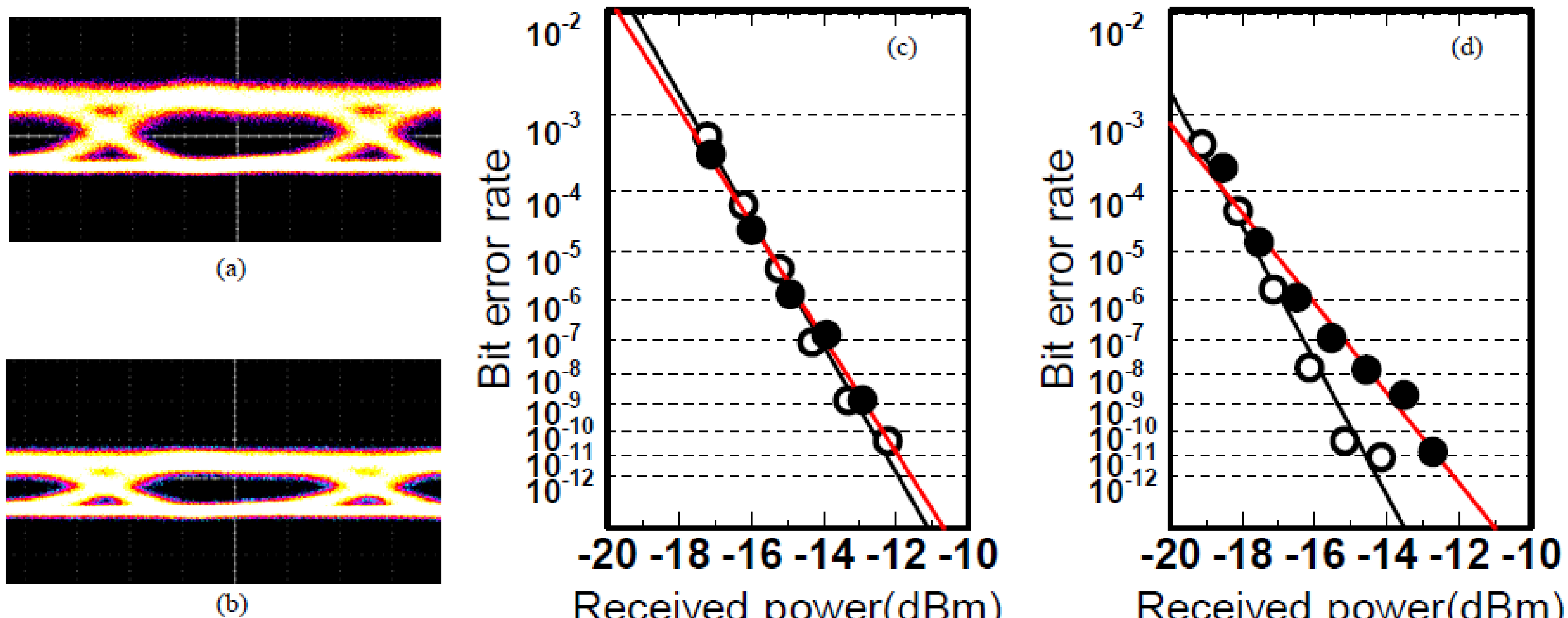
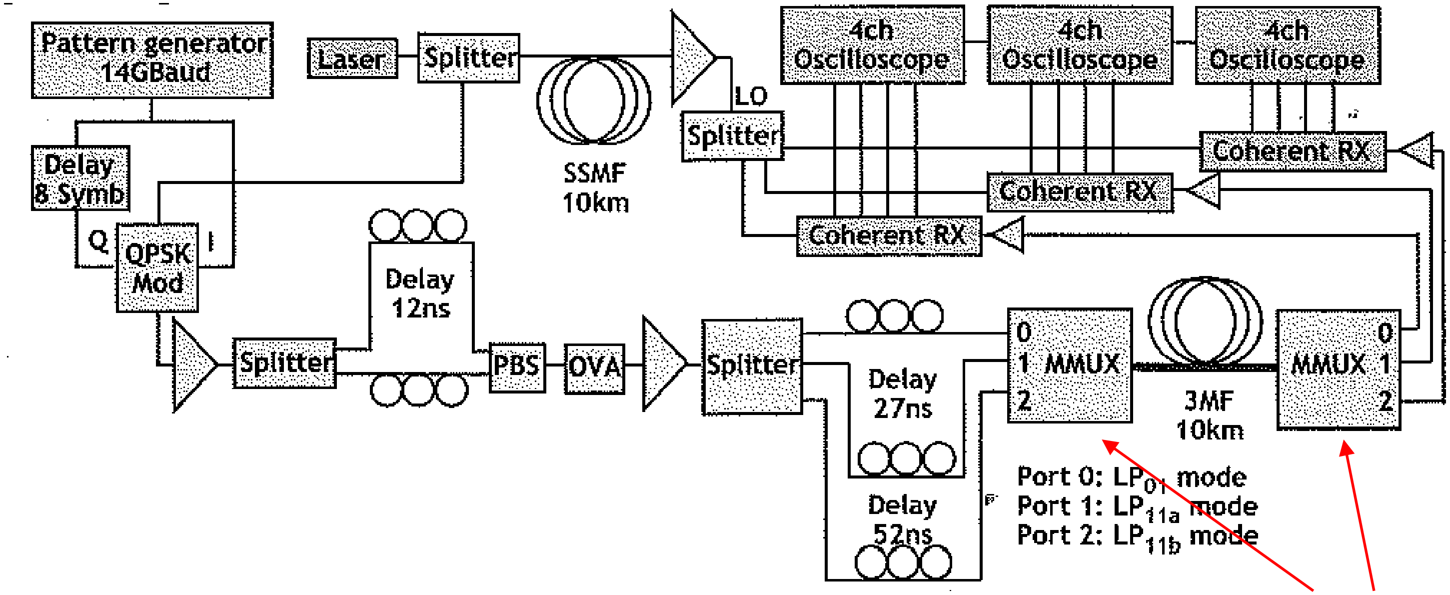


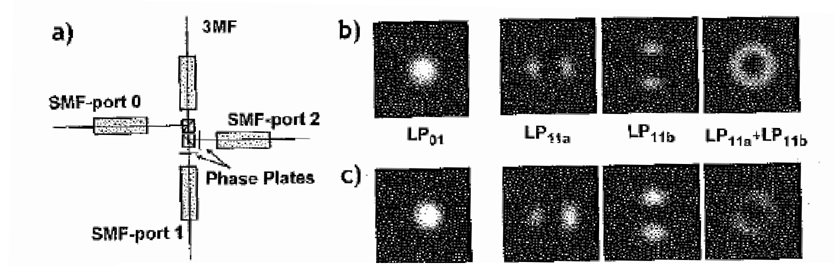
Fig. 3. MDM transmission characteristics. (a) Eye pattern after LP_{01} mode transmission. (b) Eye pattern after LP_{11} mode transmission. (c) BER for LP_{01} mode transmission, back-to-back (○), 10 km (●). (d) BER for LP_{11} mode transmission, back-to-back (○), 10 km (●).

Coupling tolerable over 10km length scales in two mode-fiber under controlled conditions

SDM over 10km with MIMO Processing



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



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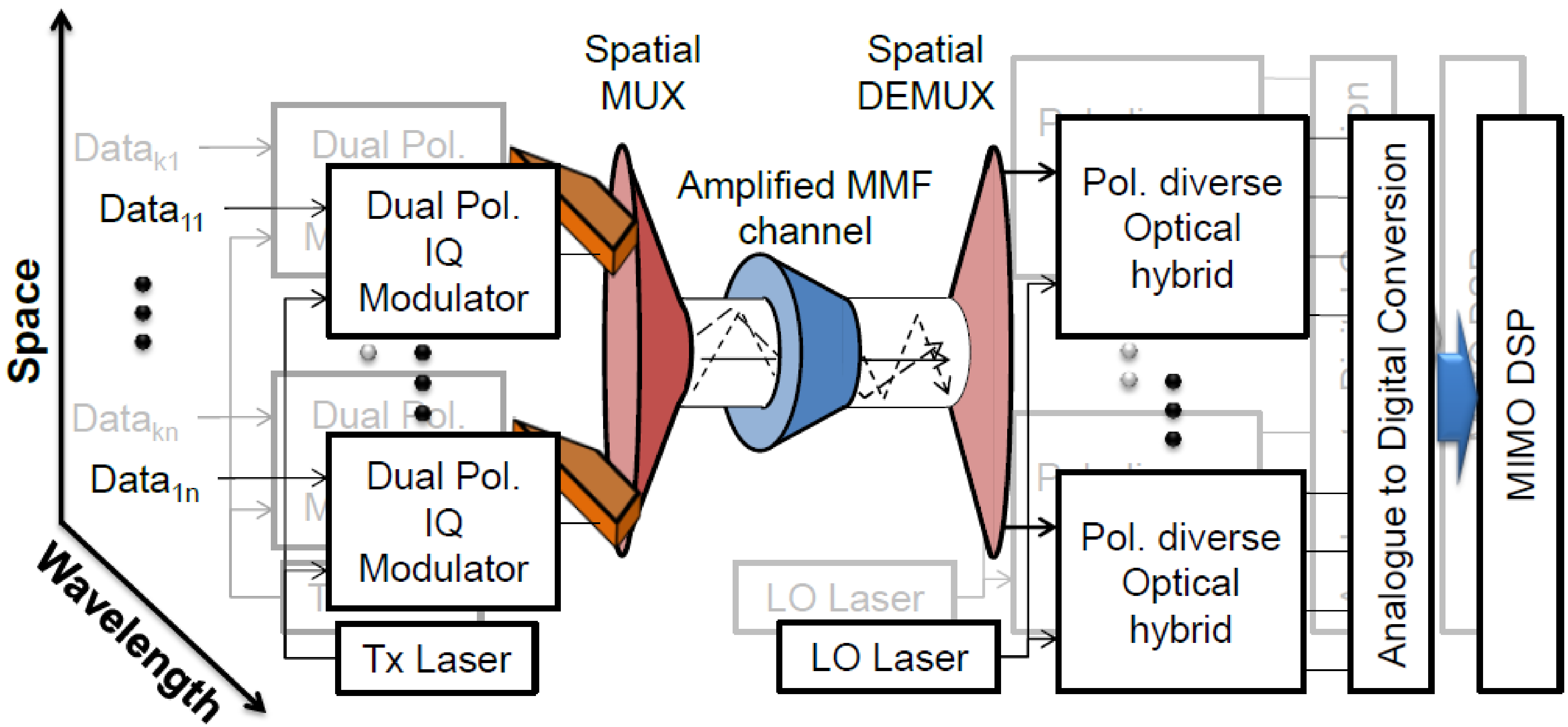
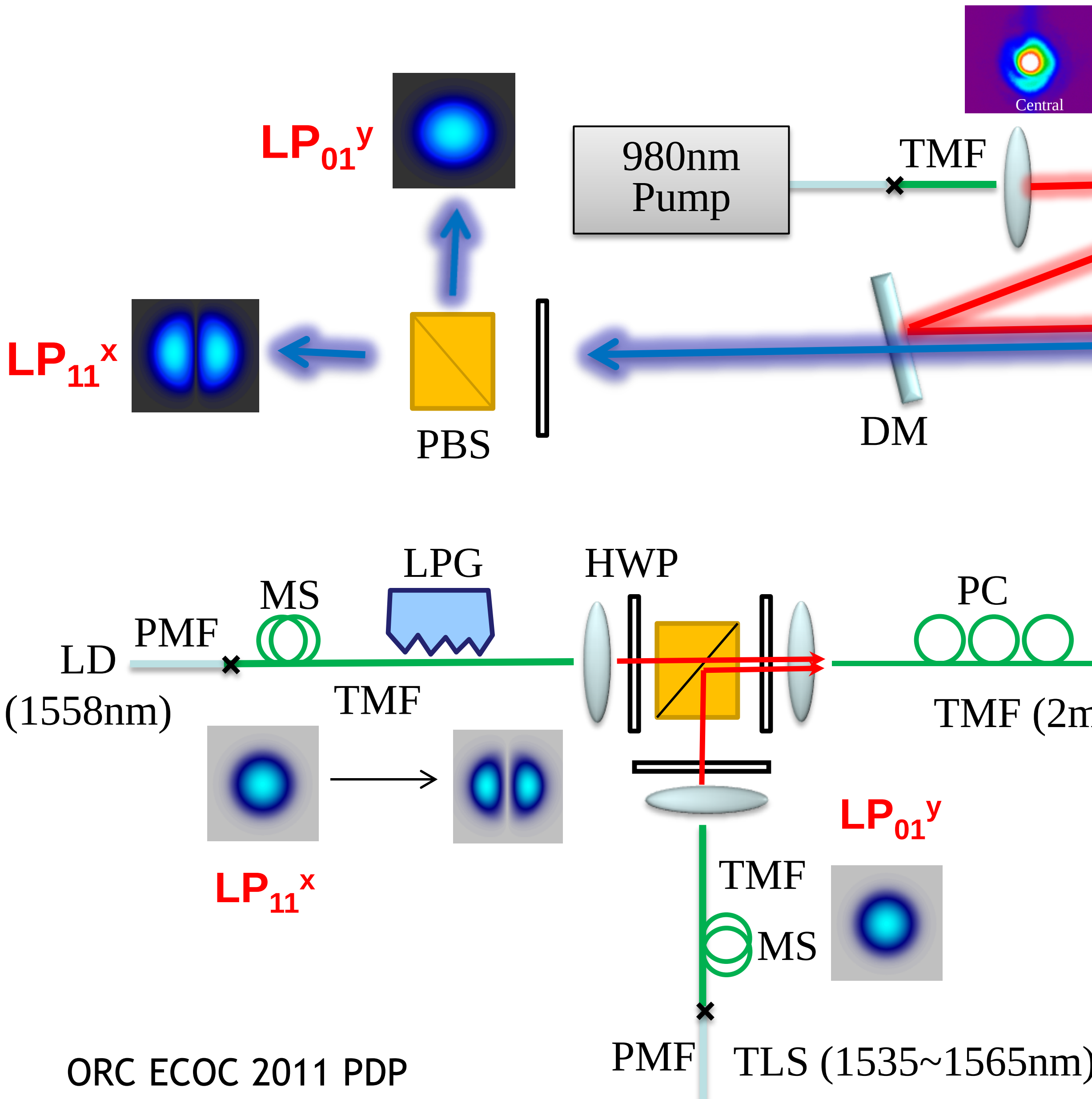
Long Haul System Configurations

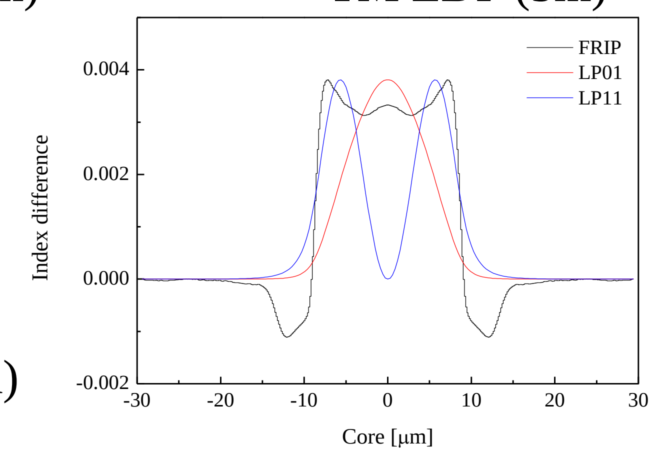


Amplification is key but realisation highly challenging

- Cross talk
- Coupling
- Gain competition etc

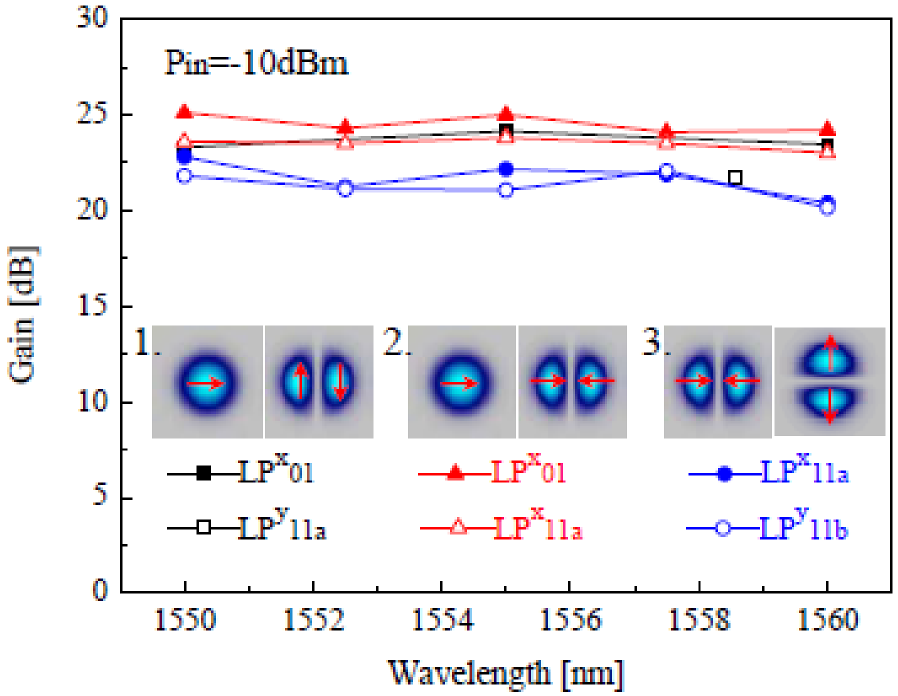
MM EDFA - Experimental setup



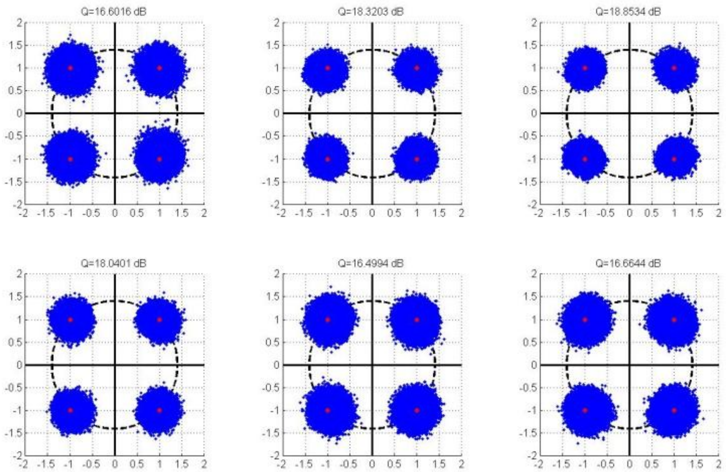


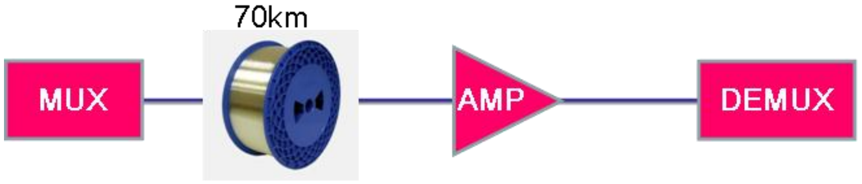
ORC ECOC 2011 PDP

Amplification of other mode pairs



(a)





- ✓ Well balanced amplification of different mode groups and polarization states
- ✓ Amplified 6x6 MIMO transmission experiments over low DGD fiber

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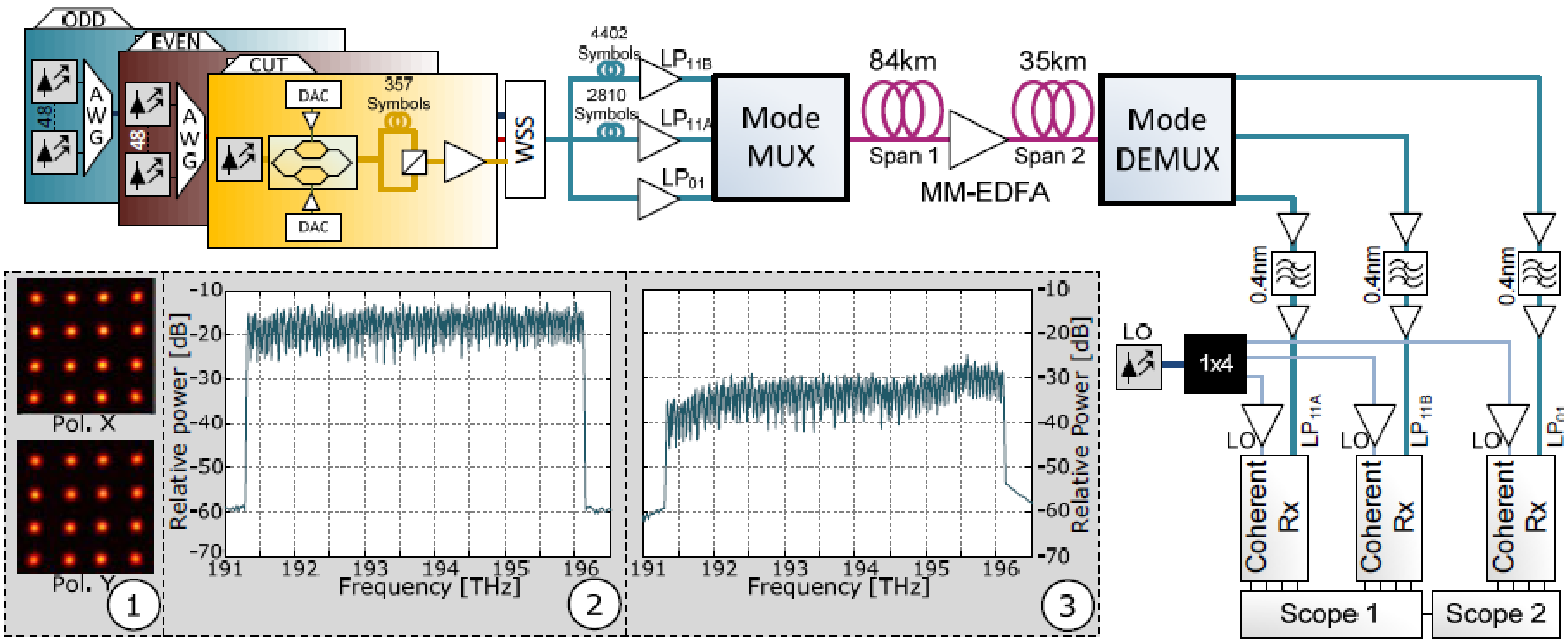
Transmission work undertaken at Nokia Siemens Network (NSN), Germany - supported by V. Sleiffer (Tu/e) and B. Inan (TUM)

70 Tbit/s amplified FMF system

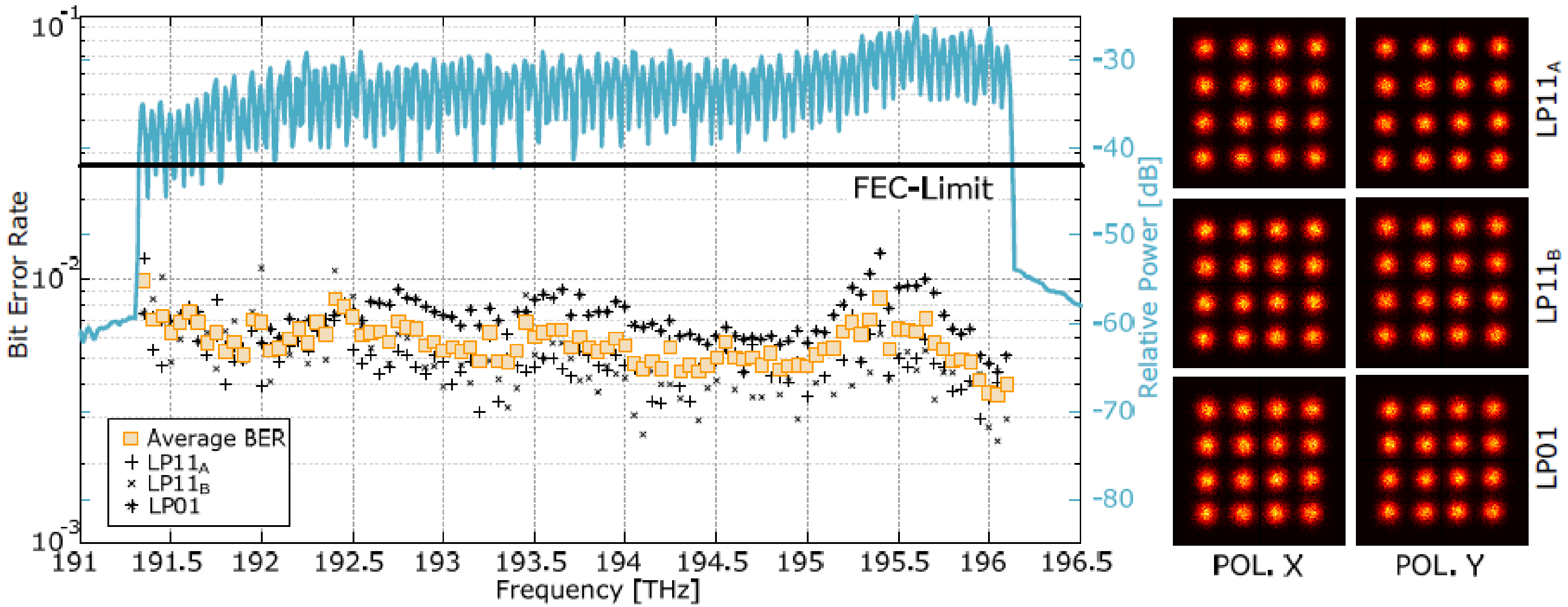


96 (WDM) x 3 (SDM) x 256Gbit/s (PDM-16QAM)

To be presented ECOC 2012 PDP

Nokia Siemens Networks

70 Tbit/s amplified FMF system



To be presented ECOC 2012 PDP

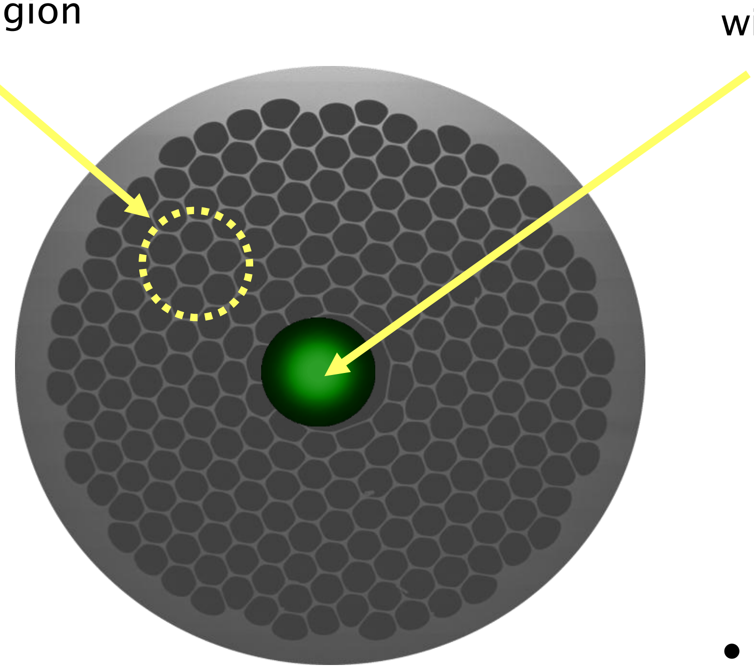
Even More Radical Solutions: Hollow Core PBGFs

Periodic lattice of holes

Optical bandgap covering a well defined wavelength region

Hollow core

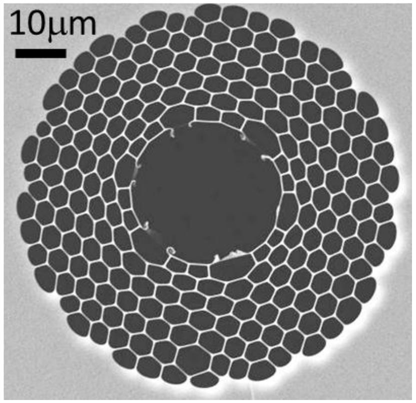
Modes in a low-index core are supported at frequencies within the bandgap



Key Attractions

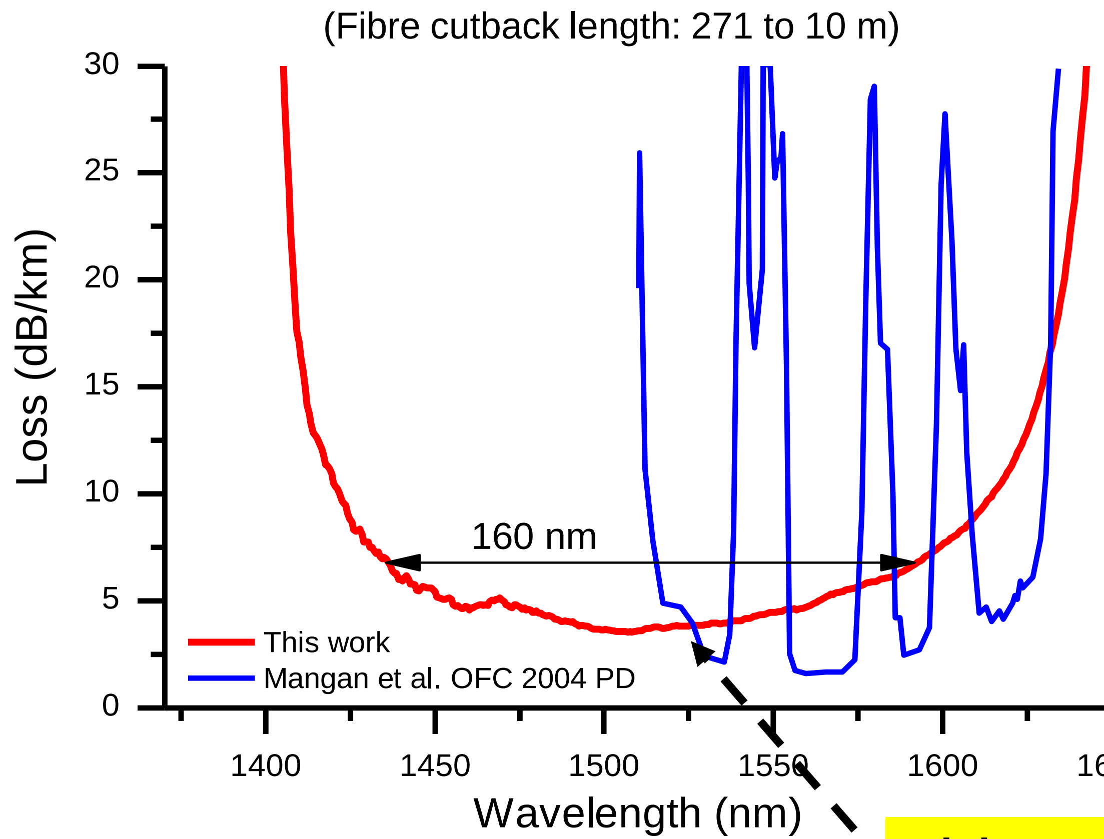
- Ultralow nonlinearity
- Potential for ultralow loss
- Minimum latency

Low loss wide BW 19-cell HC-PBGF

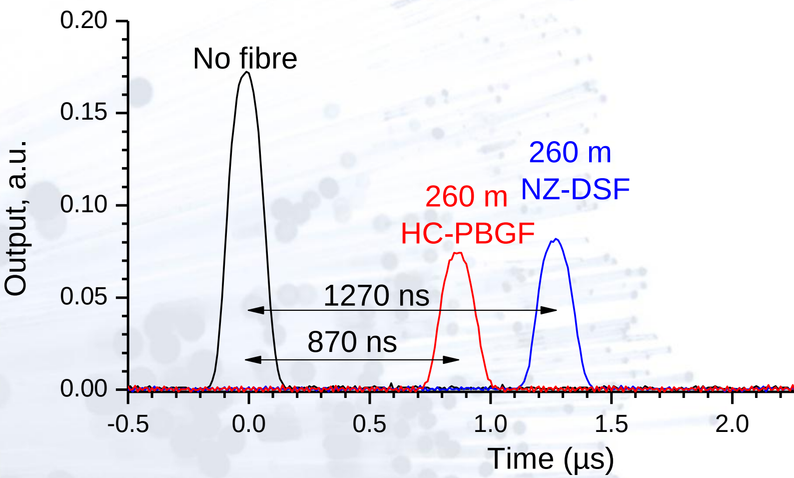


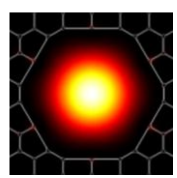
19c core
Λ ~ 4.4 µm
d/Λ~ 0.976

Core diam: 26 µm



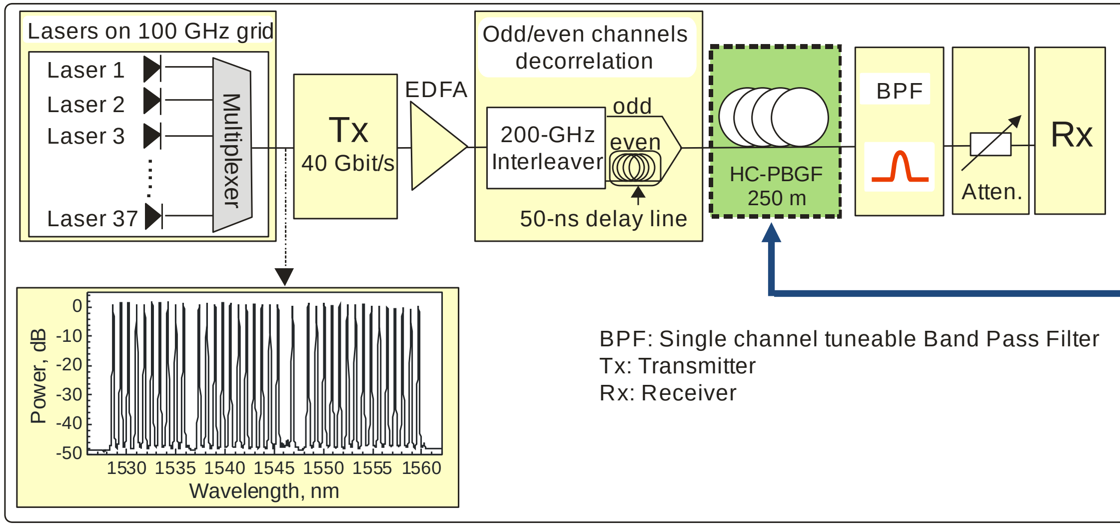
Minimum loss: 3.5 dB/km

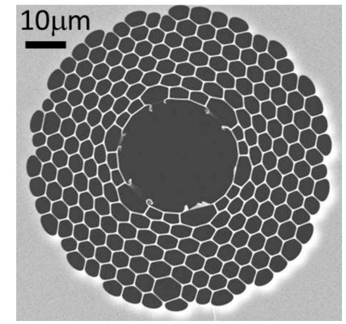


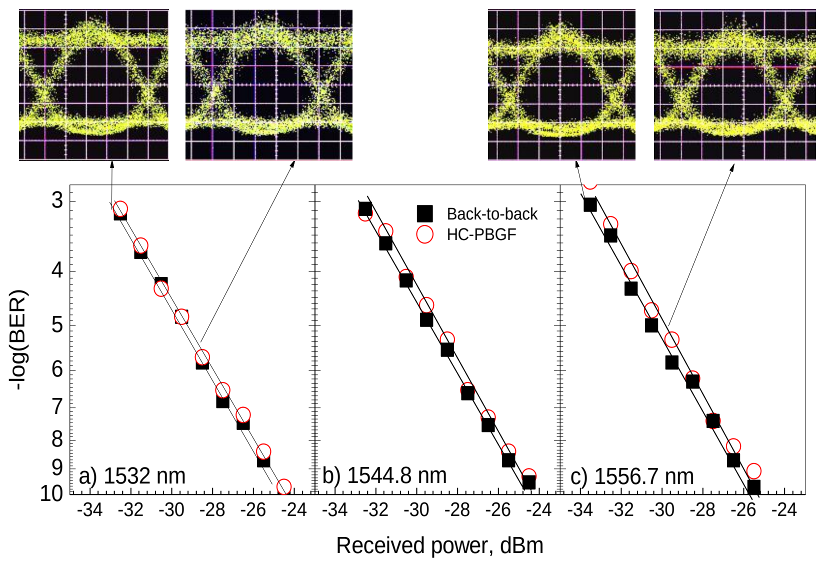


1.33 x faster propagation
1.54ms/km lower latency

1.45Tbit/s low-latency WDM transmission

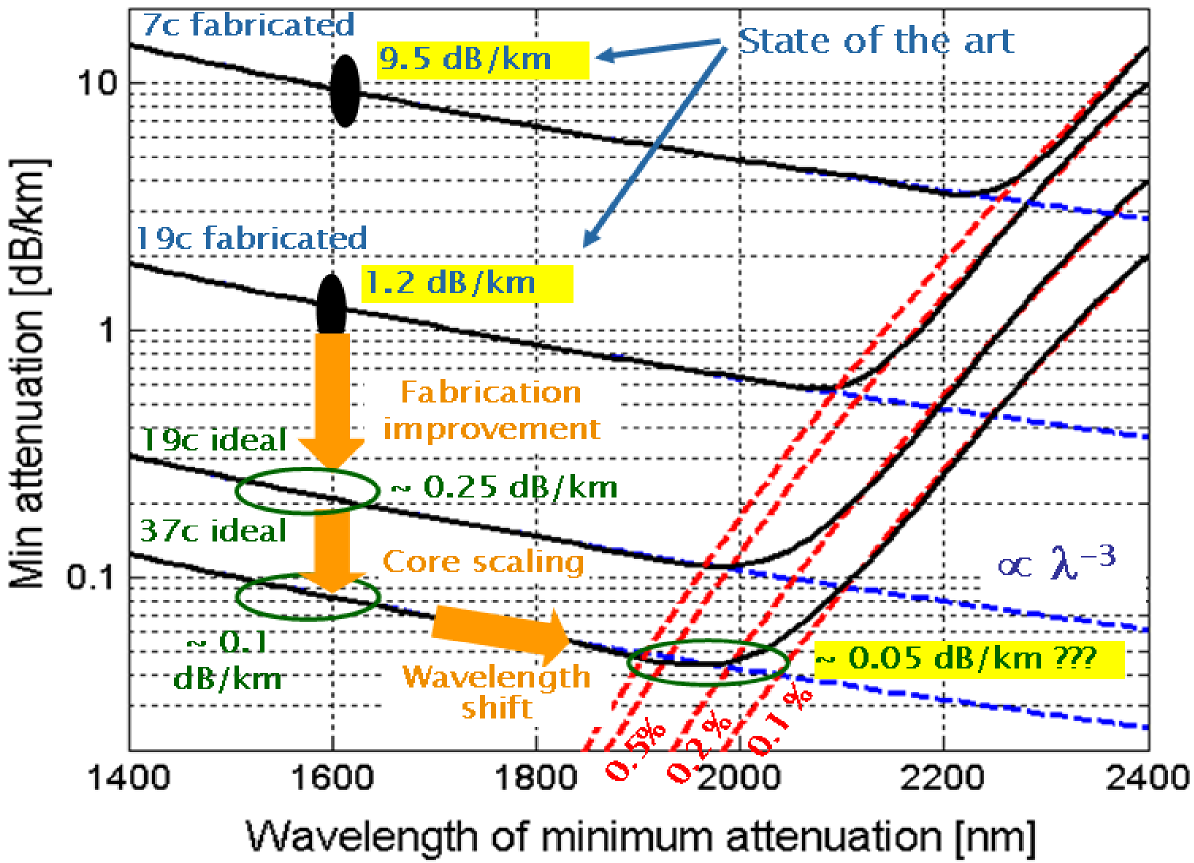






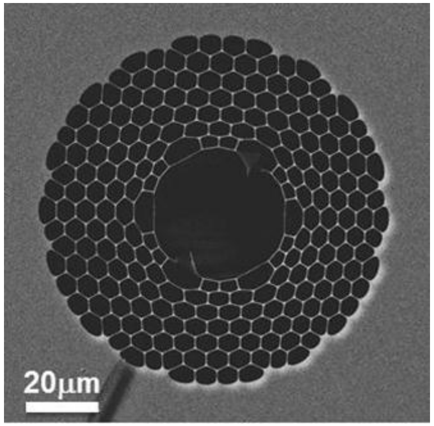
- 250m, 3.5dB/km PBGF
- >30dB HOM extinction observed
- 37x40Gbit/s C-band channels on a 100-GHz ITU grid (1528-1560 nm)
- BER & eye diagrams of 3 representative channels compared to back-to-back
- Sub-dB power penalty observed across the full C band

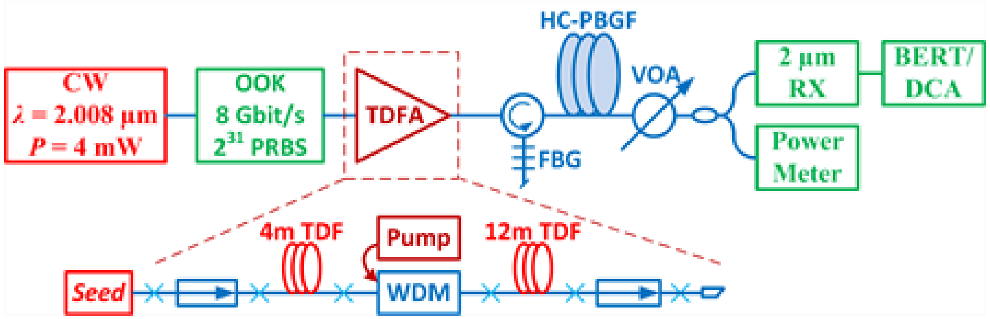
PBGF loss reduction strategy

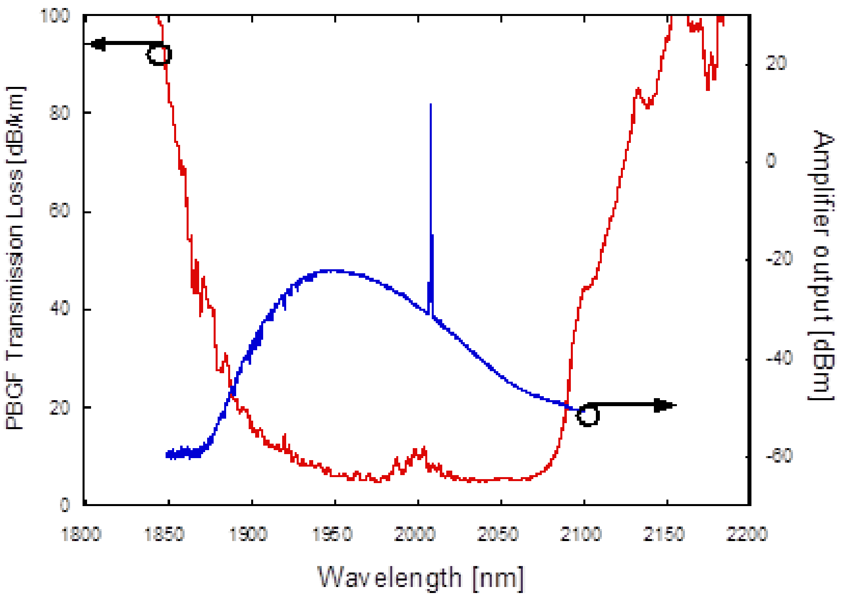


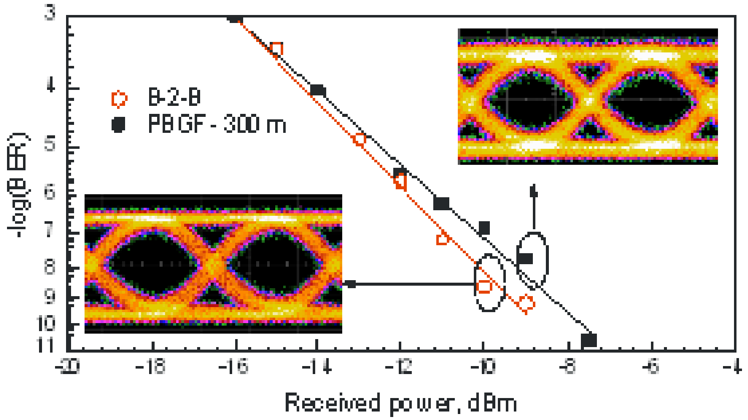
Strategy	Expected Loss Improvement Factor
Reduction of Surface Roughness	**2x**
Higher Air filling factor	**2x**
Larger Cores	**2.5x**
Longer Operating Wavelengths (~2μm)	**2x**

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









To be presented ECOC 2012 PDP

Conclusions

- An exciting time in communications research ahead – innovation now required at the basic infrastructure level to avoid future capacity problems
- Need for new fibers, amplifiers and associated technologies - lasers, modulators, detectors etc.
- Major opportunities in adjacent technology areas

Light

Acknowledgements

Transforming the Internet Infrastructure:
The Photonics Hyperhighway

UNIVERSITY OF Southampton

EPSRC
Pioneering research and skills

University of Essex

MODE GAP

Nokia Siemens Networks

eblanaphotonics

Phoenix Photonics

ofs
A Furukawa Company

TU/e Technische Universiteit Eindhoven University of Technology

UCC

UNIVERSITY OF Southampton
Optoelectronics Research Centre

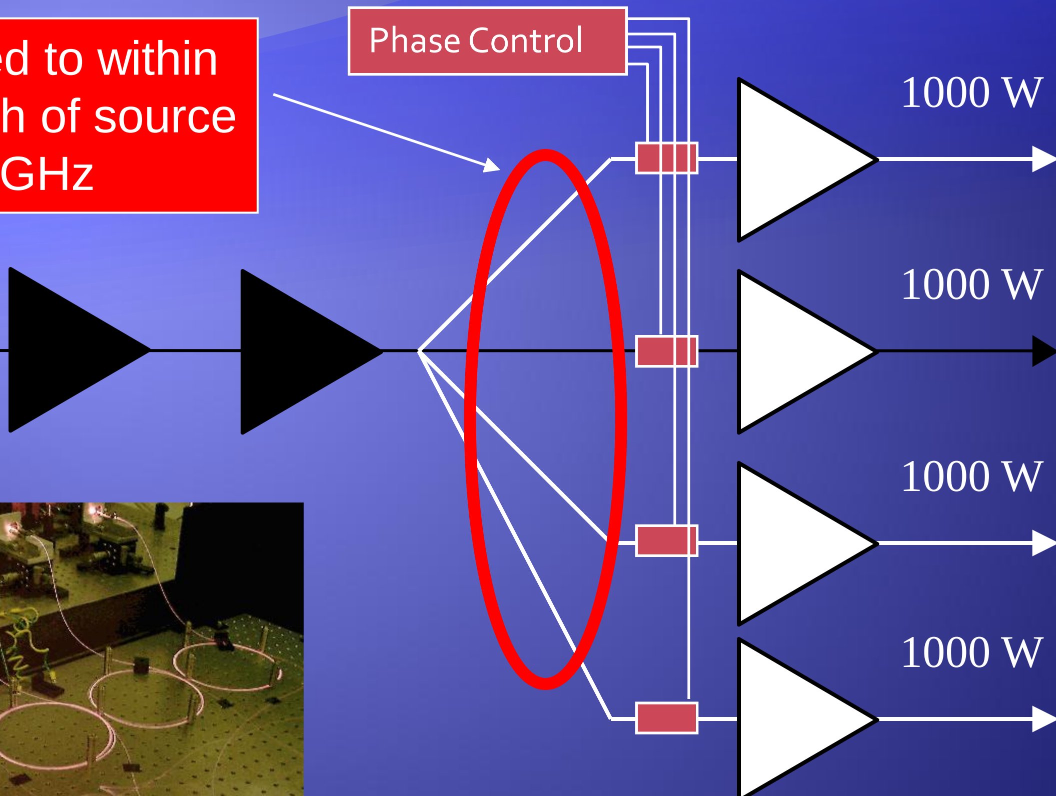
ESPCI ParisTech

The Fibre laser
Another fibre revolution

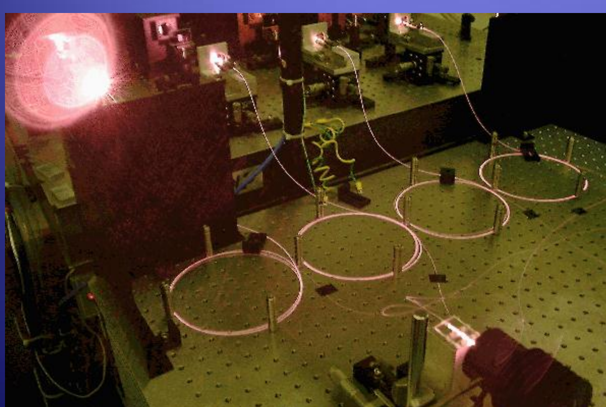
Cutting 35mm thick steel

Future Steerable 1 MW Design?

Multi-path fiber MOPA



Phase-coherent output for beam combination, steering and adaptive optics



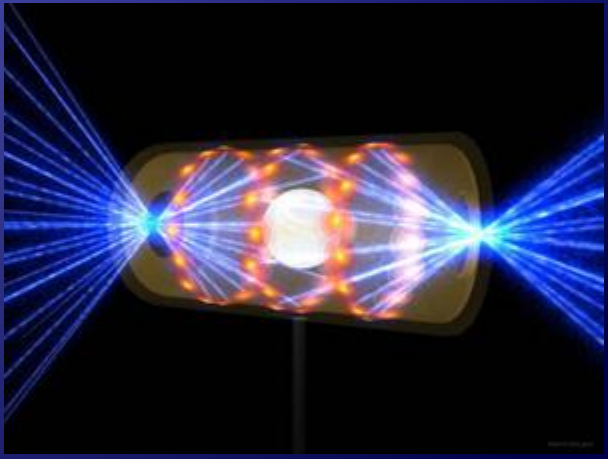
1.4 kW Brillouin-free obtained

Single-mode
Single-frequency
Single-polarization

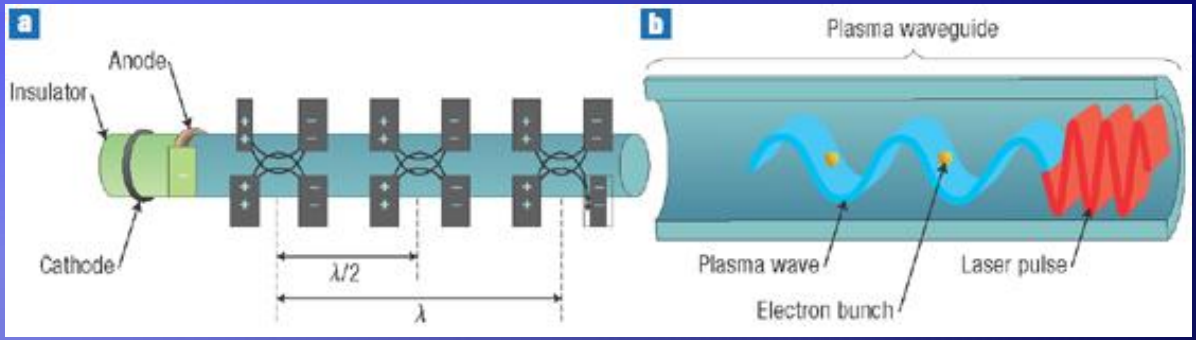
SOUTHAMPTON

Laser Initiated Nuclear Fusion

The worlds most powerful laser at
Lawrence Livermore National Labs
seeded using a fibre laser!



The limits? ICAN – fibre lasers for particle accelerators



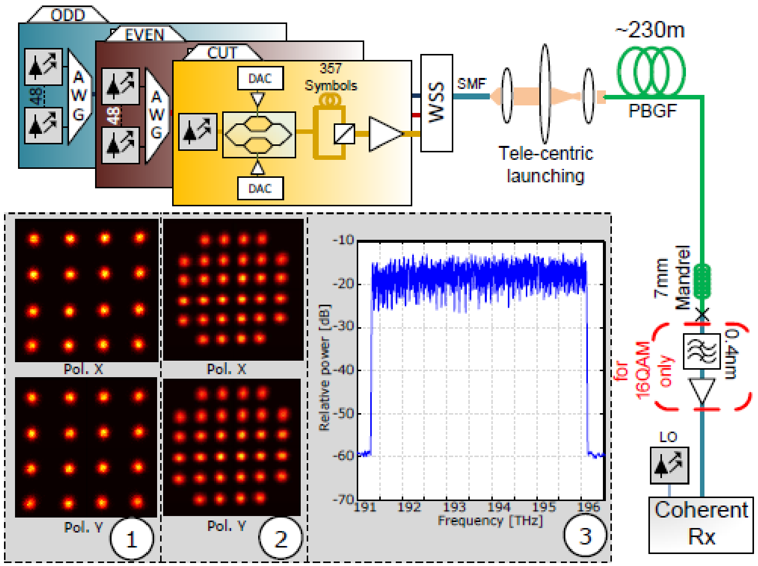
Toshiki Tajima,
Nature Photonics 2, 526 - 527
(2008)

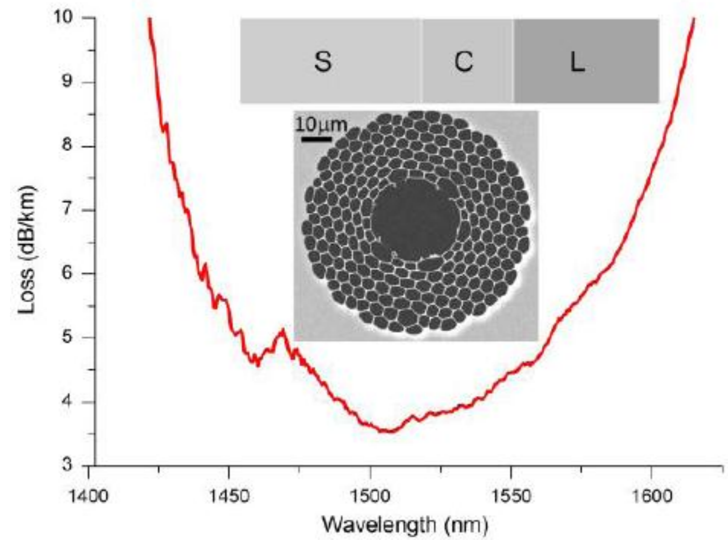
- Accelerate electrons via laser wake field acceleration
  - Electrons 'surf' on plasma wave caused by ponderomotive force of pulse
  - Very high energy femtosecond pulses needed : >10J
- Coherent combination of pulses from fibre CPA systems
  - International Coherent Amplification Project (ICAN) (Ecole Polytechnique, Jena, CERN, Soton) –
  - use 100k-1M lasers to make 1 TeV accelerator

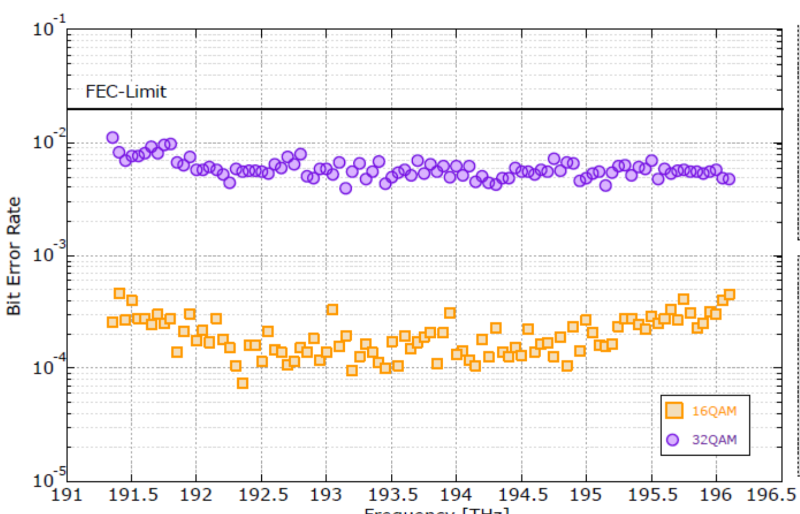
Photonics: The Future is Bright

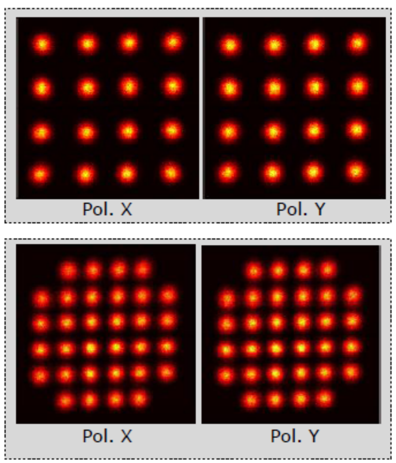
- Innovation is again required at the transmission line level to satisfy societies growing need for bandwidth - else we face a capacity crunch crisis within the next decade
- Photonics underpins vast areas of human endeavour - from the environment to sensing to security to the biosciences
- The 21st Century is the century of light

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









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