Frontiers in Optical Communications

Part 1: Some History and Fundamentals

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UNIVERSITY OF Southampton

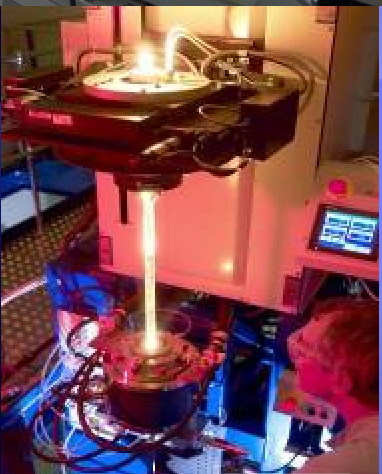
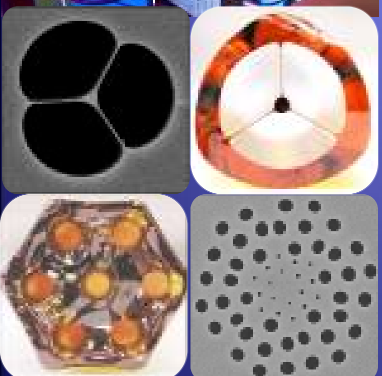
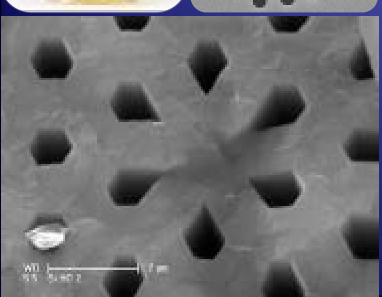
Optoelectronics Research Centre

Light

Optoelectronics Research Centre

University of Southampton

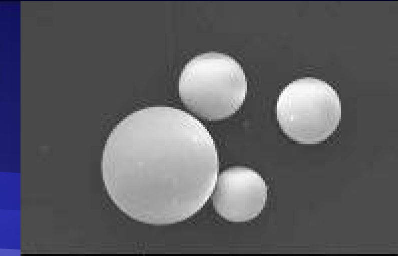
- Largest Photonics group in the UK
- 50 year history
- 200 staff / PhD students
- >80 state-of-the-art optics laboratories
- 3 EPSRC Programme Grants
- EPSRC Centre for Innovative Manufacturing in Photonics
- Major EU grants – MODEGAP, PHASORS

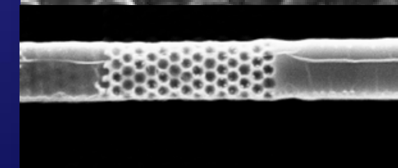
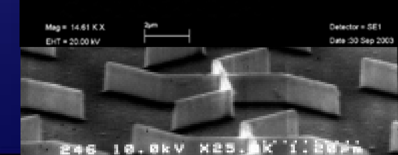
The Mountbatten Clean Rooms:

a world-leading flexible facility for materials, processes and devices

- Silica Fibre Fabrication
- Compound glass fibre fabrication
- Microstructured fibres
- Photonic planar waveguide fabrication
- Electron-beam lithography with 10nm resolution, JeolJBX 9300
- Photolithography
- Robotic aligner, EVG 620TBR
- 2 x FIB/SEM, Zeiss & FEI Nanolab
- Helium Ion Microscope
- Dry-etch and reactive ion etching
- FEGSEM Jeol JSM 7500F
- Epitaxial systems for SiGeC growth, Ge quantum dot growth
- Polycrystalline and amorphous SiGeC deposition
- Atomic layer deposition system
- Deep silicon etcher
- Ion-beam deposition
- Sputtering, e-beam and thermal evaporation
- Diffusion to 2300K
- Nanoimprint tools
- CVD carbon nanotube growth
- PECVD Nanofab for Si and Ge nanowire growth
- Oxide and nitride deposition
- Rapid thermal annealer, furnaces, wet chemistry facilities
- AFM, metrology equipment for layer thickness measurements
- DC and RF on-wafer device characterisation
- Chalcogenide materials deposition
- Microscopy, profilometry, & SEM





Alignment with RCUK and Global Research Challenges

ORC

LIFE LONG HEALTH & WELLBEING :
photonic lab-on-a-chip
biophotonics

ENERGY:
green photonics
& energy-efficient
manufacturing

NANOSCIENCE:
nanostructured materials
and nanophotonic devices

GLOBAL SECURITY:
defense lasers
secure communications
chemical detection

ENVIRONMENTAL CHANGE:
biosensors and
mid-IR techniques

DIGITAL ECONOMY:
Next Generation Networks,
fibre to the home

RESEARCH SUSTAINABILITY

750 alumni in key position around the world

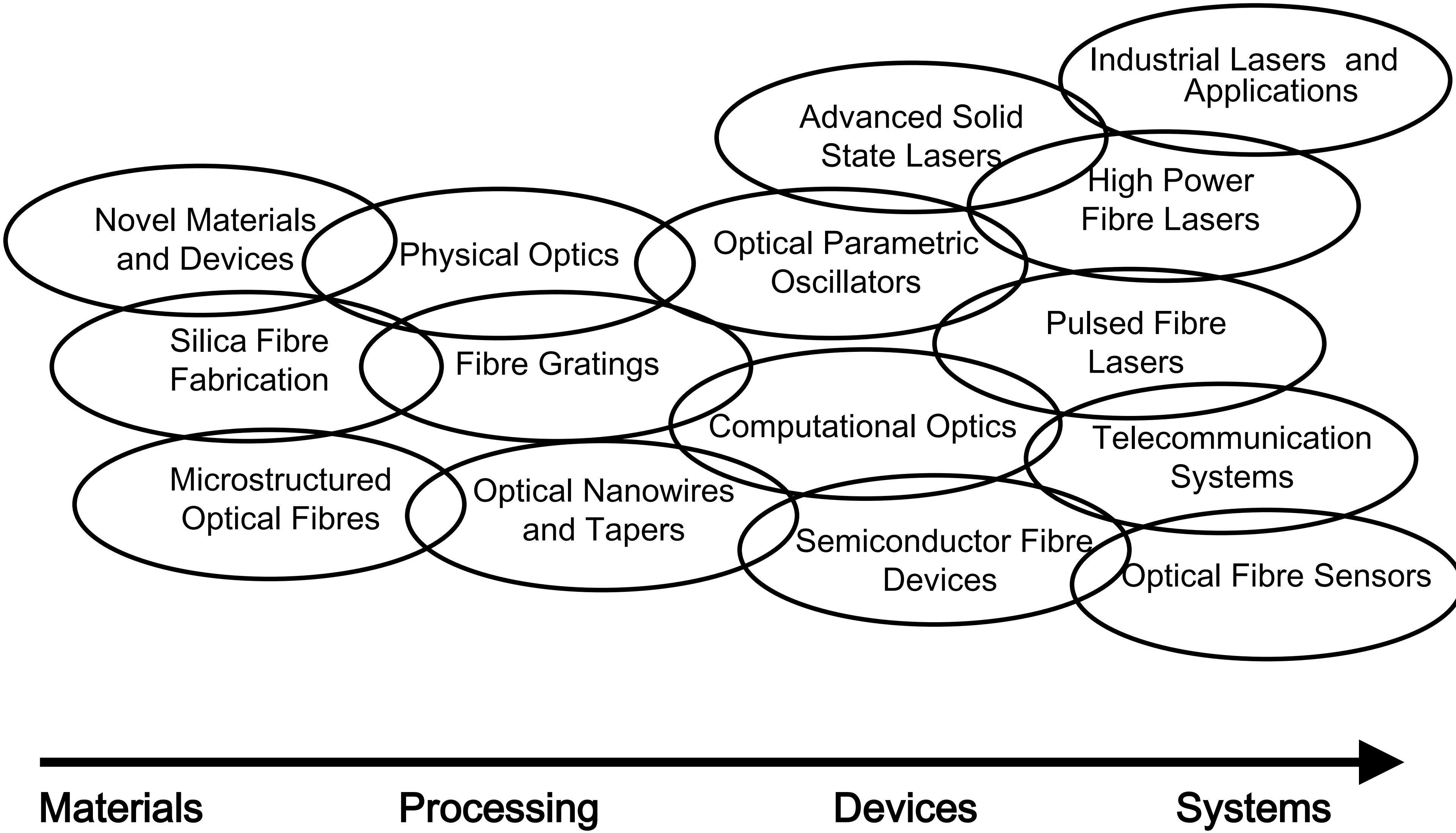
National research facility

ECONOMIC IMPACT

10 spin-out companies

Interaction with 100+ companies

Fibre and Laser Division



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ofs – A Furukawa Company

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Phoenix Photonics

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Ian Giles

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MODE GAP

Nokia Siemens Networks

eblana photonics

Phoenix Photonics

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UCC

University of Southampton Optoelectronics

ESPCI ParisTech

THE ROYAL SOCIETY

UCL

COMIMO

University of Oxford

University of Southampton

EPSRC Pioneering research and skills

University of Cambridge

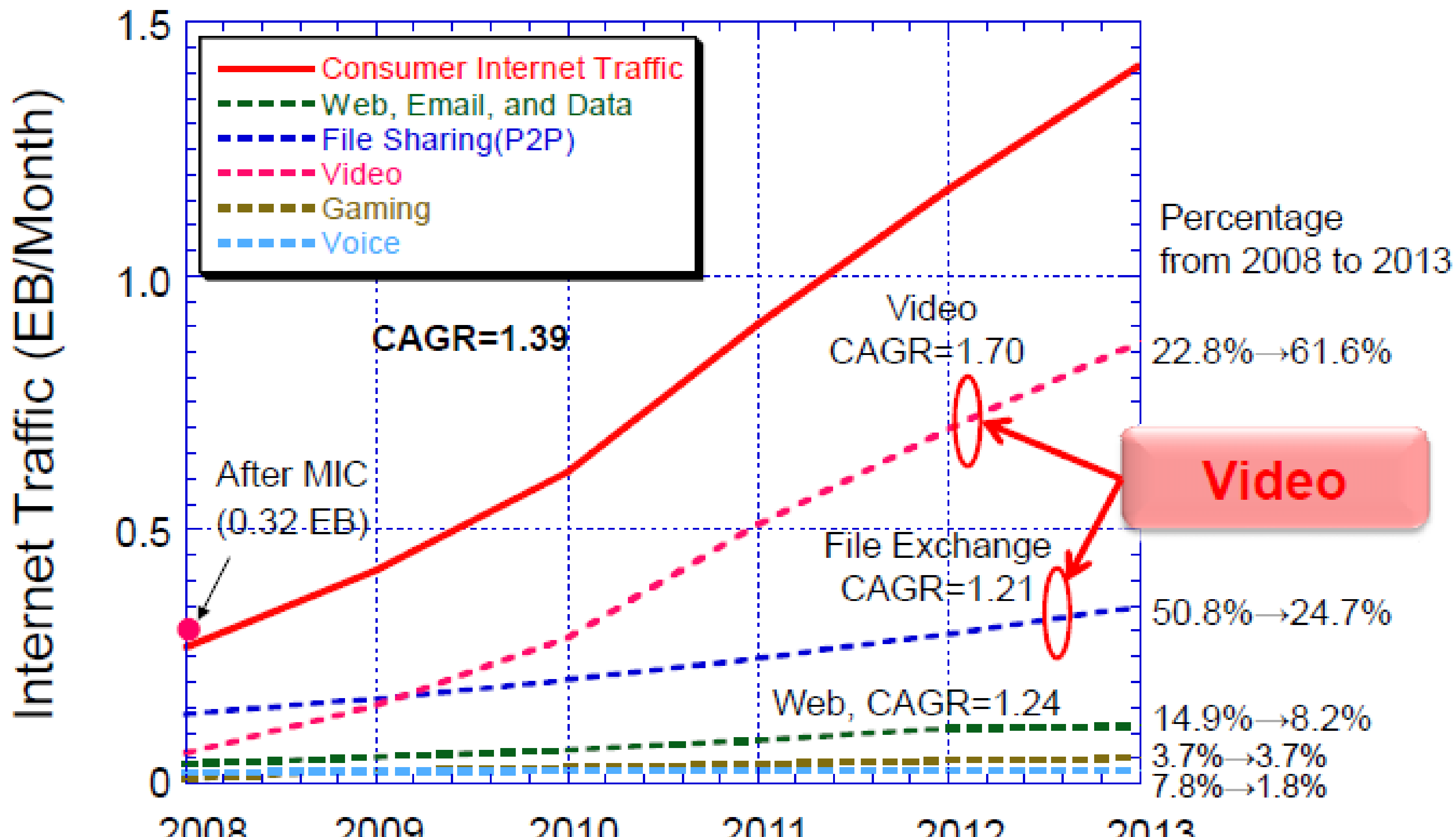
University of Southampton

EPSRC Pioneering research and skills

University of Bristol

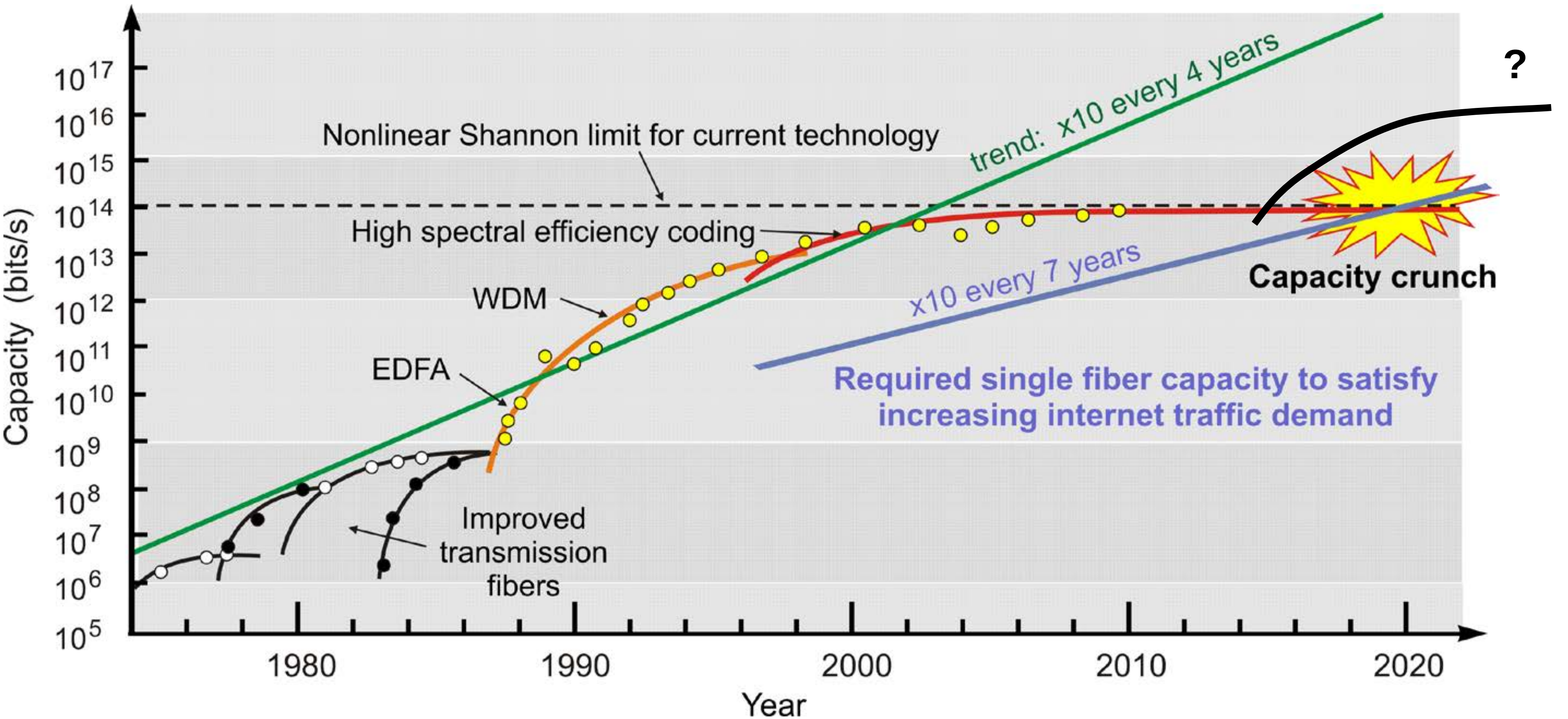
Unrelenting Growth in Data Traffic

Traffic Growth Projected by CISCO



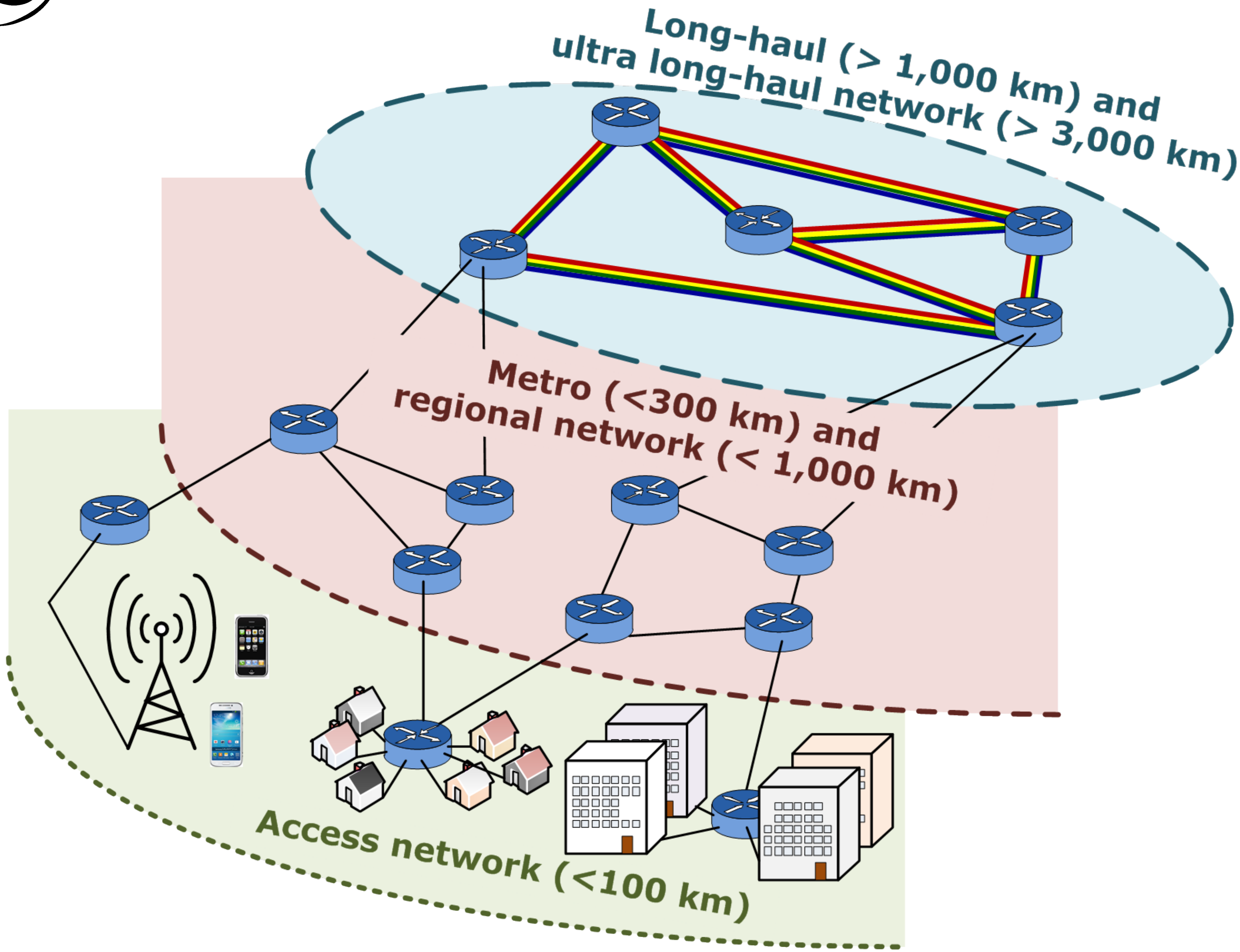
source: Cisco Visual Networking Index: Forecast and Methodology, 2008-2013

The Telecomms Challenge



- Potential crunches ahead in both Capacity and Energy!

Modern Networks

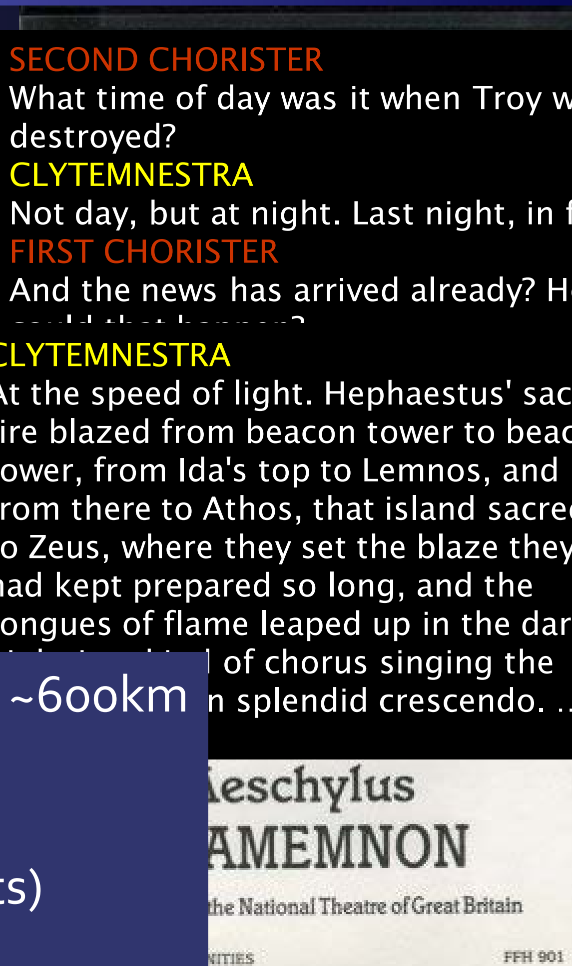


Early Days of Optical Communications

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

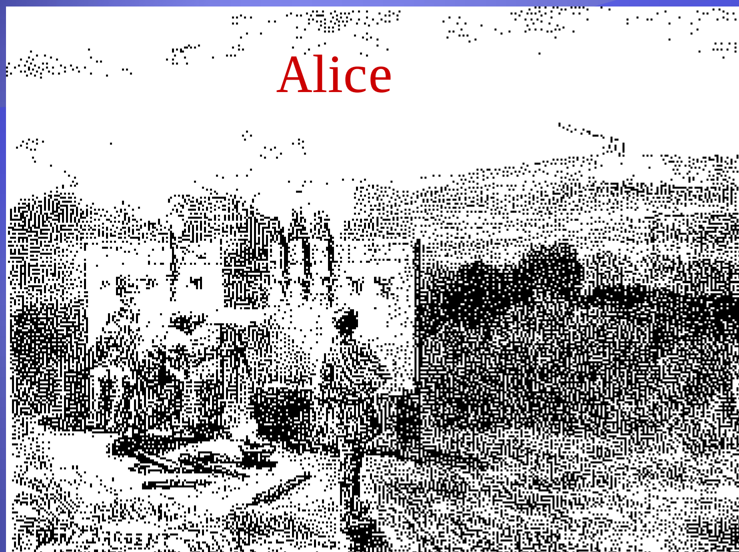
CLYTEMNESTRA
At the speed of light. Hephaestus' sacred fire blazed from beacon tower to beacon tower, from Ida's top to Lemnos, and from there to Athos, that island sacred to Zeus, where they set the blaze they had kept prepared so long, and the tongues of flame leaped up in the dark
of chorus singing the
n splendid crescendo. ….

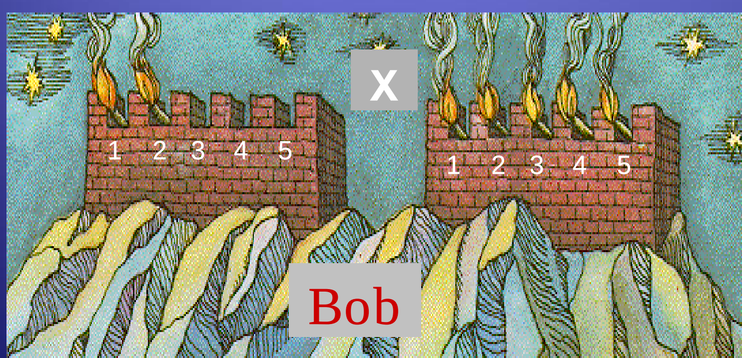


- First free-space optical link transmission ~600km
- Longest span 150km
- 1 bit/night
- 5-10m wood-pile fire (tens of MegaWatts)
- Too bad if it rained!

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)

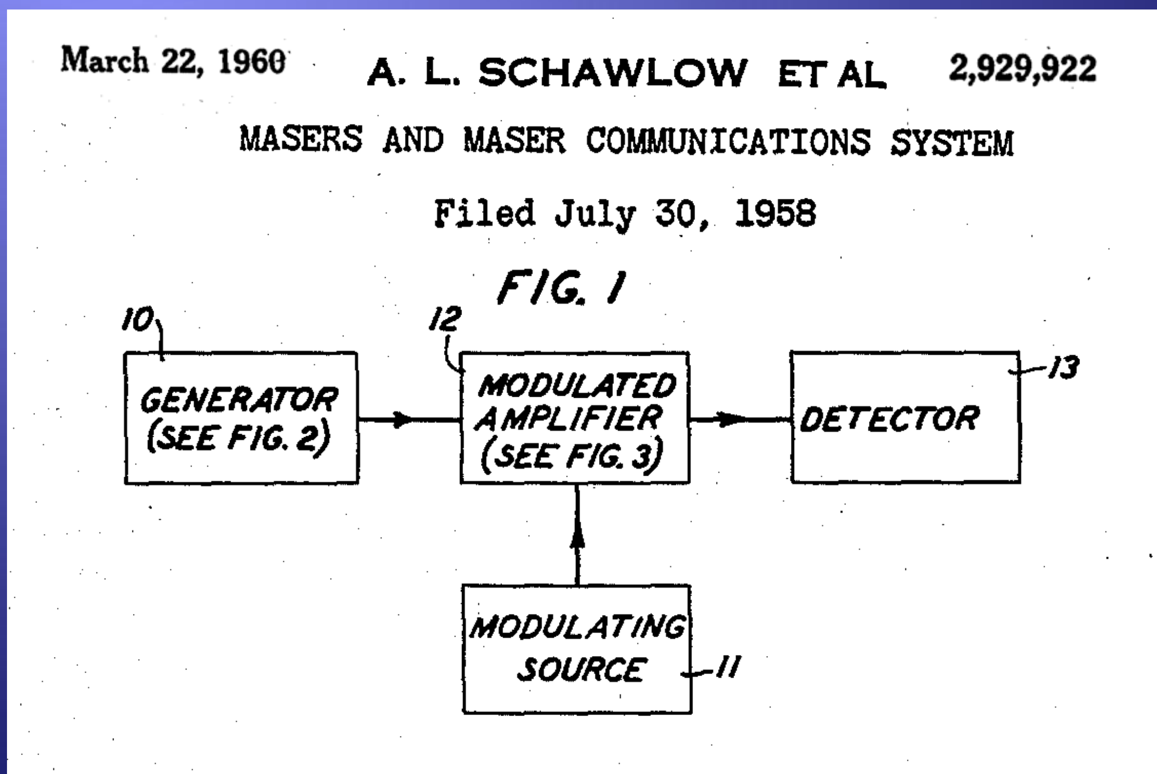
Ω = (4,5)

"Pyrsia": instrument using fire lights to communicate information

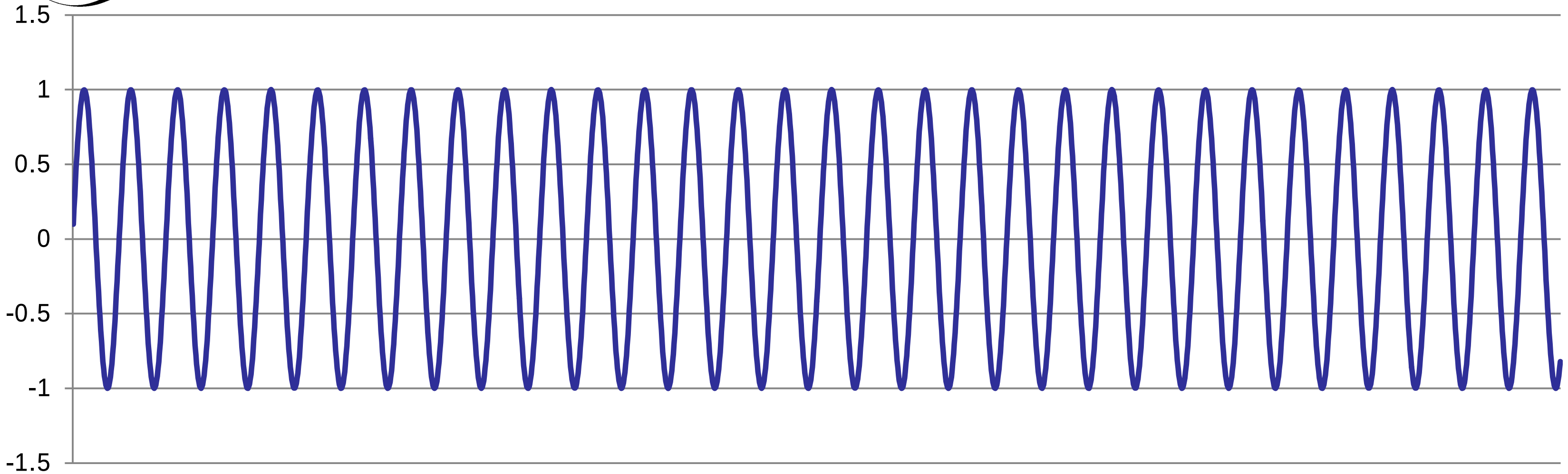
Modern Optical Communications

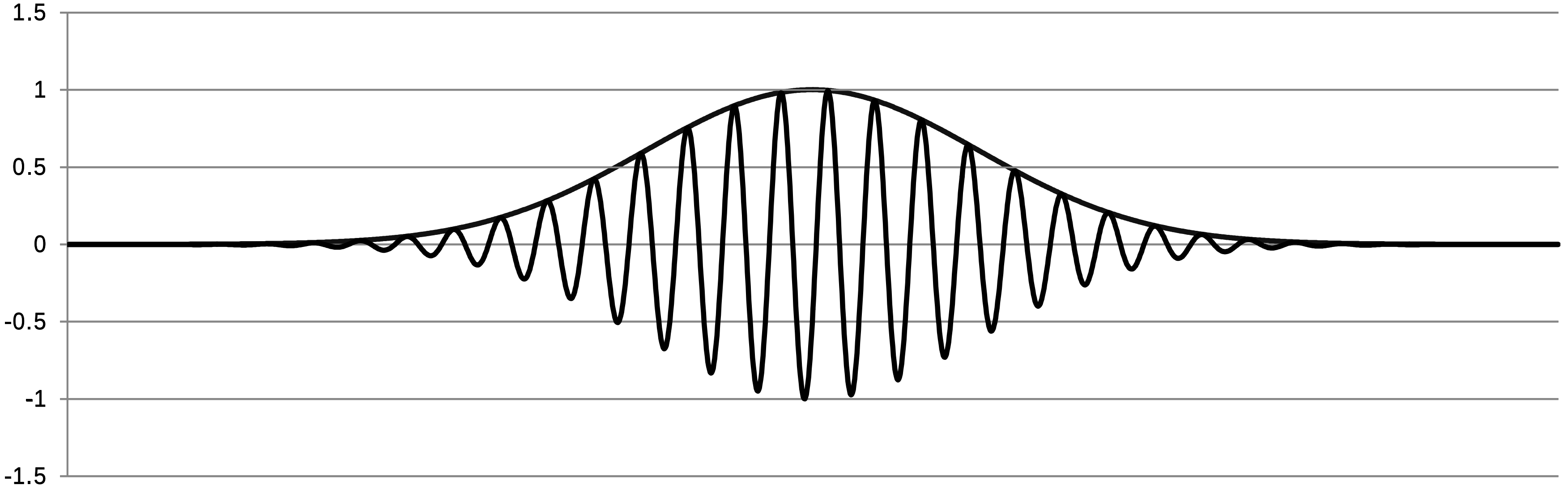
> What is claimed is:
> 1. A communications system for operation in the infrared, visible, or ultraviolet regions of the electromagnetic wave spectrum comprising a monochromatic maser generator, a coherent modulated maser amplifier, a modulating source, and a detector;

- A transmitter source
- A modulator
- A detector

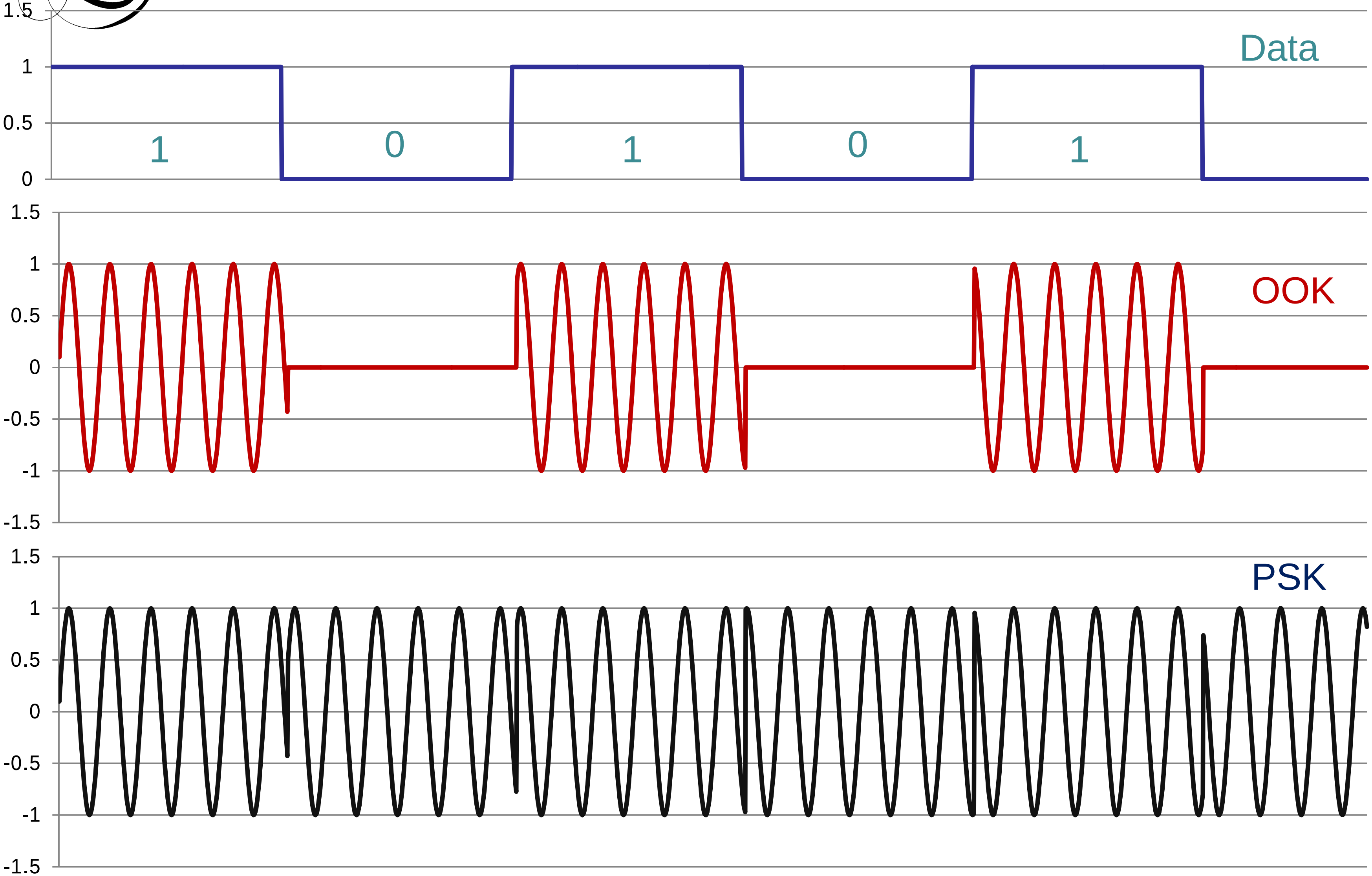


Continuous vs. Pulsed Waves

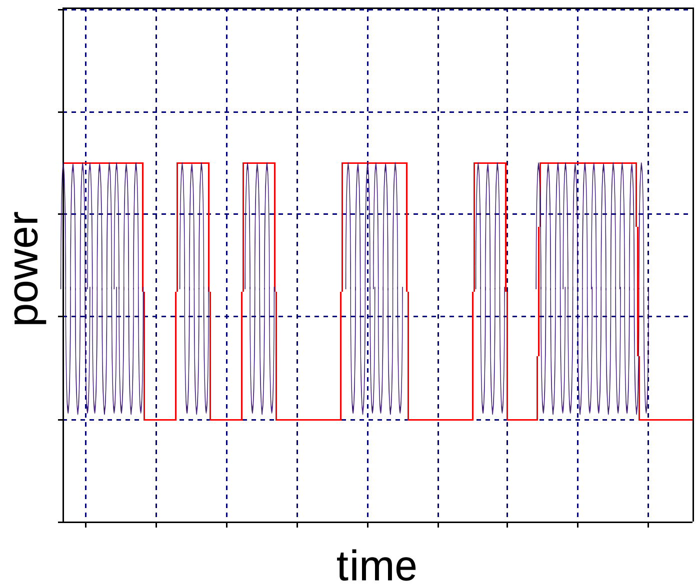


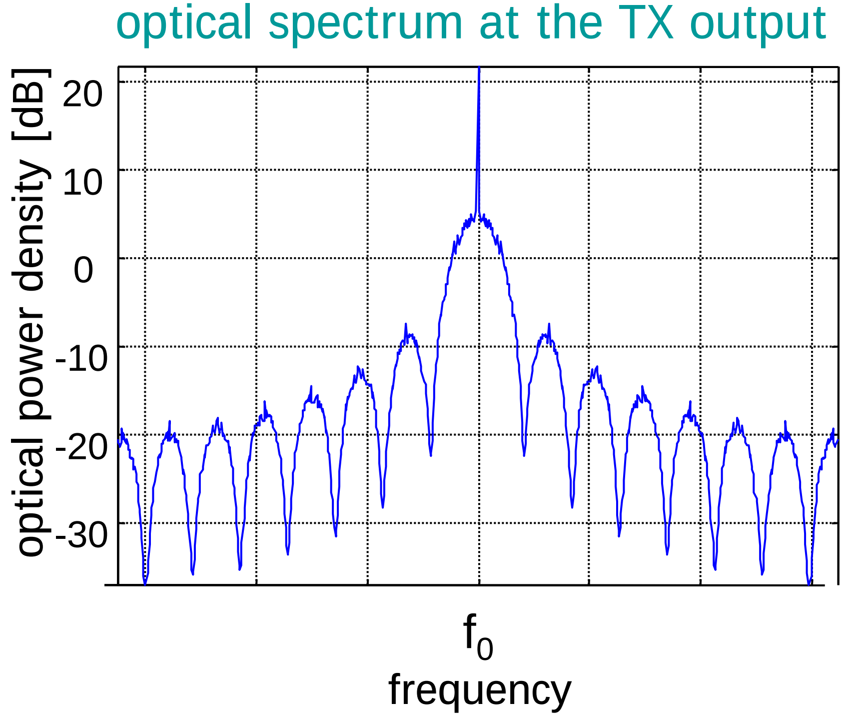


Data modulation



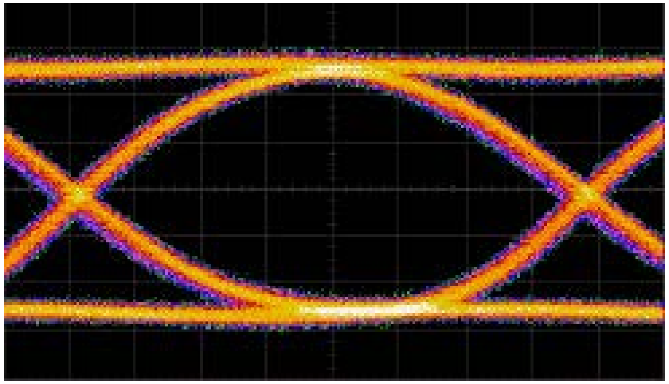
Digital Optical Signals





- **The vast majority of lightwave systems use a digital format**
- **The signal is a stream of 0 and 1 bits**
- **The shorter the bit slot the higher the repetition rate (bit rate) of the signal and the broader the optical spectrum**

Eyes and constellations



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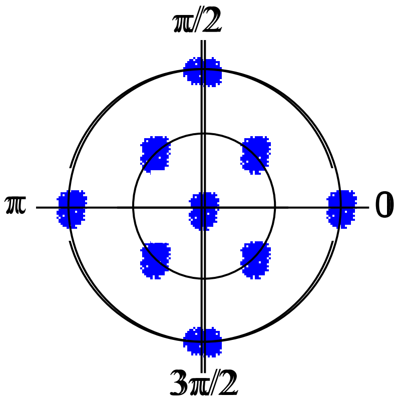


DPSK, DQPSK, QAM…

- **Virtually ‘infinite’ bandwidth of optical fibres has allowed simplistic modulation formats to be employed**
  - **On-Off Keying has been traditionally used**
- **Ever increasing demand for bandwidth calls for communication techniques to become more complex**
  - **Mimic the modulation techniques used in RF systems**

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;

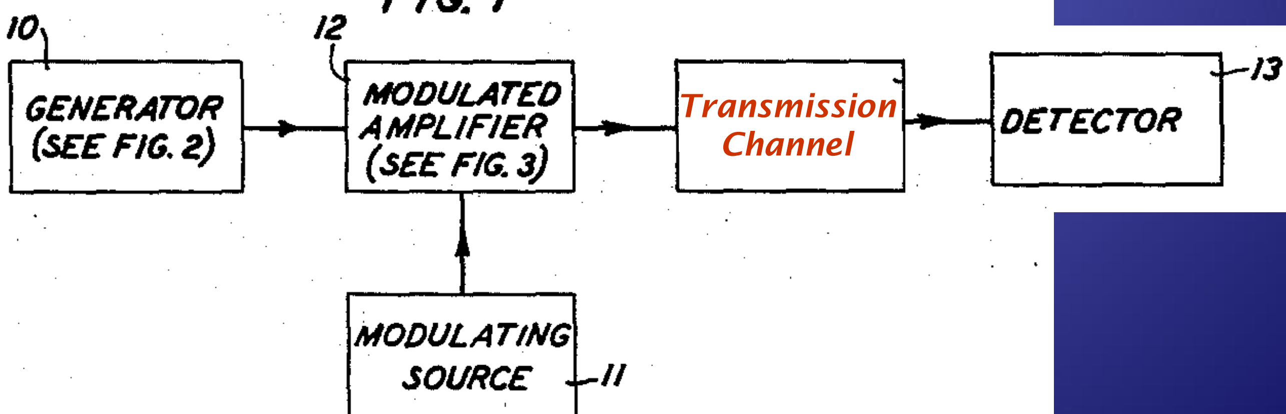
- A transmitter source
- A modulator
- A detector
- A transmission channel

March 22, 1960 A. L. SCHAWLOW ET AL 2,929,922

MASERS AND MASER COMMUNICATIONS SYSTEM

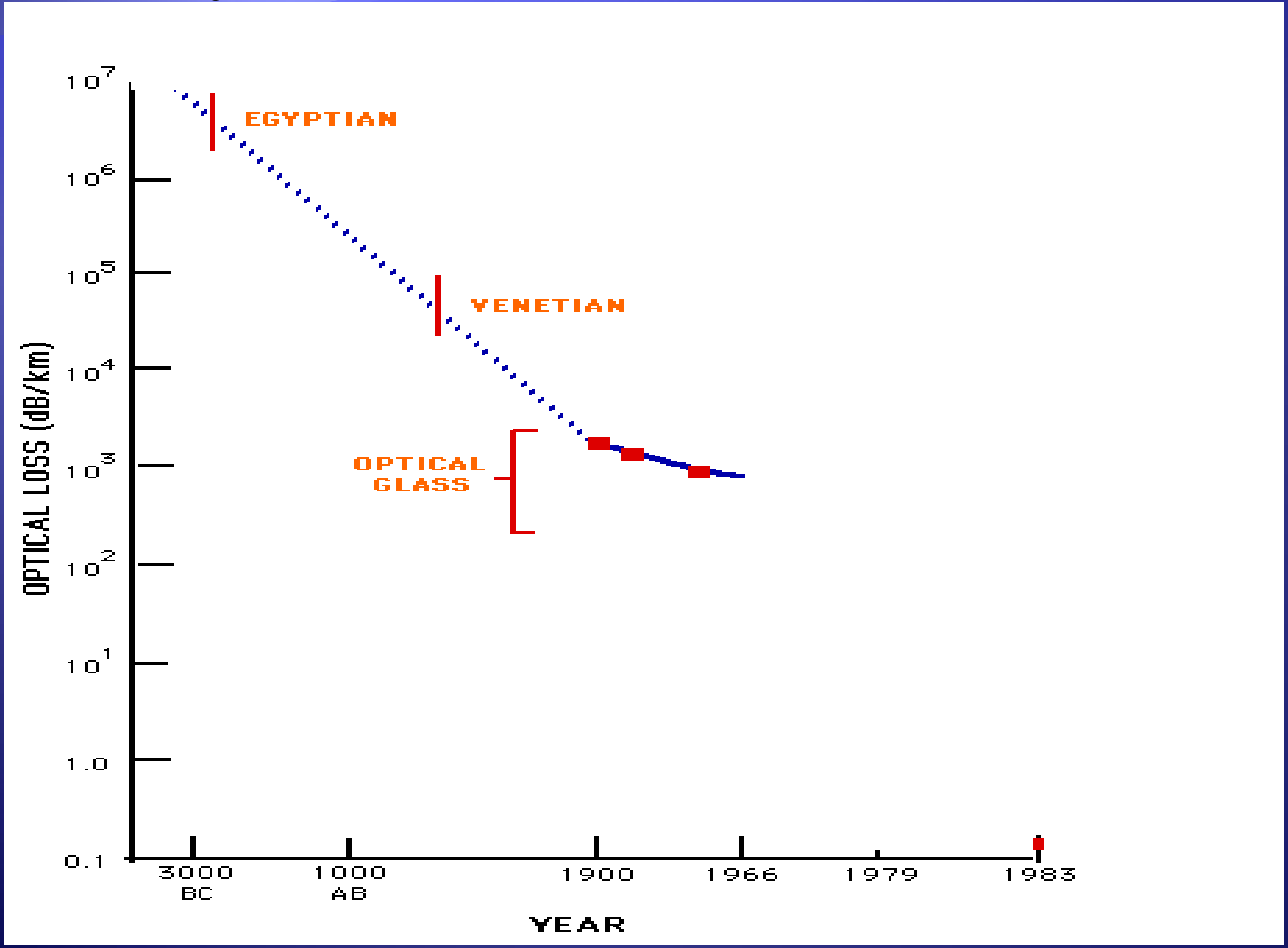
Filed July 30, 1958

FIG. 1

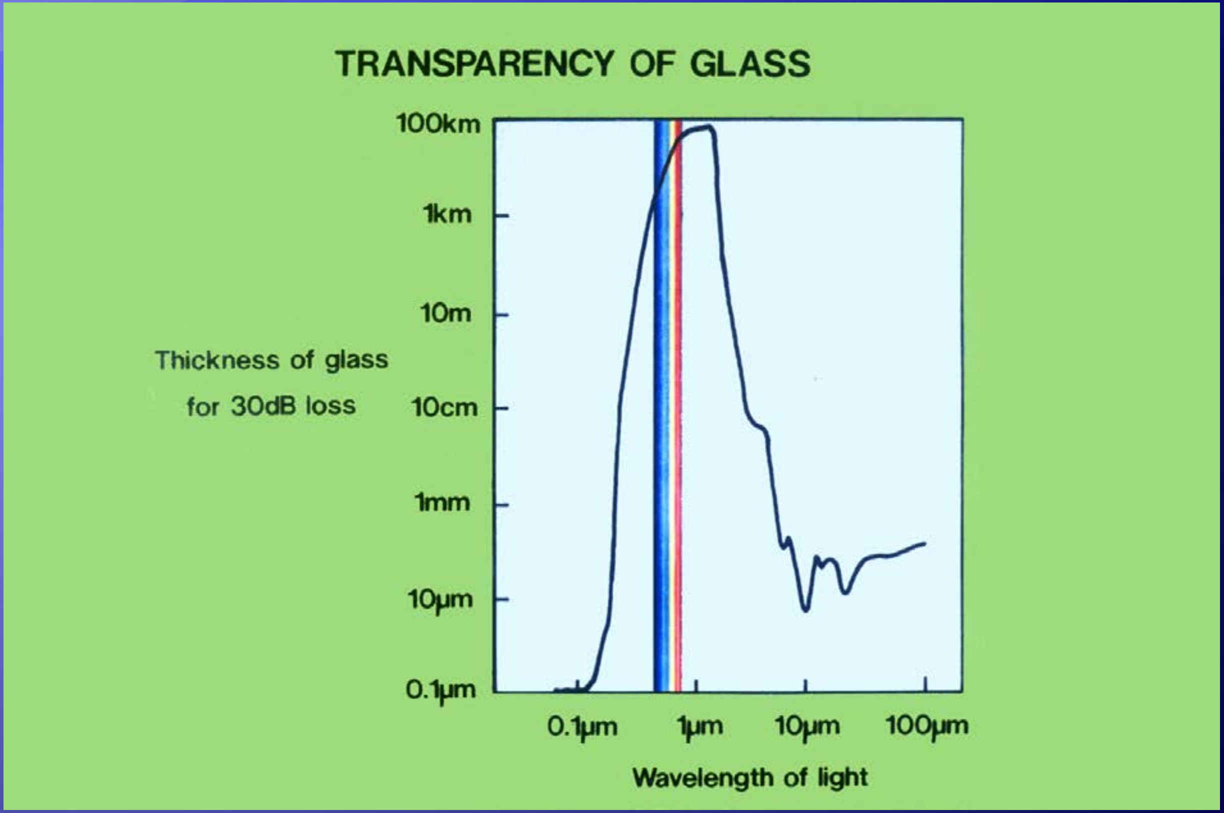


Optical Attenuation in Silica

Source: S. Nagel



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

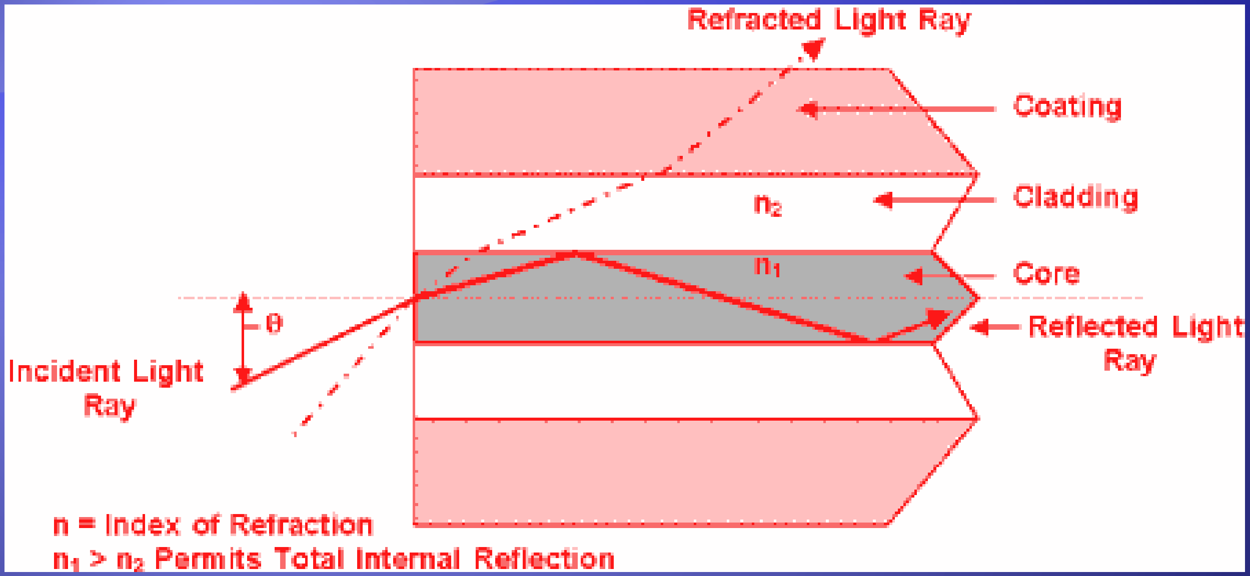


Kao and Hockham
'Dielectric-fibre surface waveguides for optical frequencies'
IEE Proceedings 1966

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

Light

Requirement for SM Guidance



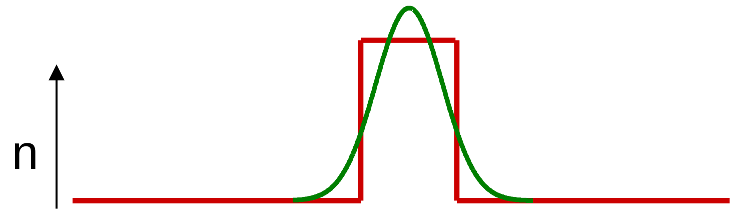
$$NA=(n_1^2-n_2^2)^{0.5}$$

$$V= \frac{2\pi a}{\lambda} NA < 2.405$$

The higher the contrast between n1 and n2 the greater the acceptance angle

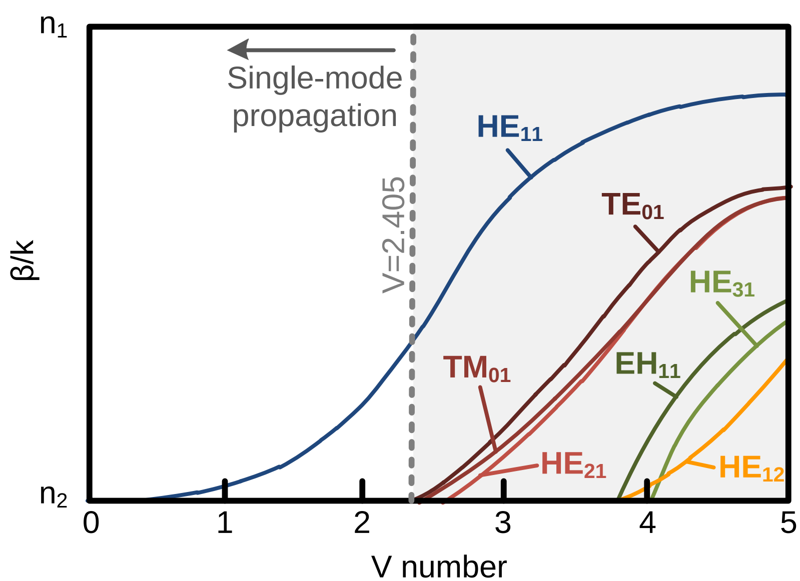
The higher the NA the smaller the core dimension for SM guidance (a ~ 5µm at 1550nm)

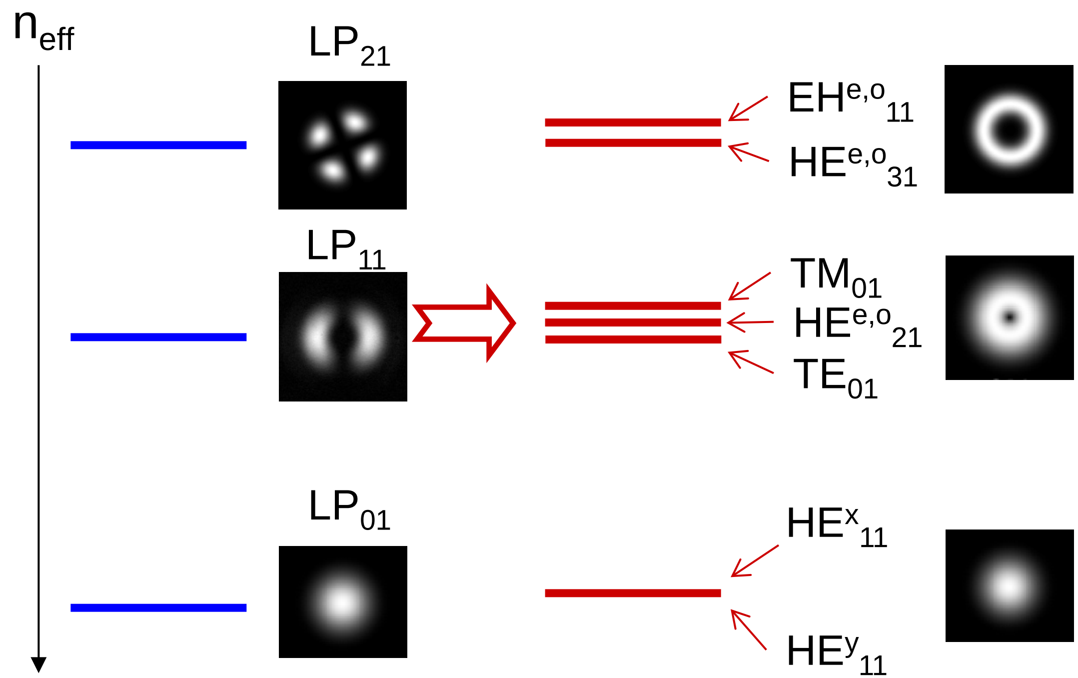
Fiber modes: vector and scalar



$$\{\nabla_t^2 + n^2k^2\}\vec{e}_t = \tilde{\beta}^2\, \vec{e}_t$$

$$\{\nabla_t^2 + n^2k^2\}\vec{e}_t + \nabla_T\{\vec{e}_t \cdot \nabla_T[\ln(n^2)]\} = \beta^2 \vec{e}_t$$





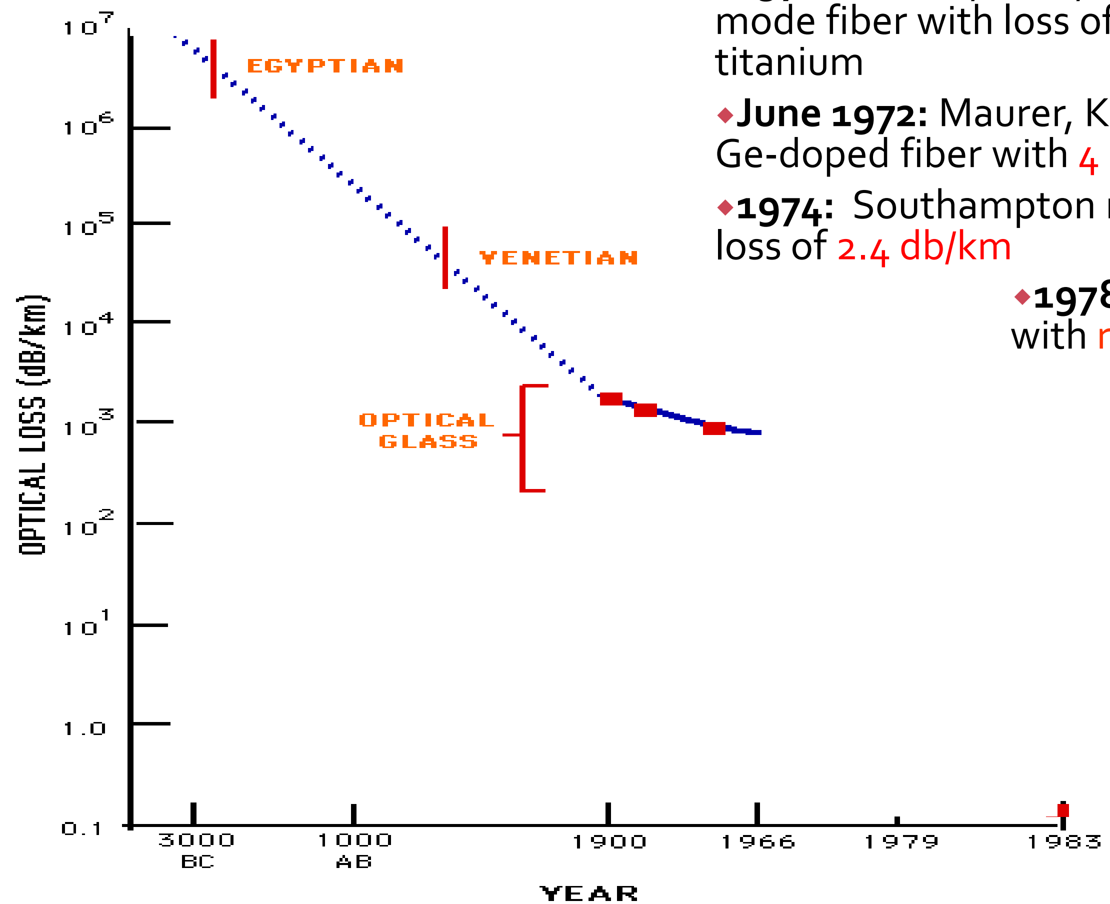
A.W. Snyder and J.D. Love, Optical Waveguide Theory, 1983

The early days in Harlow - 1966

Charlie Kao

Optical Attenuation in Silica

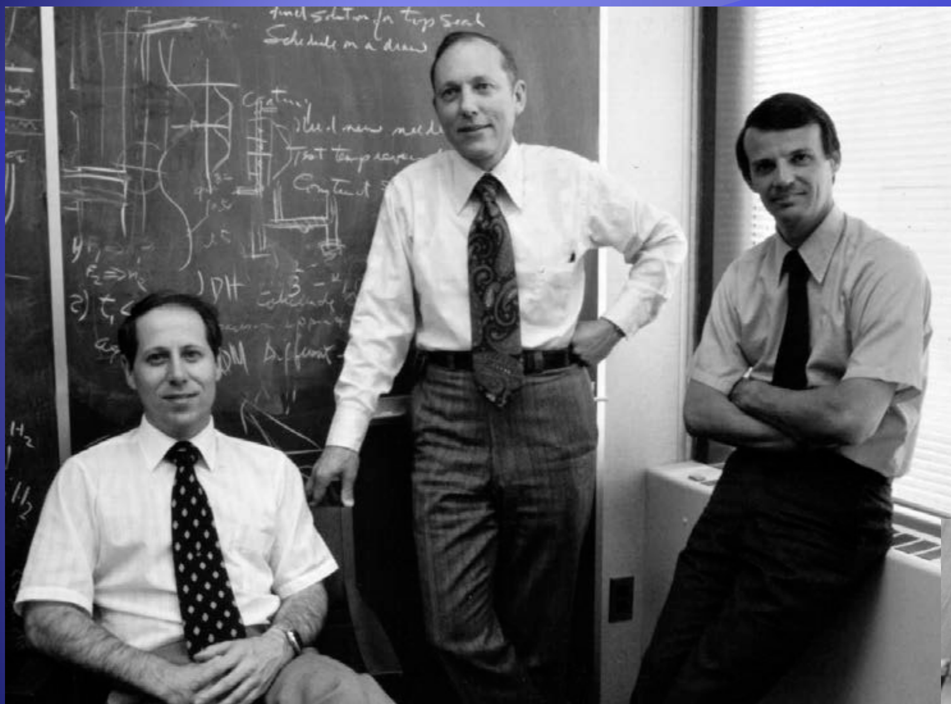
Source: S. Nagel



- **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 Shultz

Early Fibers at Southampton

Vintage Payne
1969

2005

The historic drawing machine
lost forever

Preform Fabrication

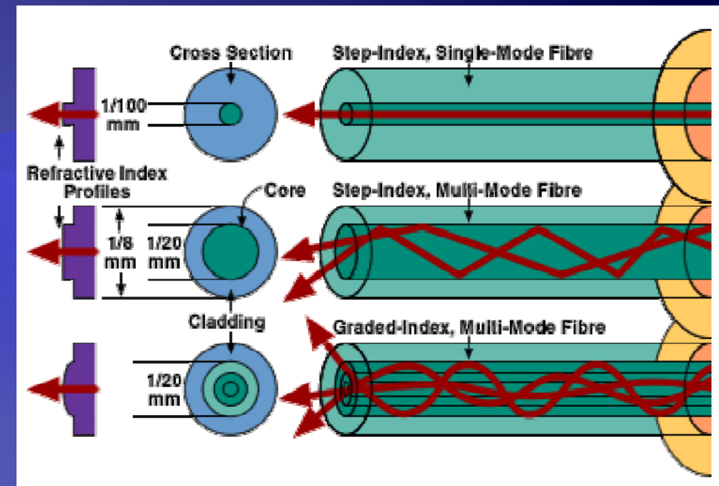
Optical Fibre Preform: glass rod composed of cylindrical layers with well-defined composition and aspect ratio

Preform Manufacture

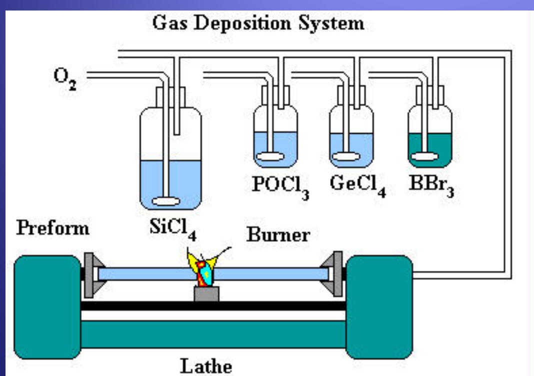
-Modified Chemical Vapour deposition (MCVD)

-Vapour Axial Deposition (VAD)

-Outside Vapour Deposition (OVD)



Basic Doping Profiles



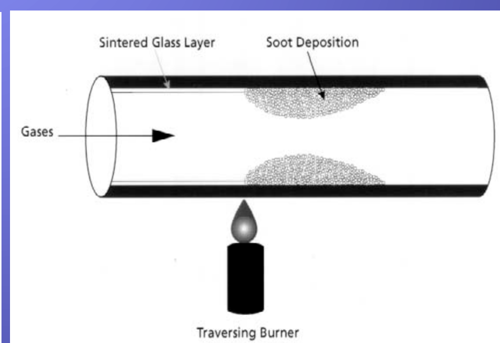
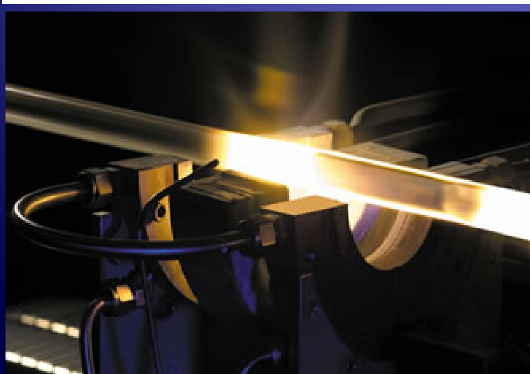
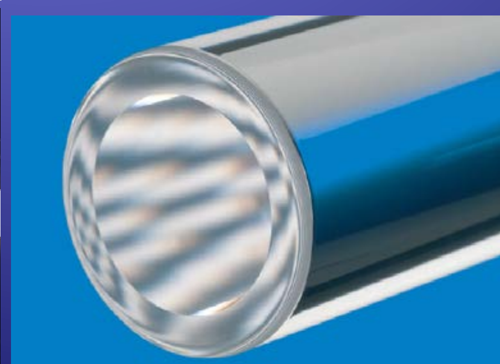


Figure 2 PREFORM FABRICATION



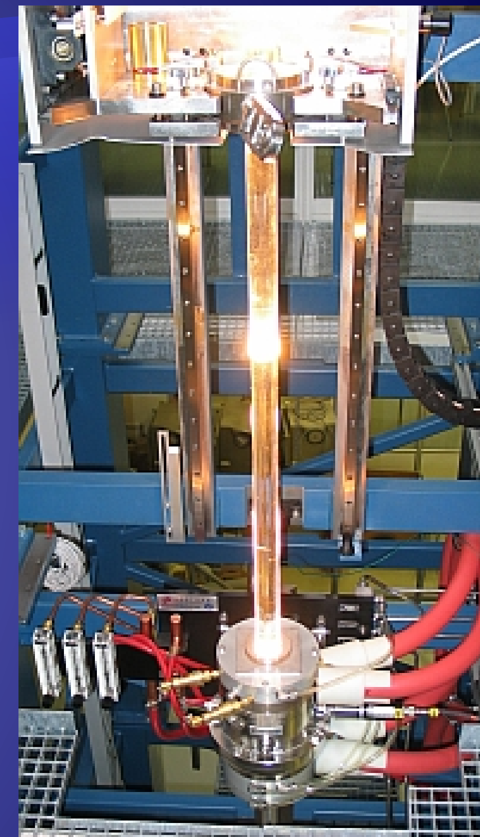


MCVD Lathe (ORC)

MCVD Preform Manufacture Process

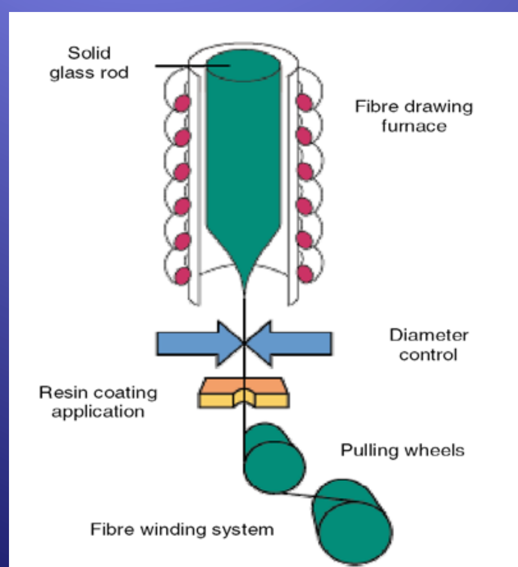
Fiber Drawing

- The preform is fed into the furnace (T=2000C) at a specified speed.
- The glass softens and forms a “neck”, allowing it to be pulled into a fiber.
- The fiber is collected by a take-up drum at a given draw speed
- The time averaged fiber diameter is governed by the conservation of mass.
- One or two layers of UV curable polymer are applied for mechanical and chemical protection

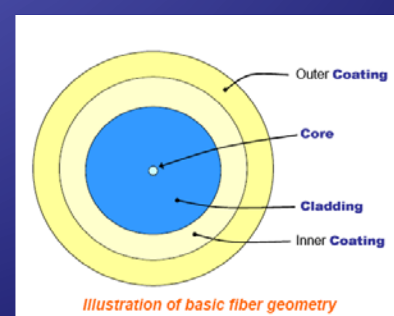


Preform in a furnace

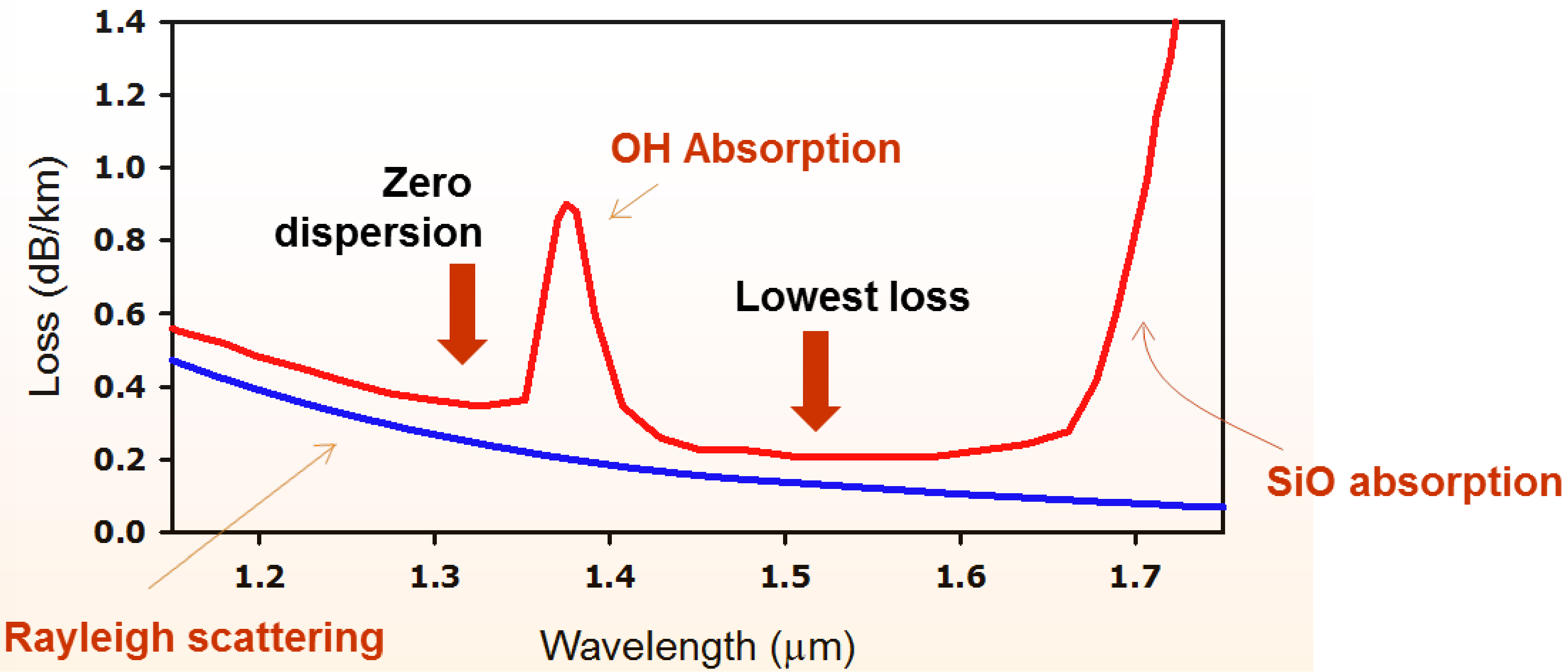
Preform “Neck”



Schematic of Fibre Drawing

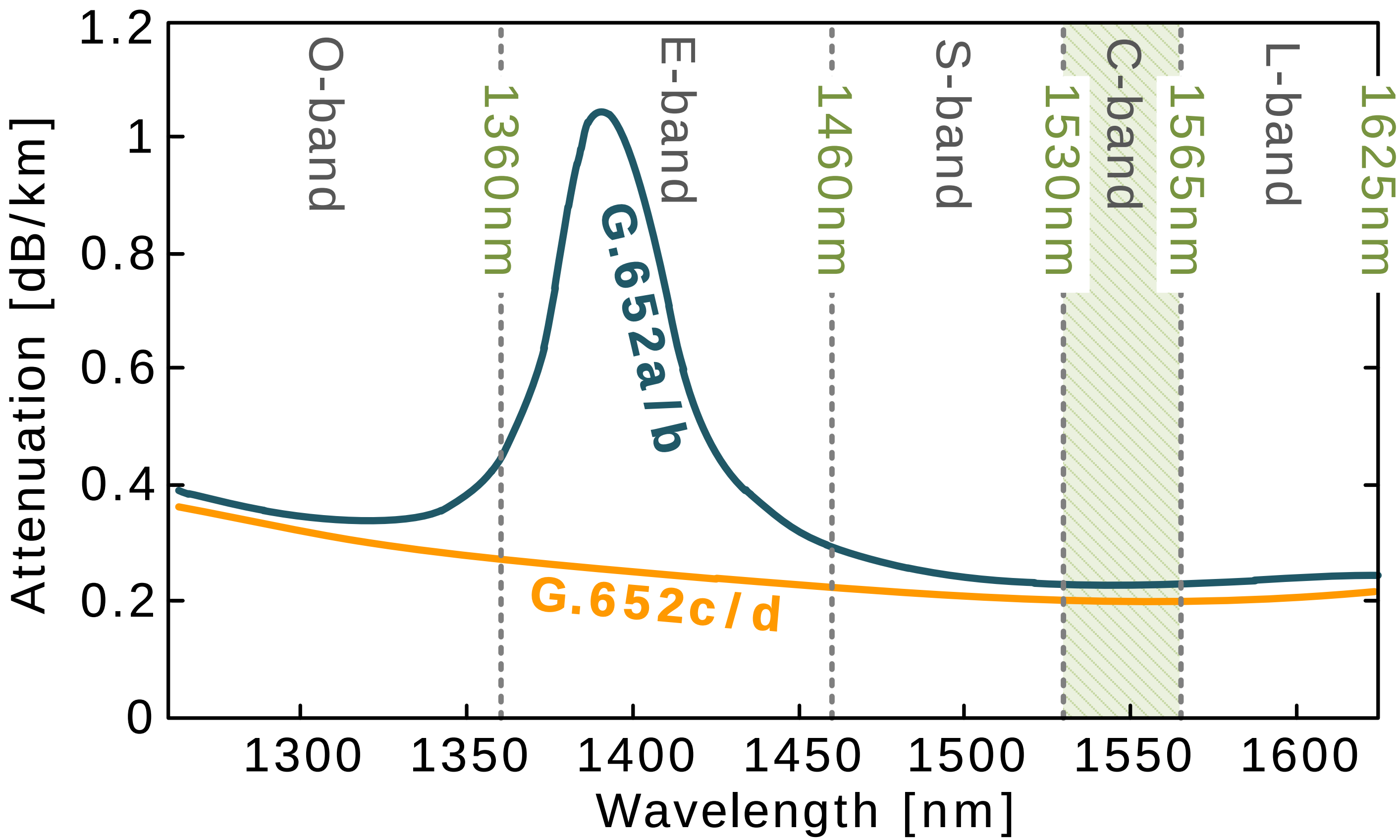


Limits of Loss in Fibres



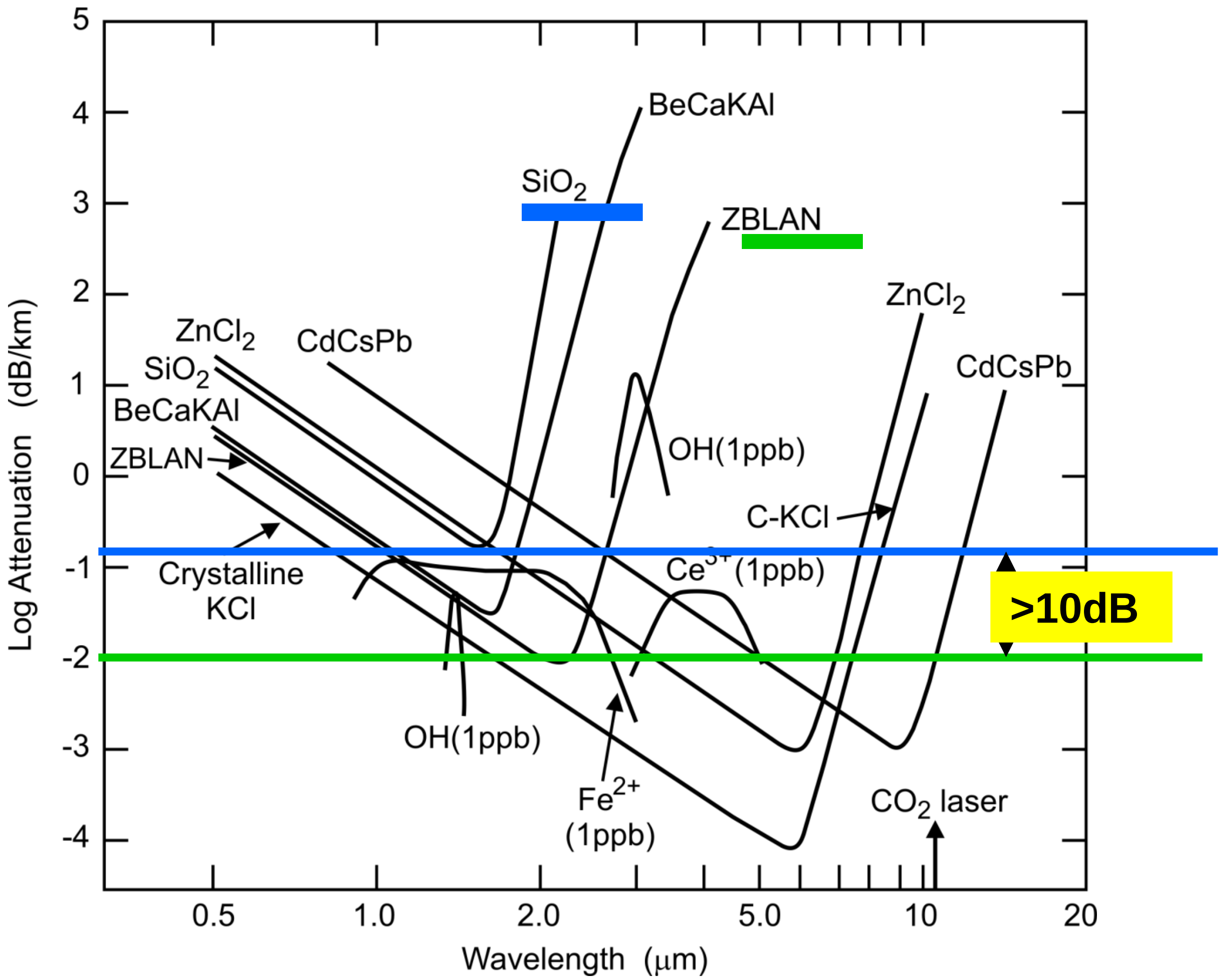
- Rayleigh scattering ($\propto 1/\lambda^4$)
- The Urbach tail (band tail of SiO vibrations)
- OH absorption

SOTA in Low Loss Fibres



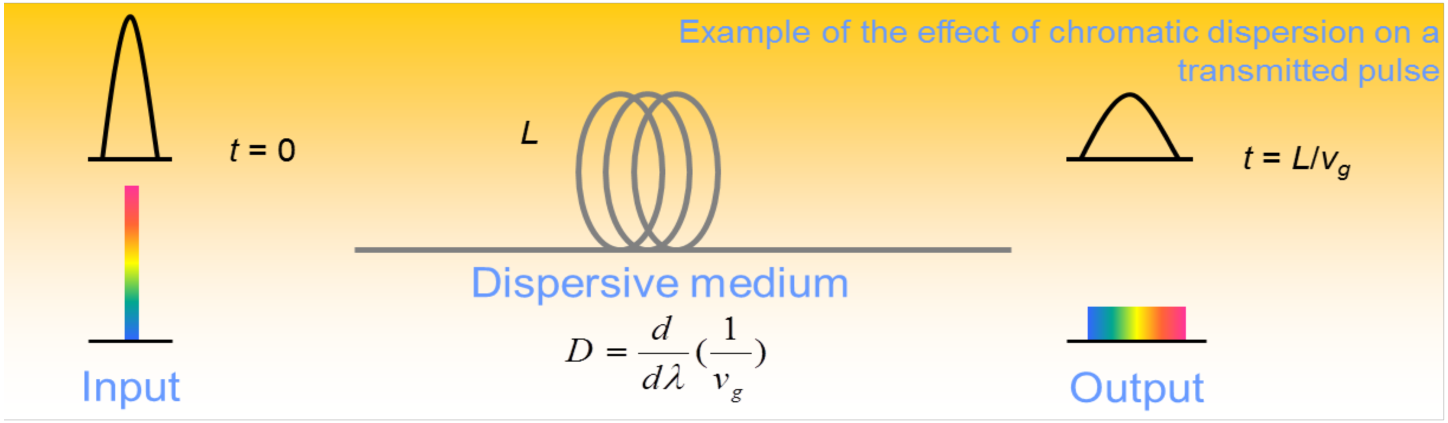
– **Water loss effectively eliminated**
– **Lowest loss reported = 1.48 dB/km**
– **Little scope for further improvement**

Other Materials?



- 0.65 dB/km @ 2.7μm achieved in ZBLAN by BT almost 25 years ago.
- Theoretically 0.03 dB/km possible.
- Minimum loss around 2μm
- Mechanical/chemical robustness?
- Can we do better now using modern chemical purification and glass processing technologies?

Group Velocity Dispersion



- Modal propagation constant is frequency dependent

$$\beta(\omega) = \beta_0 + (\omega - \omega_0)\beta_1 + \frac{1}{2}(\omega - \omega_0)^2\beta_2 + \frac{1}{6}(\omega - \omega_0)^3\beta_3 + \cdots$$

$$\beta_m = \left(\frac{d^m\beta}{d\omega^m}\right)_{\omega=\omega_0} \qquad (m = 1, 2, \ldots).$$

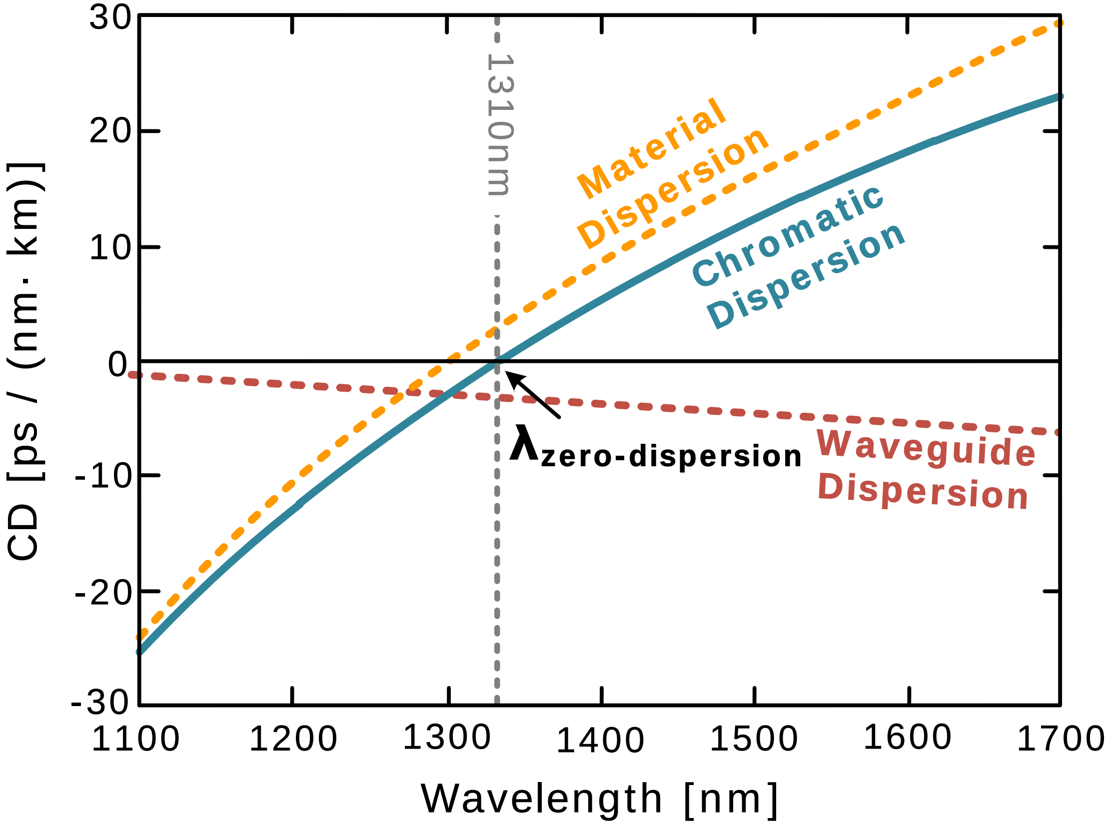
- Leads to pulse broadening as defined by

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2 = -\frac{\lambda}{c}\frac{d^2n}{d\lambda^2}.$$

- Leads to pulse walk off as defined by

$$d_{12} = \beta_1(\lambda_1) - \beta_1(\lambda_2) = v_g^{-1}(\lambda_1) - v_g^{-1}(\lambda_2).$$

Fibre Dispersion

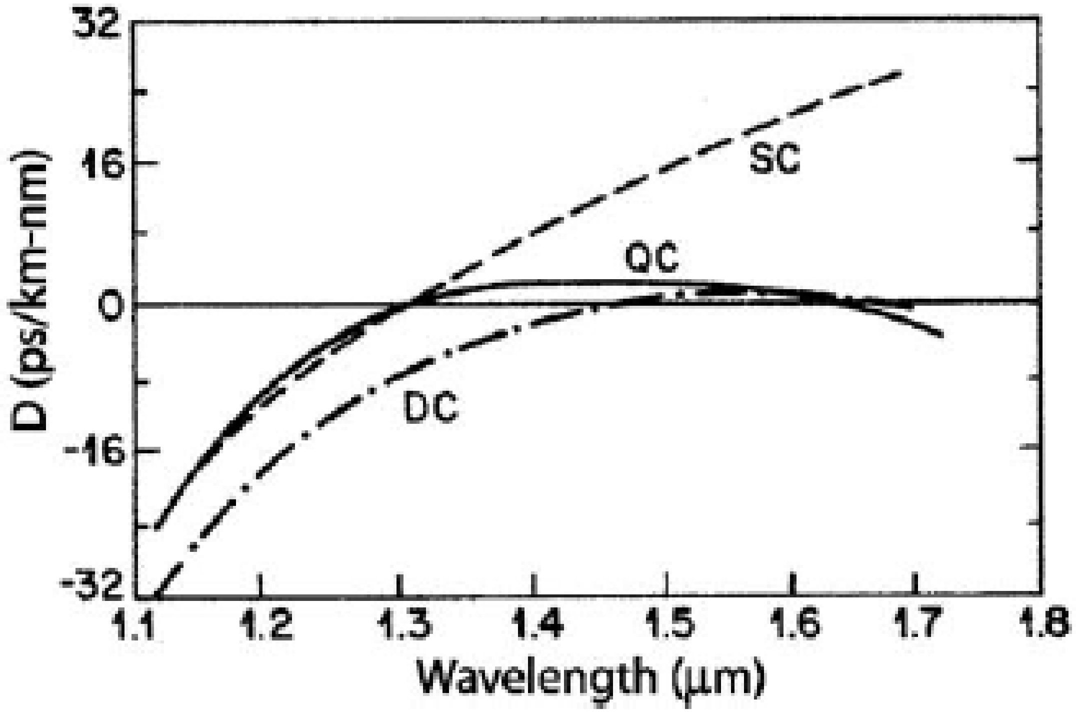


$$v_g \equiv 1/\beta_1$$

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2 = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2}.$$

- Fibre dispersion comprises material and waveguide components
- Waveguide component readily engineered
- Defines linear broadening of an optical pulse (data bit)
- Very strong influence on nonlinear pulse evolution

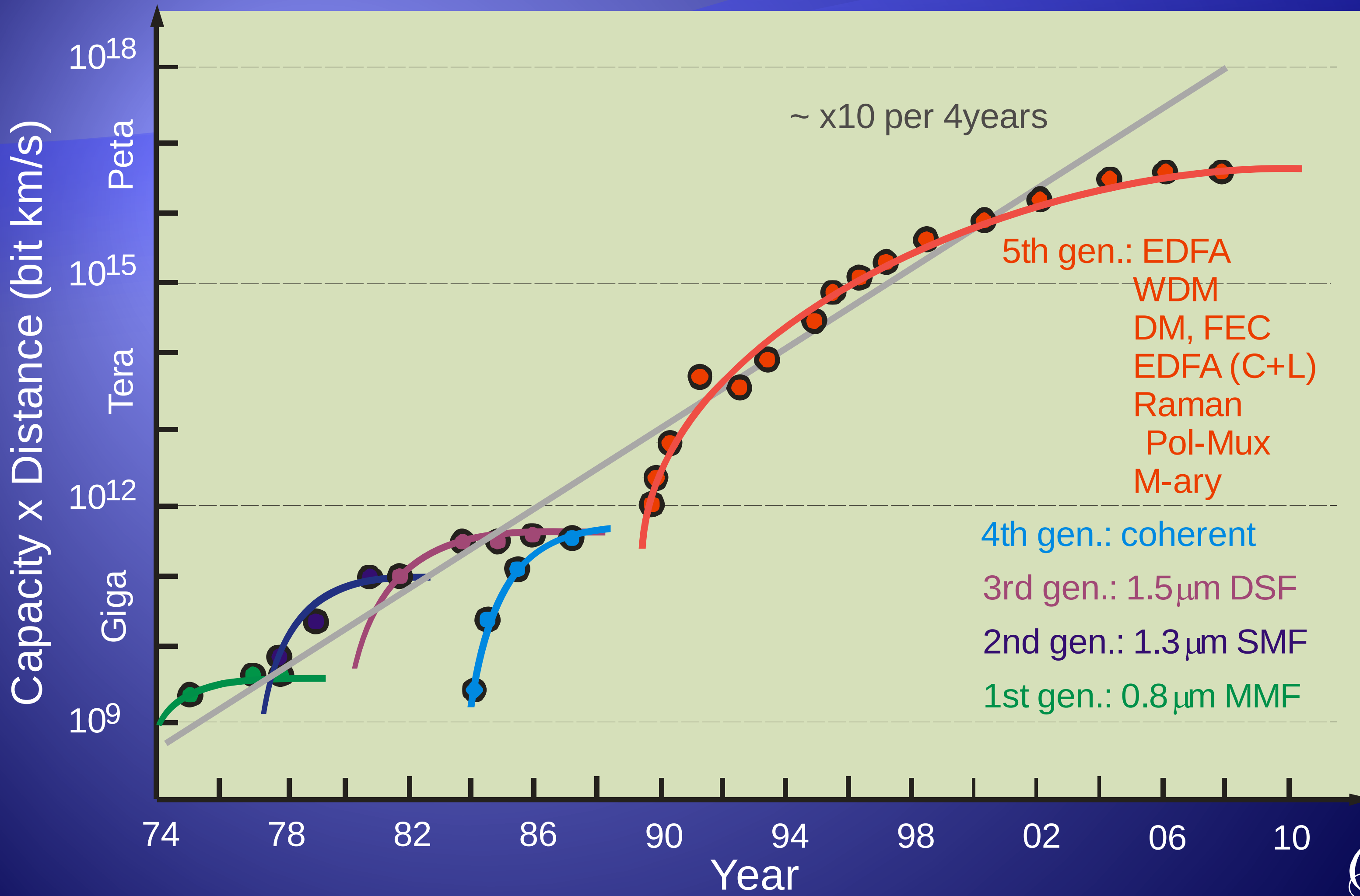
Engineering Fibre Dispersion



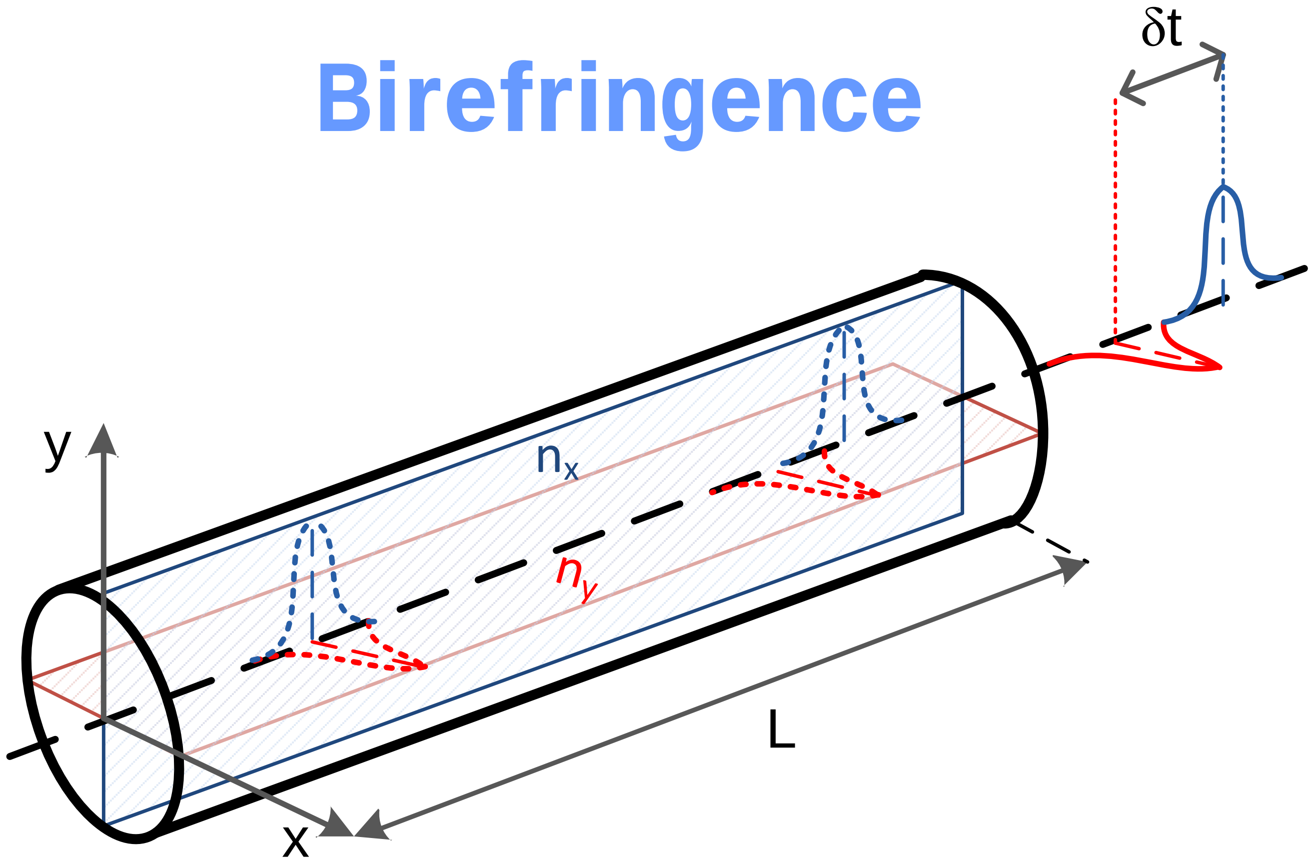
- Over the years dispersion management has been a key issue in system design and has driven various new fibre types e.g.
  - Dispersion-shifted (to 1550nm band)
  - Truewave RS
  - Dispersion compensating fibres

- More recently though advances in DSP have enabled the effects of dispersion to be corrected electronically with standard single mode fibres becoming the fibre of choice.

Capacity x Distance Growth
(over single fibre)

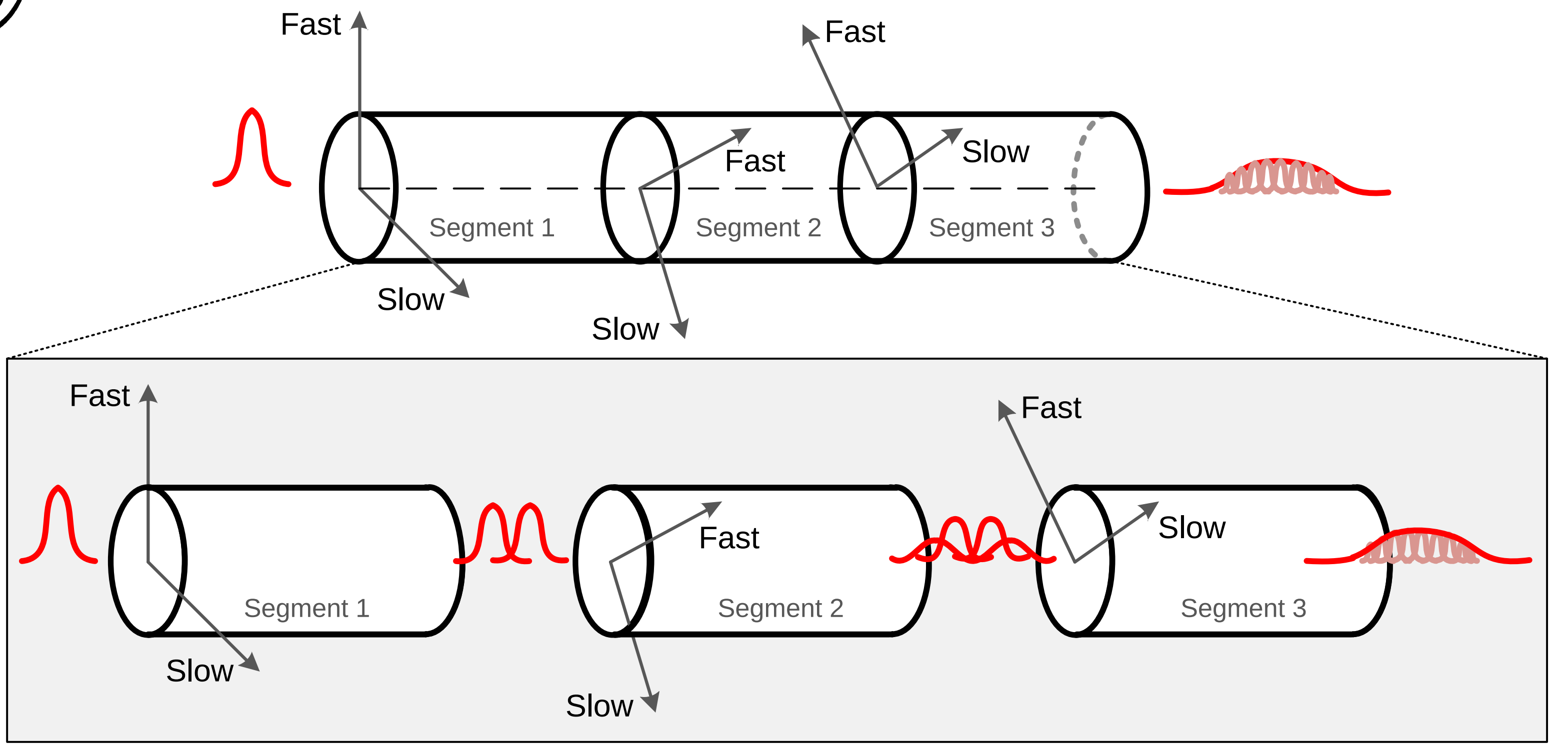


Birefringence



- SM fibres support two degenerate orthogonal polarisation modes
- Core asymmetry however breaks degeneracy resulting in walk-off between polarisation components of a signal
- Random coupling of signal between modes unless very high values of birefringence achieved
- Compromises transmission quality without mitigation

Polarisation Mode Dispersion



- Random coupling along length of fibre causes polarisation components to mix during propagation which can cause significant problems.
- Solution is to spin fibres during draw to ensure strong mixing in this way the total spread of pulse energy is constrained (becomes a random walk problem with delay scaling with sqrt(L) rather than with L).
- More recently DSP based MIMO techniques can be used to enable use of each polarisation mode as a separate information channel.

Nonlinear Effects in Fibre

$$\frac{dE}{dz} + \frac{\alpha(z)}{2}E + \frac{i}{2}\ddot{\beta}(z)\frac{d^2E}{dt^2} - \frac{1}{6}\dddot{\beta}(z)\frac{d^3E}{dt^3} = i\gamma\left|E\right|^2 E$$

↑ Loss ↑ Dispersion ↑ Dispersion Slope ↑ Kerr nonlinearity

$$\boldsymbol{E}(\boldsymbol{r},t) = \frac{1}{2}\hat{p}\left(F(x,y)\cdot E(z,t)\cdot e^{i(\beta_0 z - \omega_0 t)}\right)$$

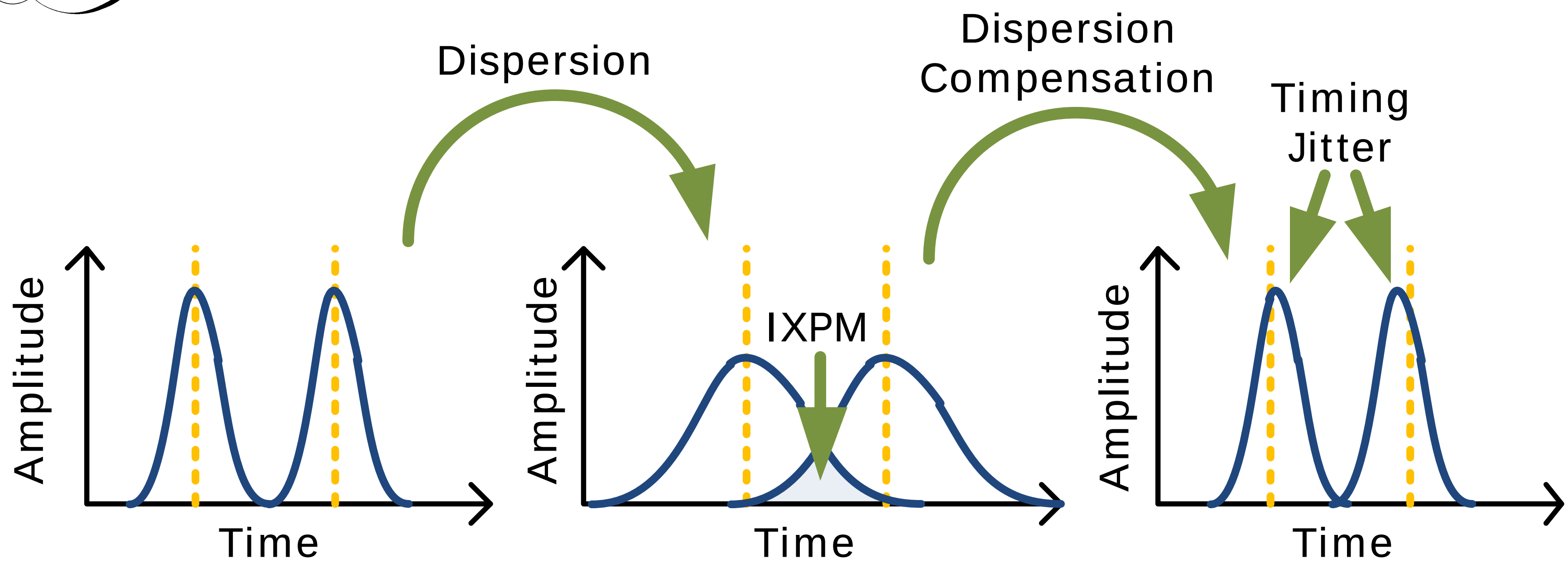
$$n\left(\omega, |E|^2\right) = n_{lin}(\omega) + \frac{n_{nl}(\omega)\,|E|^2}{A_{eff}}$$

- Nonlinear effects governed by NLSE
- Rich body of phenomena and effects
  - SPM, XPM, FWM, solitons, etc
- Readily soluble numerically: particular cases analytically
- Significant control through fibre design
- Ultimately limiting for communications

$$\gamma = \frac{2\pi\cdot n_{nl}}{\lambda\cdot A_{eff}}$$

$$A_{\mathrm{eff}} = \frac{\left(\iint_{-\infty}^{\infty}|F(x,y)|^2 dx\,dy\right)^2}{\iint_{-\infty}^{\infty}|F(x,y)|^4 dx\,dy}.$$

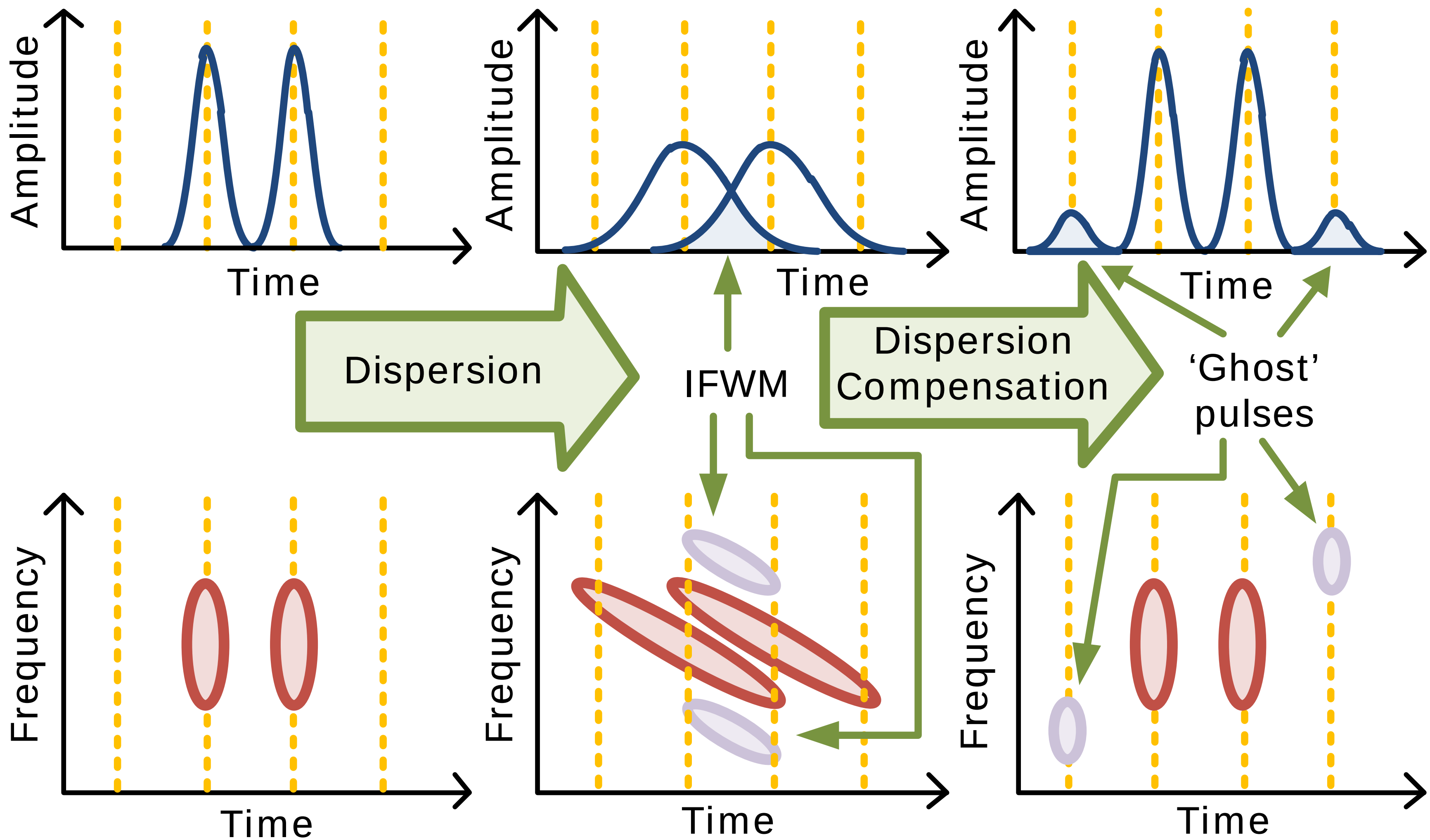
Interchannel XPM



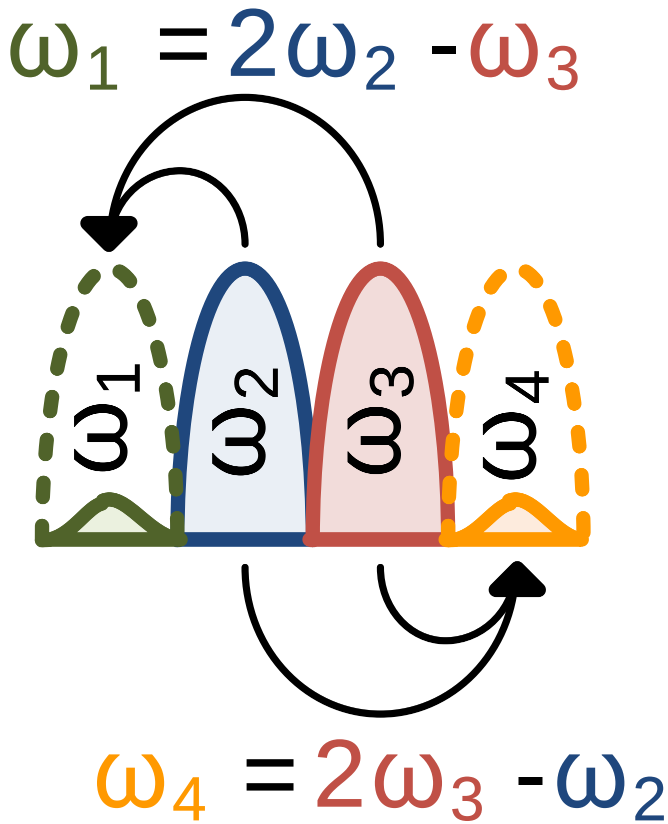
$$\frac{\partial A_1}{\partial z} + \frac{1}{v_{g1}}\frac{\partial A_1}{\partial t} + \frac{i\beta_{21}}{2}\frac{\partial^2 A_1}{\partial t^2} + \frac{\alpha_1}{2}A_1 = i\gamma_1(|A_1|^2 + 2|A_2|^2)A_1,$$

$$\frac{\partial A_2}{\partial z} + \frac{1}{v_{g2}}\frac{\partial A_2}{\partial t} + \frac{i\beta_{22}}{2}\frac{\partial^2 A_2}{\partial t^2} + \frac{\alpha_2}{2}A_2 = i\gamma_2(|A_2|^2 + 2|A_1|^2)A_2,$$

Interchannel FWM



FWM in Fibres

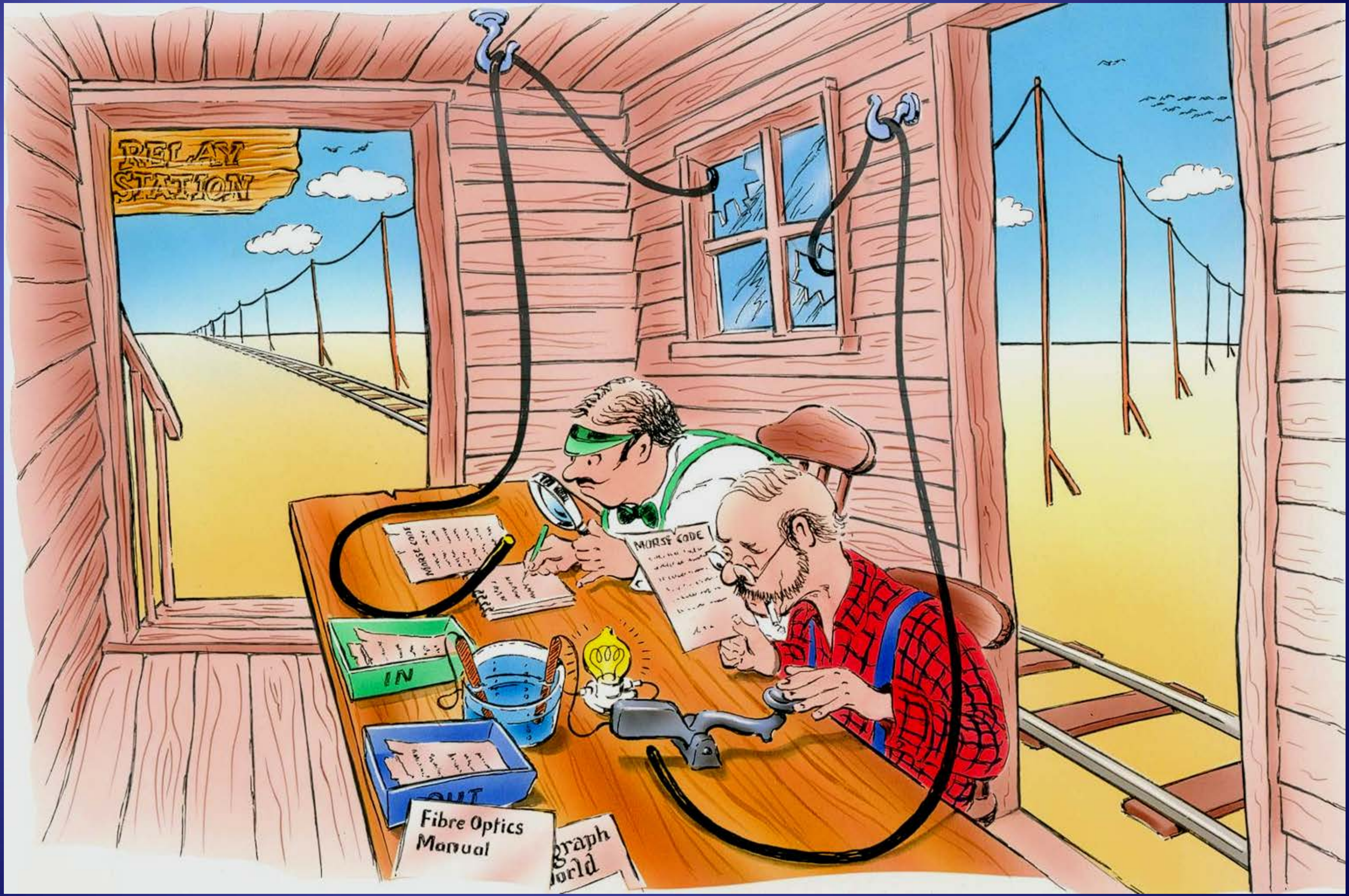


$$\kappa = \Delta k_M + \Delta k_W + \Delta k_{NL} = 0,$$

- Only really a problem in low GVD fibre where necessary phase matching preserved over long lengths.
- Killed-off the use of Dispersion-Shifted Fibres (DSF)
- Mitigated by using high local dispersion

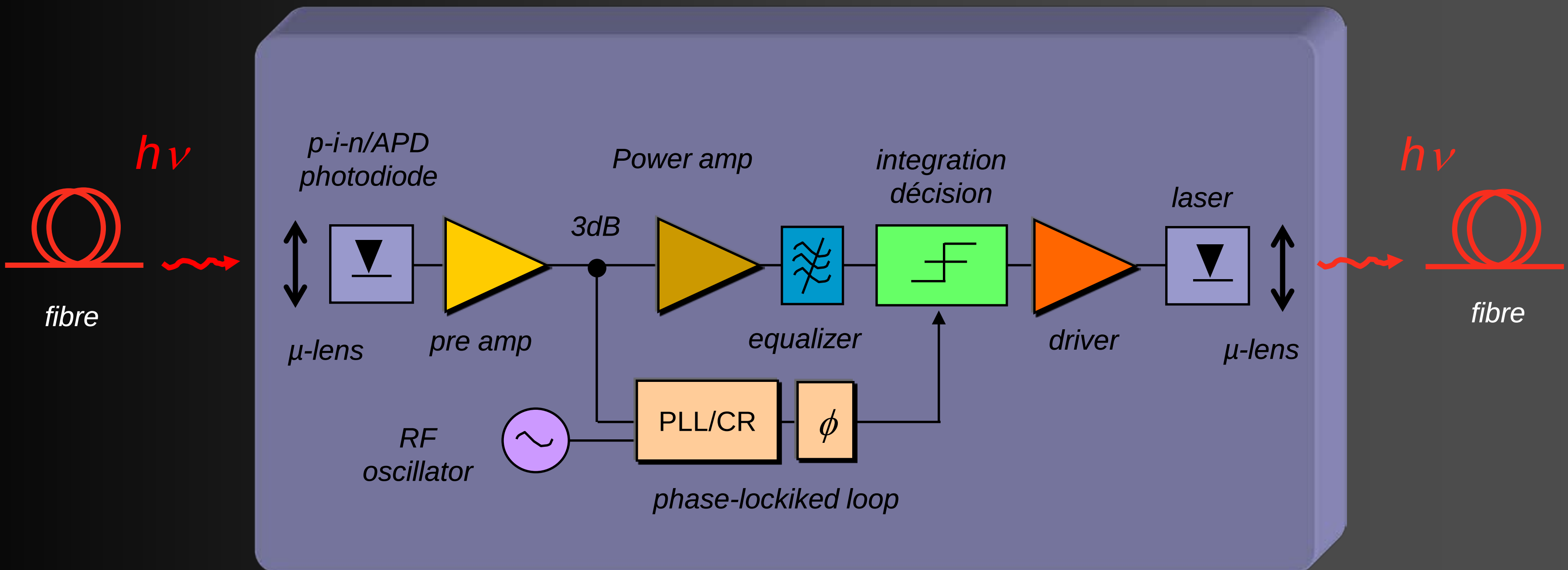
Who needs an amplifier....?

There was just one further problem



No amplifier!

Electronic « 3R » repeater

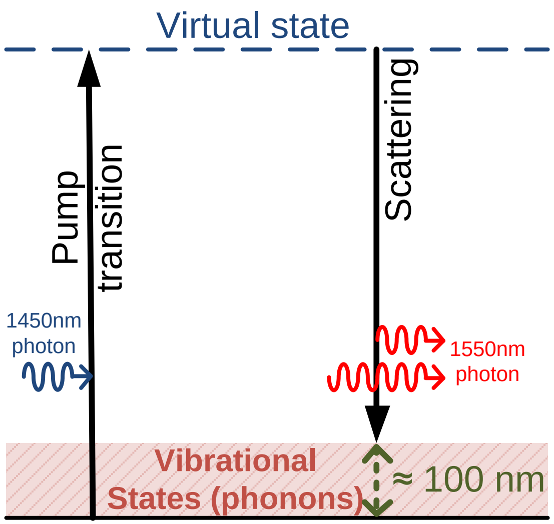


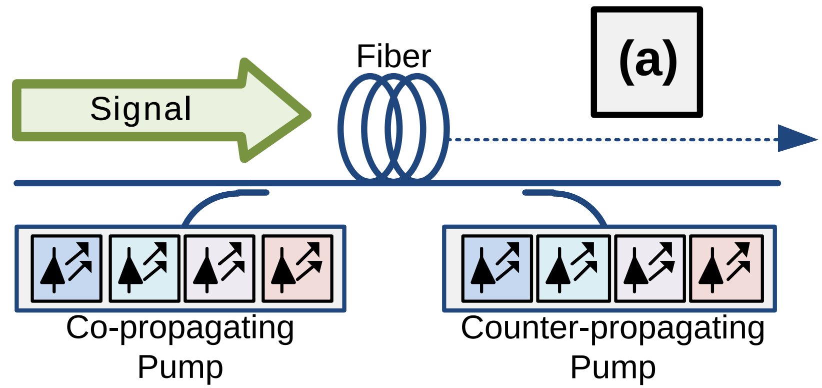
- Bit rate and modulation format fixed → no flexibility, one wavelength channel
- Bandwidth limited → electronic bottleneck (1-10 GHz)
- Complex and costly apparatus, high power consumption

Optical Amplifiers

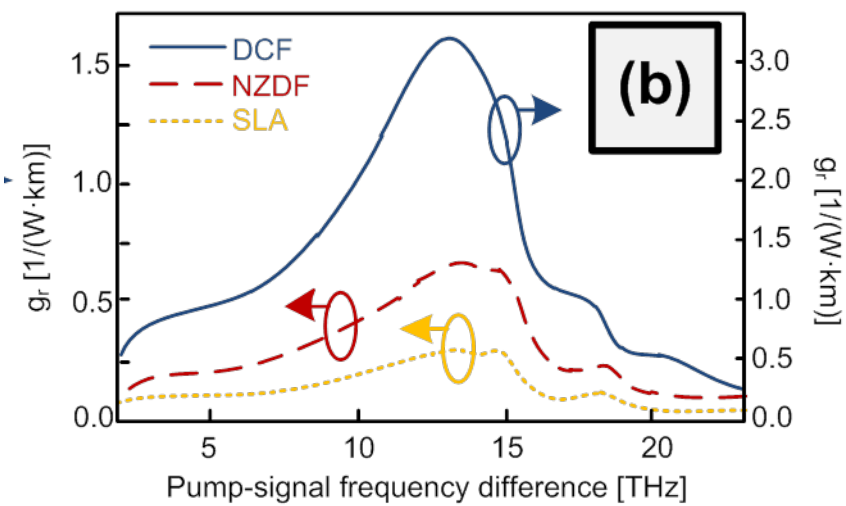
- **Requirements:**
  - High small signal gain
  - High saturation power
  - Low added noise
  - Broad gain bandwidth
- **Erbium-doped fibre amplifiers (EDFA's)**
- **Semiconductor optical amplifiers (SOA's)**
- **Raman amplifiers**

The (lumped) Raman Amplifier



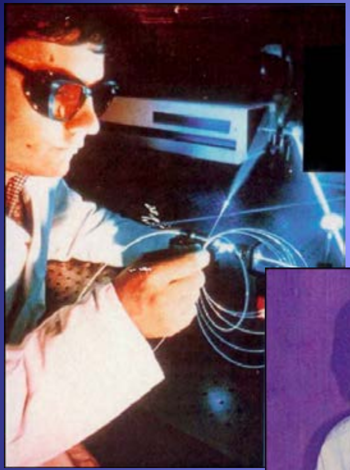


- Raman scattering can occur in any fibre
- Photons exchange energy with the material to generate a new photon at a different wavelength (and a phonon)
- Broad gain bandwidth (~5THz or more)
- Can operate at any wavelength
- Typical value for power required to observe Raman scattering ~ 600 mW (for L = 20km)



The Erbium-doped fibre amplifier

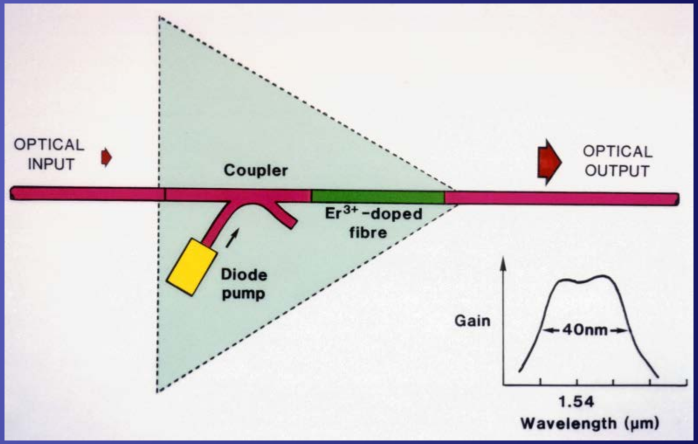
Southampton 1986



Reekie

Poole

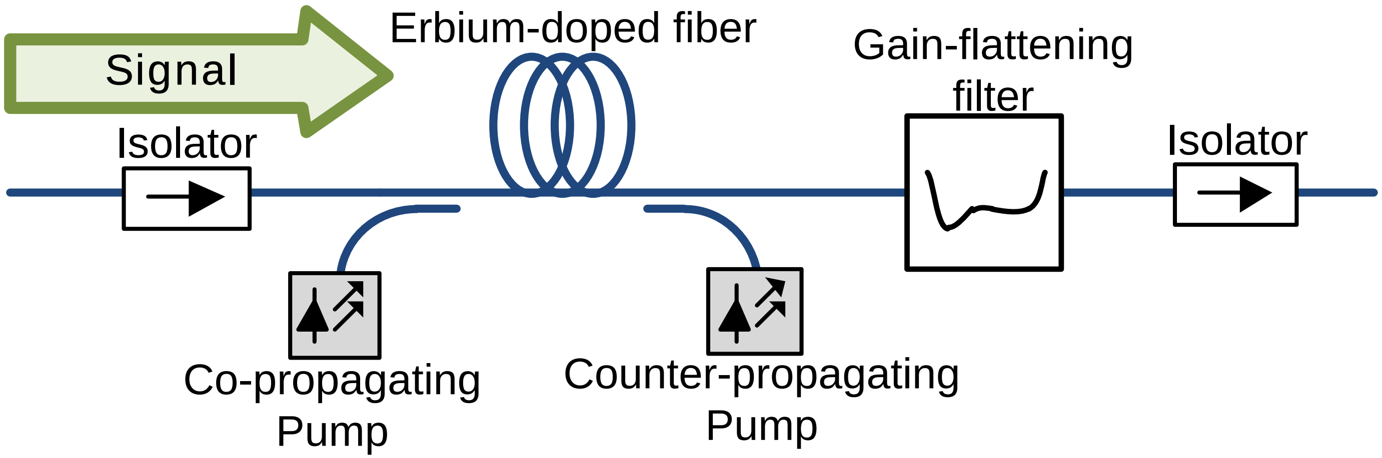
Mears

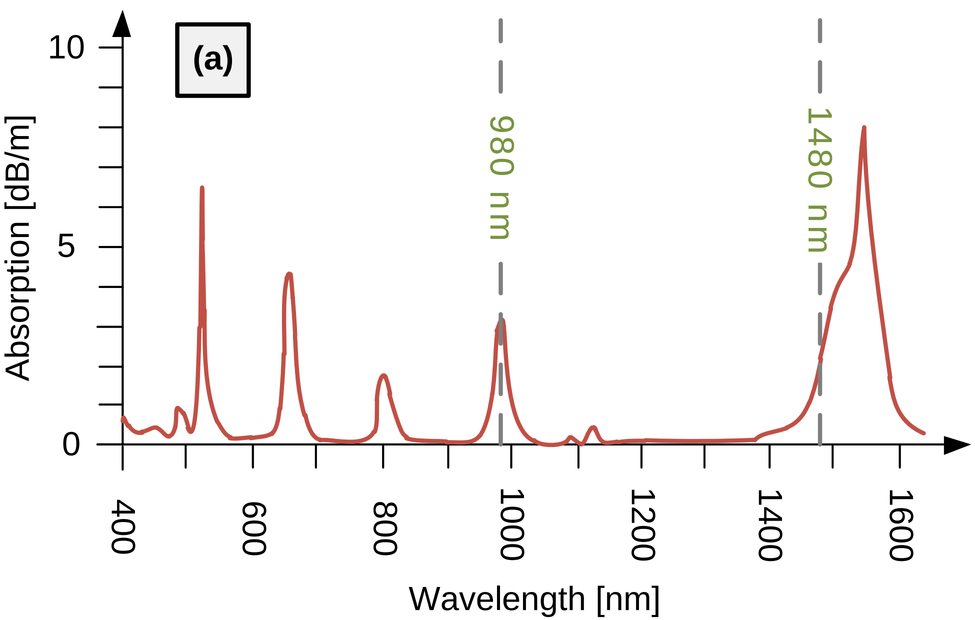


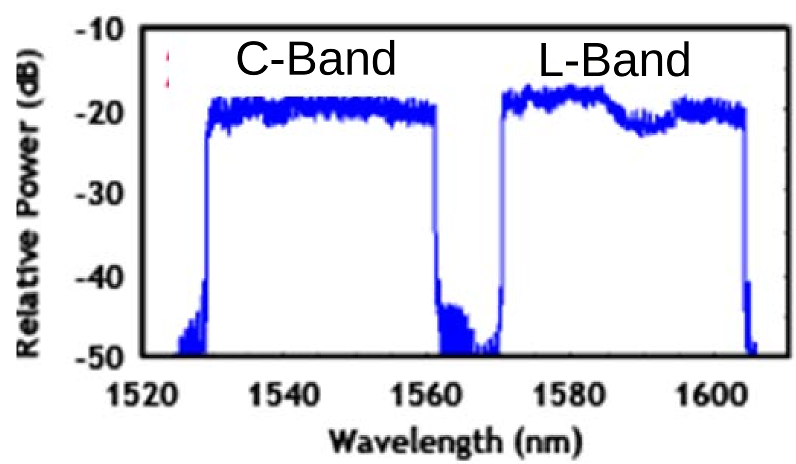
"The broad fluorescence linewidth of rare-earth ions in glass allows the construction of broadband amplifiers for use in wavelength-division multiplexing. It should be possible to use distributed amplification as a means of overcoming losses in soliton propagation"

ECOC 1985, Venice

The EDFA

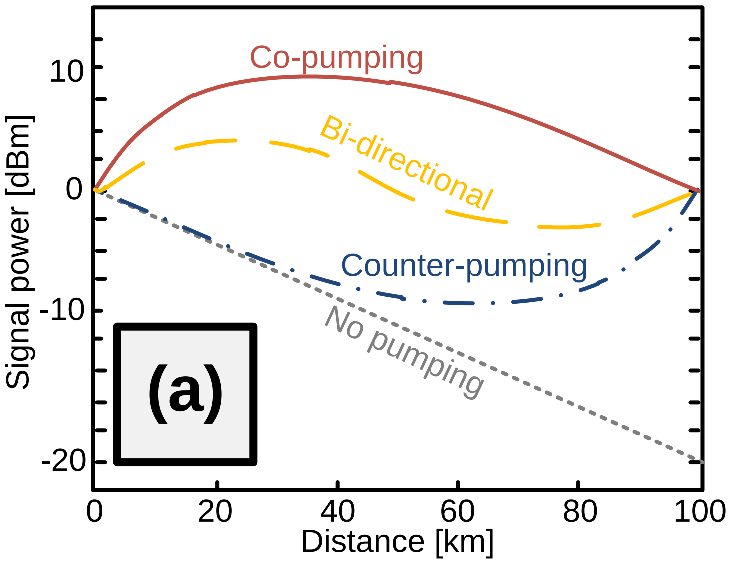


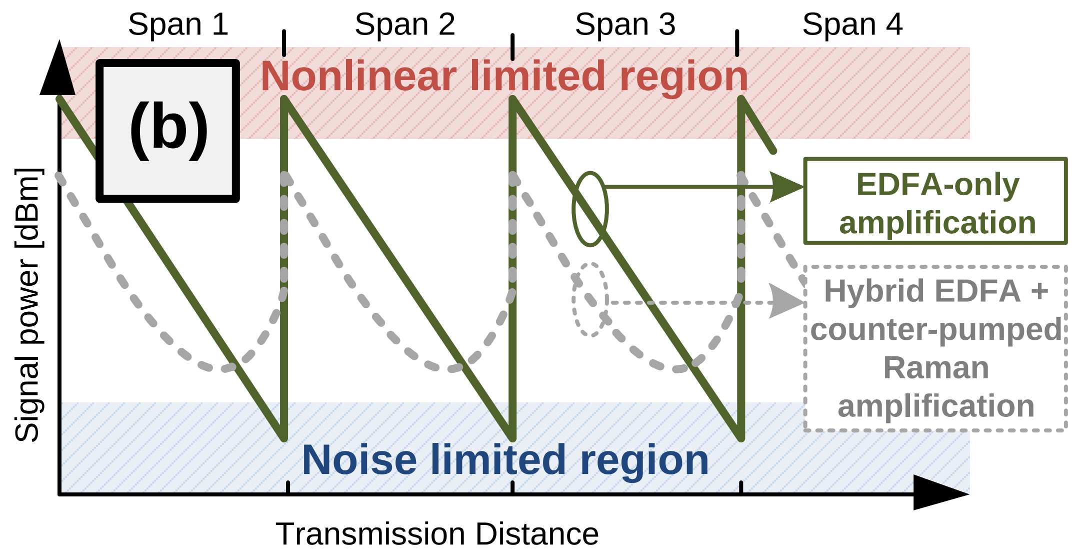




Low noise (NF ~4-5 dB), high gain (>25dB) possible over >10 THz bandwidth

Distributed Raman + EDFA



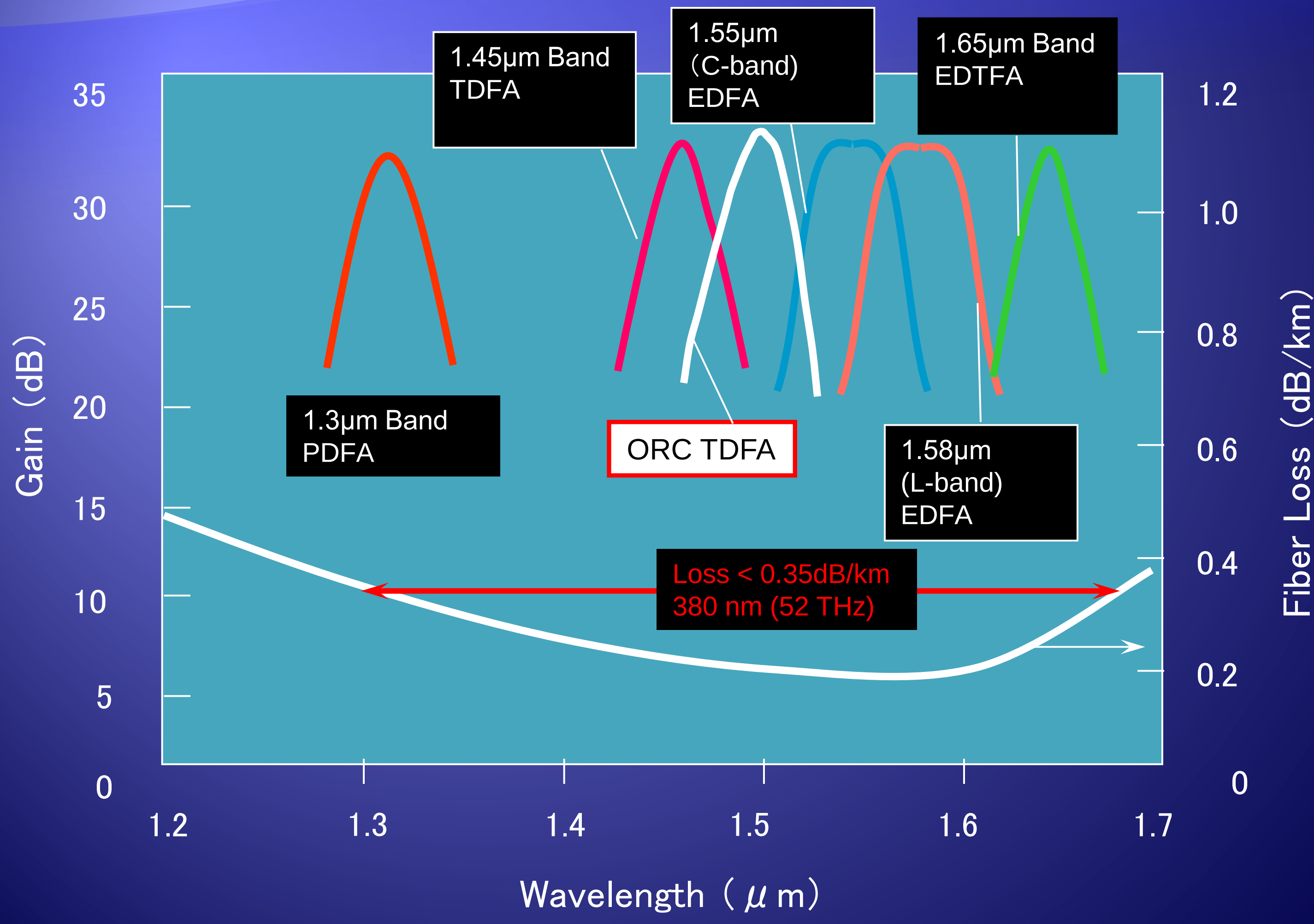


- Transmission fibre itself used to provide distributed in-line amplification
- DRA can reduce peak and minimum powers within the link
- Of significant value in long-haul systems

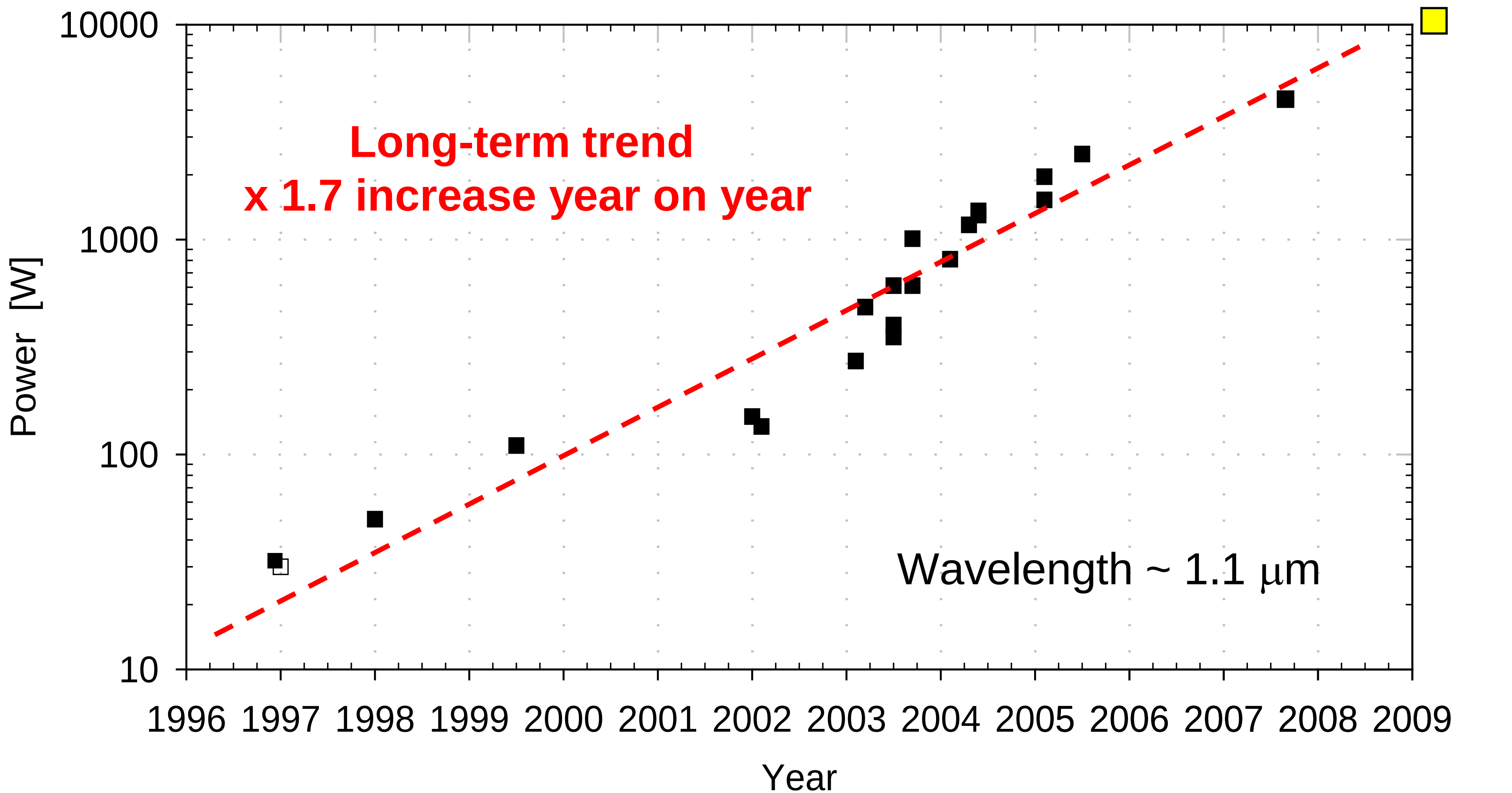
Improved OSNR/reaches possible combining EDFA + DRA

Spectral Region covered by Fiber Amplifiers

PDFA : Praseodymium-doped FA
TDFA : Thulium-doped FA
EDTFA : Erbium-doped Tellurite FA

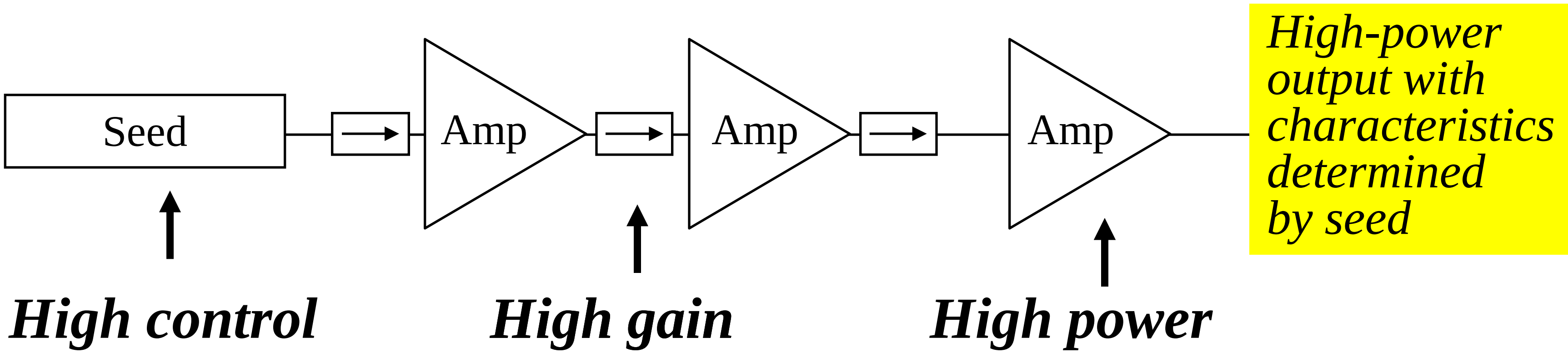


The Remarkable Increase in CW Fibre Laser Power



Same picture of growth for all wavelengths and modes of operation

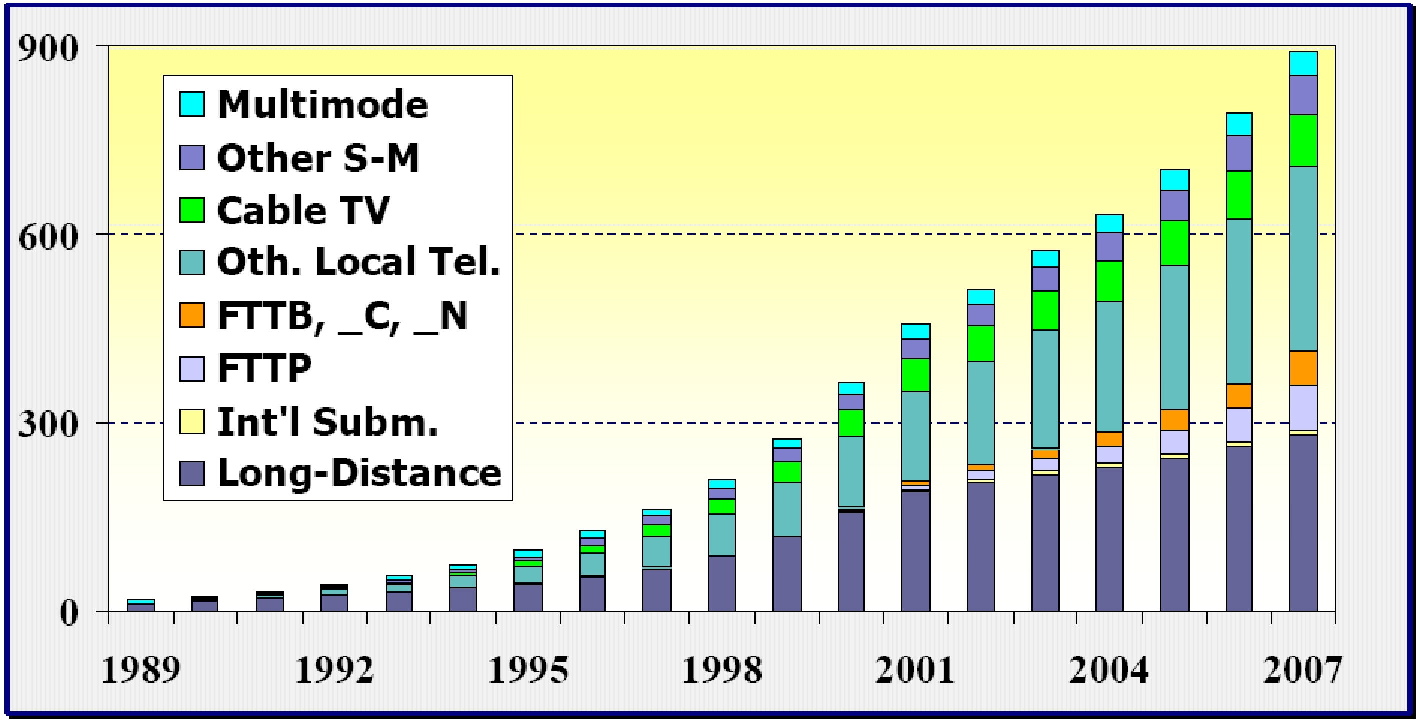
High-power fiber MOPAs
Beyond raw power



- **Fibers provide high gain, high power, broad bandwidth and ready cascadability**
- **Precision provided by (low power) seed oscillator**
- **Combination allows projection of seed properties to ultra high power levels**
- **High powers allow efficient wavelength conversion**

Challenge is to maintain seed fidelity in presence of noise, gain dynamics, nonlinearity, dispersion, birefringence etc..

Global Fibre Deployment (Mkm)

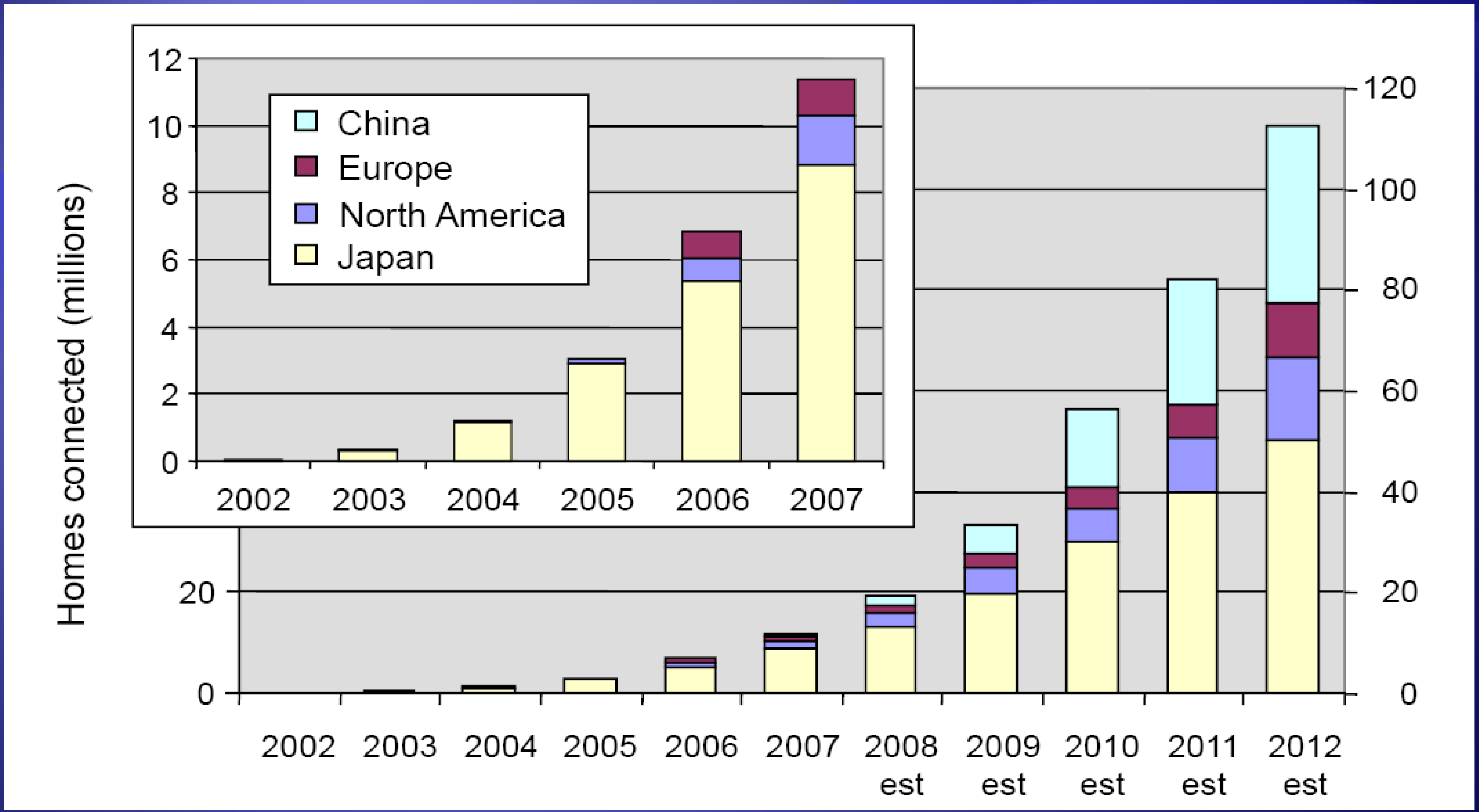


Other S-M = utility, railway, highway, government, military, premises, etc.

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

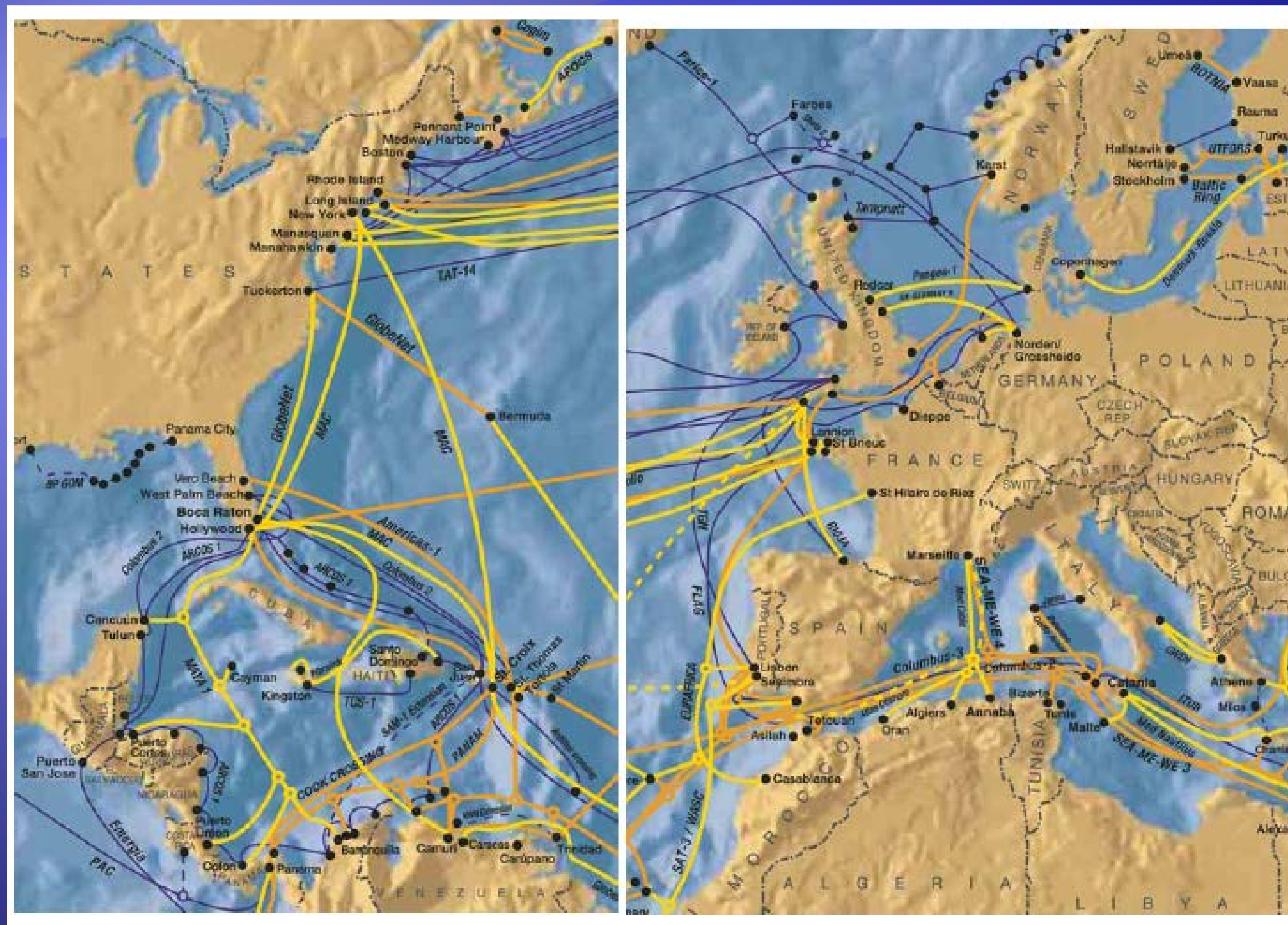
- Total deployment approaching 1 Billion km!
- Growth in all sectors
- Greatest in the Metro/Access
- Most rapid growth in FTT-P

Global FTTH deployment



- **Far East (Japan, Korea) well ahead in deployment of FTTH due to government investment.**
- **100 MBit/s services typical with 1 Gbit/s available**
- **Cost/regulation has been an impediment to deployment in Europe/USA, however now areas of rapid growth**

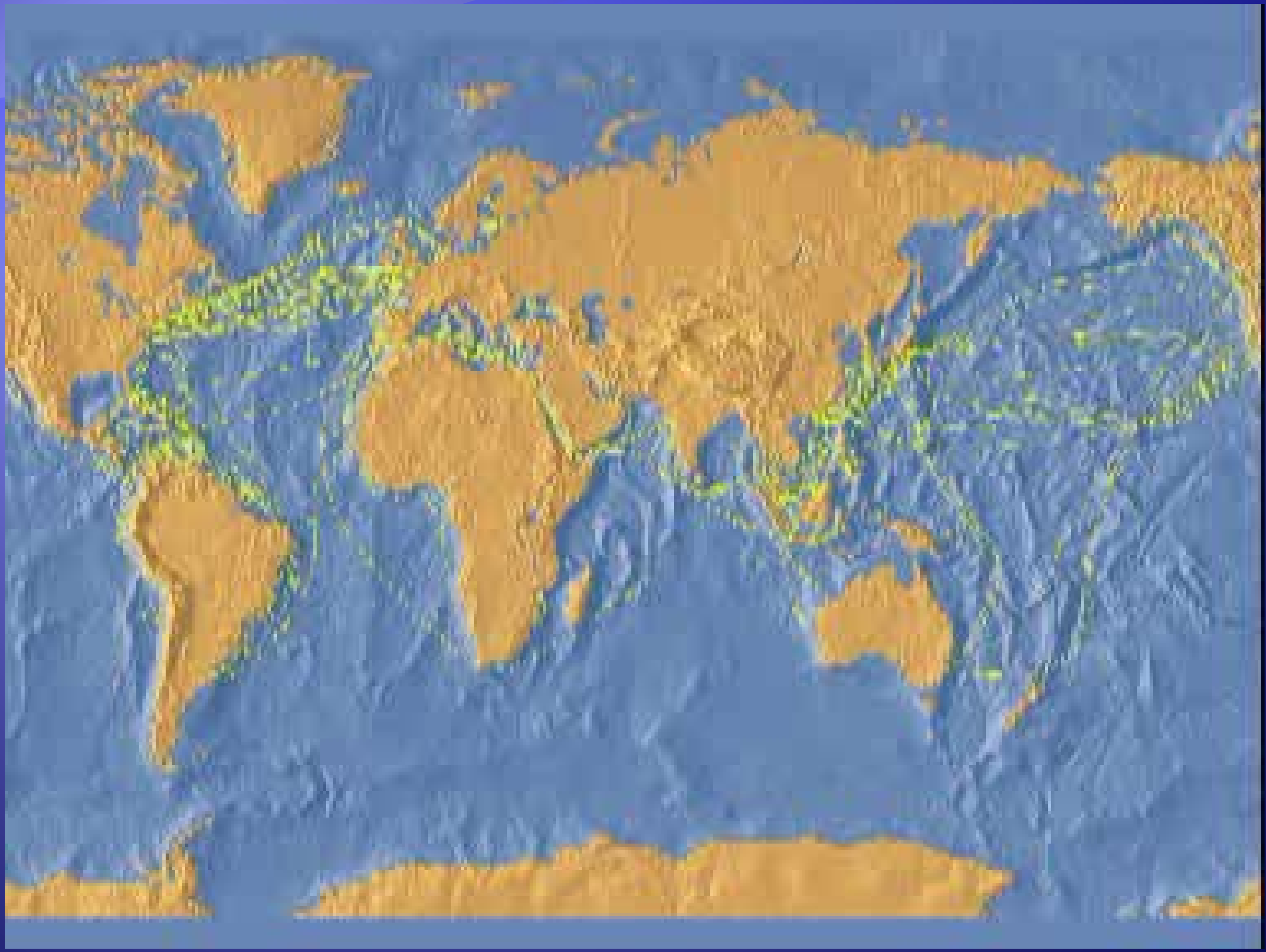
Submarine System Deployment



> 500,000km of undersea fiber optic cables

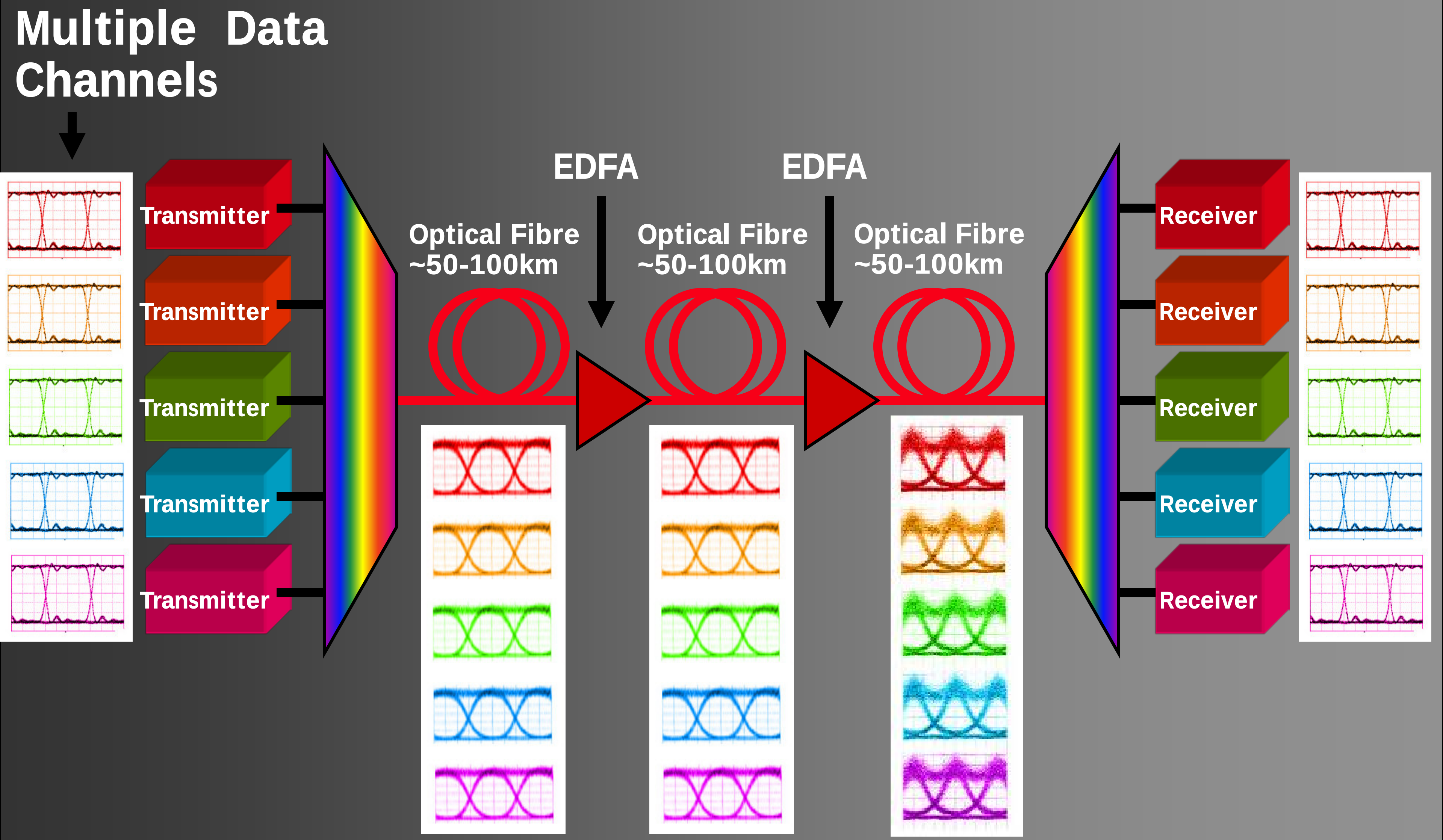
Connecting the planet

Deployed optical fibre today could encircle the earth 23,000 times



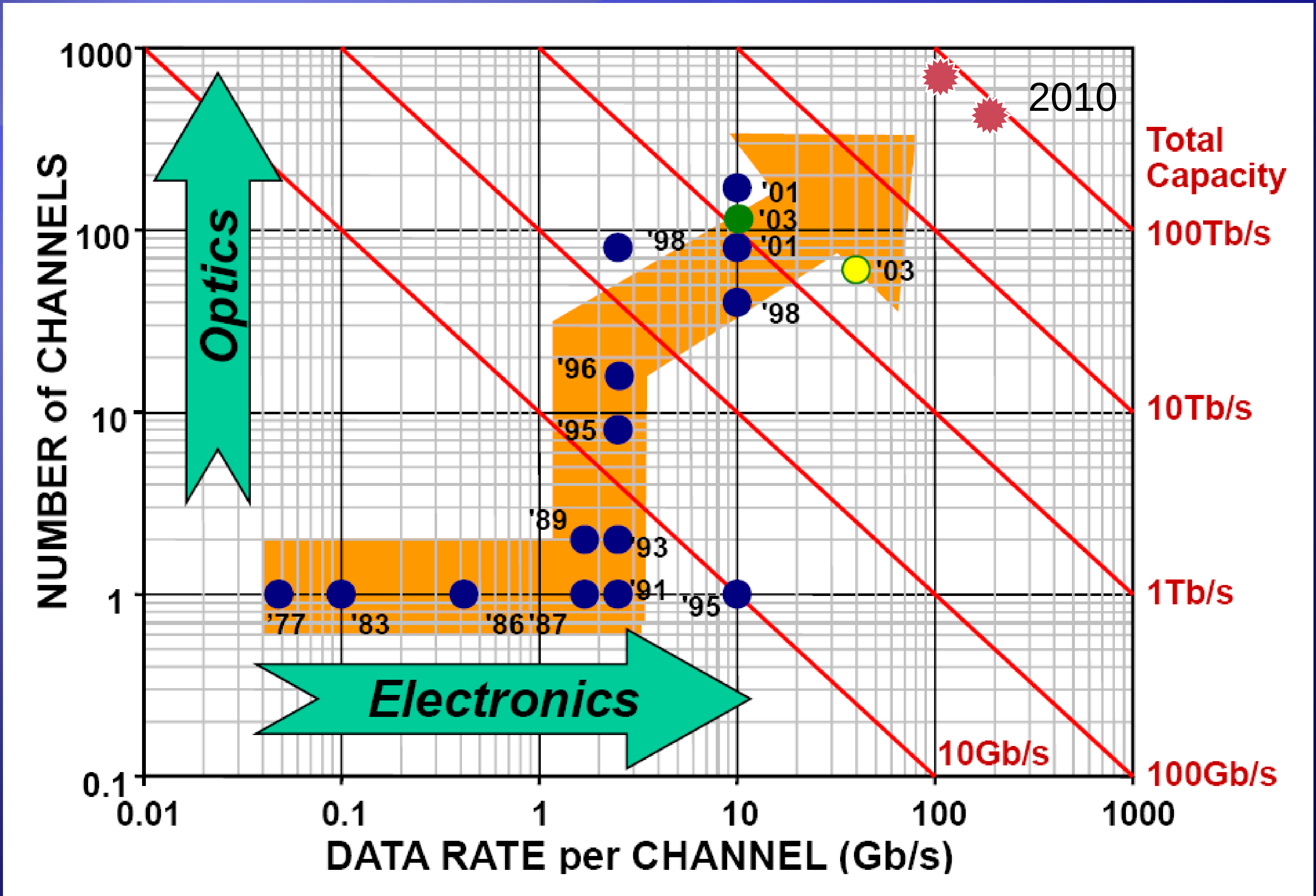
Courtesy of E. Desurvire

Optically-Amplified Transmission of Wavelength Division Multiplexed Signals

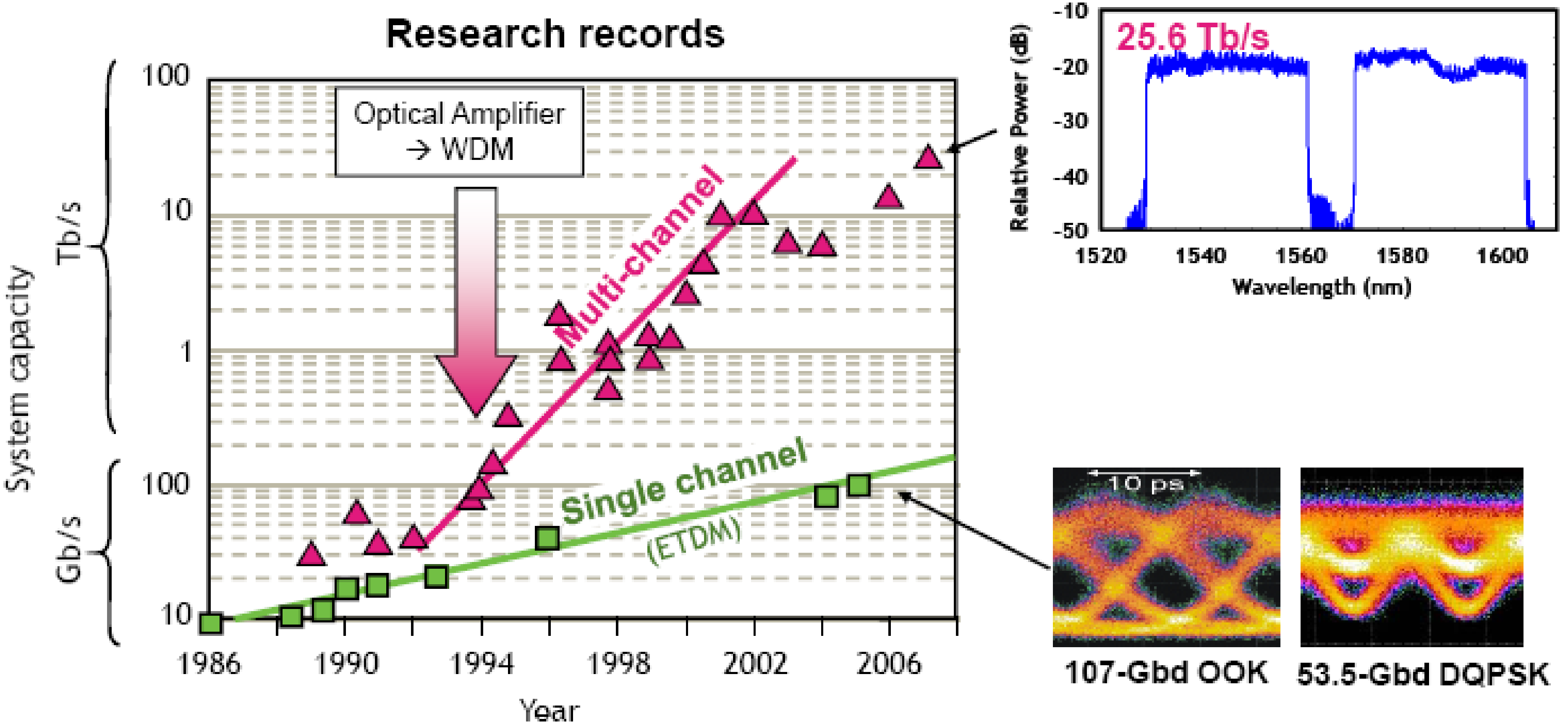


10s to 100s of WDM channels in a single optical fibre

Commercial Lightwave System Capacity

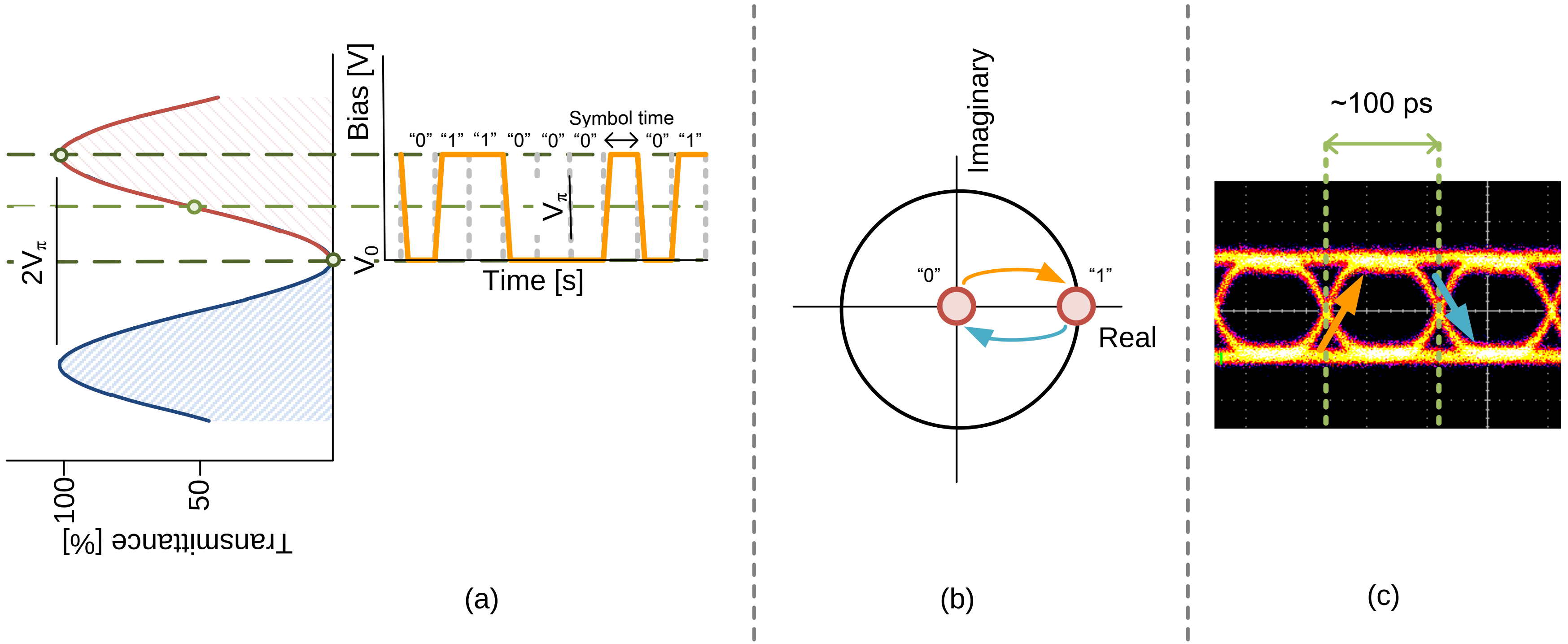


State-of-the-art Transmission



New world record 69 Tbit/s = 432 x 171 Gbit/s = 16 QAM format

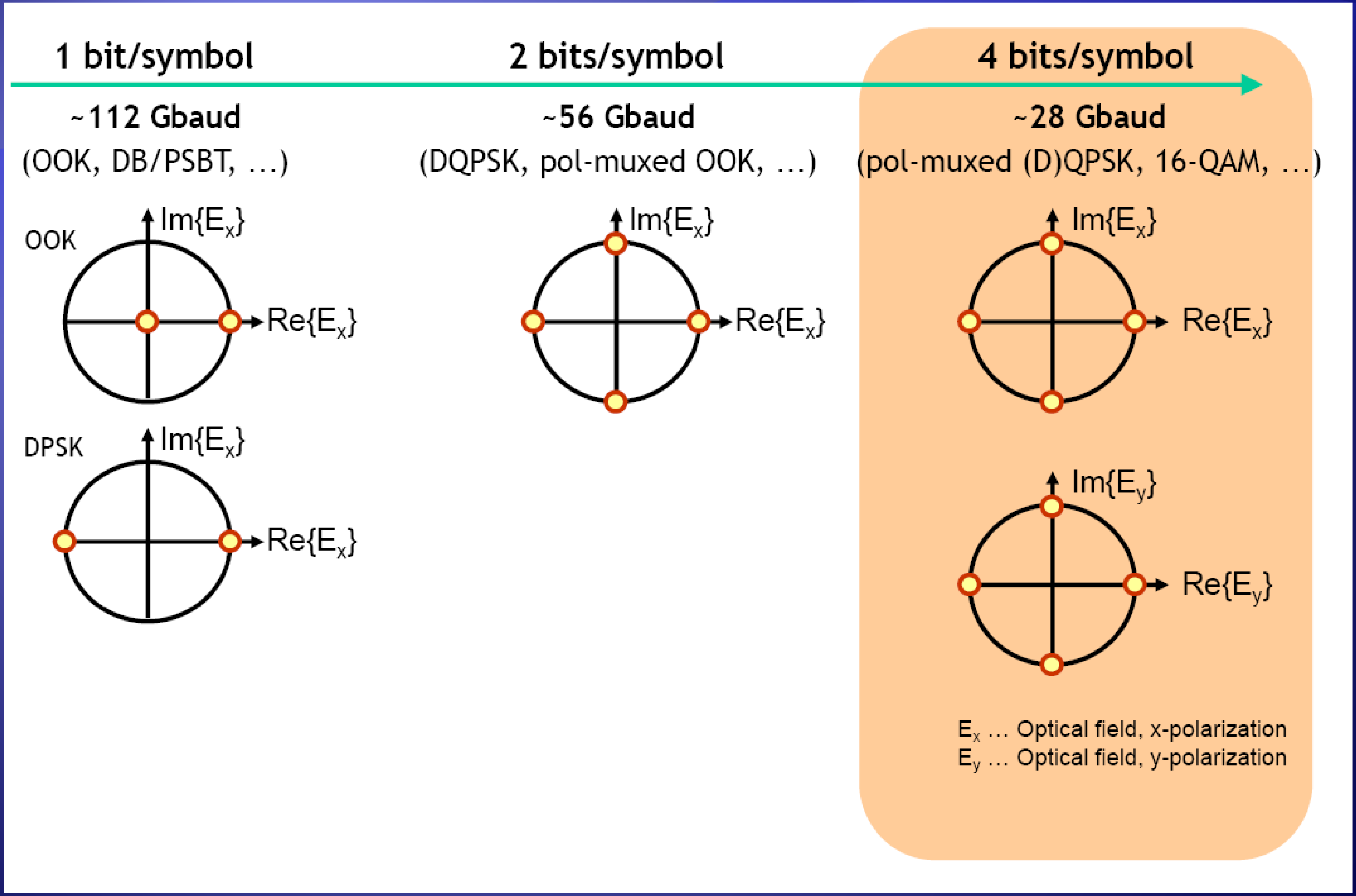
Generating RZ binary signals



- Simple modulation technique
- Easy to implement and very simple detection
- Low power use
- But highly sensitive to fibre impairments and poor spectral efficiency

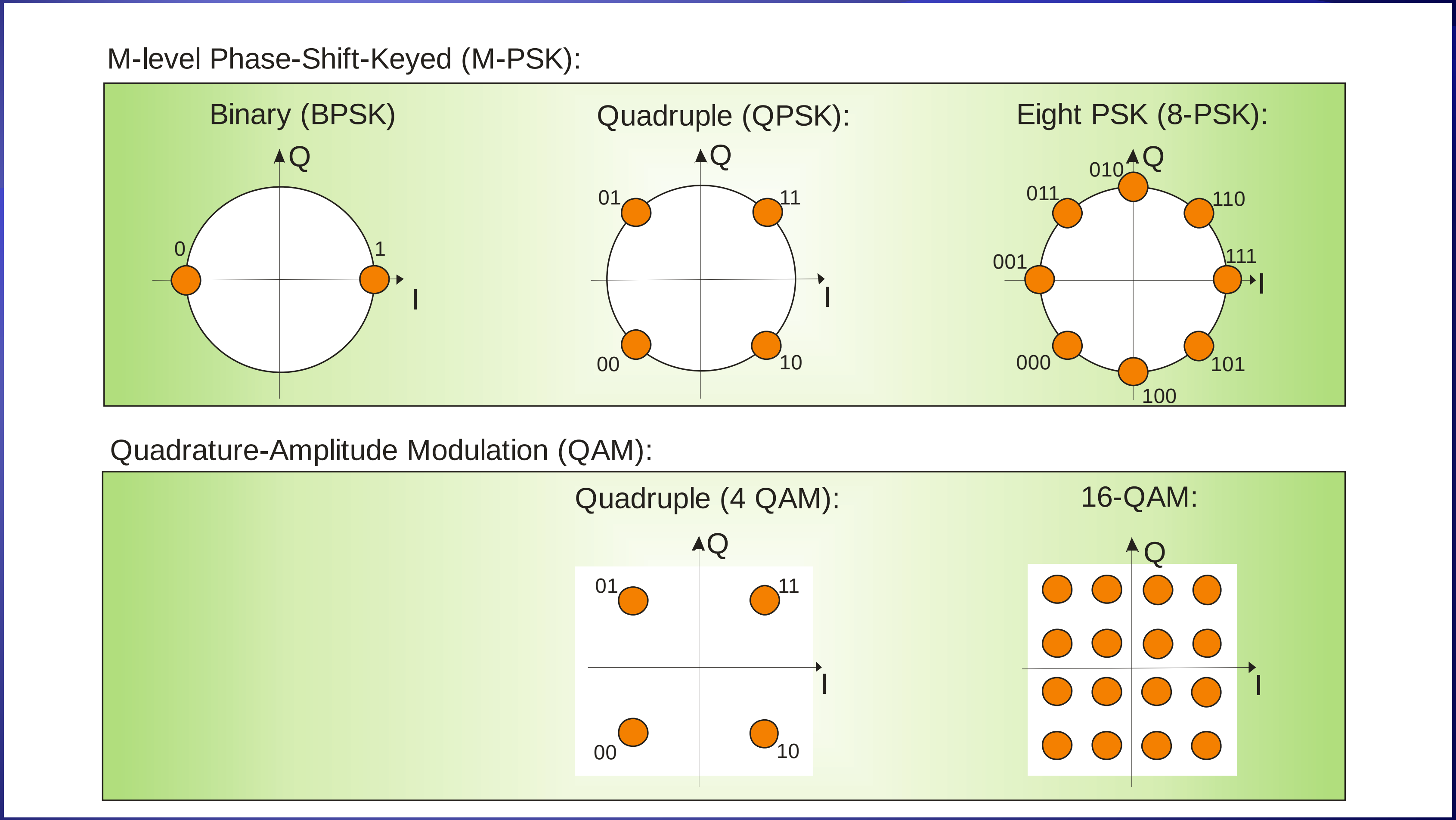
Advanced Modulation Formats

The rebirth of coherent communications



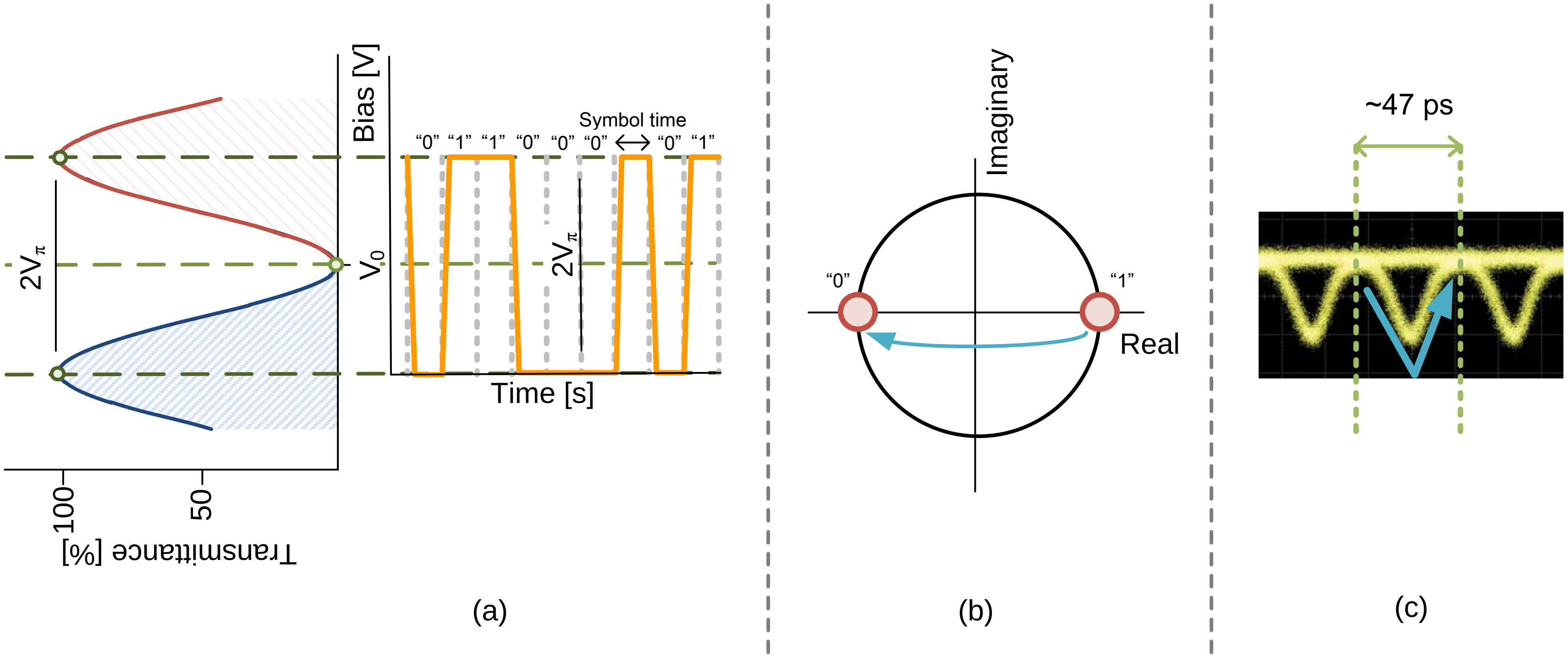
- Research into truly coherent systems (with LO at receiver) reborn

Advanced Modulation Format Signalling

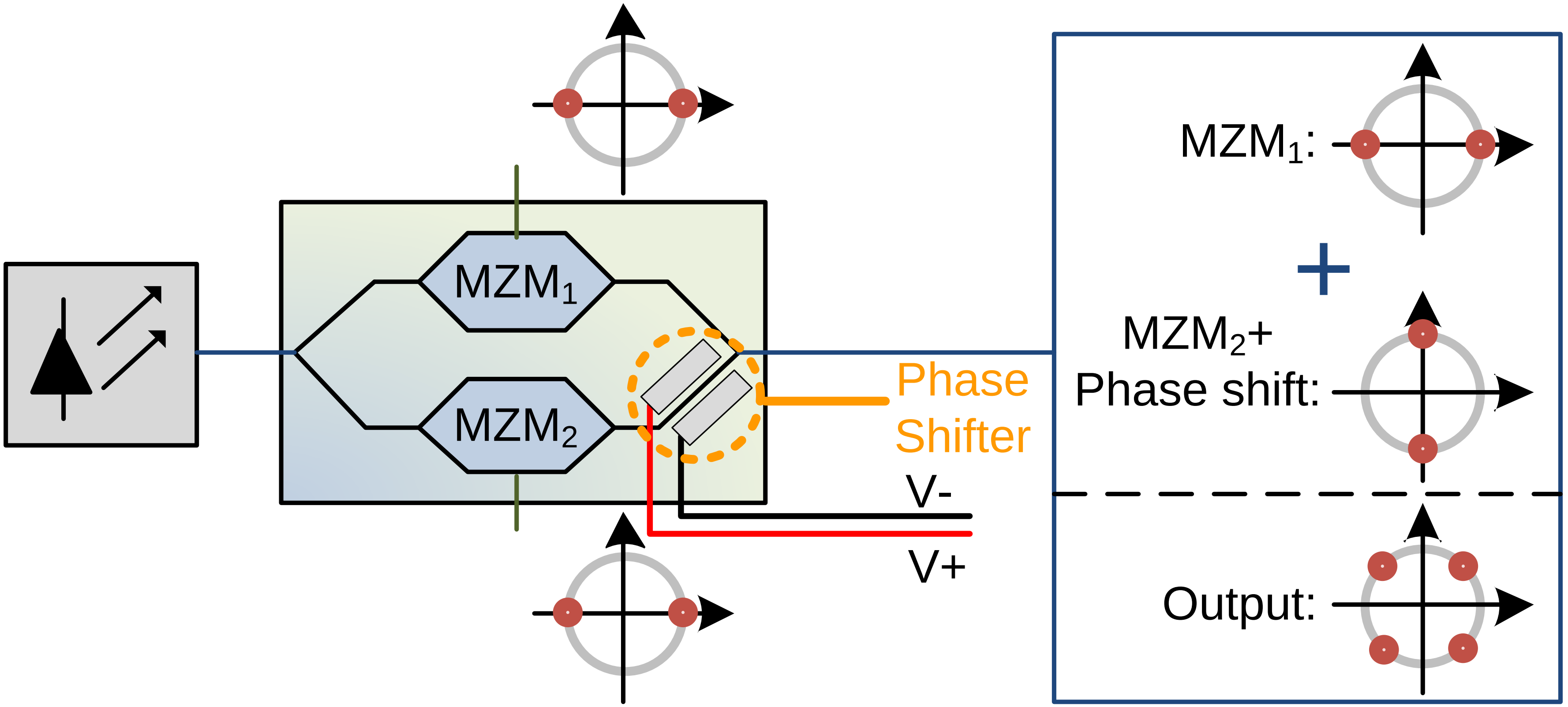


- Exploit phase and amplitude of electric field
- Use electronic DSP to make practical
- Higher spectral efficiency, increased tolerance to transmission impairments
- Better receiver sensitivity

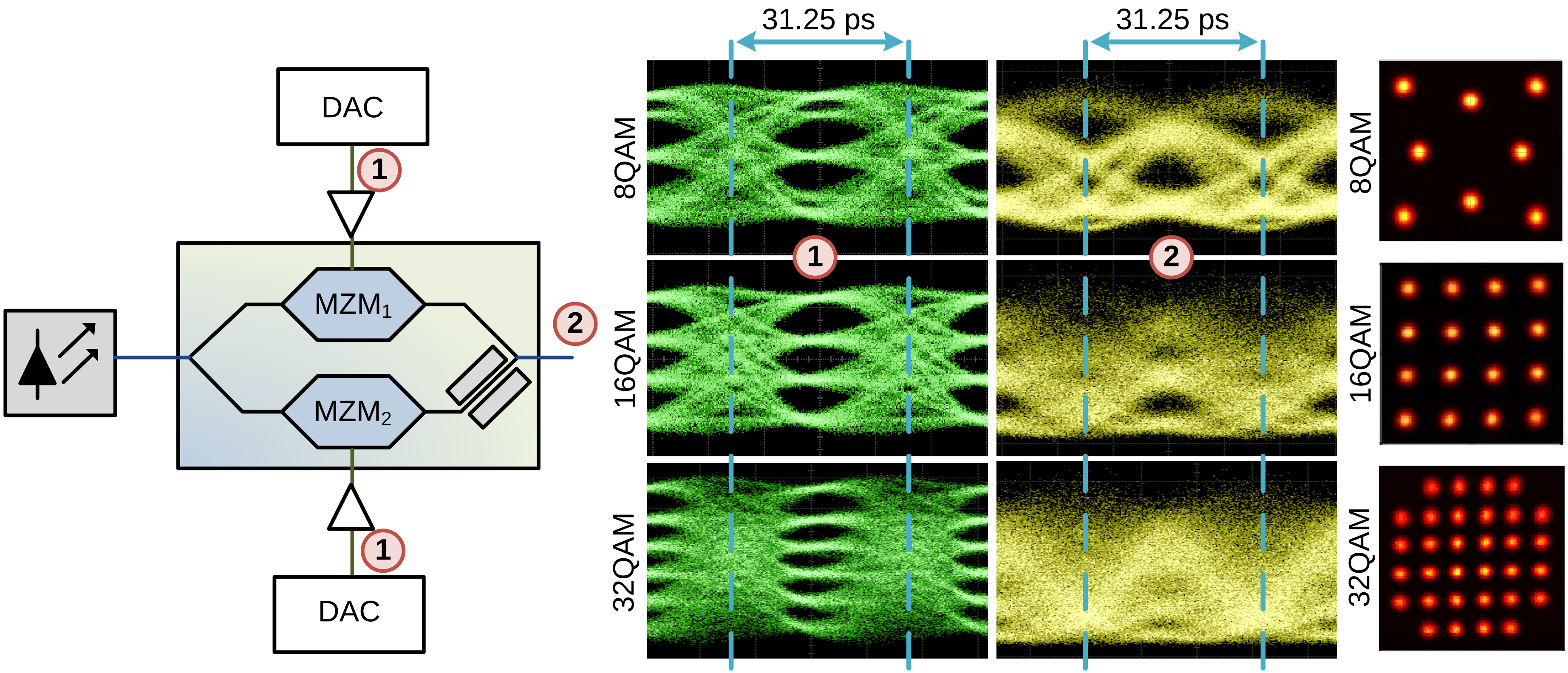
Generating BPSK signals



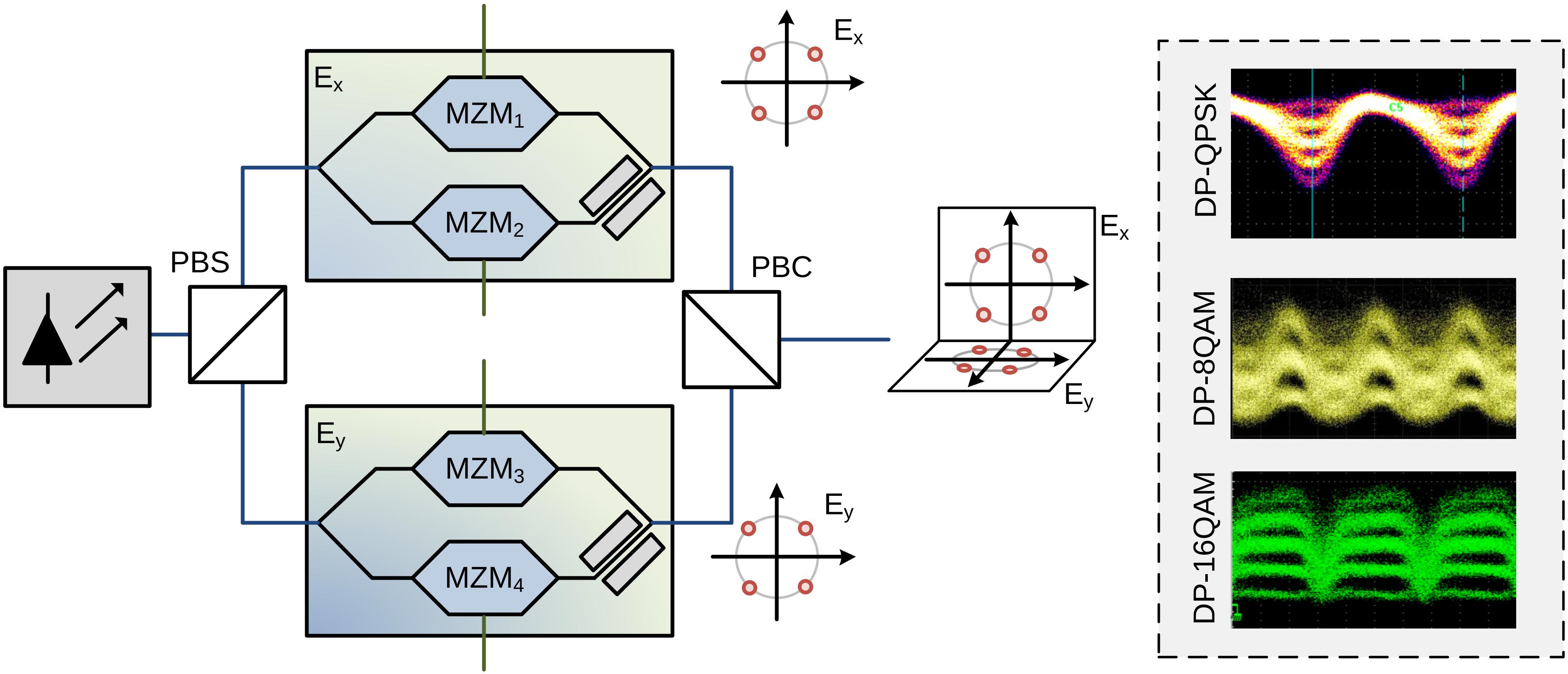
Generating QPSK signals



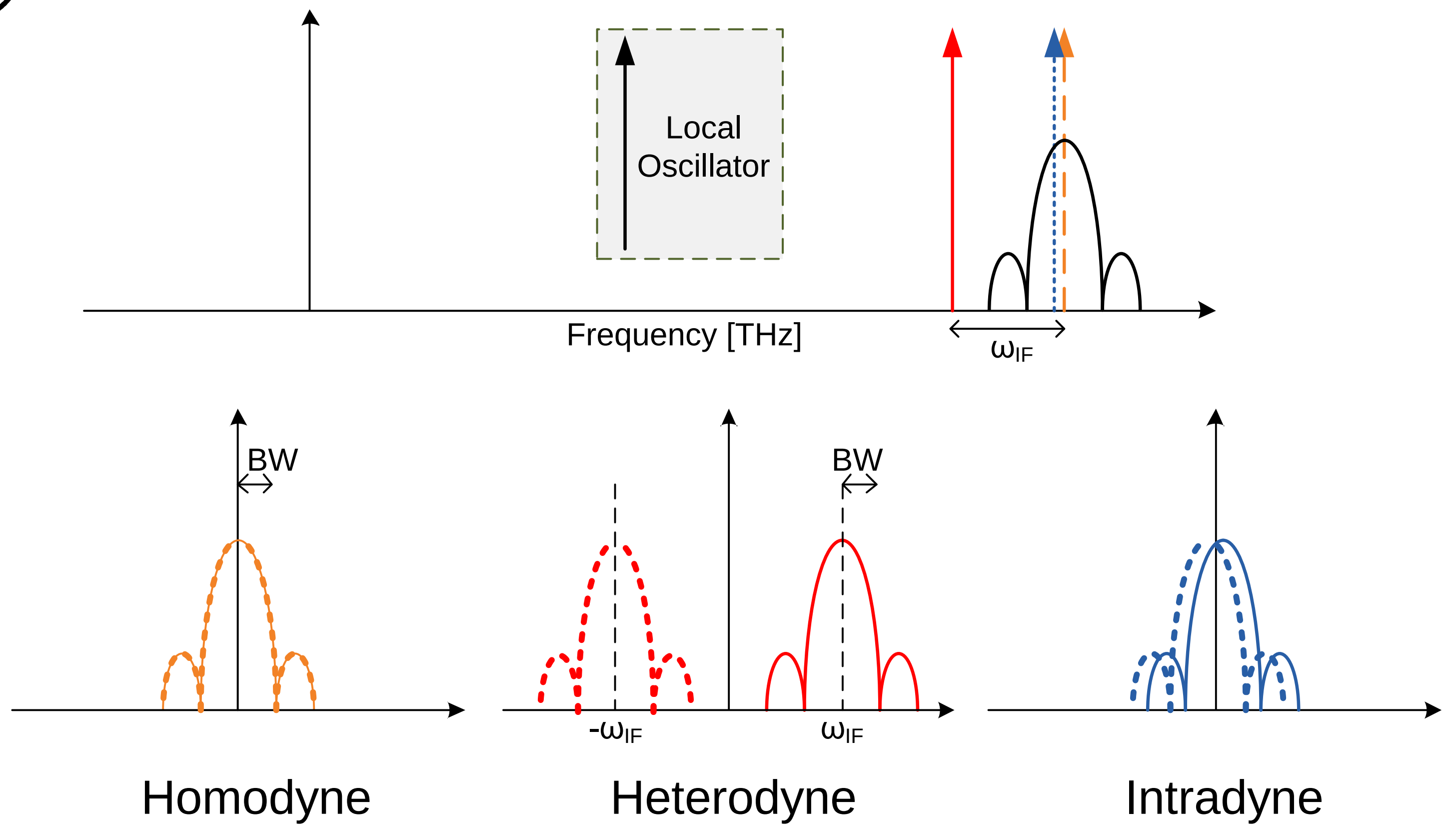
Generating QAM Signals



Generating Pol-Mux QPSK

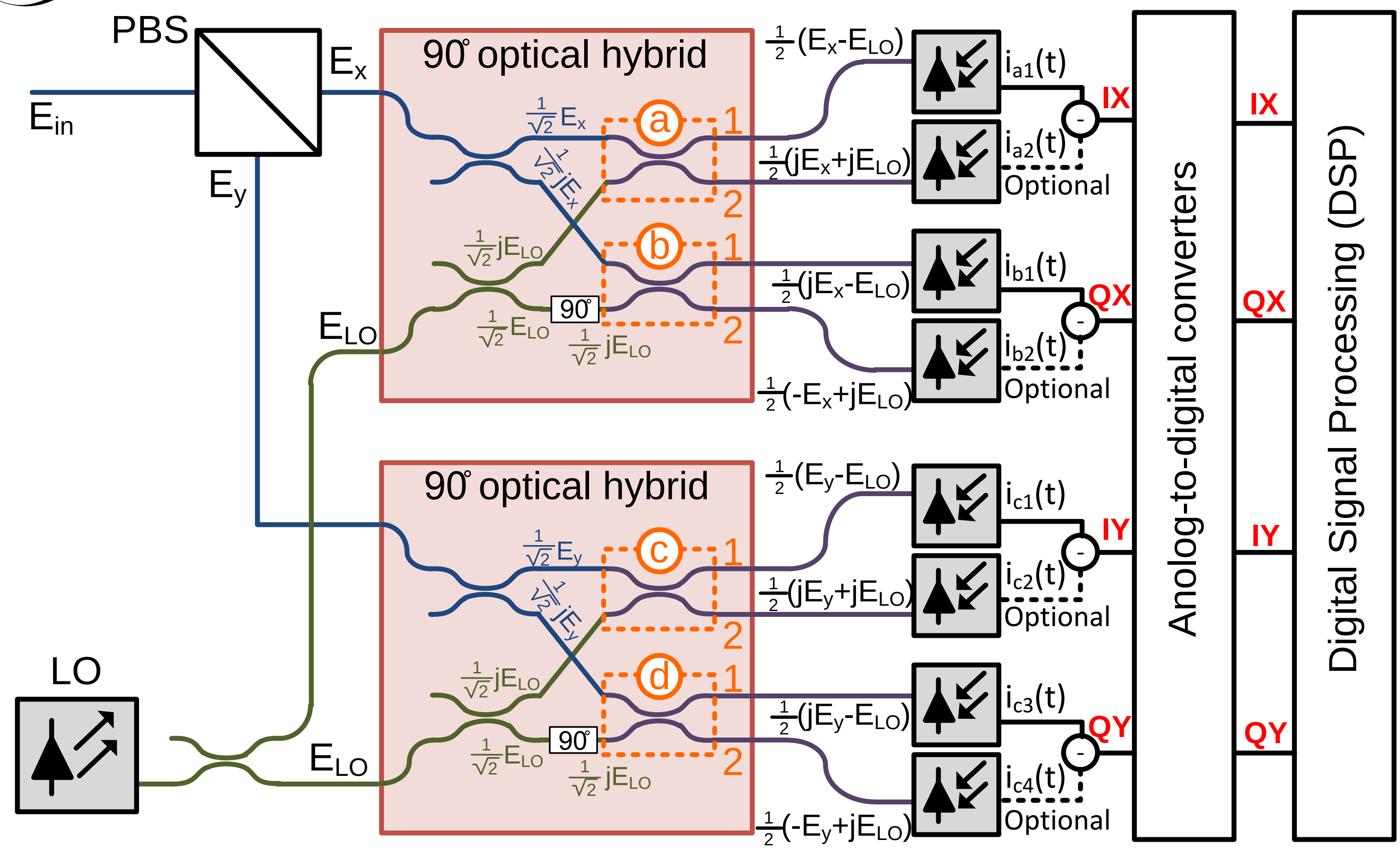


Coherent Detection Options



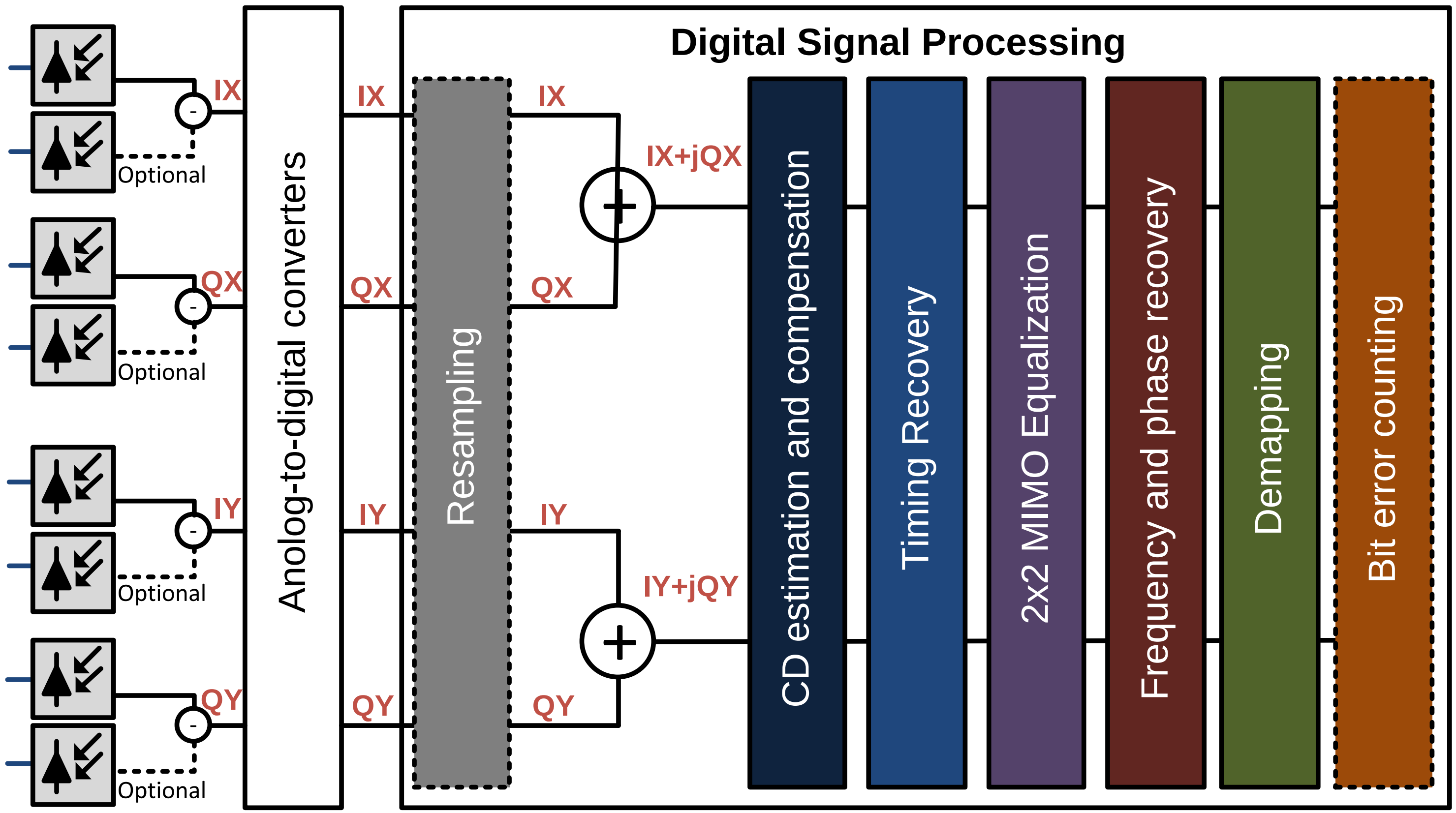
- Each approach has its own advantages and disadvantages
- Intradyne best compatibility with DSP
  - increased laser stability/linewidth tolerance etc
  - Reduced bandwidth requirements

Full Coherent Reception



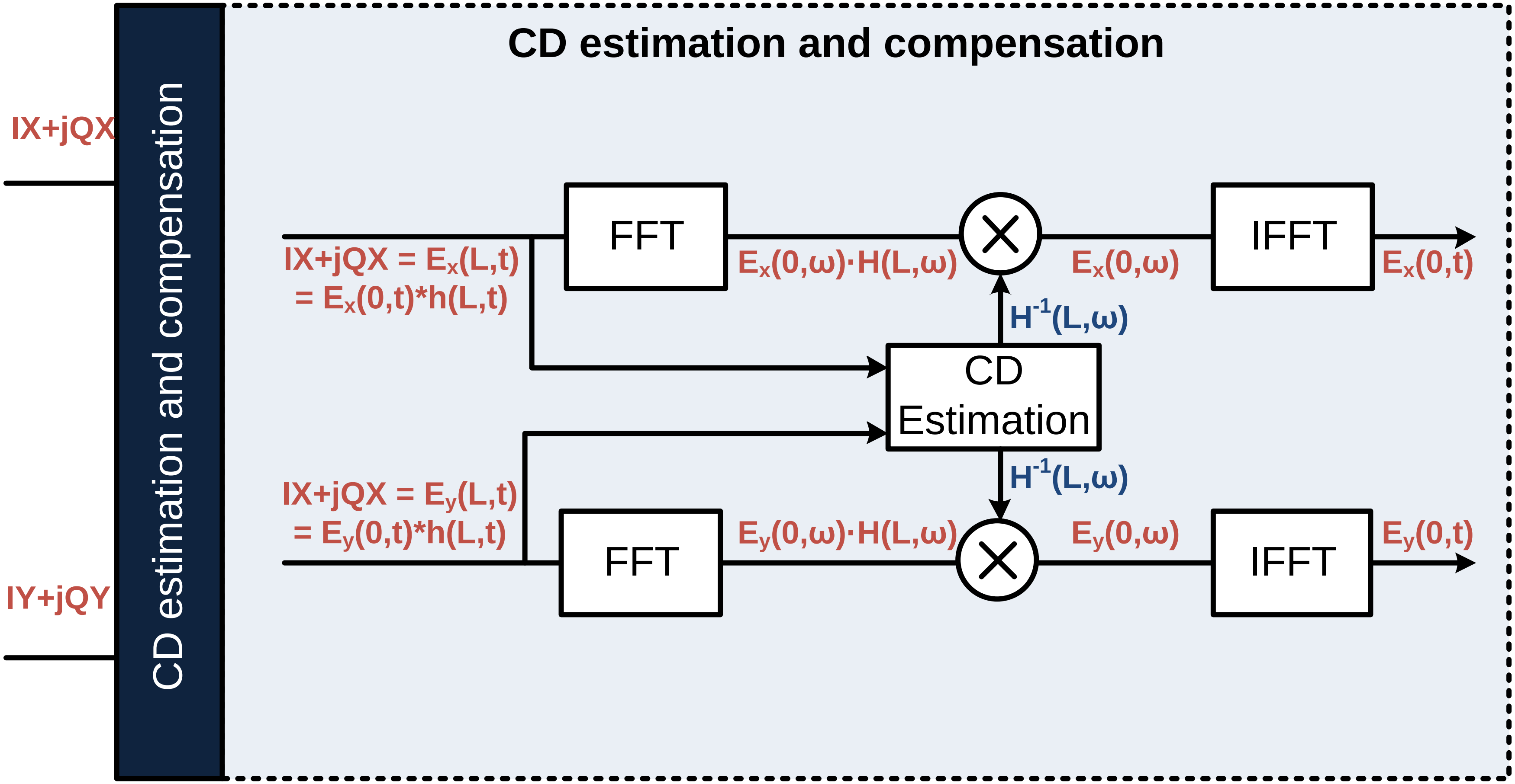
- Price to be paid in receiver complexity!
- Allows full recovery of complex field facilitating DSP impairment correction

Digital Coherent Reception

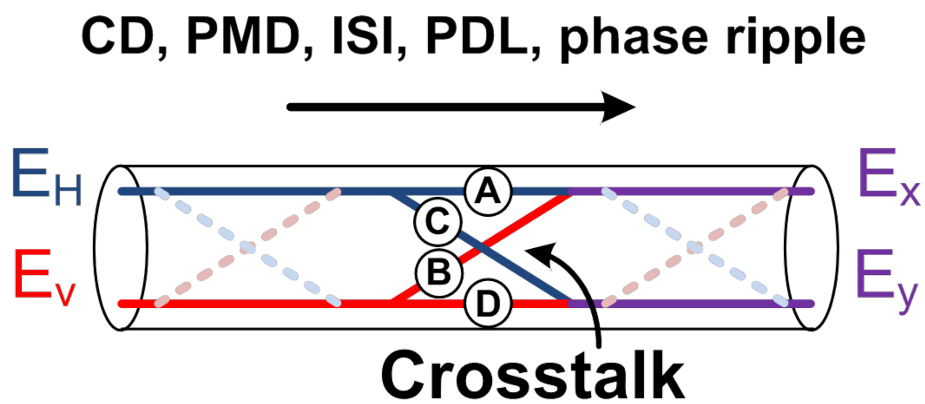


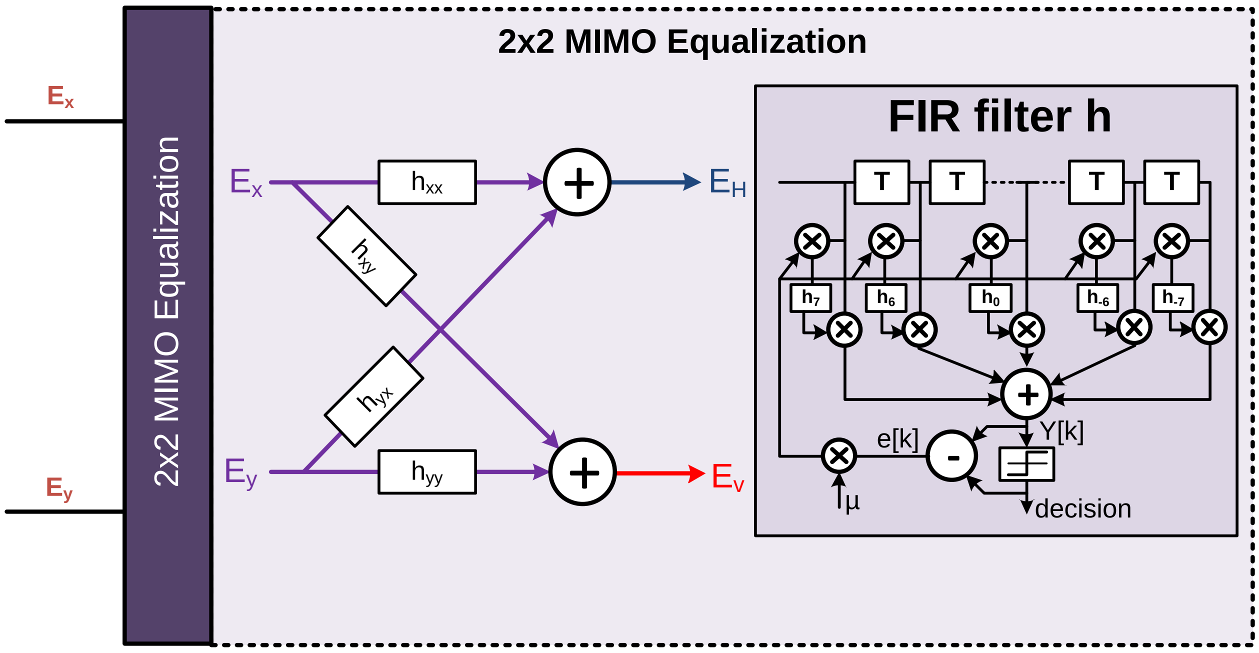
- DSP enables a significant reduction in optical system tolerance/specification
- However, does present a significant power demand

Electronic Dispersion Compensation

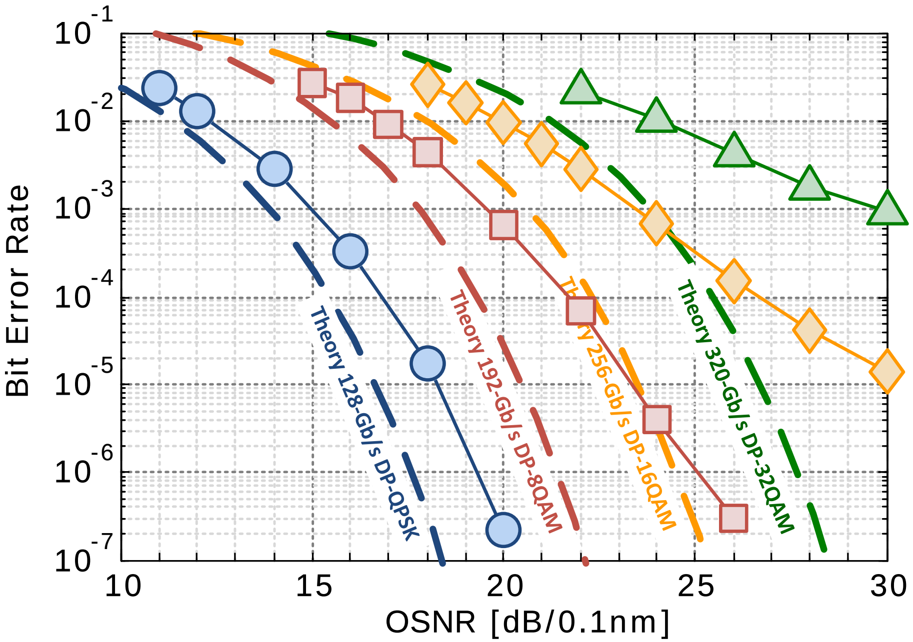


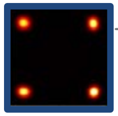
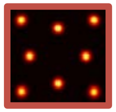
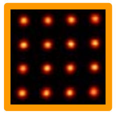
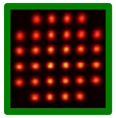
Cross-talk correction via MIMO





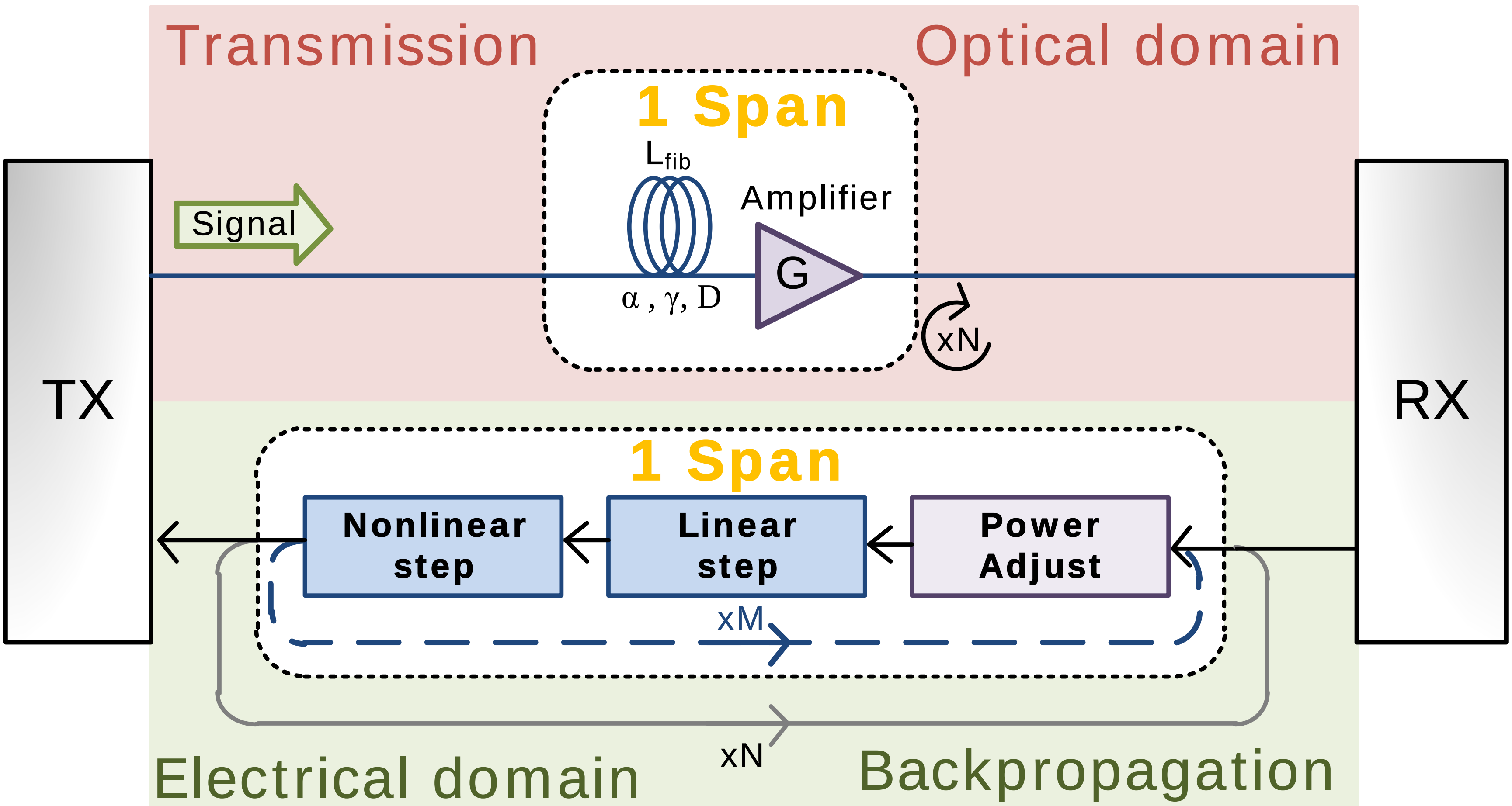
Typical Implementation Penalties



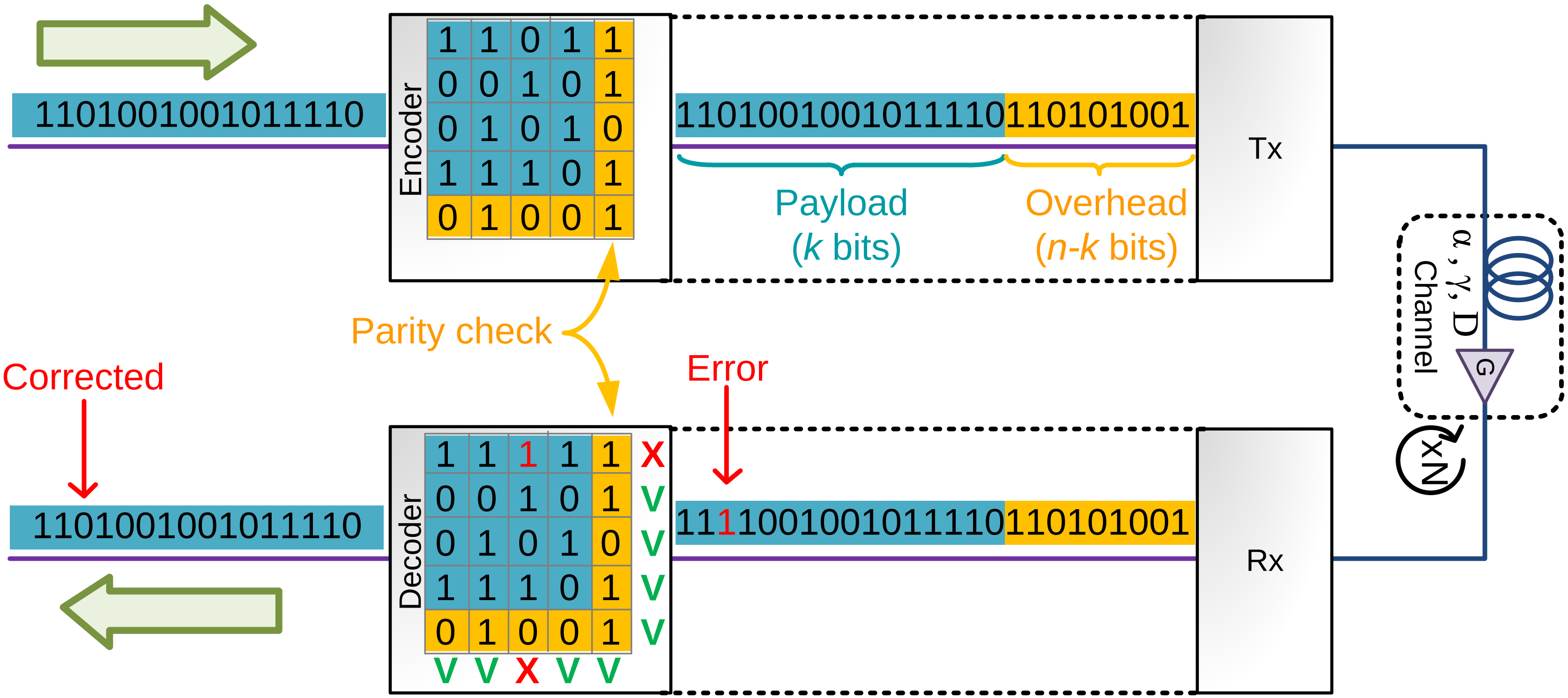
	Gross Bitrate [Gb/s]	Net Bitrate [Gb/s]	SE (50Ghz) [bit/s/Hz]	ΔOSNR wrt QPSK @ BER 1e-2[dB]	Implementation Penalty @ BER 1e-2 [dB]
	128	100	2	0	1
	192	150	3	4.05 (1.76)	1.4
	256	200	4	6.6 (3)	1.9
	320	250	5	9.82 (3.98)	2.8

- Typical implementation penalties1-2 dB
- Higher complexity patterns require higher OSNR
- Up to 1024 QAM now demonstrated in lab!
- In practice 16-QAM probably as complex as one might use due challenges with OSNR/complexity versus SE benefit

Even nonlinearity correction!

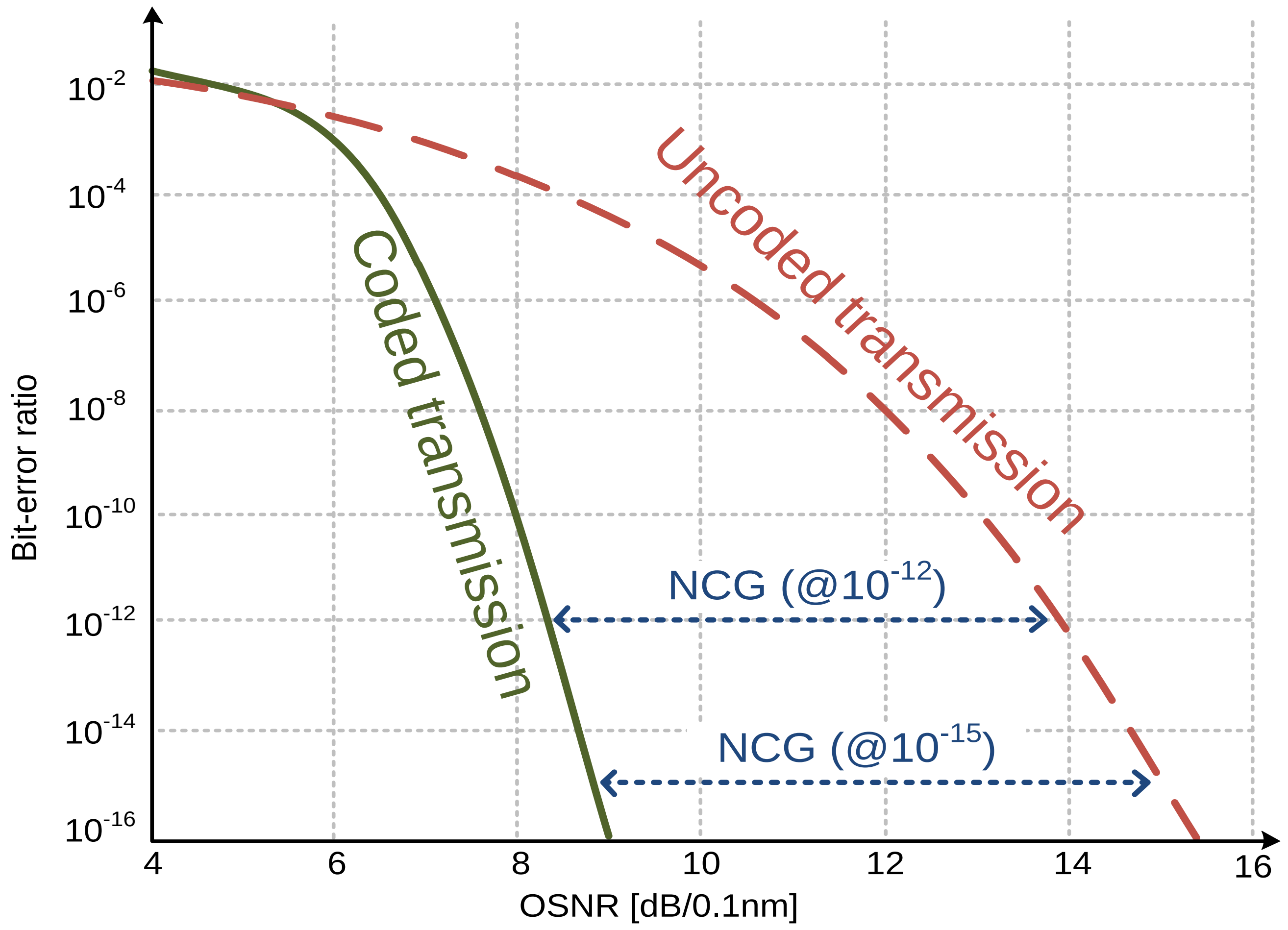


Forward Error Correction

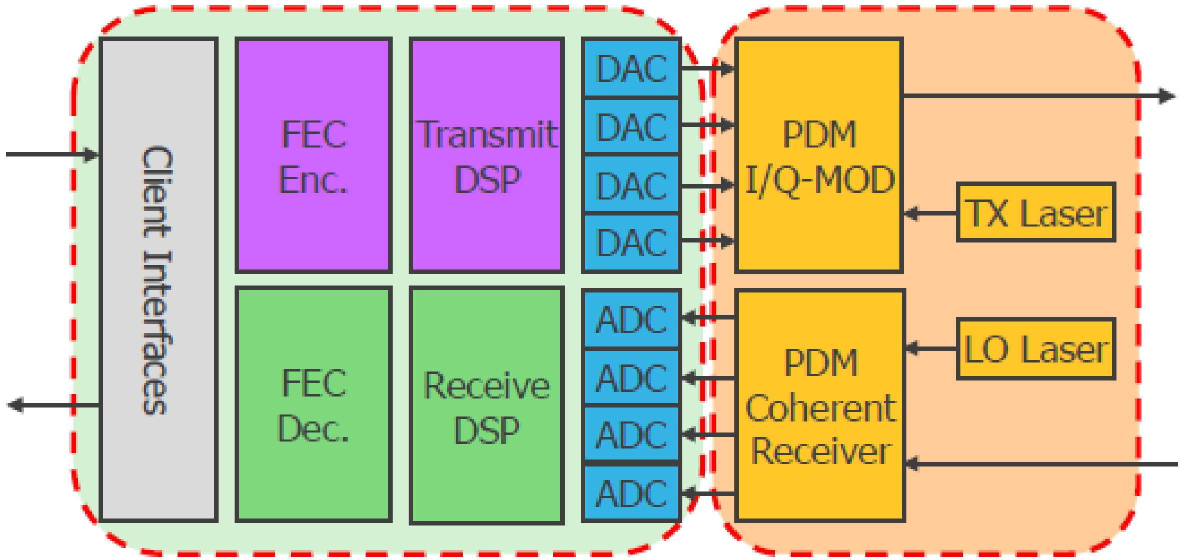


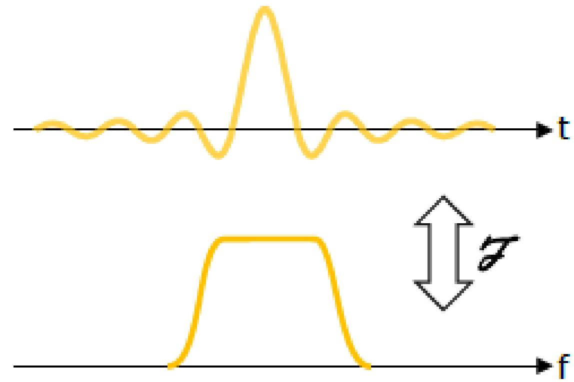
- Allows system operation in low OSNR regimes
- Coded data with overhead required to identify and correct errors via parity checking
- e.g. 9dB coding gain for 7% overhead allowing quasi error free transmission at BER= 10^{-3}

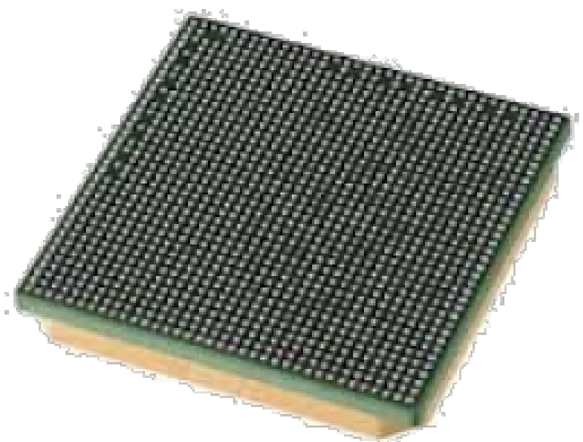
Performance of FEC



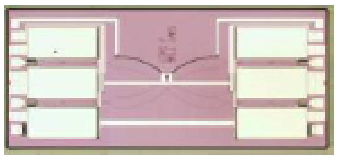
MODERN OPTICAL TRANSPONDERS
LOTS OF DIGITAL PROCESSING







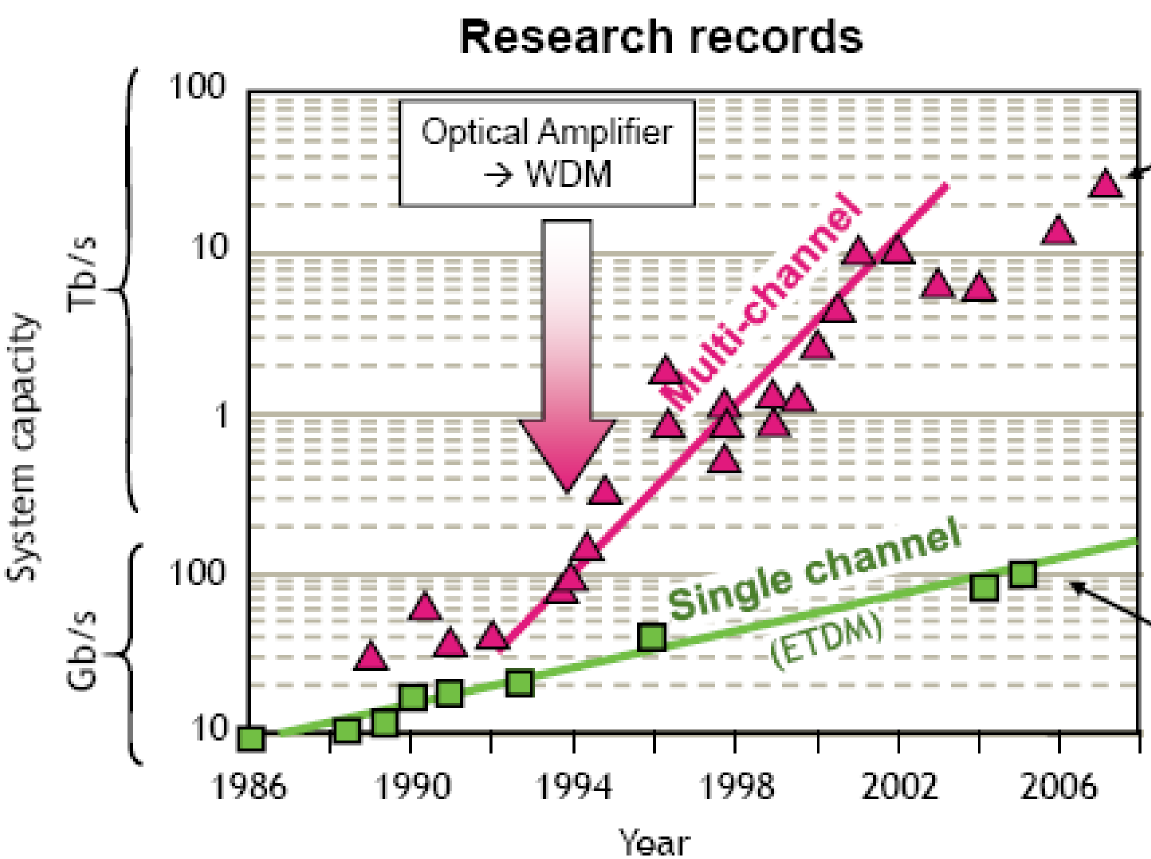
[Doerr et al., OFC 2009]

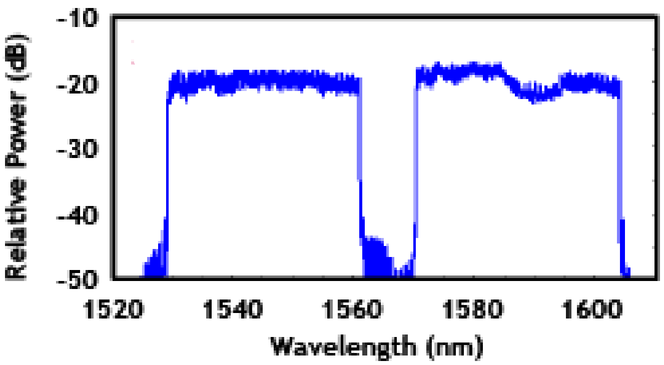


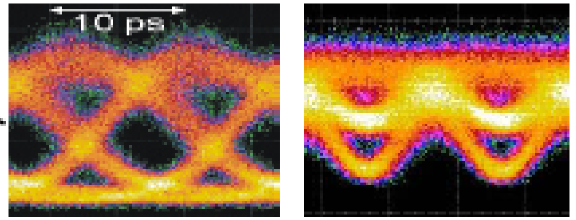
Monolithic Silicon Coherent Receiver

FEC: Forward error correction
PDM: Polarization-division multiplexing
DSP: Digital signal processing
DAC: Digital-to-analog converter
ADC: Analog-to-digital converter

State-of-the-art Transmission





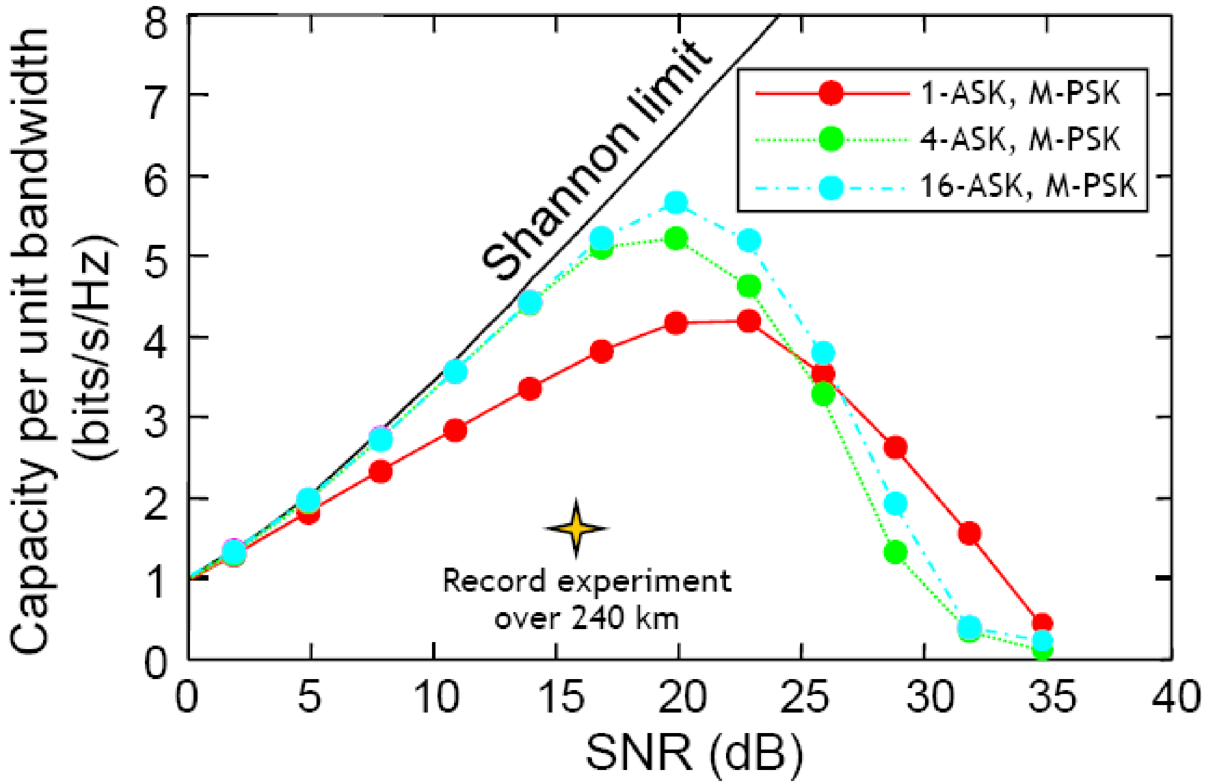


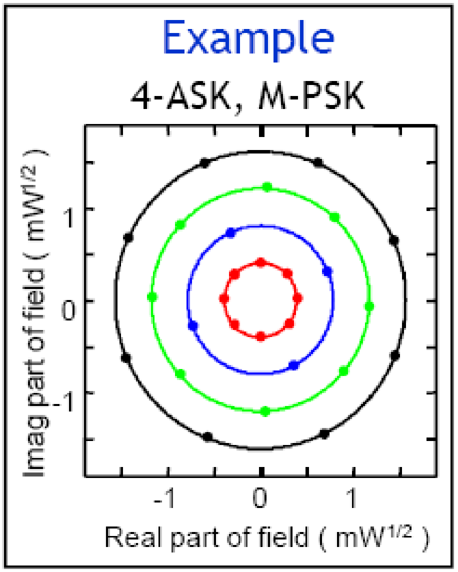
107-Gbd OOK

53.5-Gbd DQPSK

New world record 69 Tbit/s = 432 x 171 Gbit/s = 16 QAM format

The ultimate spectral density limits





(2000km transmission)

Maximum information spectral density (ISD) limited by fiber nonlinearity
Up to 5.5 bits/Hz possible per polarisation

>8bits/Hz SE routinely achieved e.g. 32QAM + 2 polarisations

Routes to higher SE

Reference Case

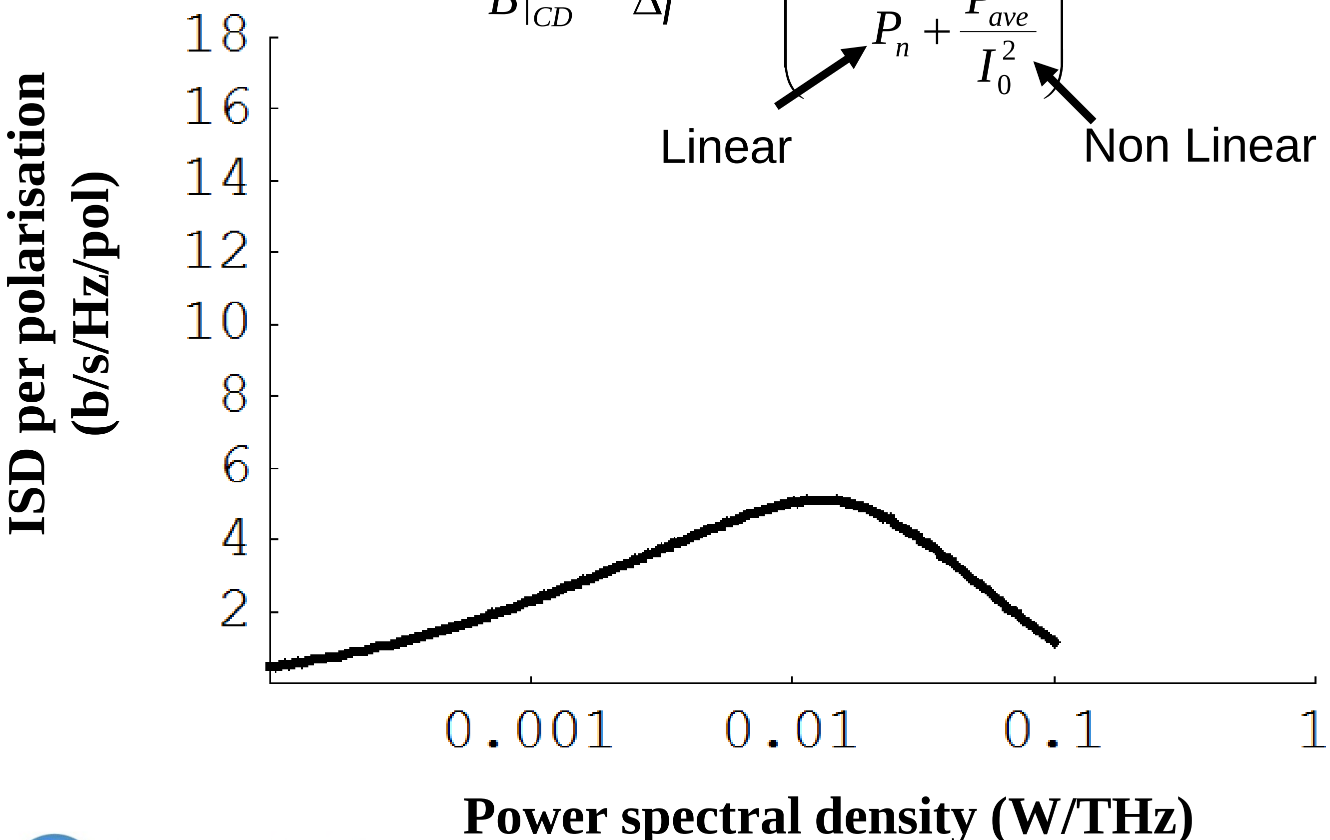
$$I_0^2 \approx \left(\Delta f \frac{\lambda^2}{2.c}\right) \frac{B}{\ln\left(N_{ch}/2\right)} \frac{\alpha.D}{\gamma^2}$$

$$\left.\frac{C}{B}\right|_{CD} \approx \frac{B}{\Delta f} \log_2\left(1 + \frac{P_{ave}}{P_n + \frac{P_{ave}^3}{I_0^2}}\right)$$

Linear (P_n) — Non Linear ($\frac{P_{ave}^3}{I_0^2}$)

$$P_n \approx N_a.e^{\alpha L}.n_{sp}.h.\nu.B$$

Parameter	Value
System Length	2,000 km
Spacing	80 km
Noise Figure	4.5 dB
Spacing	50 GHz
Baud Rate	50 Gbaud
Fibre Loss	0.22 dB/km
Non-linearity	1.4 W^{-1} km^{-1}
Dispersion	16 ps/nm/km
Wavelength	1550 nm
Bandwidth	5 THz
Channels	101



A.D. Ellis et al., JLT, 28, 423, (2010).

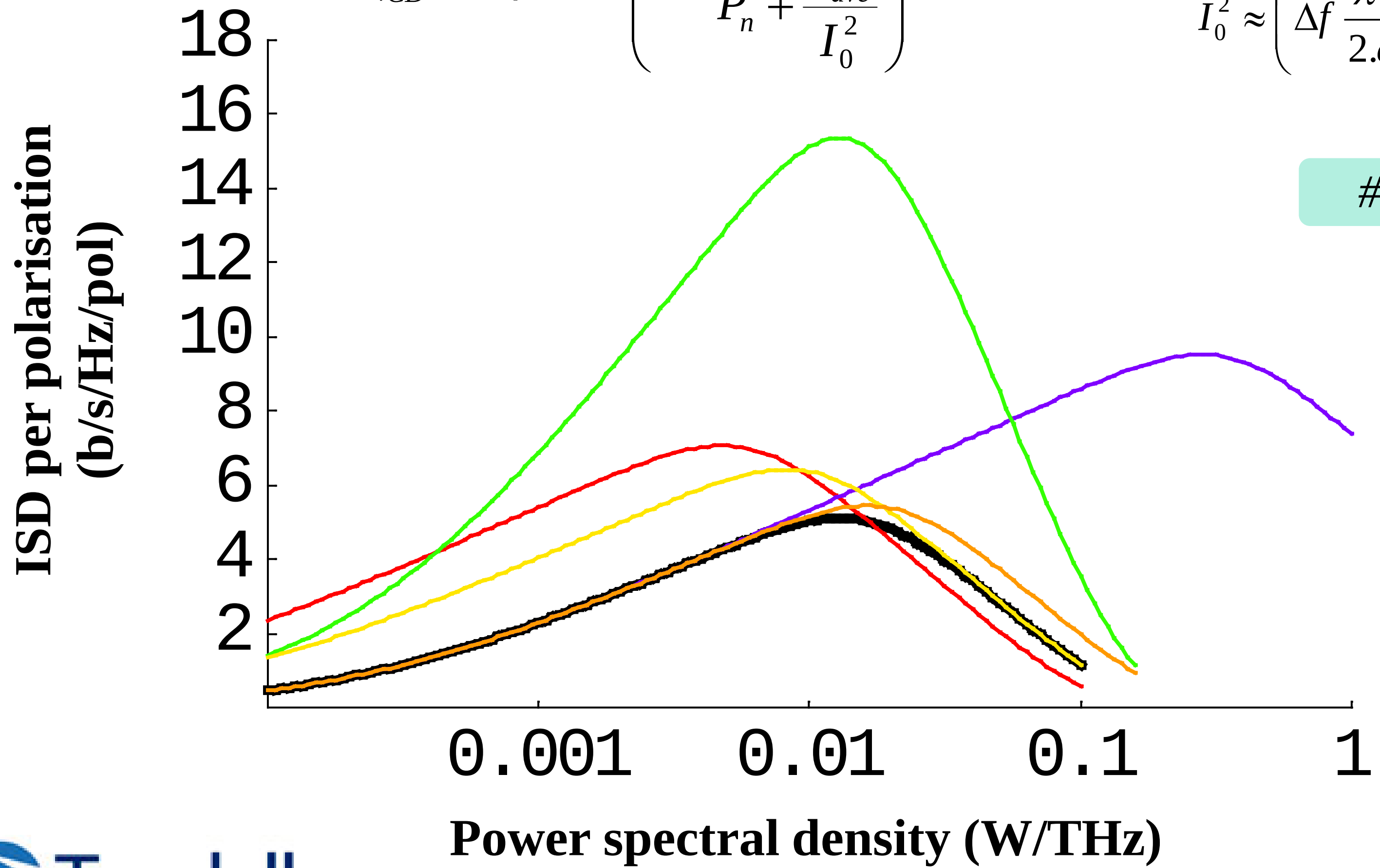
Factors to Improve

$$\left.\frac{C}{B}\right|_{CD} \approx \frac{B}{\Delta f}\log_2\left(1+\frac{P_{ave}}{P_n+\frac{P_{ave}^3}{I_0^2}}\right)$$

$$P_n \approx N_a.e^{\alpha L}.n_{sp}.h.\nu.B$$

$$I_0^2 \approx \left(\Delta f\,\frac{\lambda^2}{2.c}\right)\frac{B}{\ln(N_{ch}/2)}\frac{\alpha.D}{\gamma^2}$$

channels



A.D. Ellis et al., JLT, 28, 423, (2010).

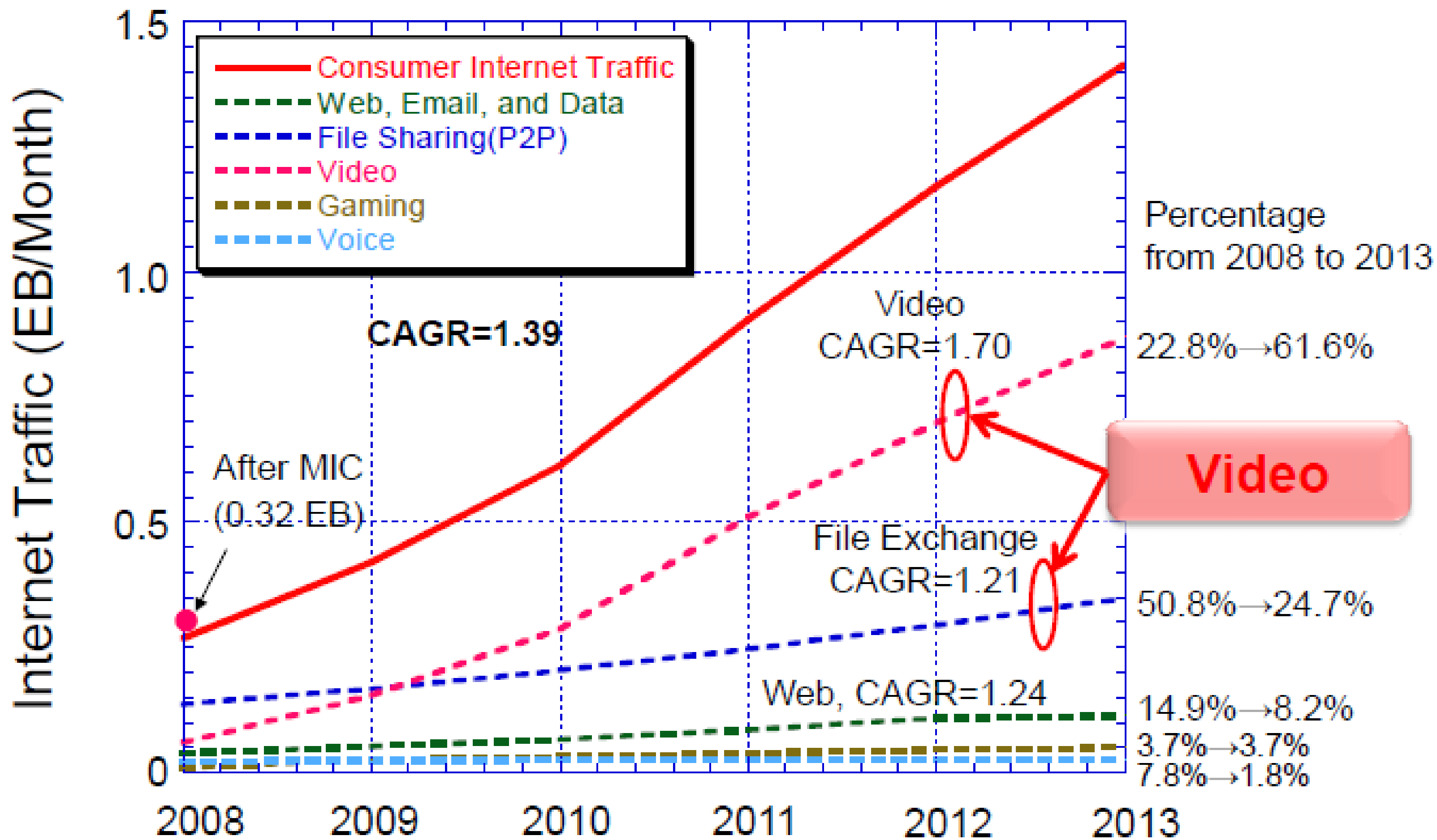
New Frontiers in Optical Communications
Part 2: Future Directions

David Richardson

Optoelectronics Research Centre
Southampton University
United Kingdom
djr@orc.soton.ac.uk

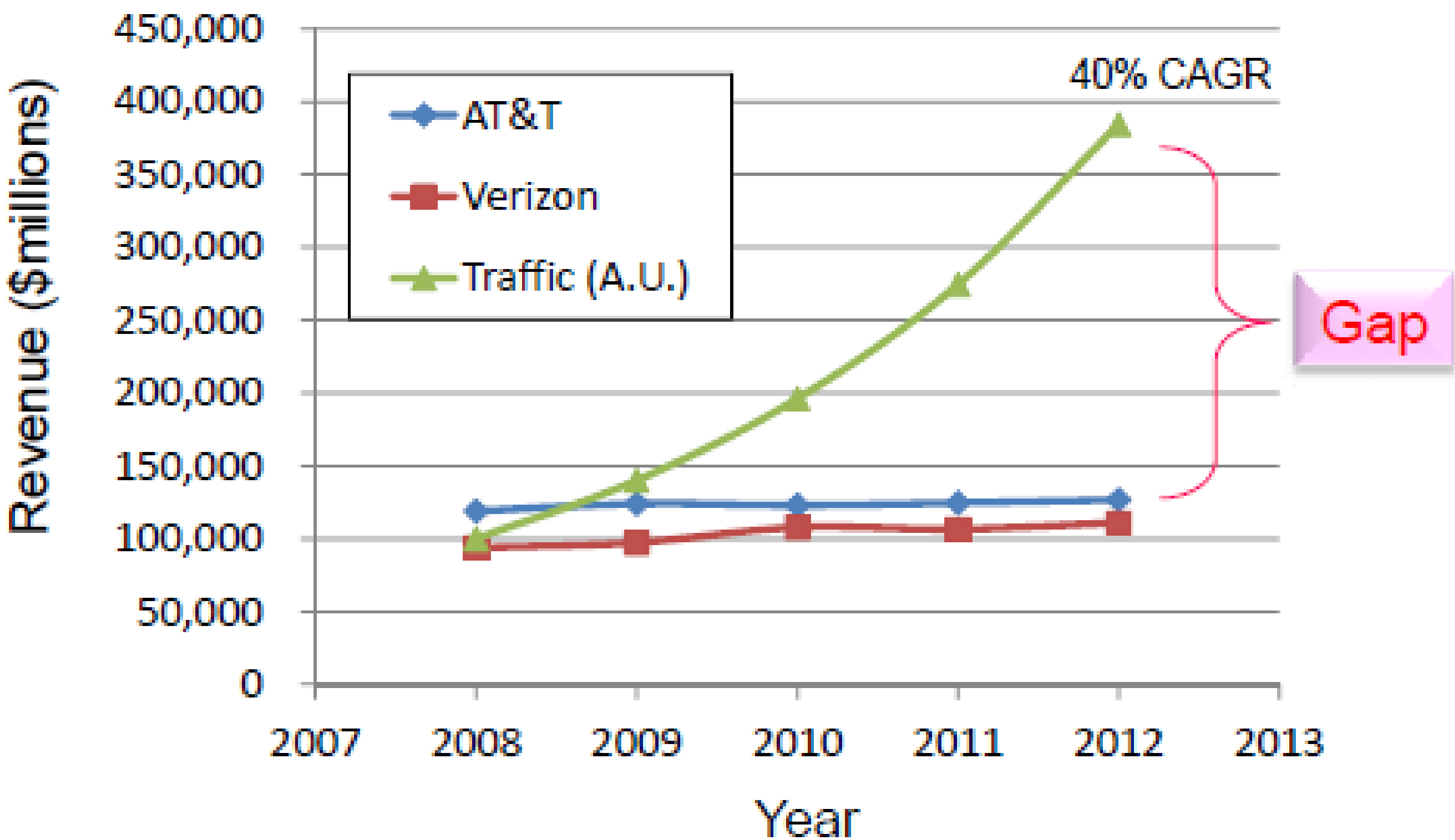
Unrelenting Growth in Data Traffic

Traffic Growth Projected by CISCO



source: Cisco Visual Networking Index: Forecast and Methodology, 2008-2013

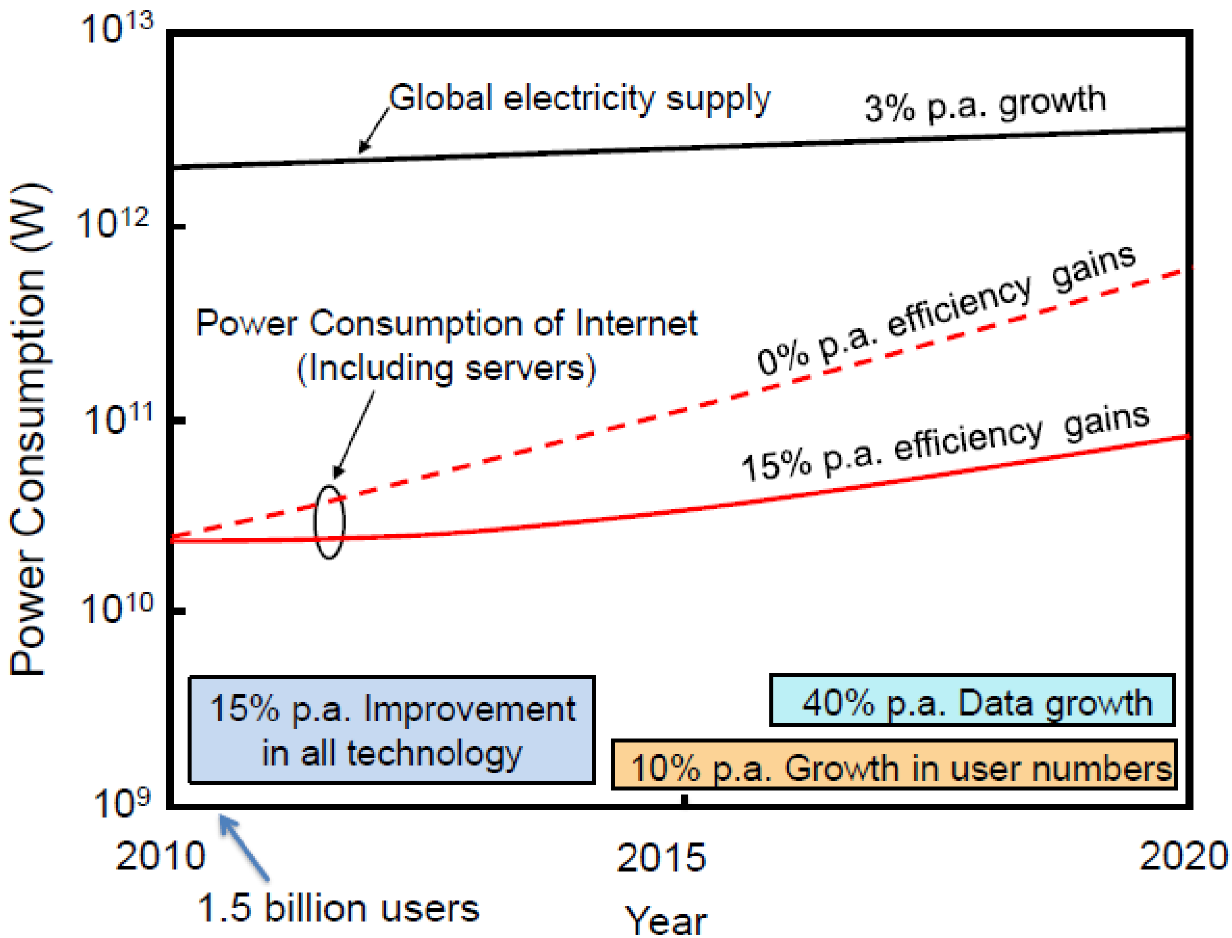
Unfavourable Economics



Source: Fortune 500

T.J. Xia (Verizon at WIN 2012, Inuyama)

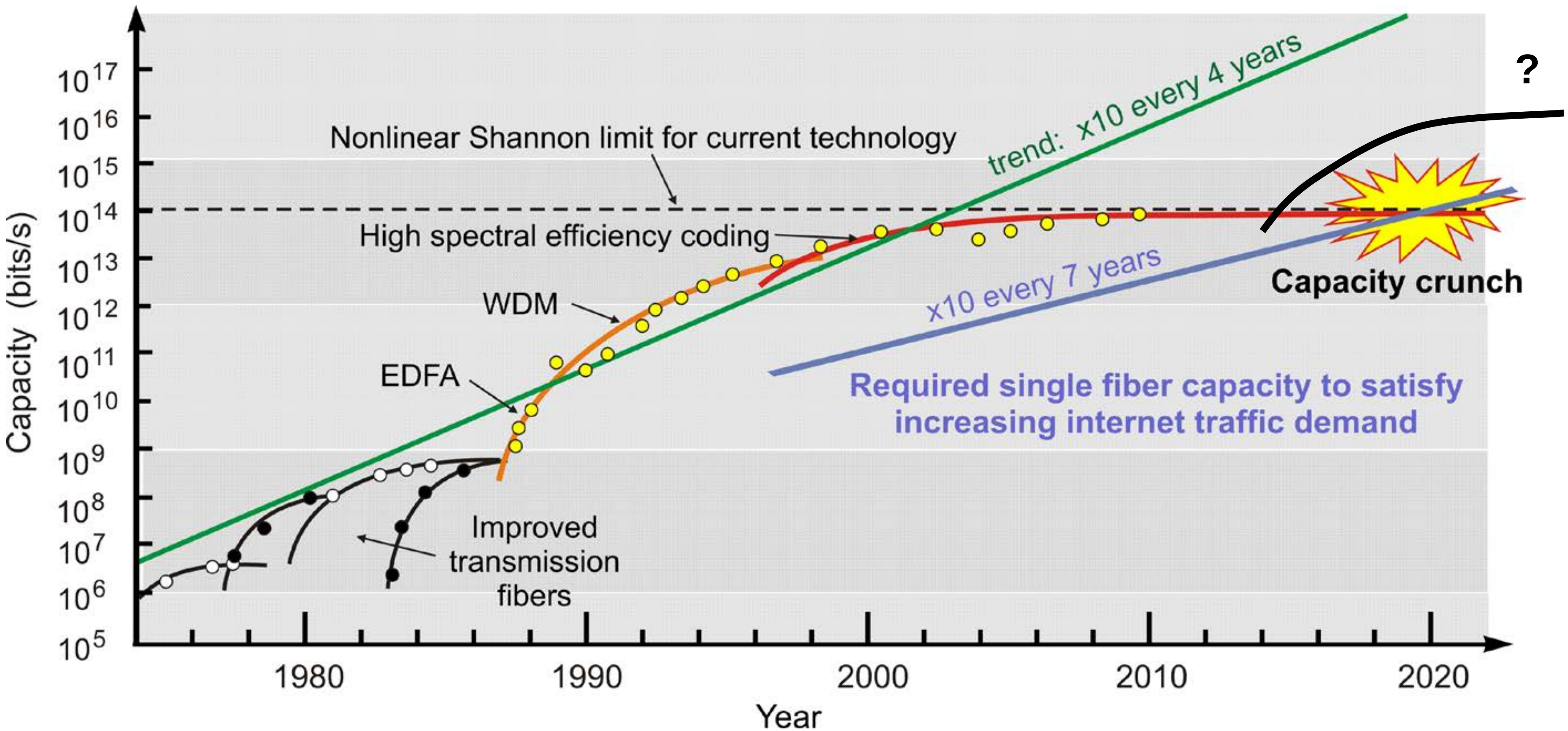
An Emerging Power Crunch



- 2% of global power production in support of ICT infrastructure in 2012
- In certain countries, e.g. Japan, numbers are even higher
- Most consumed in electronic routers/ data centres

R. Tucker GREEN TOUCH Open Forum 2012

A Saturating Transport Technology



D.J.Richardson, Science 2010 Vol.330(6002) pp.327-328

Routes to Higher Capacity

Overall Fibre Capacity =

New amplifiers
Extended low loss

Available Bandwidth

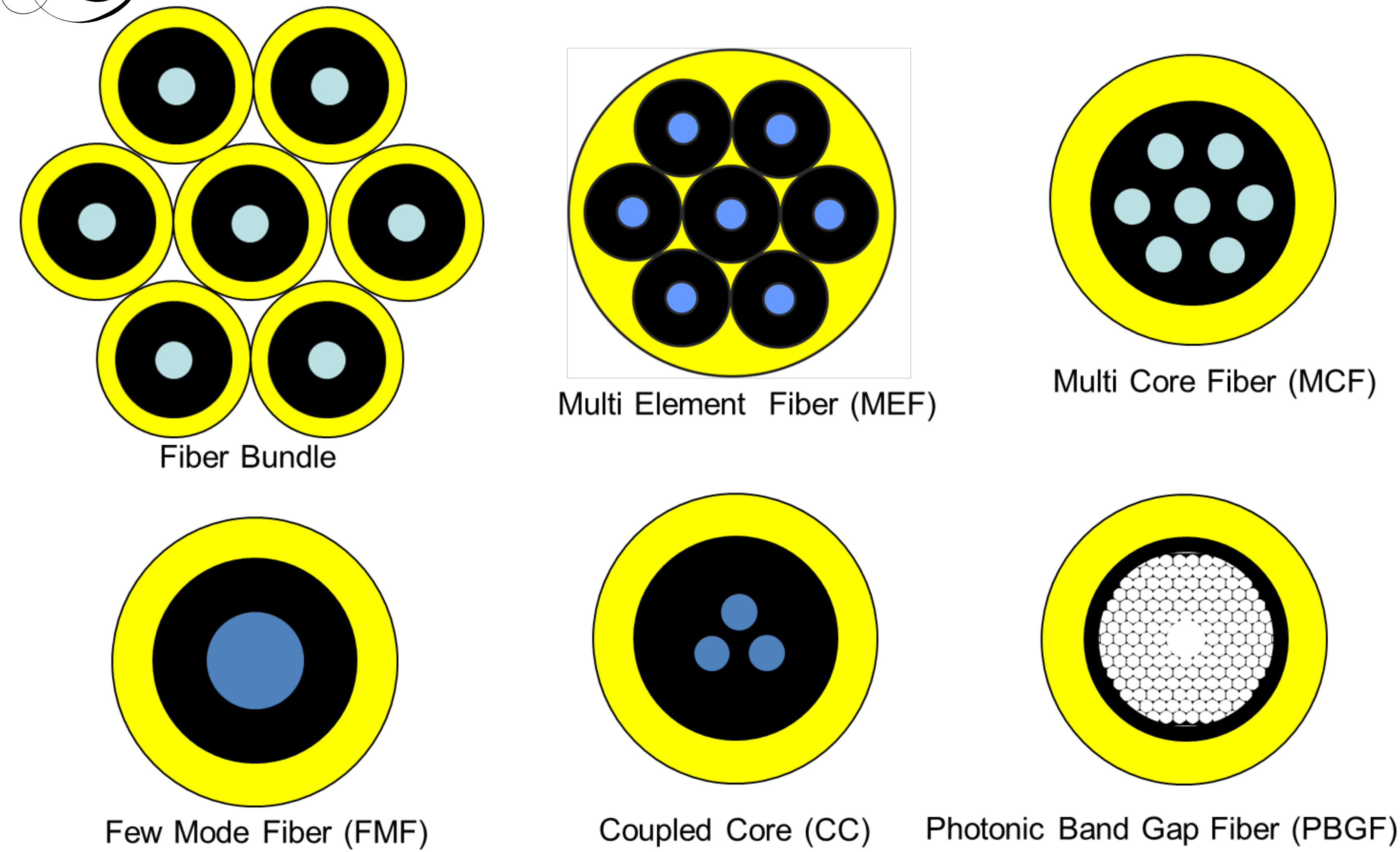
Exploit electronics…
Low nonlinearity
Ultralow loss

x Spectral Efficiency

Multi core fibre
MM fibre

x Number of Information Channels

Contender Fiber Solutions



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

Key Commercial Requirements

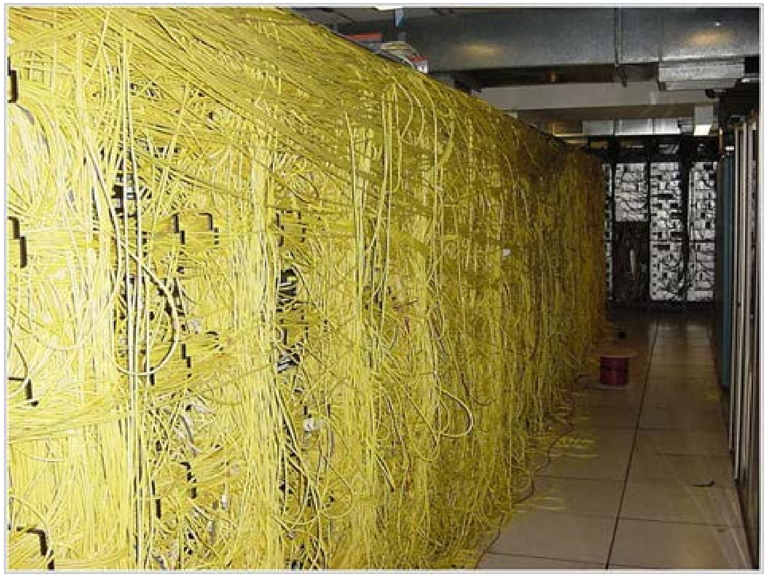
- Significant proven capacity gains/technical merit with overall reliability comparable/better than existing technology
- Reduced costs-per-bit (CAPEX/OPEX)
- Networking compatibility
- Graceful upgrade scenario
- High volume manufacture

Some Key Common Issues

- Channel Mux:Demux
- Fundamental propagation characteristics
- Channels per unit area
- Channel coupling
- Amplification
- Practicality / cabling / interconnection
- Potential for cost reduction

Potential applications in both long-haul, short-haul systems

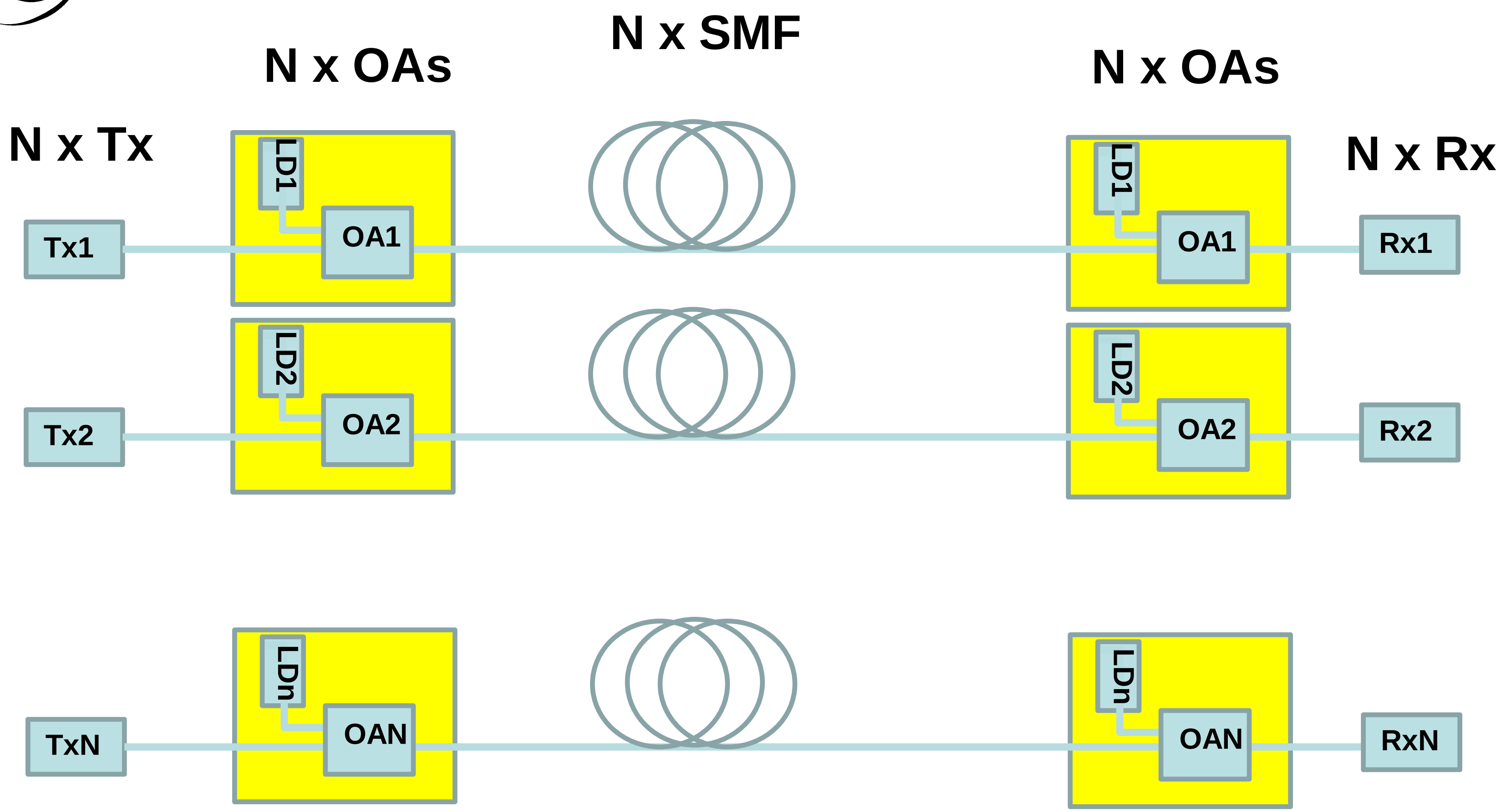
Data Center Interconnection



Information flow per unit area and latency key in supercomputers and datacenters

New high spatial density fiber solutions required

Scaling Capacity: N x SMF Systems



Once optimised transmitters/receivers adopted further capacity scaling can only be achieved by lighting new fibers at an effectively fixed cost per bit

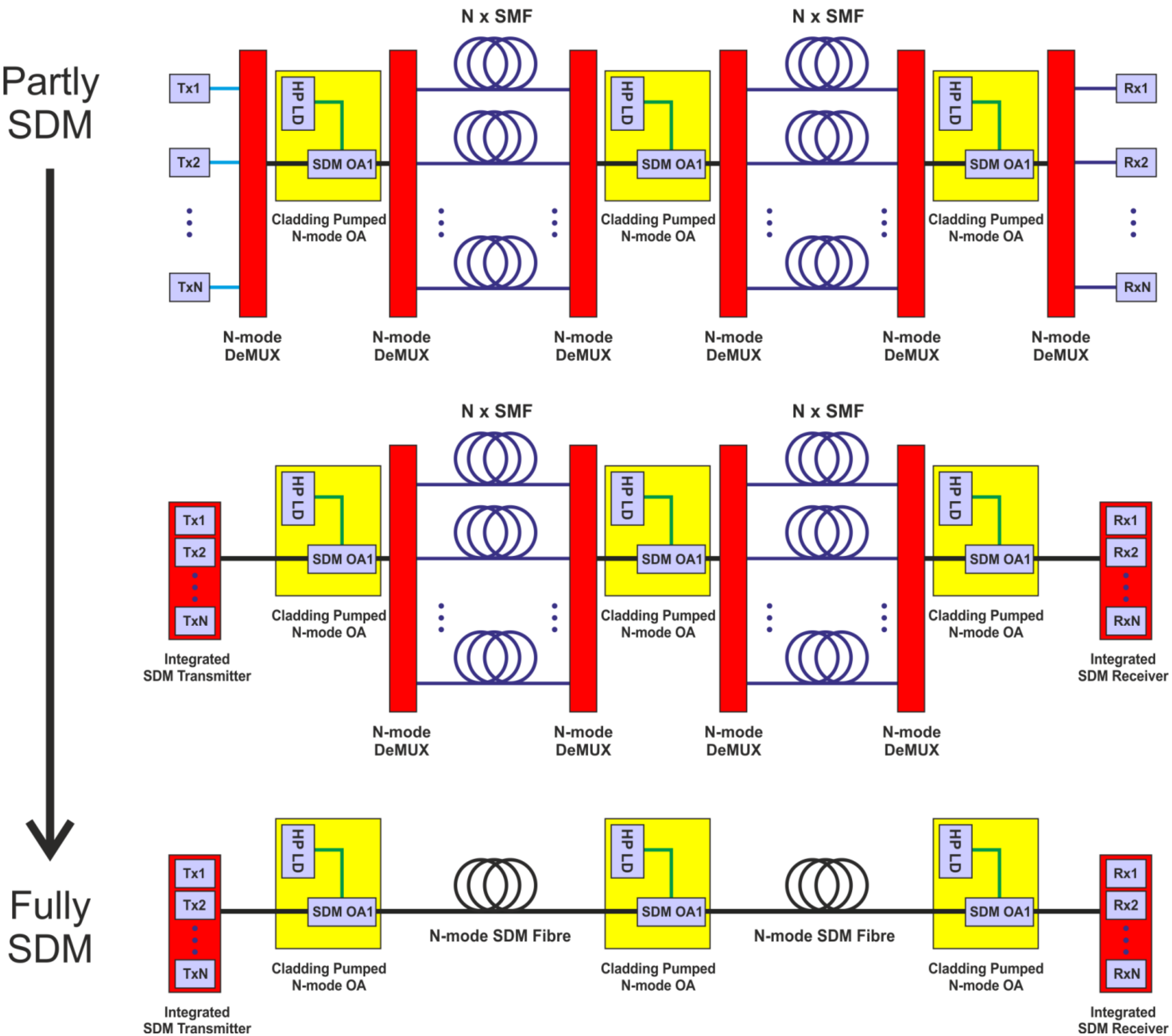
SDM Cost Reduction Opportunities

- Integrated Transmitter/Receivers
- Integrated optical amplifiers
- Integrated optical ROADMs
- Reduced connectivity/splicing costs
- Reduced duct space requirements
- Fiber manufacturing benefits?

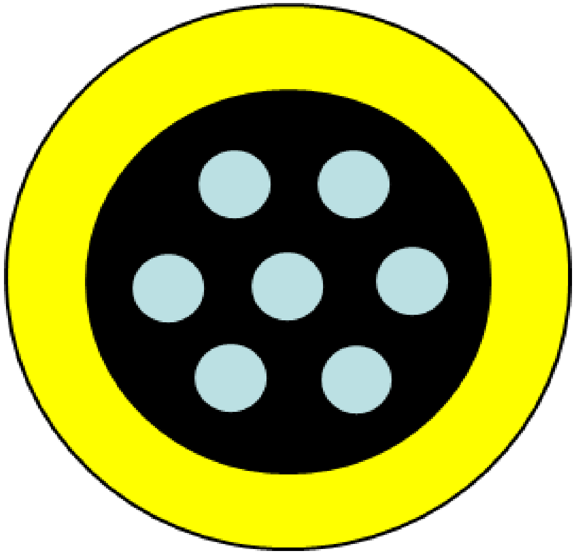
Primary benefits derive from potential for device integration

Possible Upgrade Scenarios

Partly SDM

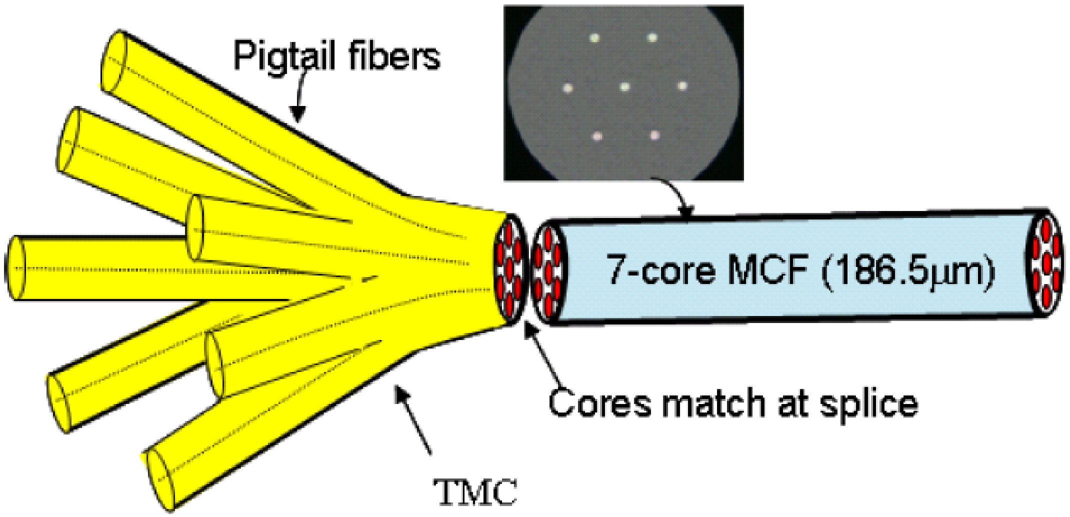


Fully SDM

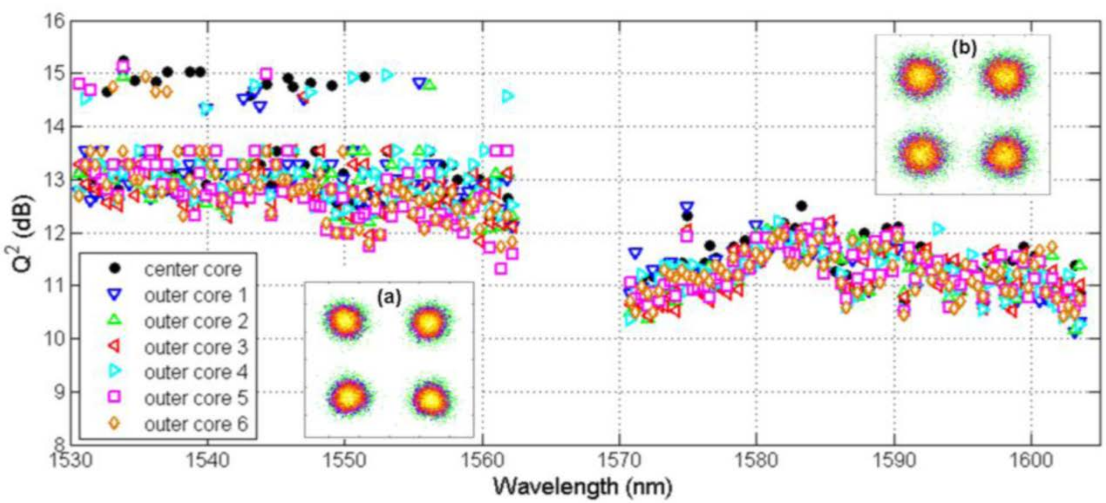


Multicore Fiber

56 Tbit/s over 76.8km of 7-C MCF



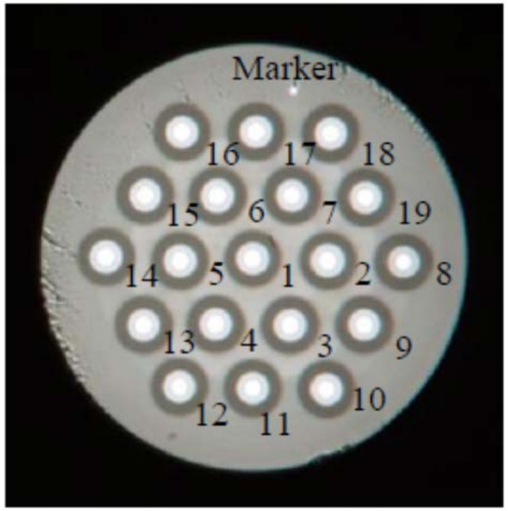
	TMC#1		TMC#2	
Core #	Loss (dB)	Crosstalk (dB)	Loss (dB)	Crosstalk (dB)
Center core	1.11		0.55	
Outer core1	0.75	-48.0	2.10	-49.0
Outer core2	2.77	-47.5	0.90	-46.5
Outer core3	1.95	-45.0	0.45	-46.0
Outer core4	0.98	-48.0	1.13	-47.0
Outer core5	1.42	-48.0	2.05	-48.5
Outer core6	1.37	-47.8	1.61	-45.5
average	1.48	-47.4	1.26	-47.1

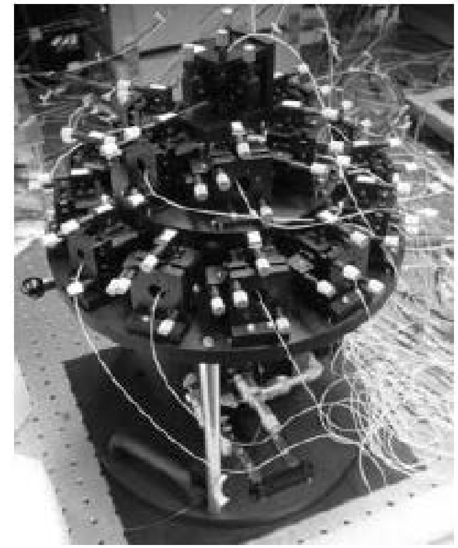


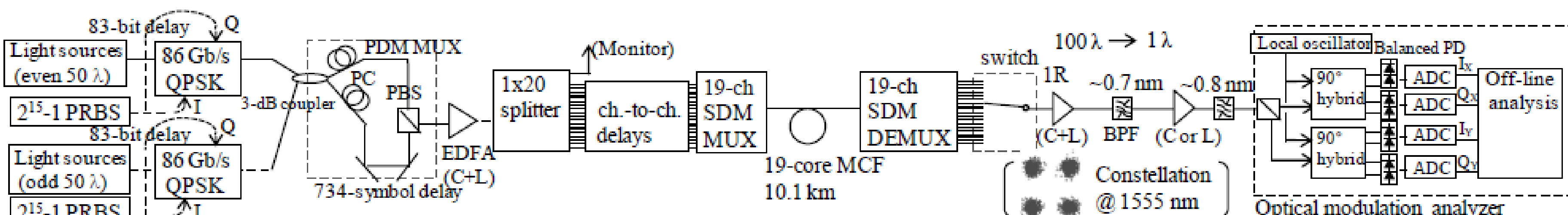
- 9/47µm core diameter/spacing
- Fiberised Mux:Demux with low loss and X-talk
- 76.8km length (1 in-line splice)
- Total X-talk<30 dB (centre core)
- SE=14 bit/s/Hz

B. Zhu et al. OFC 2011 PDPB7

19-core Transmission Experiment



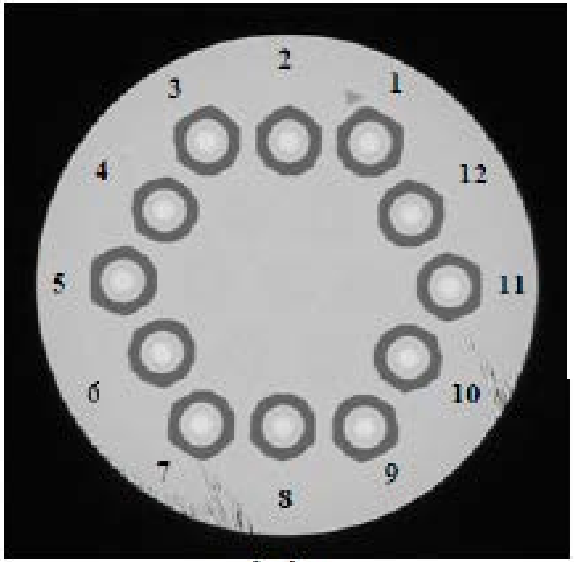


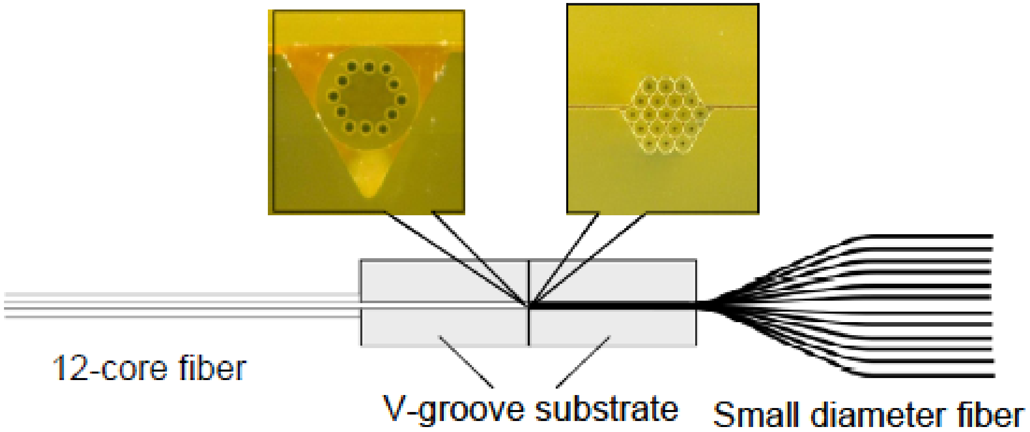


- Bulk Optic Launch Assembly
- SDM(19 core) x WDM(100ch) x PDM-QPSK (2×86 Gb/s) signals
- 305 Tbit/s total capacity
- 10.1 km span

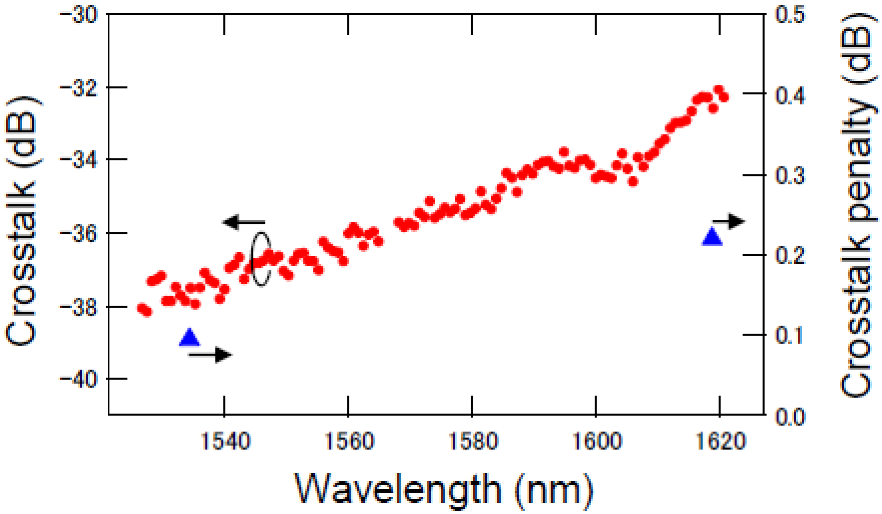
J. Sakaguchi, et al., OFC 2012, paper PDP5C.1.

12-core fiber for Pbit/s transmission



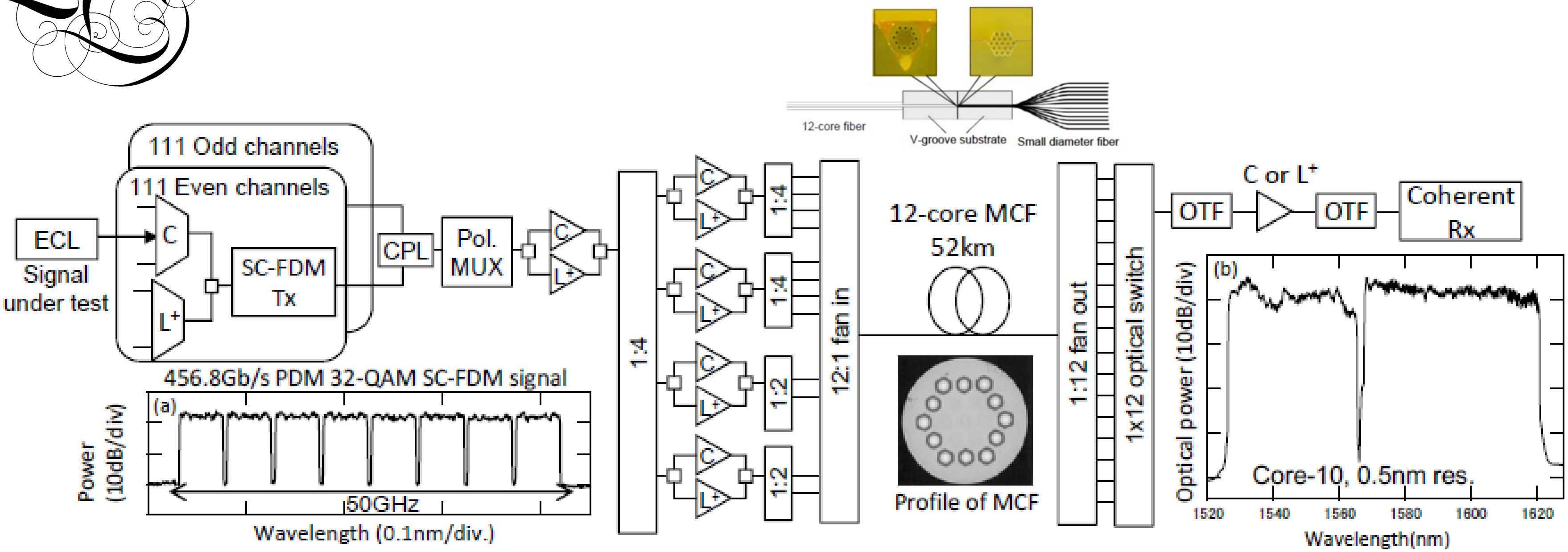


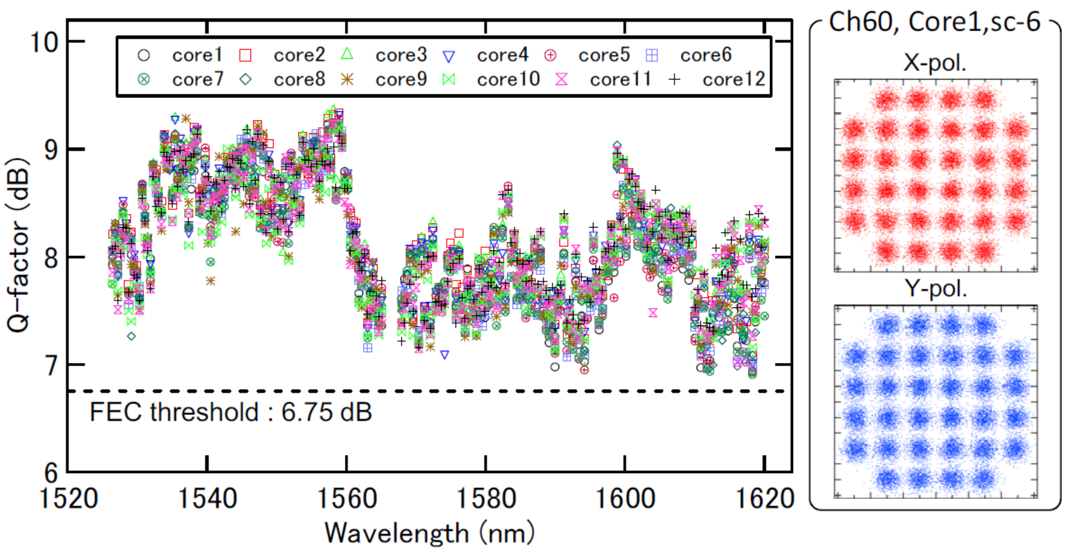
Geometry optimised to minimise crosstalk and maximise coupling from small diameter fiber bundle.



H. Takara et al. ECOC2012 PDP Th3.C.1

1 Pbit/s Transmission in 12C Fiber

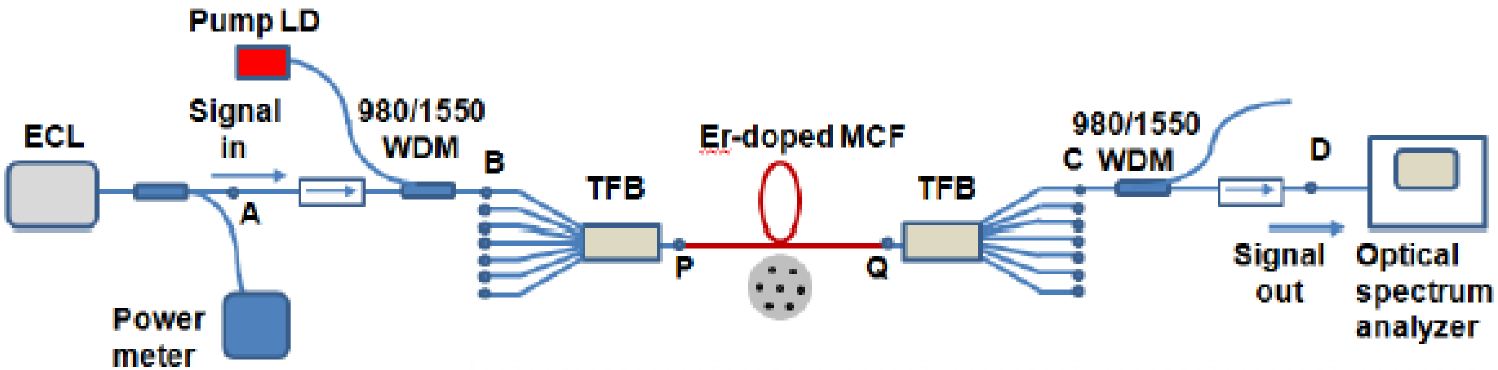


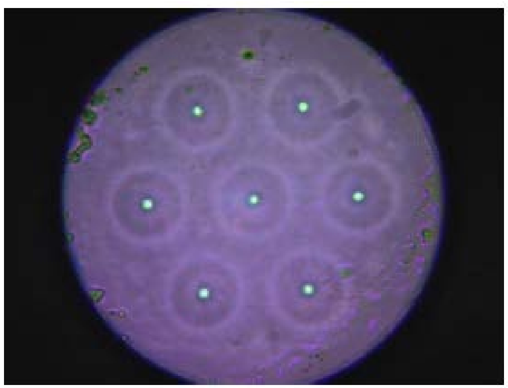


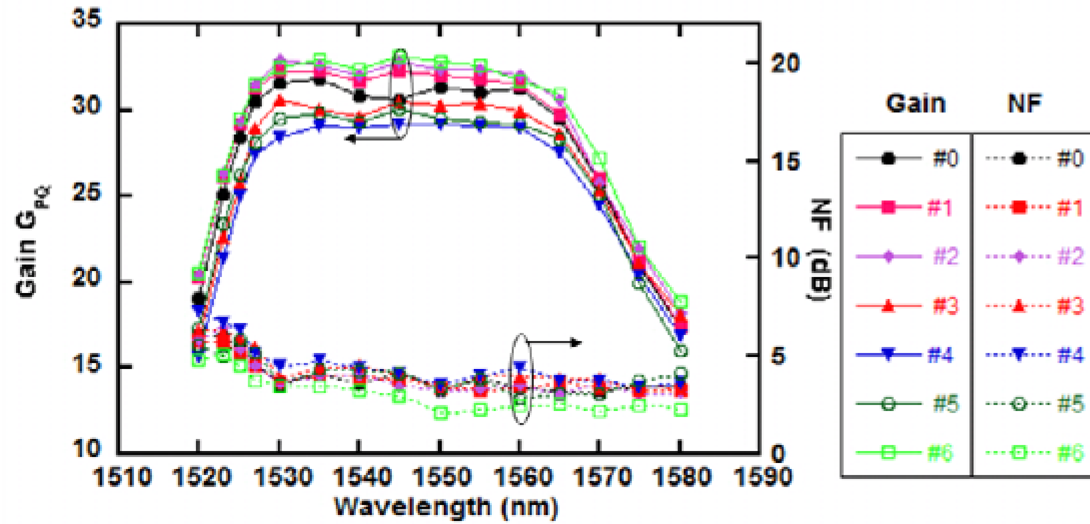
- 222 (WDM) x 12(SDM) x 486 Gbit/s (PDM 32-QAM SC-FDM)
- Total Capacity = 1.01PBit/s
- SE=91.4 bit/s/Hz
- L= 52km

H. Takara et al. ECOC2012 PDP Th3.C.1

MCF Amplifier



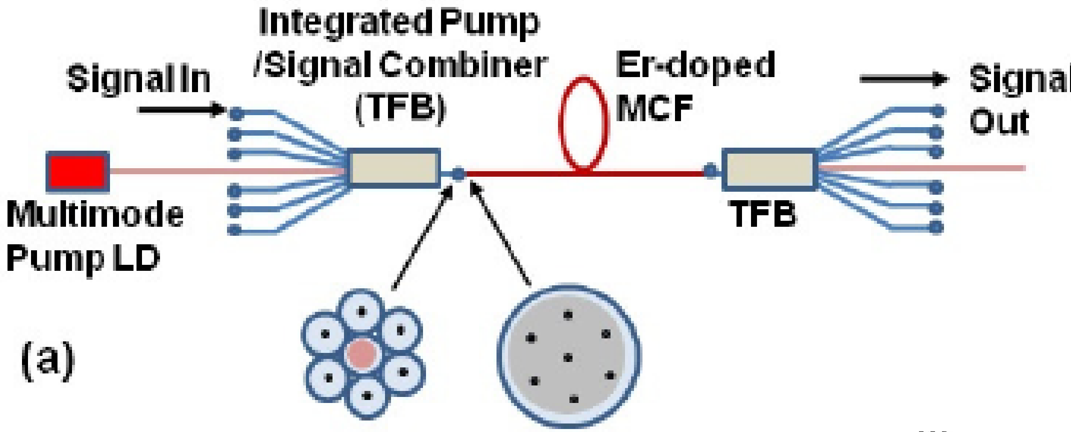


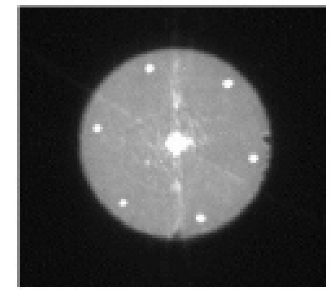


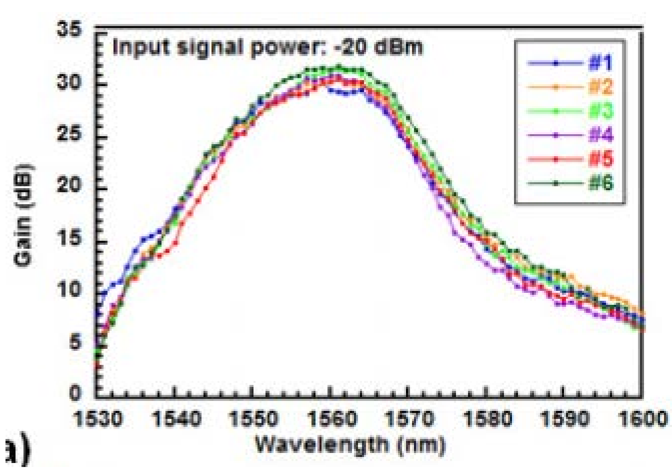
- Signal cross-talk<30dB
- Low cross coupling of ASE
- Internal NF~4dB
- Passive losses ~ 5dB
- Net external gain ~ 25dB

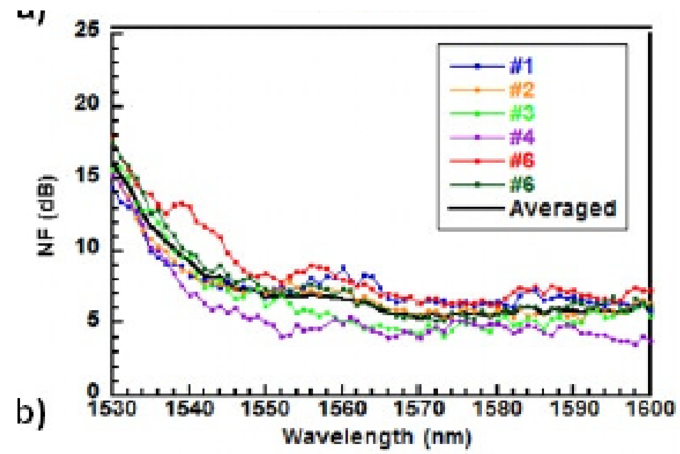
K. Abedin et al. OE 19(17), 16715-16721, 2011

Cladding pumped MCF-EDFA





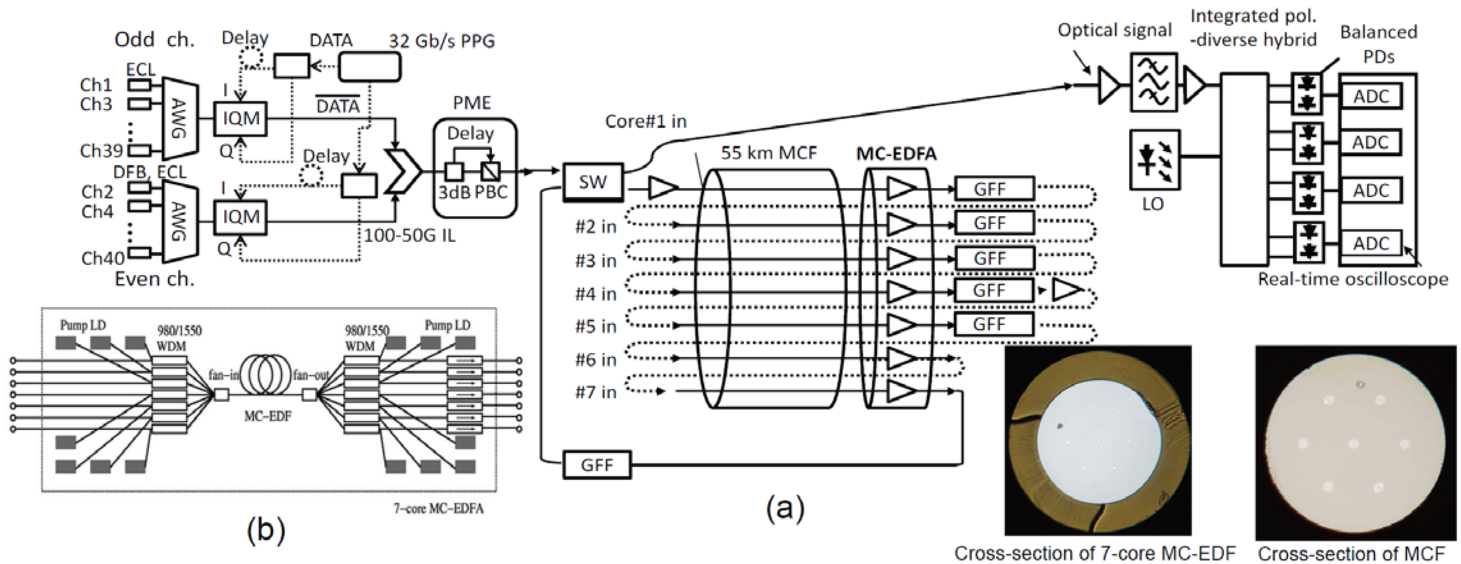


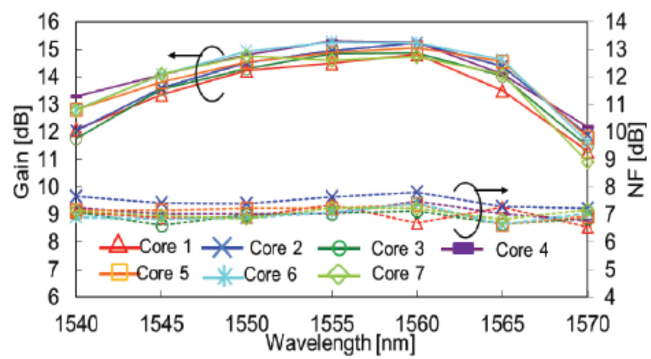


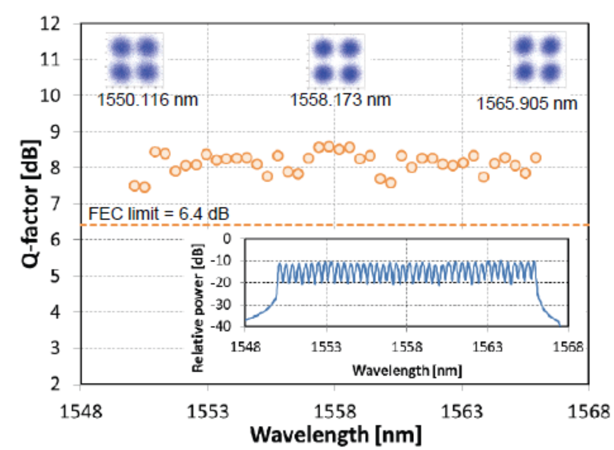
- Good potential for cost reduction
- Gain shifted to longer wavelengths due to lower pump intensity (inversion)
- Lose precise control of gain of individual channels.

K. Abedin et al. OE, 19, pp16715-16721, (2012)

Amplified all-MCF Transmission



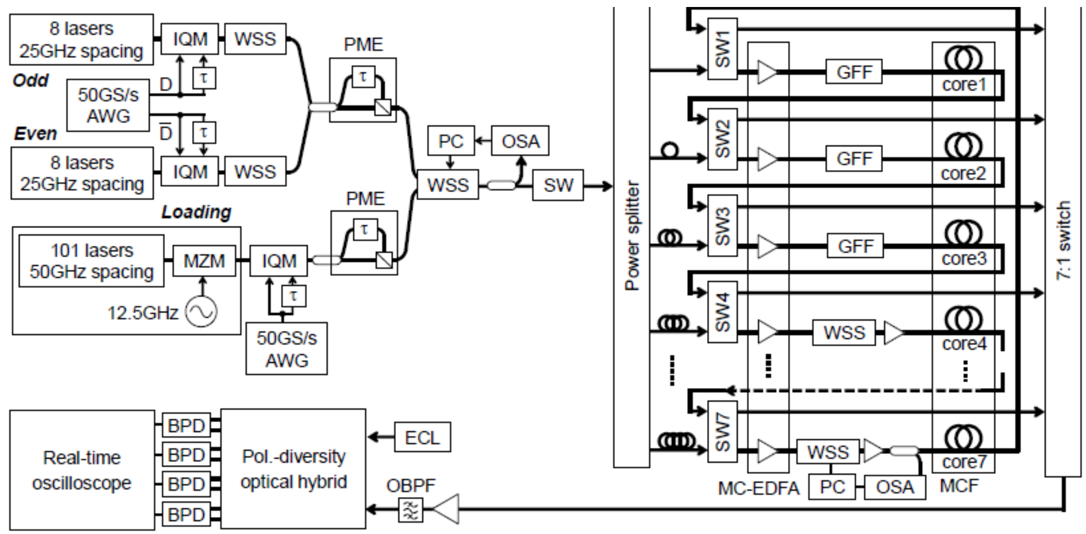


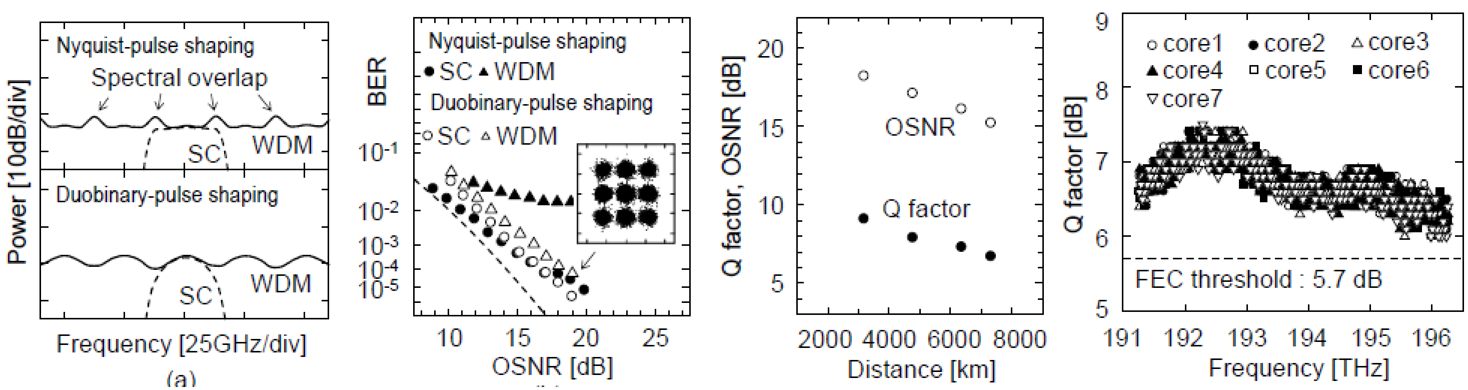


- 7-core MCF transmission line + EDFA
- 40(WDM) x 7(SDM) x 128Gbit/s (PDM-QPSK)
- 6160 km total transmission distance

H.Takahashi et al. ECOC 2012 PDP Th3.C.3

1.03 Exabit/s.km MCF Transmission

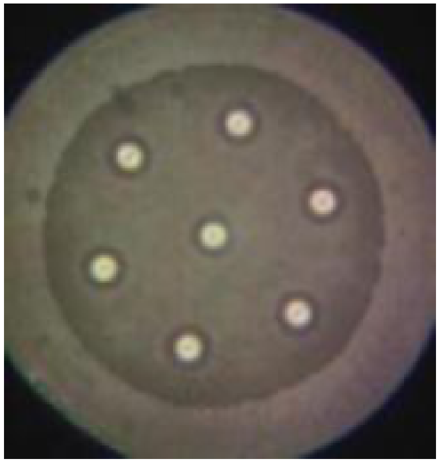


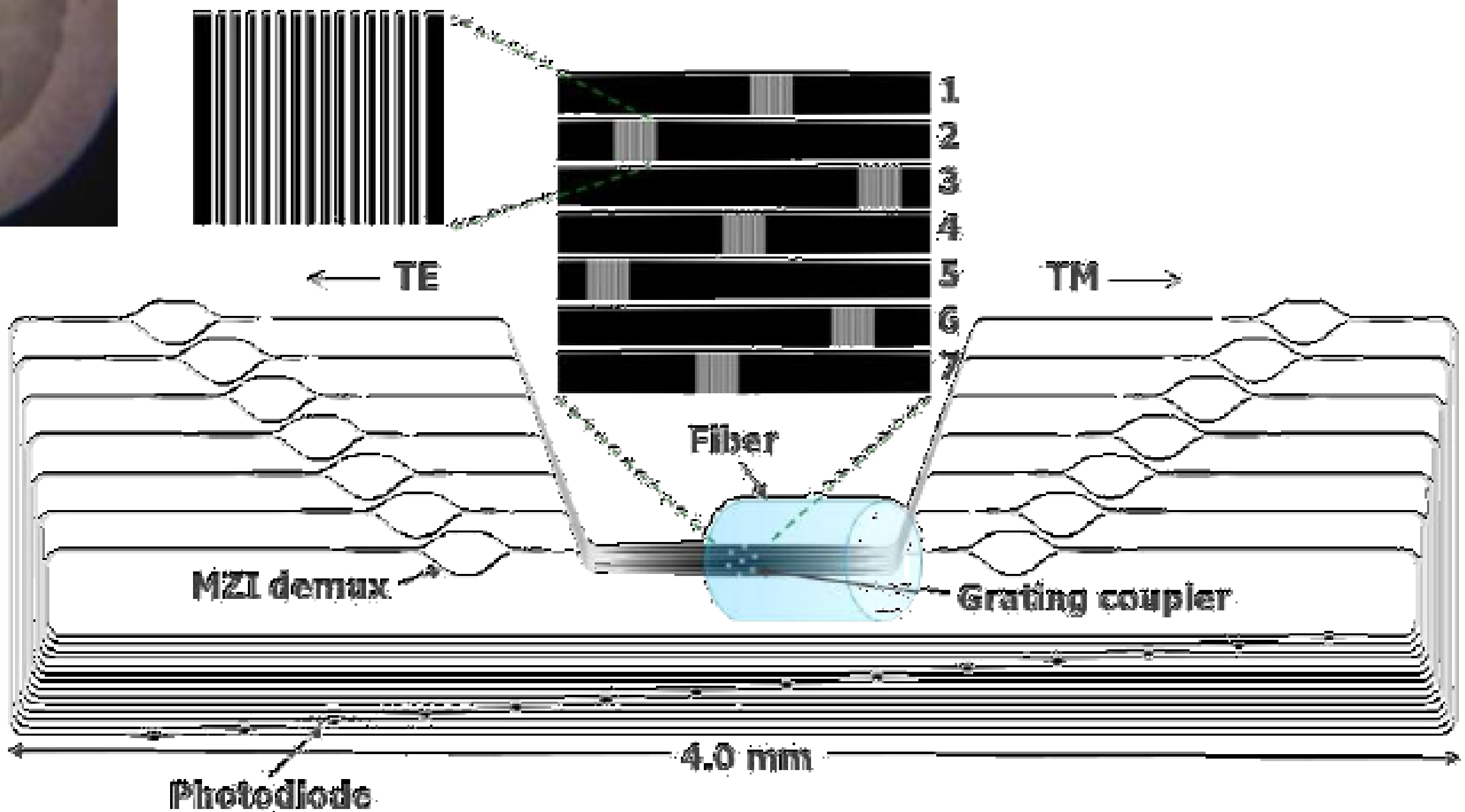


- 140.7-Tbit/s, 7,326-km transmission
- 7 x 201-channel 25-GHz-spaced Super-Nyquist-WDM 100-Gbit/s (30 Gbaud DP-QPSK)

K. Igarashi et al. ECOC PD3.E.3 (2013)

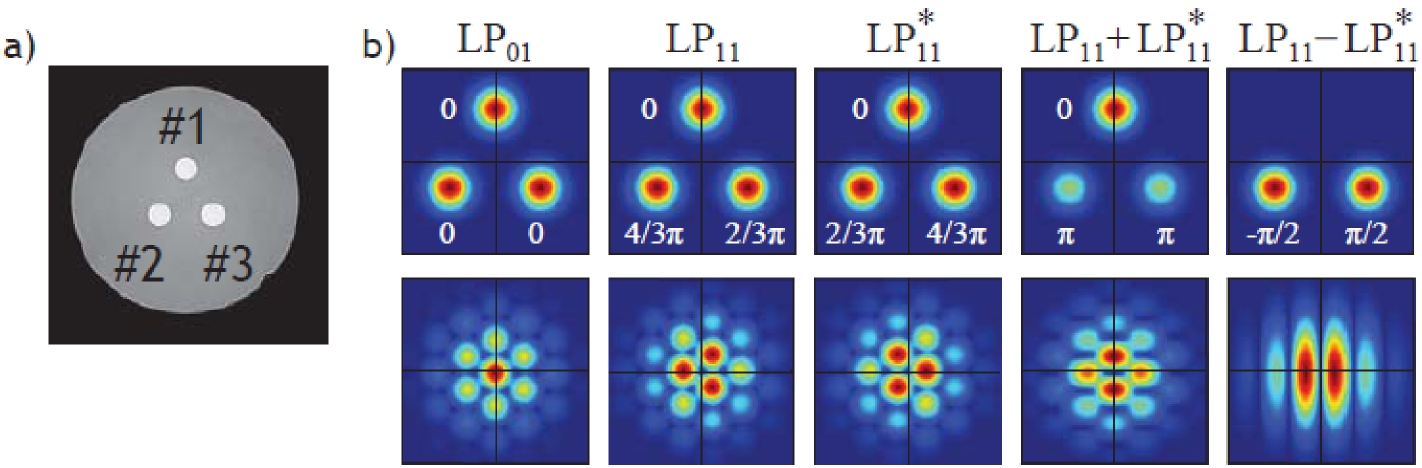
TRANSPONDER INTEGRATION
MULTI-CORE FIBER INTERFACING

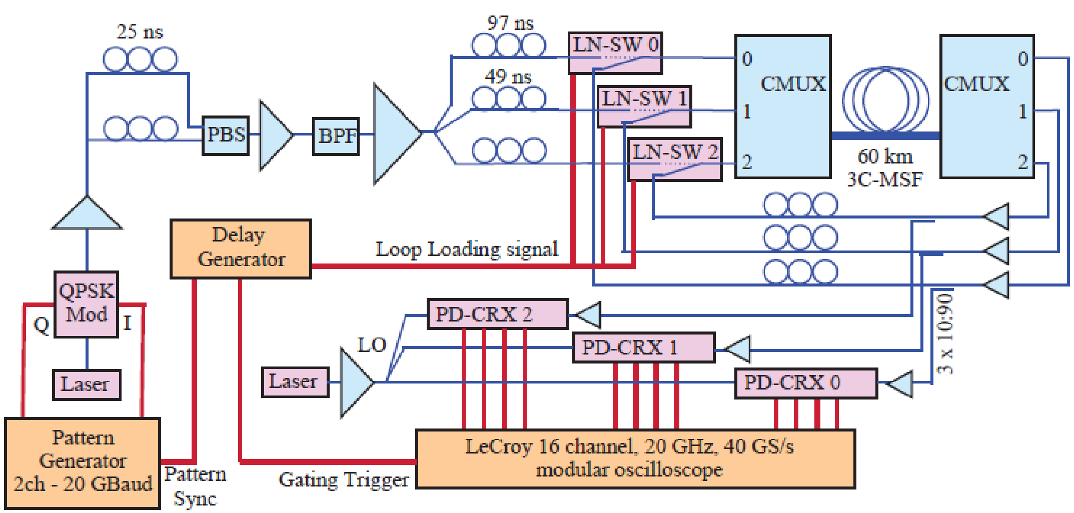




[C. R. Doerr et al., Photon. Technol. Lett. 23(9), 597-599 (2011)]

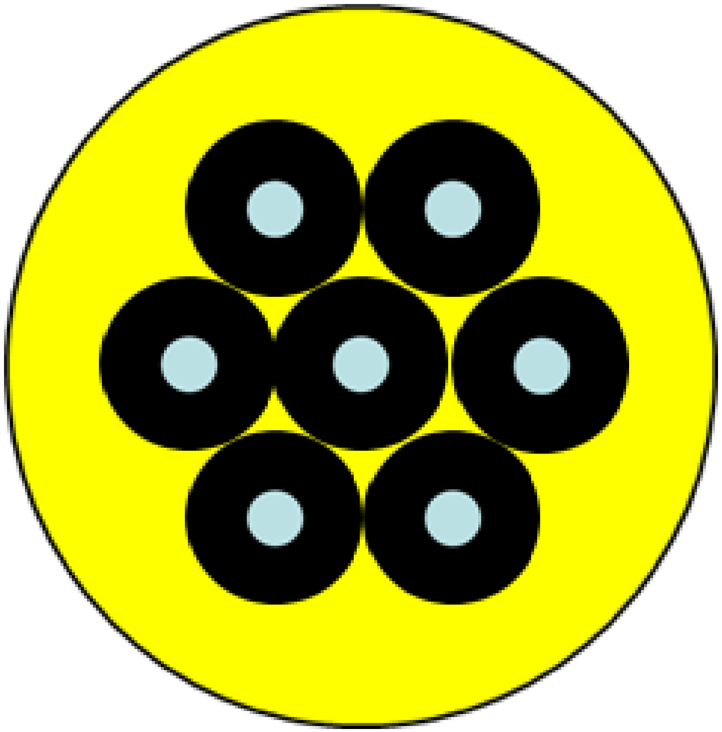
Amplified 3-core Super Mode Transmission Experiment over 1200km





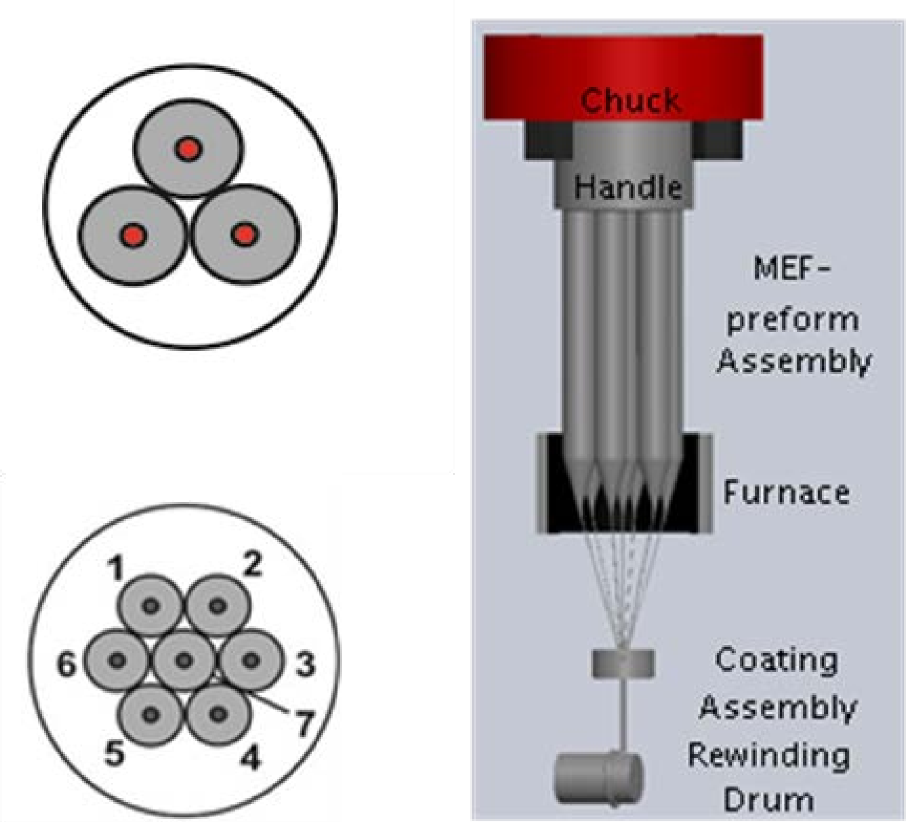
- Ready excitation of super-modes (unitary transformation of excitation modes allows MIMO)
- Engineerable mode shapes via fibre microstructuring
- Amplified low-DGD transmission over 1200km demonstrated

R. Ryf et al., ECOC 2011, PDP Th13.C.1



Multi Element Fiber

Multi Element Fiber

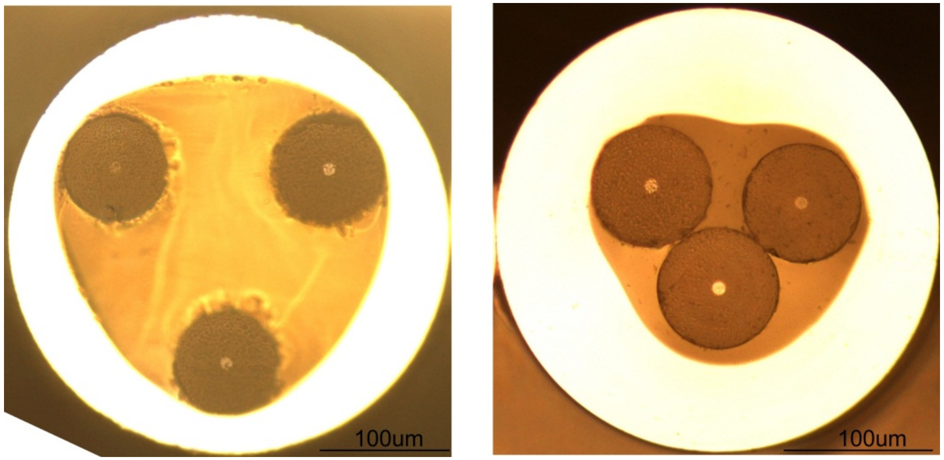


(c) (b)

- All fibers drawn in a single process
- Ultralow cross-talk
- Fibers readily split apart for Mux/DeMux
- Allows core or cladding-pumped amplifiers

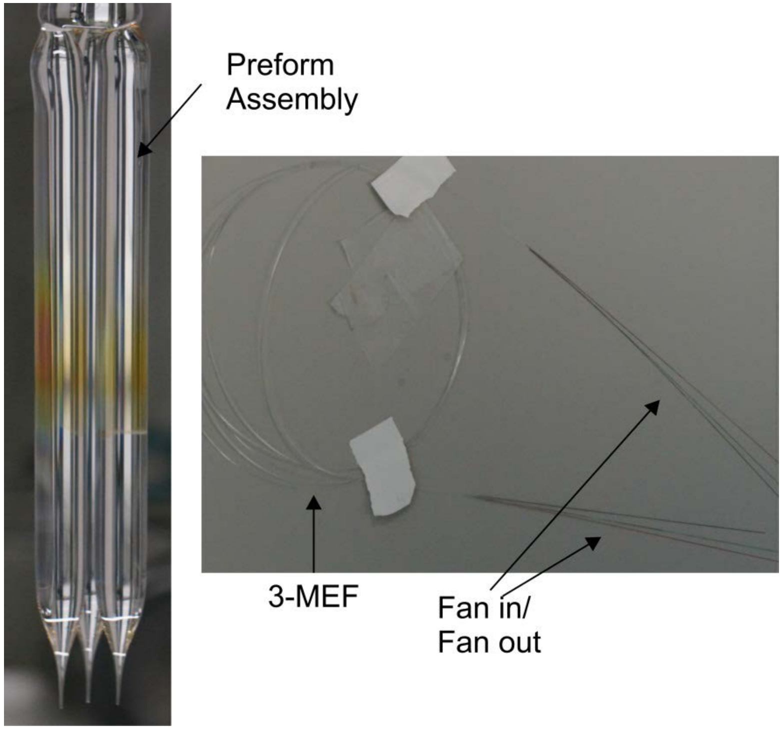
S. Jain et al. Optics Letters, 38, pp. 582-584 (2013)

Multi Element Fiber (MEF)



Non-compact and Compact 3-MEF

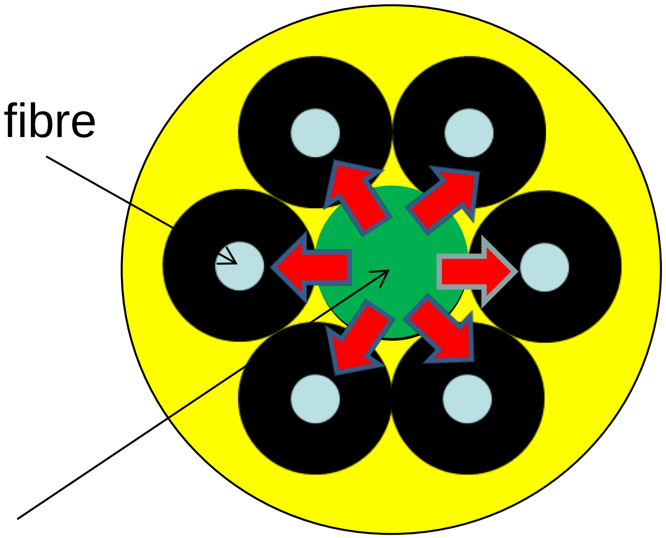
- MEFs drawn in up to 10km lengths with negligible loss as opposed to single core preform
- First transmission experiments successfully undertaken



S Jain et al. to be presented ECOC, 2013

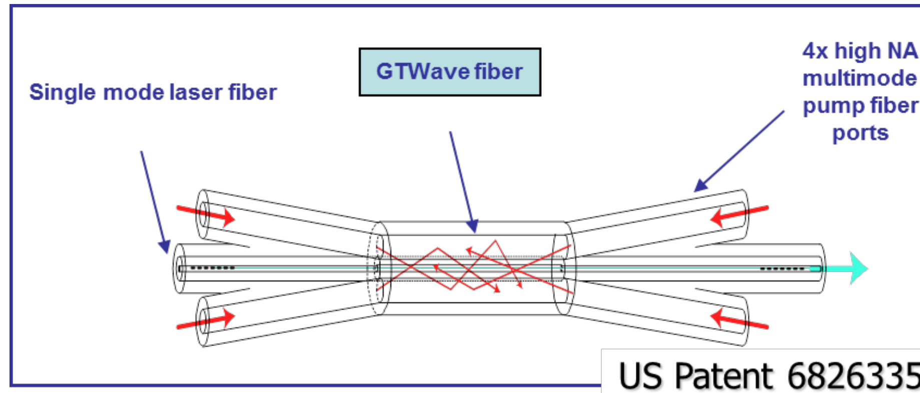
Exploiting Space
A route to lower cost amplification

Er-doped fibre



Undoped fibre for pump delivery

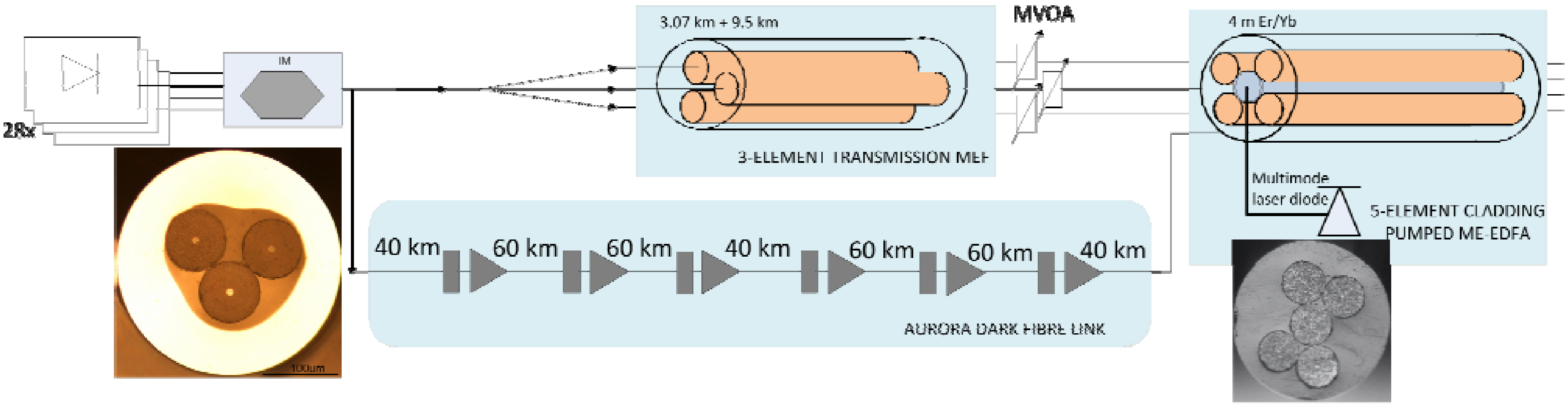
Pump light

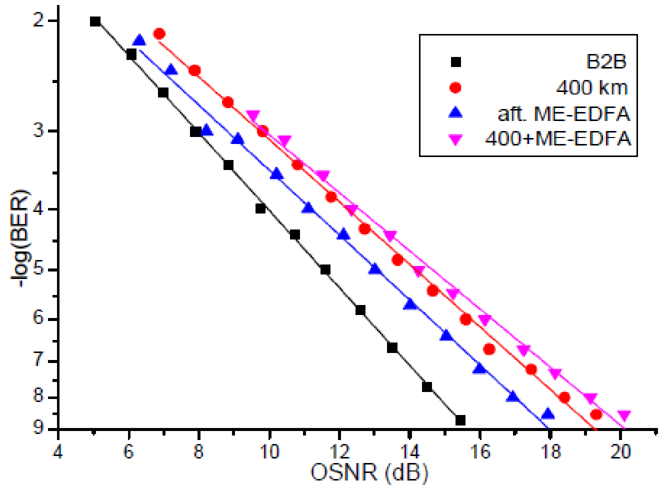


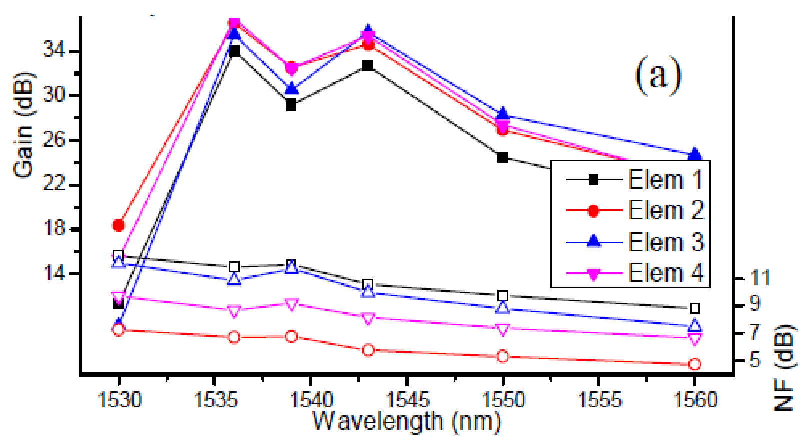
US Patent 6826335

- 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

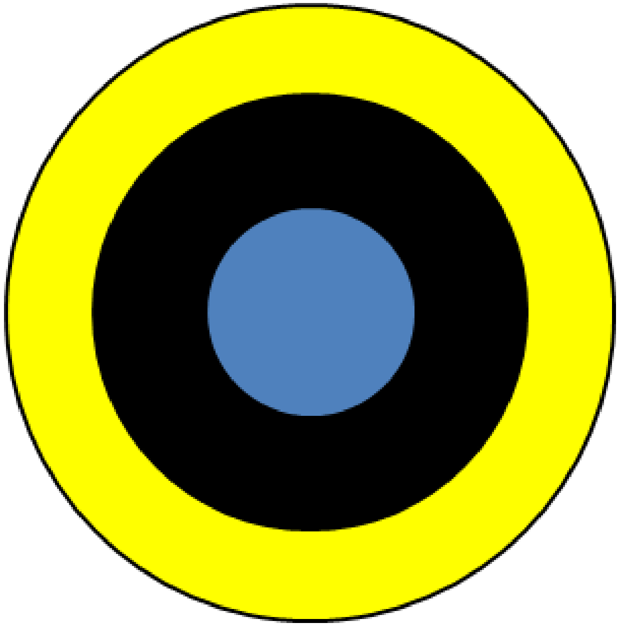






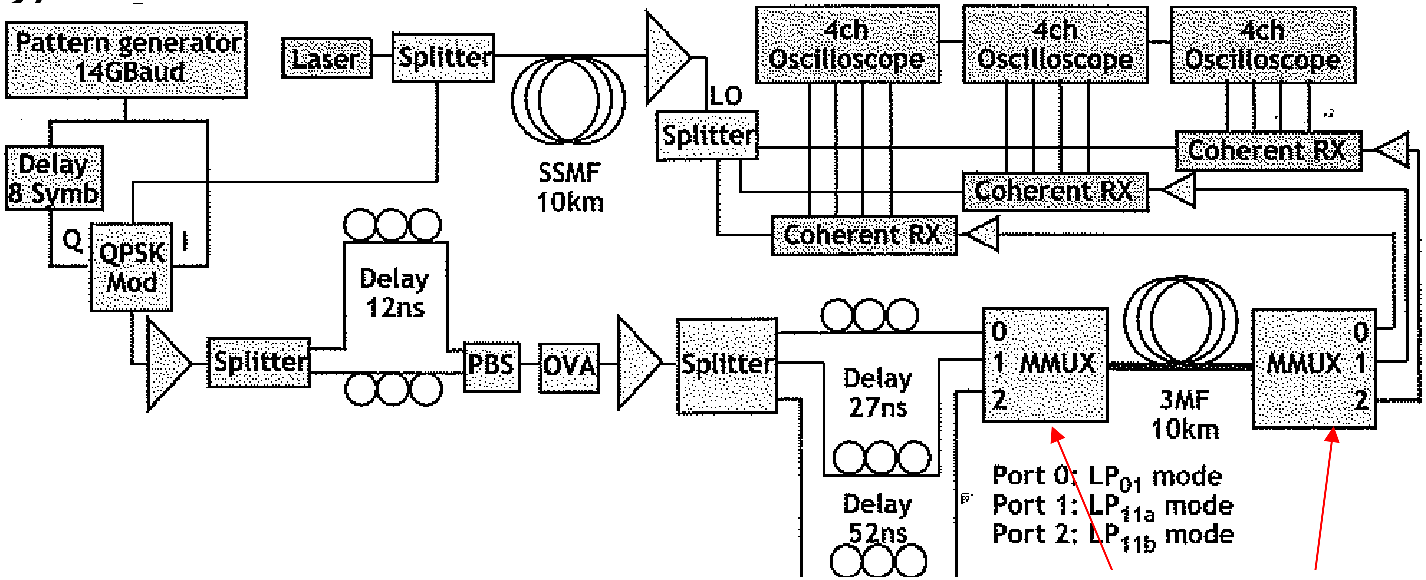
- Transmission fibre and amplifier concepts validated
- Compatibility with installed fibers shown
- Both 3 & 7 element components fabricated

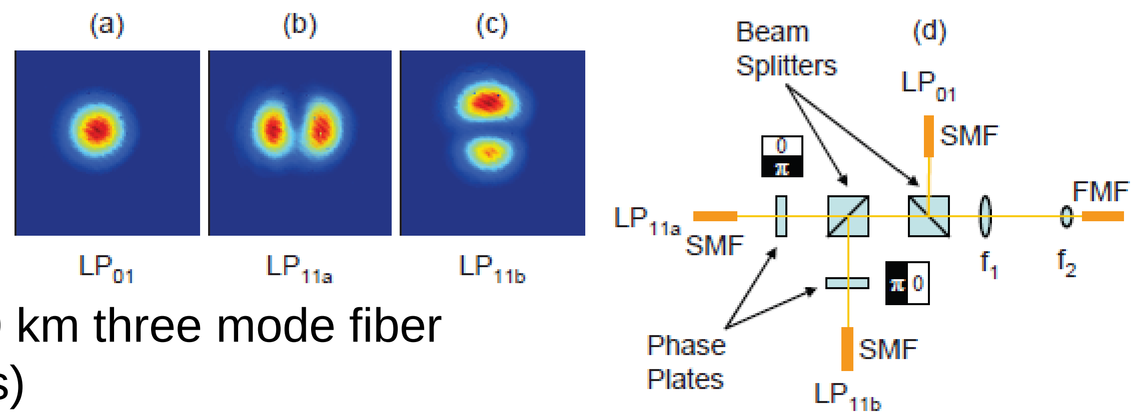
V. F. Rancano ECOC PDA1.C.2 (2013)



Few Mode Fiber

MDM over 10km TMF with MIMO DSP



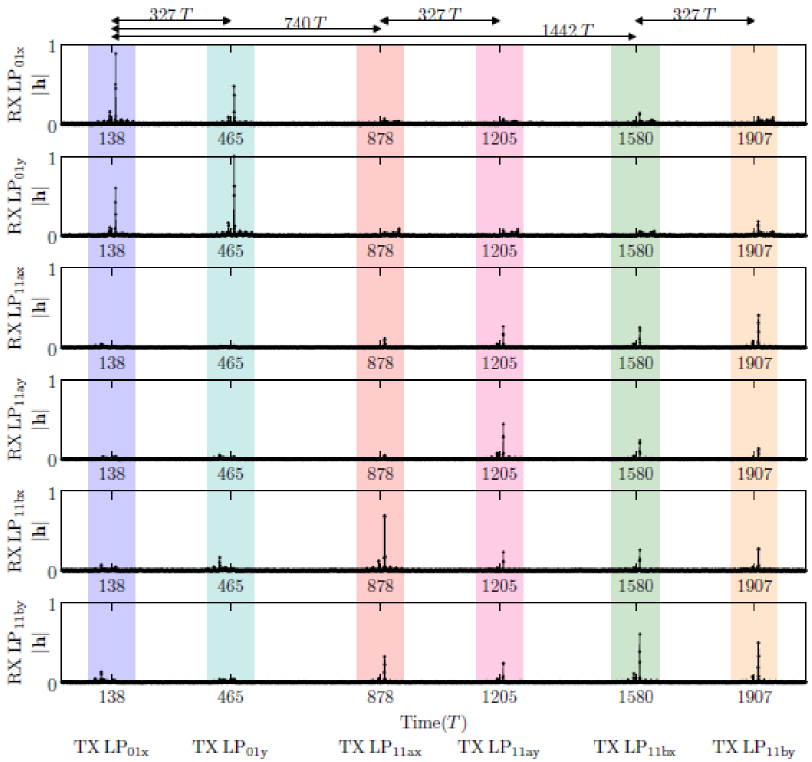


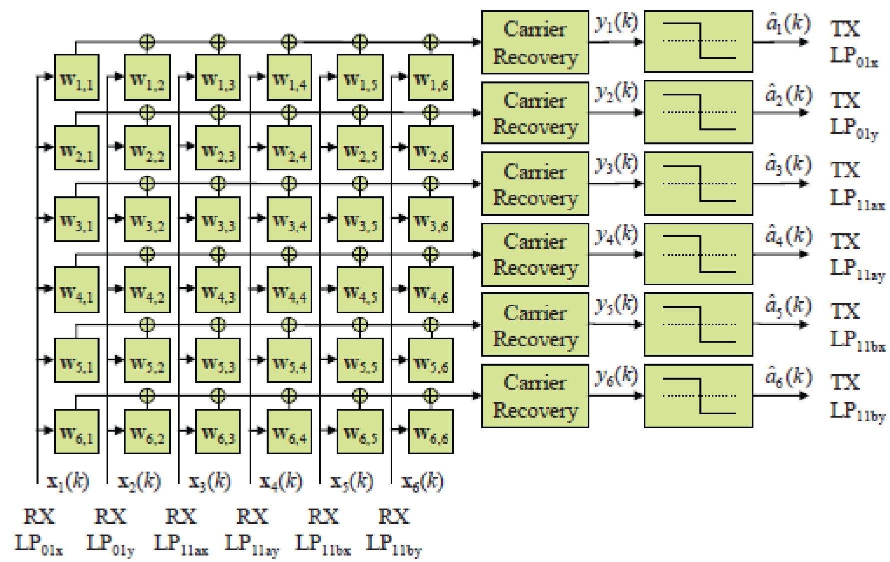
- 6-channel MDM over 10 km three mode fiber (3 modes/2 polarisations)
- Phase plate/bulk optic excitation
- MIMO correction of mode coupling effects
- Offline processing (computationally intensive)

R Ryf et al., OFC 2011 PDPB10

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

MIMO Processing

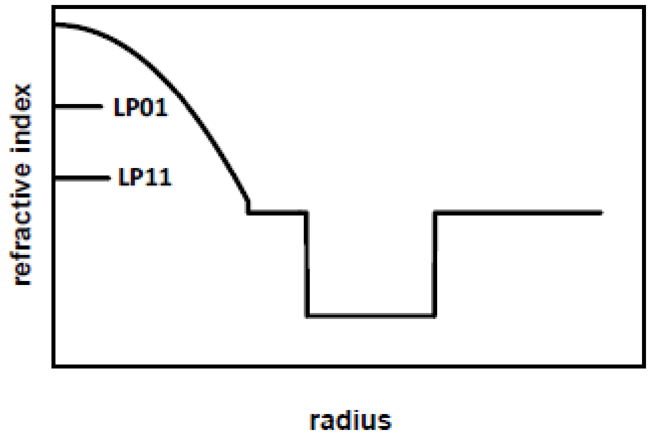




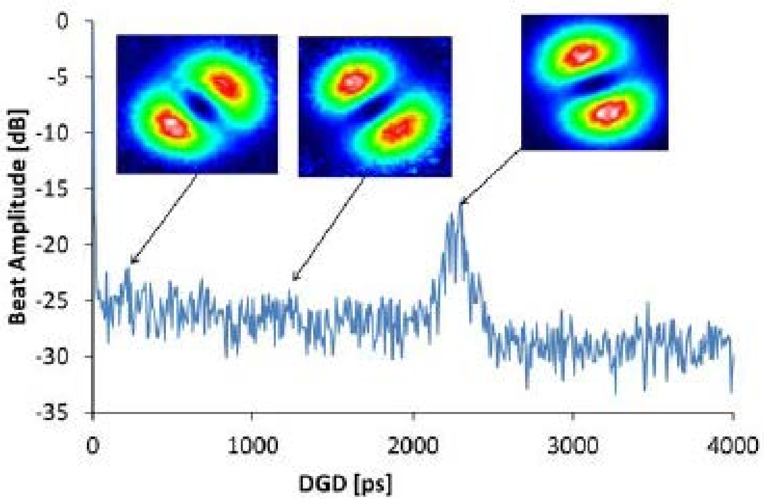
- Linear properties of system characterised by 6x6 impulse response matrix
- Need to use an N-tap DSP filter to retrieve data where N determined by the impulse response spread.
- Need to reduce fiber DGD to reduce N and complexity of processing.
- MDL/MDG ideally also needs to be small

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

Low DGD 3-Mode Fibre



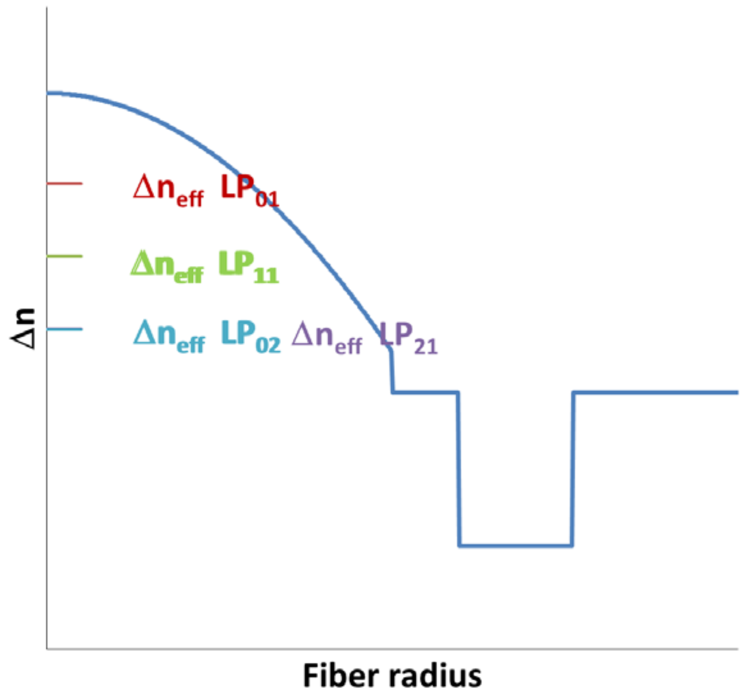
Property	Unit	Value
Spool length	m	30000
Distributed mode coupling LP_{01} to LP_{11}	dB	-25
DGD between LP_{11} and LP_{01}	ps/m	-0.076/*-0.081*
Dispersion LP_{01}	ps/(nm·km)	20.0/*19.8*
Dispersion slope LP_{01}	ps/(nm^2·km)	0.065/*0.067*
Effective area LP_{01}	µm^2	97/*95*
Dispersion LP_{11}	ps/(nm·km)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



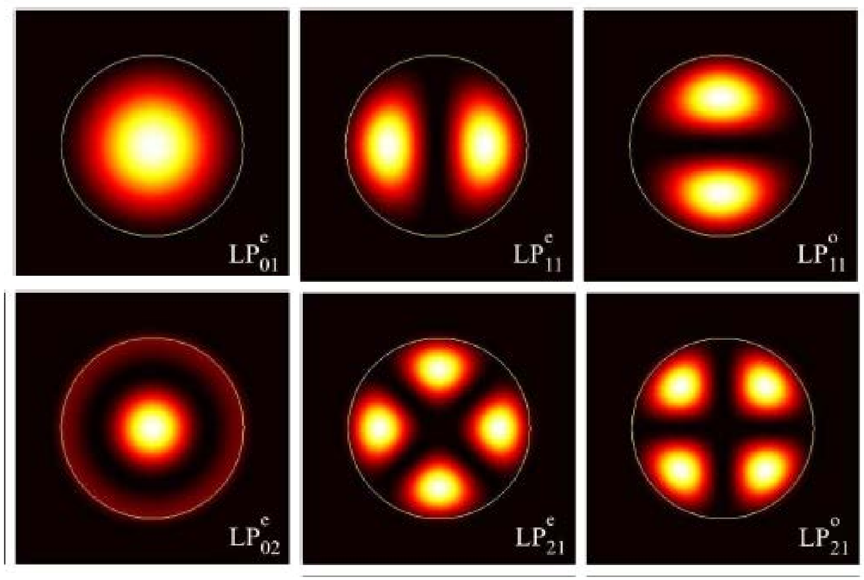
- Parabolic profile to minimise DGD
- Excellent fibre uniformity
- Low loss
- Very low intrinsic mode coupling
- Low DGD obtained (of both signs)

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

OFS graded index four LP mode fiber



Refractive index profile



Four LP mode
Six spatial modes

Requirements for Differential Group Delay (DGD)

- DGD can be compensated by combining fibers with positive and negative DGD.

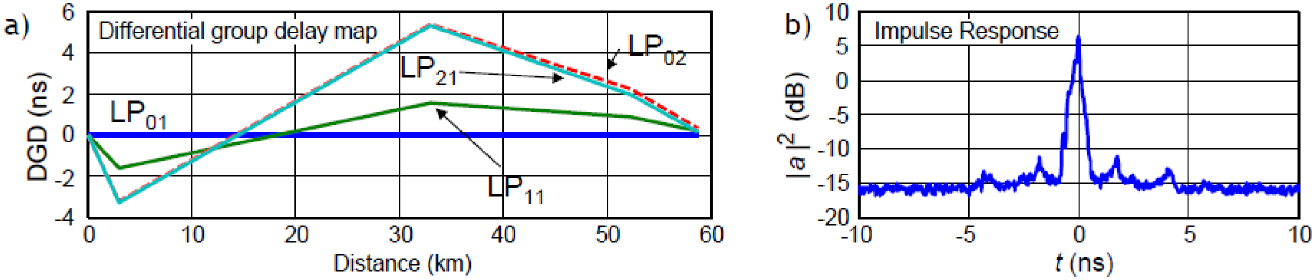
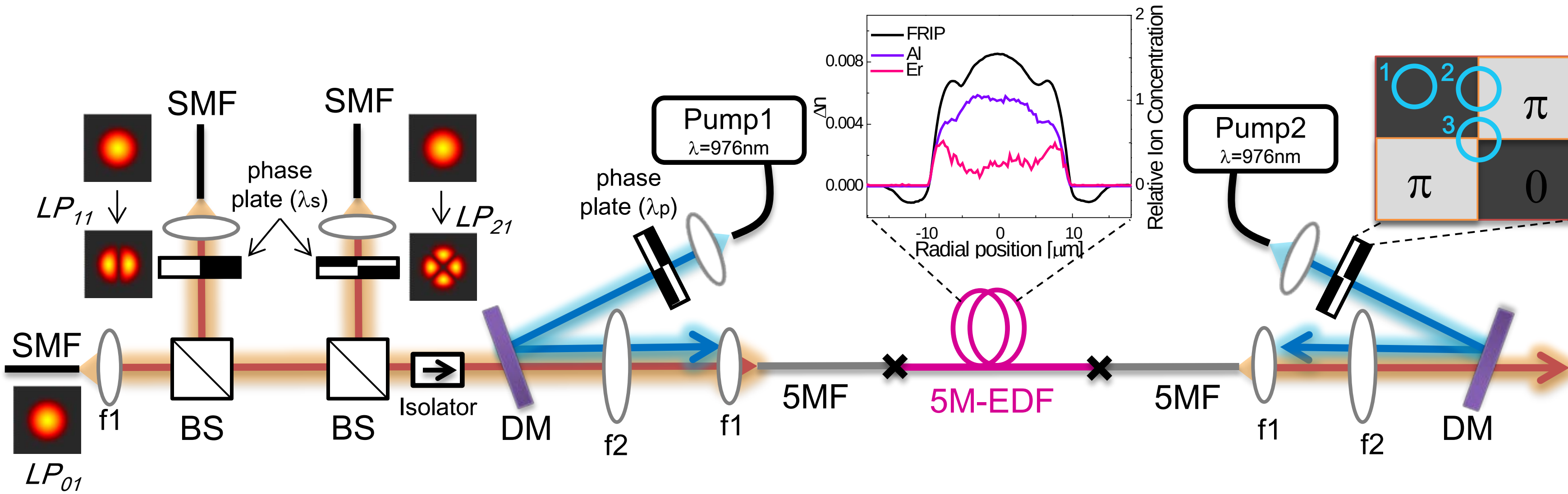


Fig. 1. a) DGD map for the 59-km compensated FMF span. b) Impulse response of the FMF span.

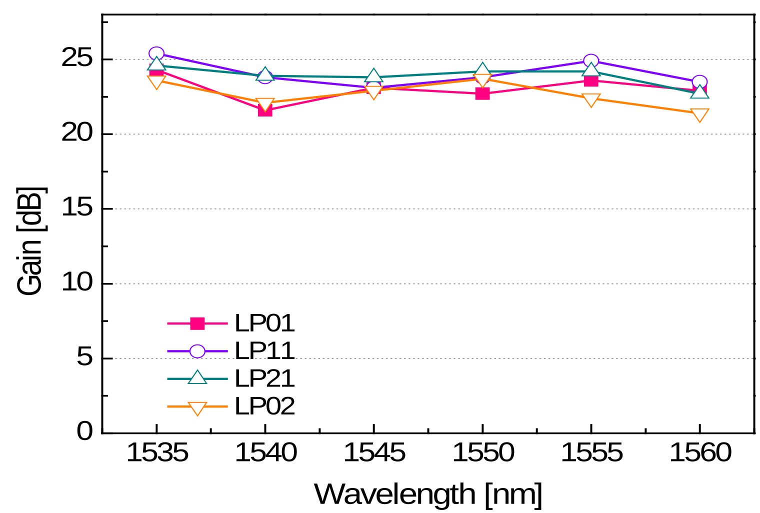
OFC'13 PDP5A.1, R. Ryf et al.

- **Local accumulated DGD not too high**
  - ❖ To minimize width of plateau in impulse respond
    - ➢ *R. Ryf et al., ECOC,12, Tu.1.C.1*
- **Local DGD not too low**
  - ❖ to suppress intermodal nonlinearities
    - ➢ *R.-J. Essiambre et al., ECOC,12, Tu.1.C.4*

Gain Equalised 6-Mode EDFA

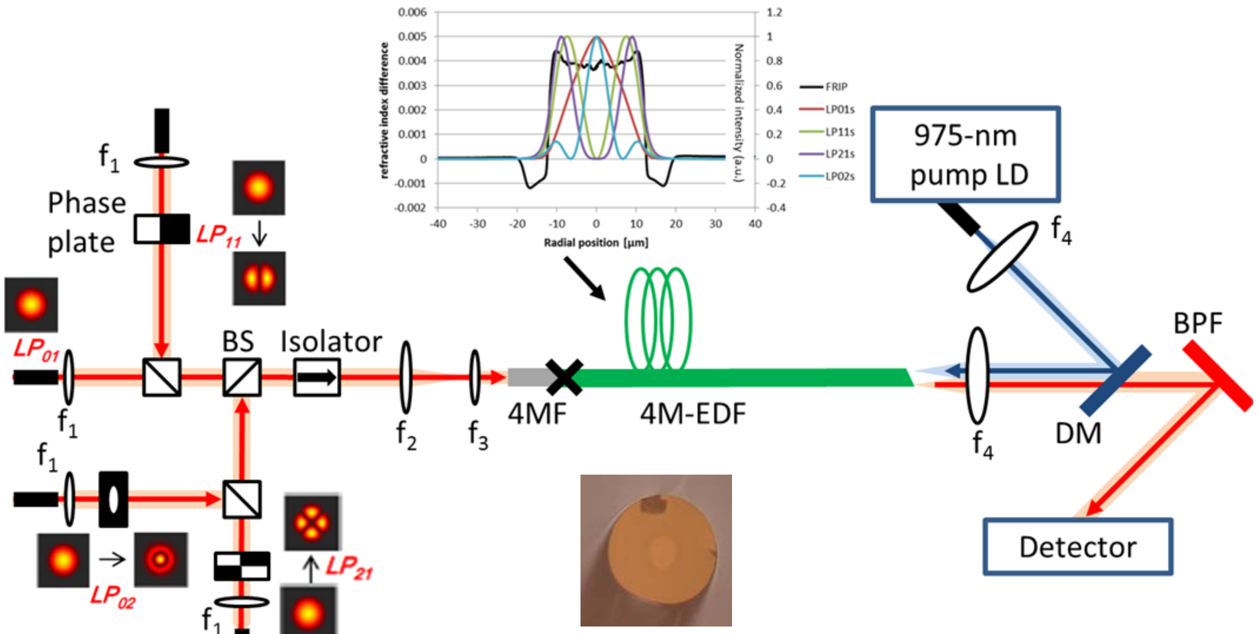


- Ring-doped fiber
- Bidirectional 980nm pumping
- Pump mode control through phase plate launch
- Gain flatness of <2.5dB across the C-band

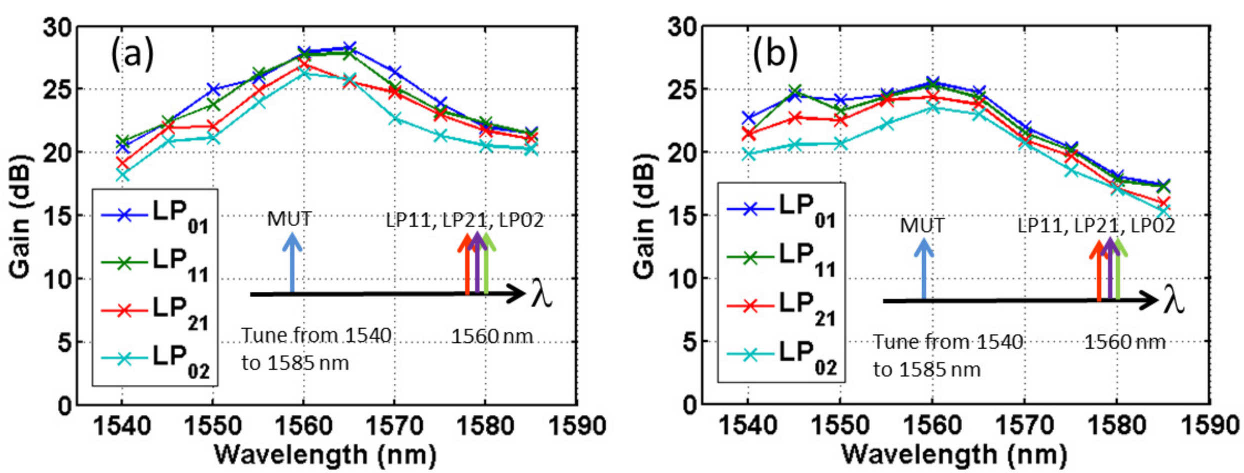


Y. Jung et al. IEEE PTL 2014

Cladding Pumped 6M-EDFA

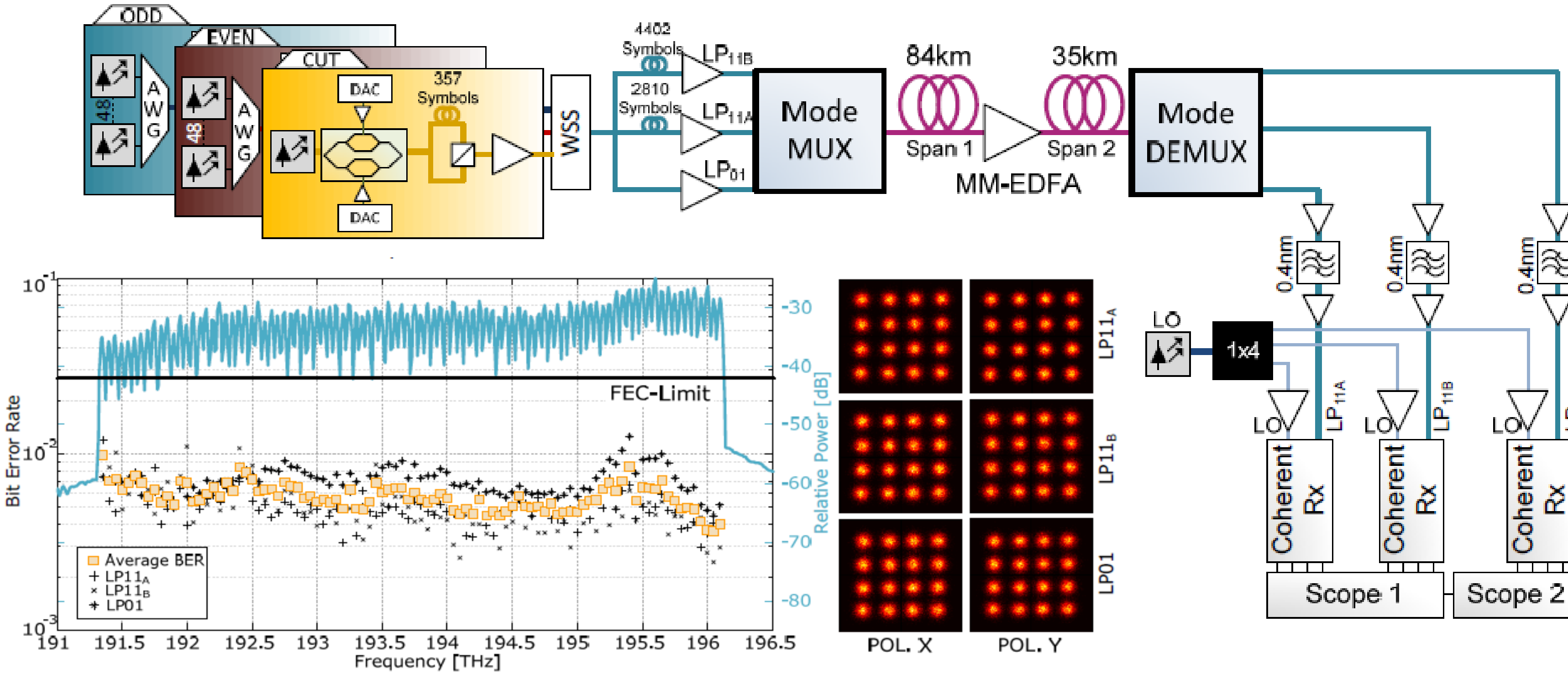


D-Shaped Cladding



E. Lim et al. OFC 2014

73.7 Tbit/s amplified 3MF system

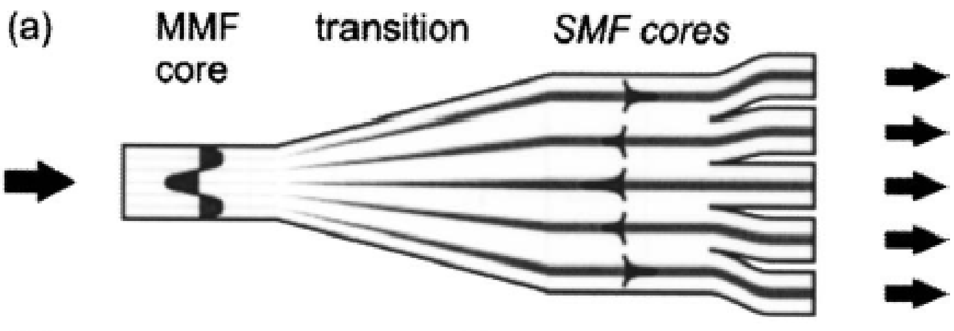


- 96 (WDM) x 3 (SDM) x 256Gbit/s (PDM-16QAM)
- Inline FMF-EDFA, 119km (84km+35 km)
- Low DGD fiber + partial DGD compensation
- Phase plate based Mux-DeMux (~10dB loss)
- TS-based DSP with 20% FEC overhead
- Net transmission rate = 55.7 Tbit/s

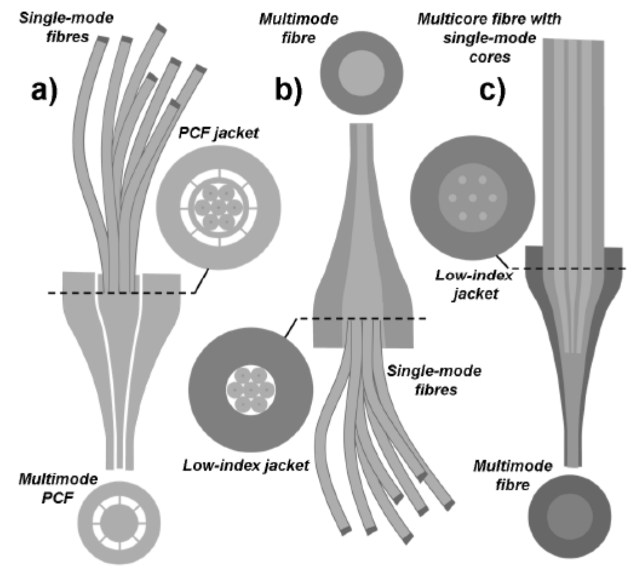
V. Sleiffer et al. ECOC 2012, paper TH3.C.4

Nokia Siemens Networks

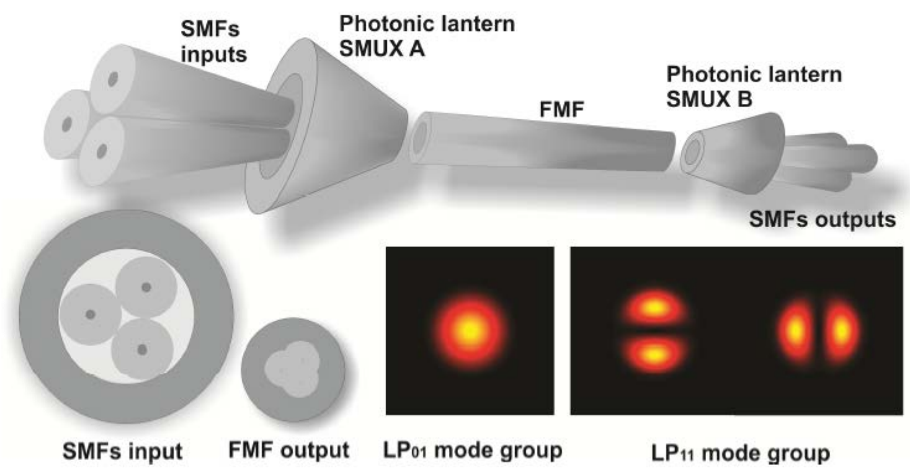
Photonic Lanterns



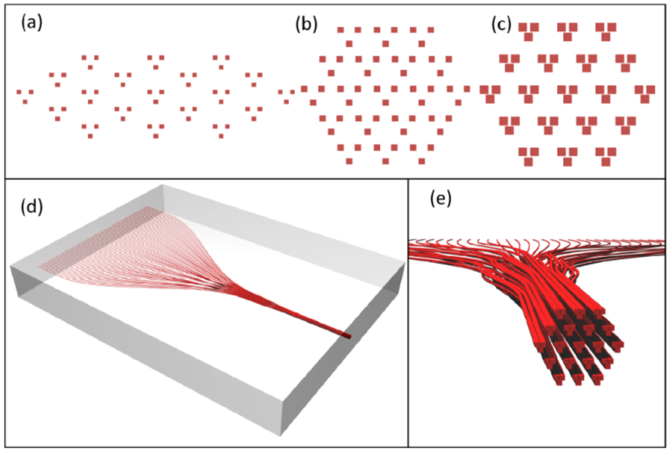
Leon-Saval et al. Opt. Letts. 30, (2005).



Leon-Saval et Opt. Exp, 18, 8435, (2010)

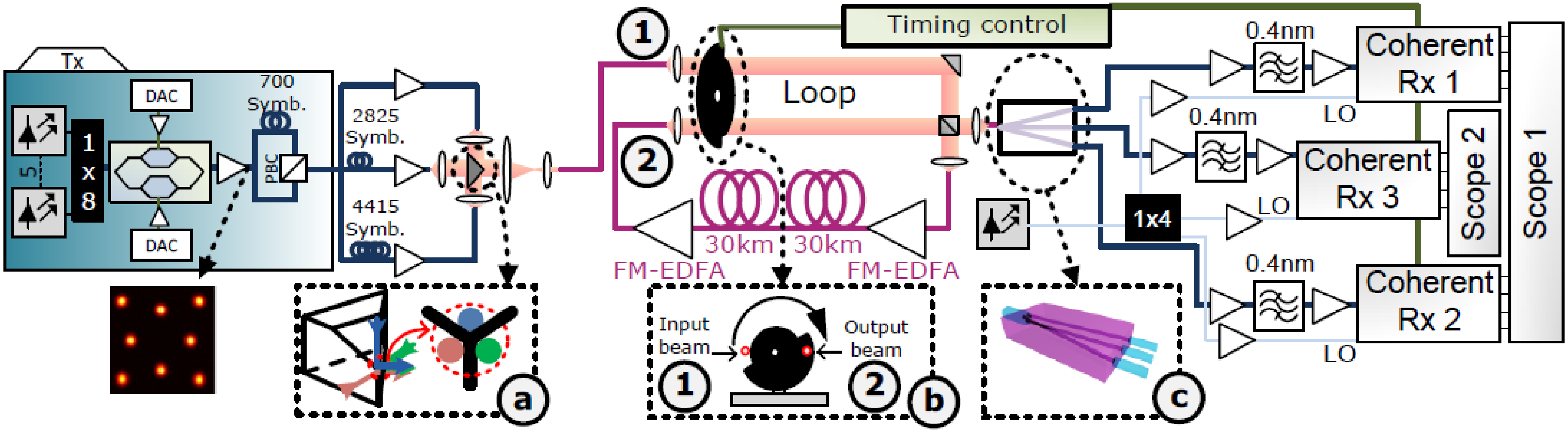


Leon-Saval et al. Opt. Exp., 22, 3 (2014).

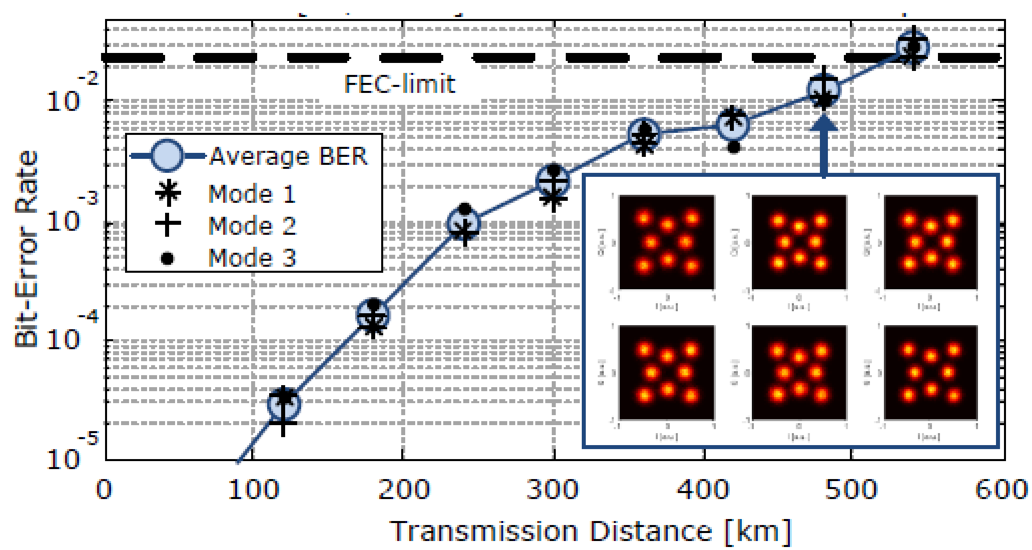


P Mitchell at al. OFC 2014 paper M3K.5

480 km MDM 576-Gb/s 8QAM Transmission



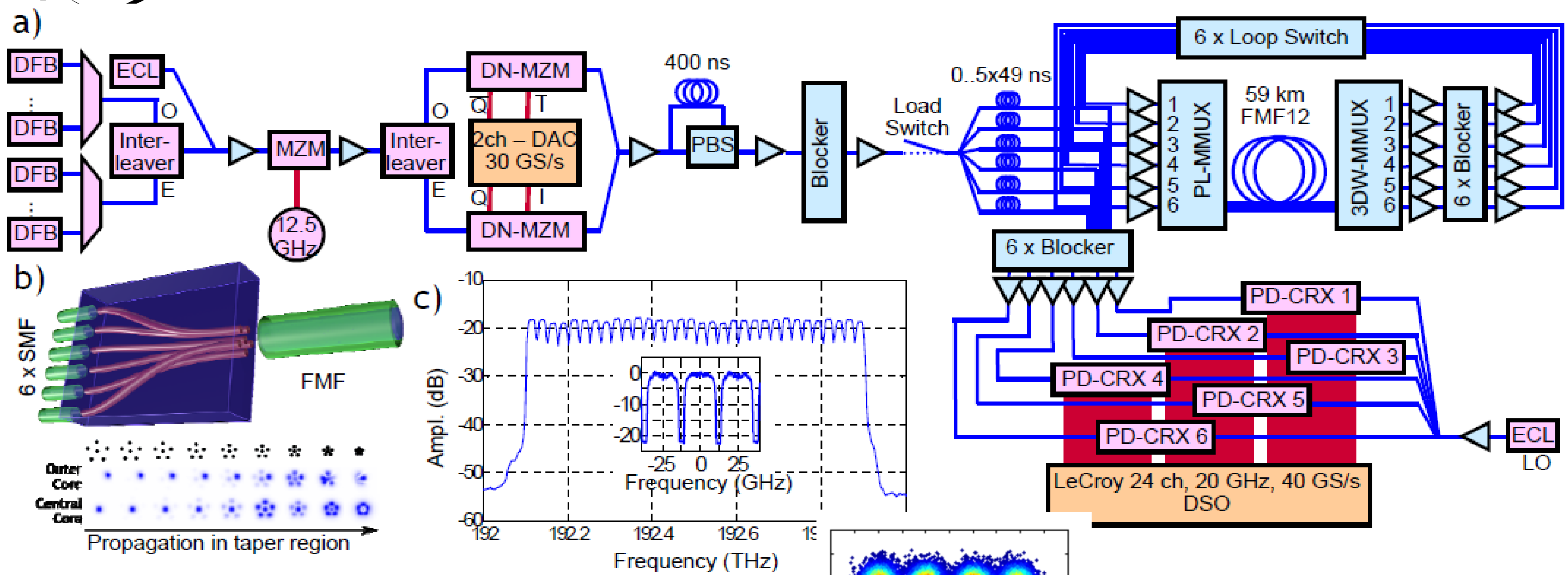
- 192 X3 Modes x 5WDM
- 32 Gbaud PDM-8PSK
- Low DGD fiber
- Ring doped EDFA
- ~480 km Error free with FEC
- >1000km with QPSK

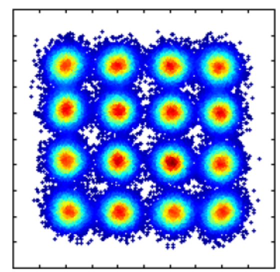


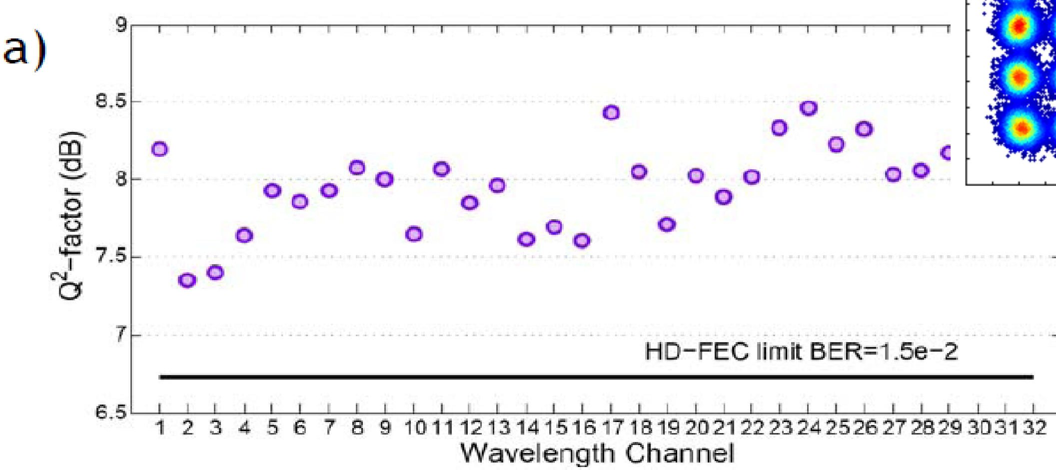
Coriant TU/e

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

6-Mode Transmission over 177km



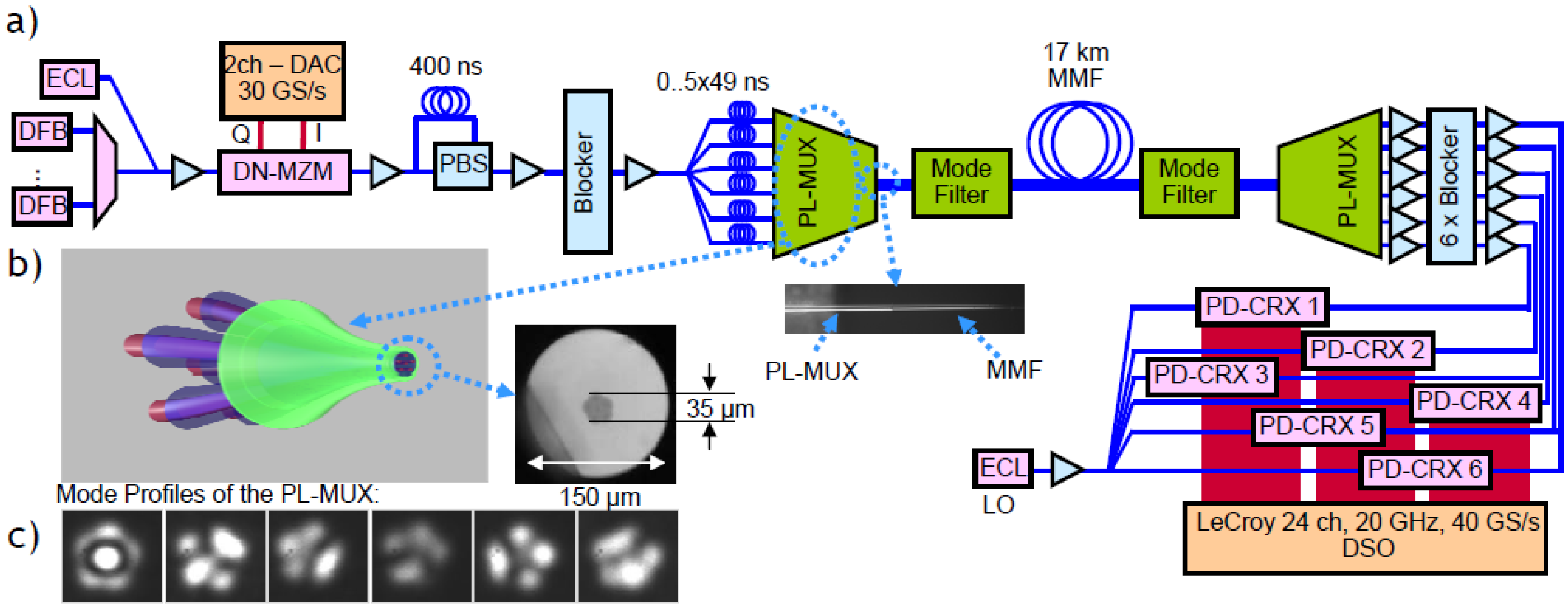




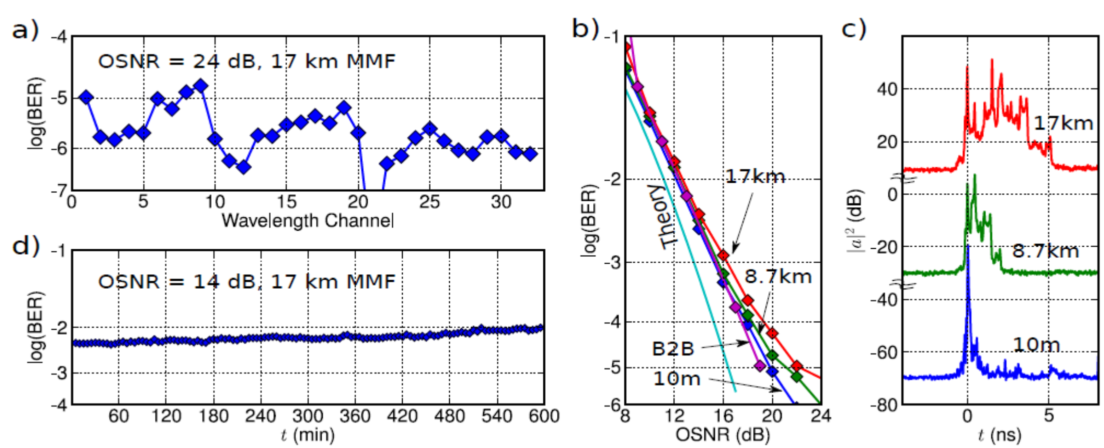
- 20 Gbaud 16-QAM
- 24.6 Tbit/s over 800 GHz
- Photonic Lantern MUX
- DGD compensated span
- Record SE=32 bit/s/Hz
- >750 km transmission now achieved

R. Rfy et al., OFC PDP5A.1 (2013)

FM Transmission in GI-MMF



- Lowest 3 order mode groups of GI-MMF excited via PL
- Transmission over 17km GI-MMF demonstrated.
- SE=7 bit/s/Hz
- Total capacity = 23 Tbit/s

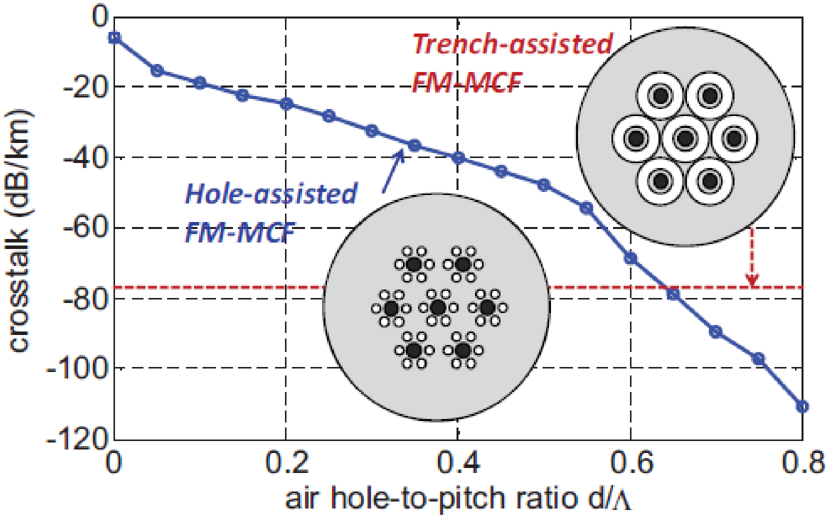


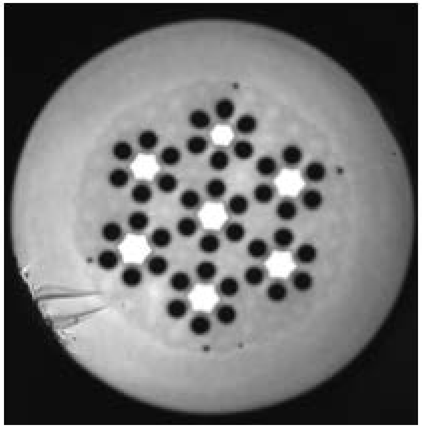
R. Ryf et al. OFC 2014, PD Th5B.1

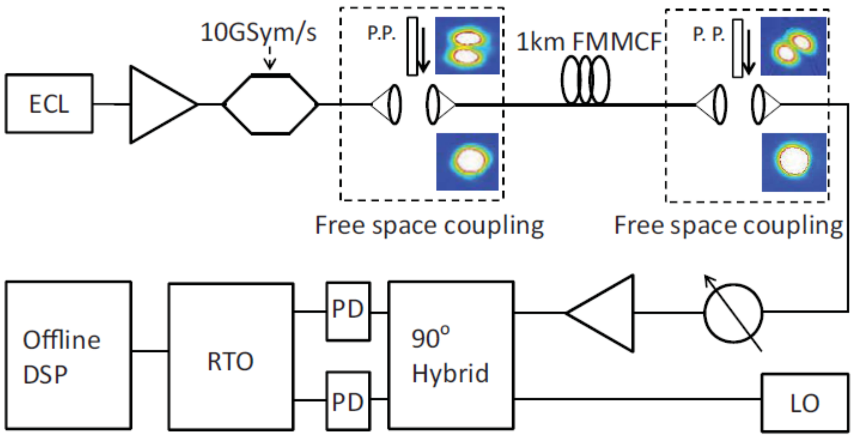
Ultimate Channel Scalability

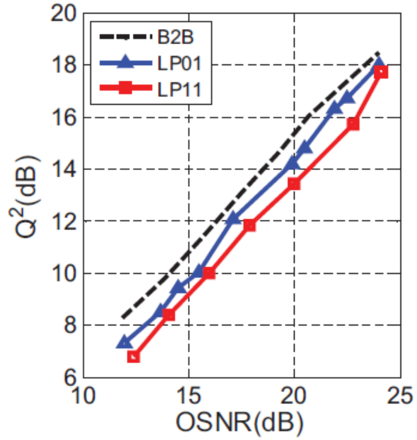
- In MCF limited by fibre strength considerations and requirement for low cross-talk 12-19 cores maximum.
- In FMF12 channels (including polarisations) so far demonstrated. Tractability of DSP and management of MDG likely to be limiting.
- Apply MIMO to higher core-count MCF?
- Combine MCF + FMF to cascade scaling benefits?

Combining MC and FMF approaches



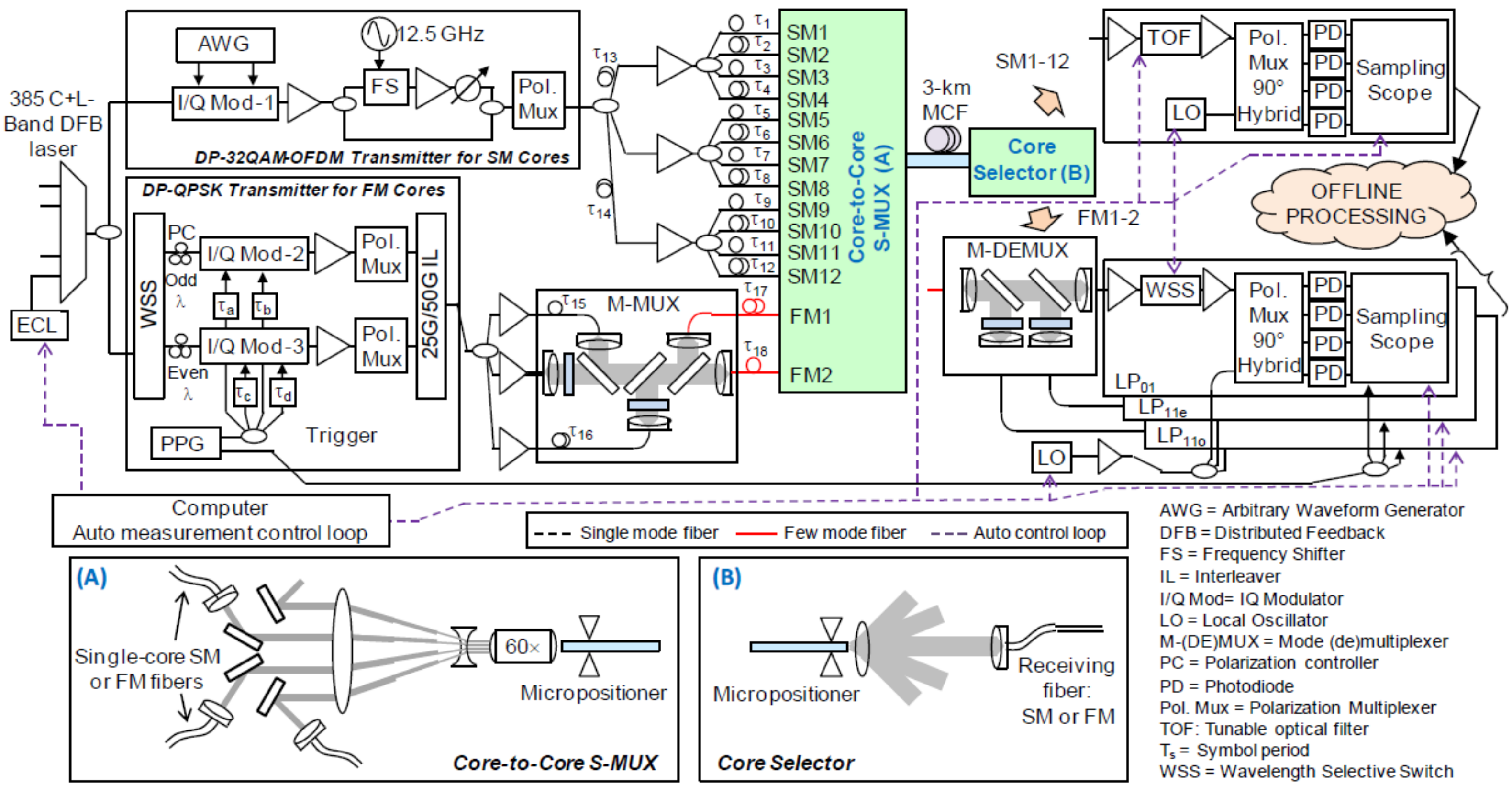






C. Xia et al., IEEE PTL 24 (21), 2012.

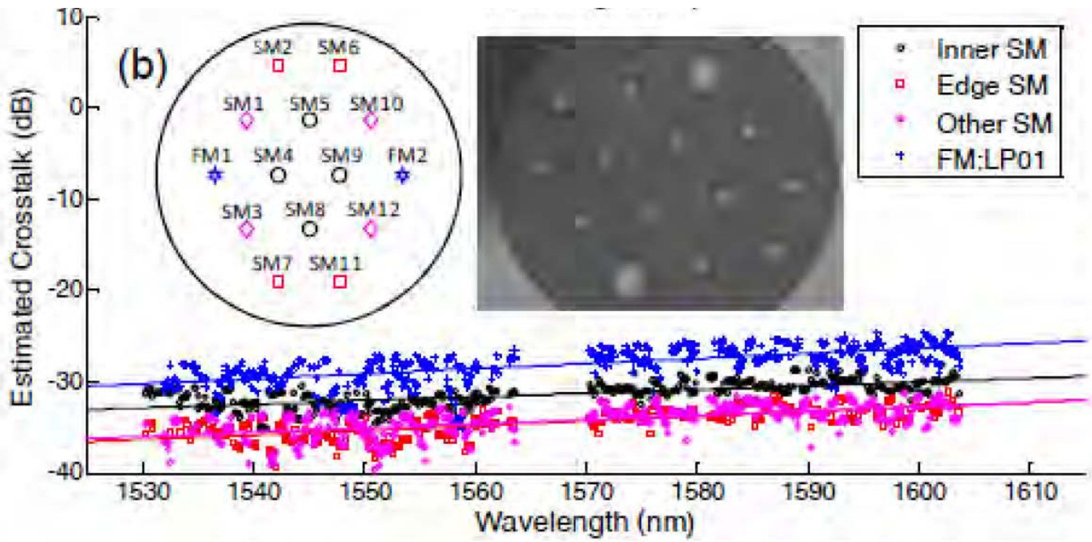
1.05 Pbit/s Transmission in MM/MCF

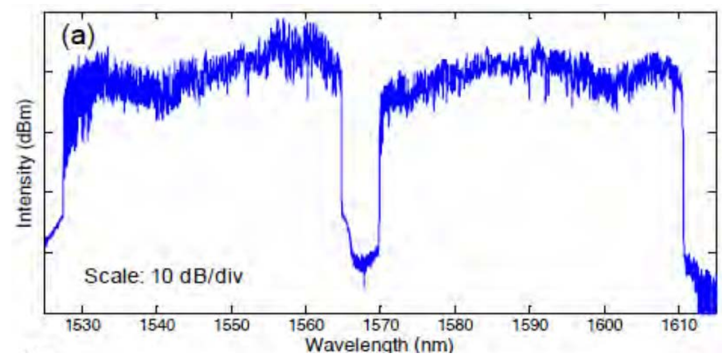


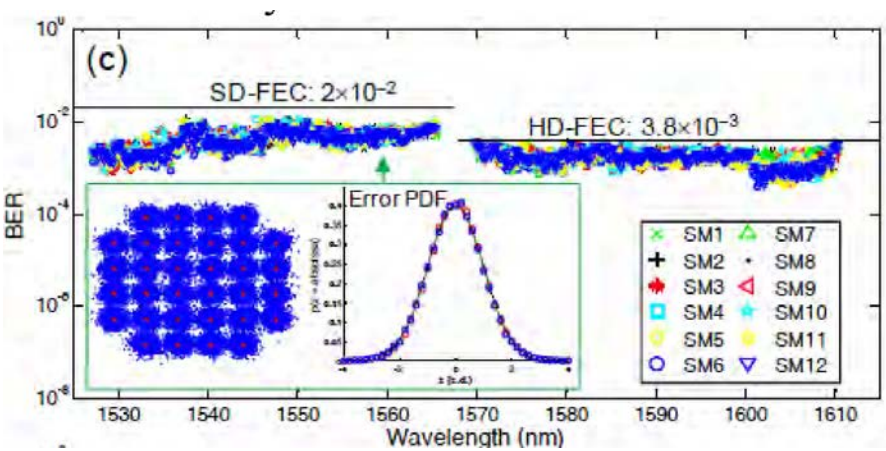
- 12 SM cores + 2 TMF cores (LP01, LP11)
- C+L band=385 Channels
- PDM-32QAM-OFDM

D. Qian, FIO 2012, PDP paper, FW6C.3

1.05 Pbit/s transmission in MCF/MMF



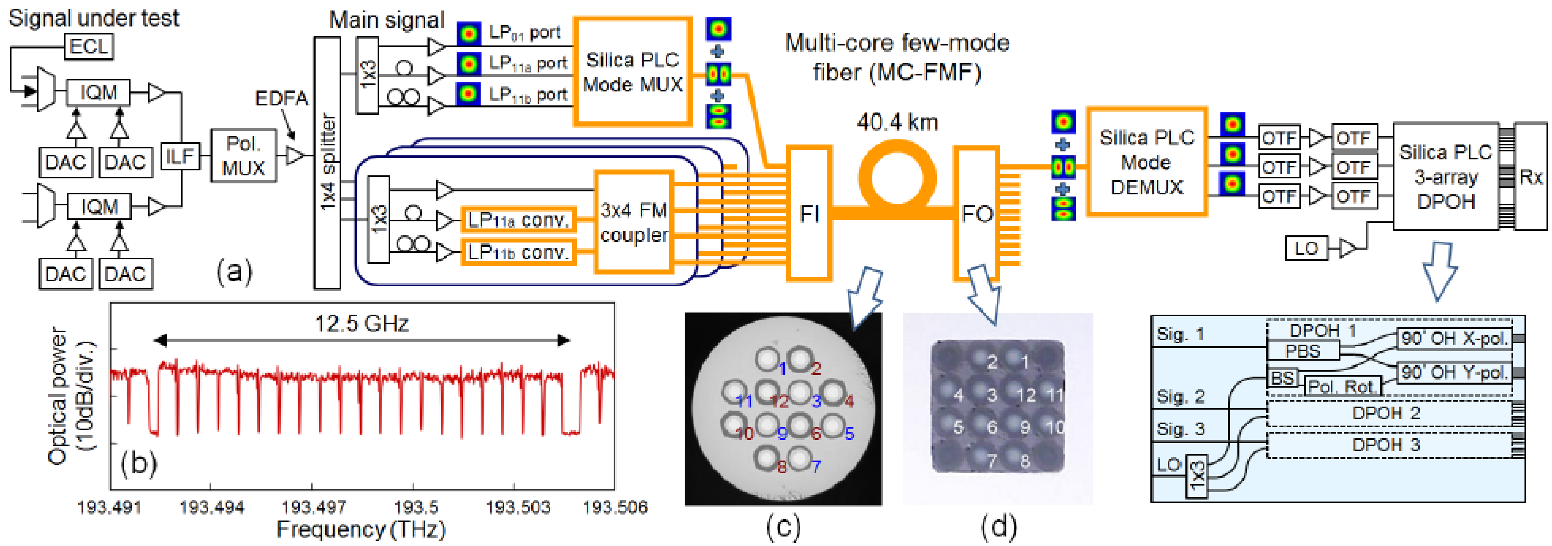


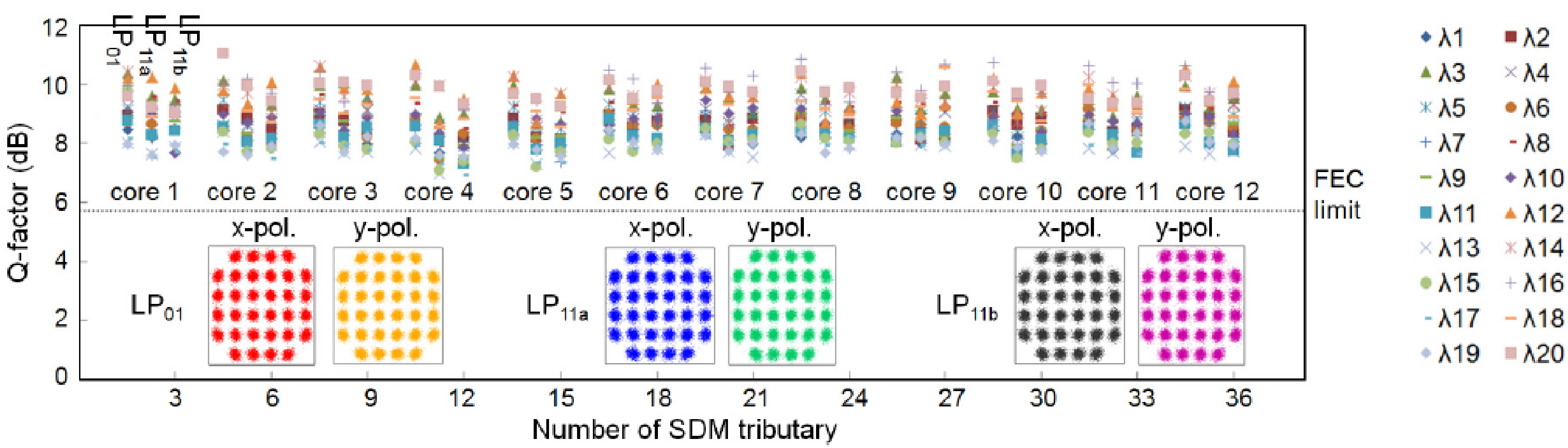


- 12 SM + 2 TMF cores
- PDM 32-QAM
- 12 x 74.77 Tbit/s + 2 x 75.44 Tbit/s
- Total Capacity = 1.05 Pbit/s
- Fibre length = 3km
- SE=109 bit/s/Hz

D. Qian, FIO 2012, PDP paper, FW6C.3

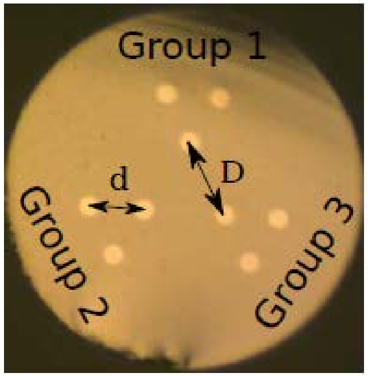
57 Channel 3MF/19MCF

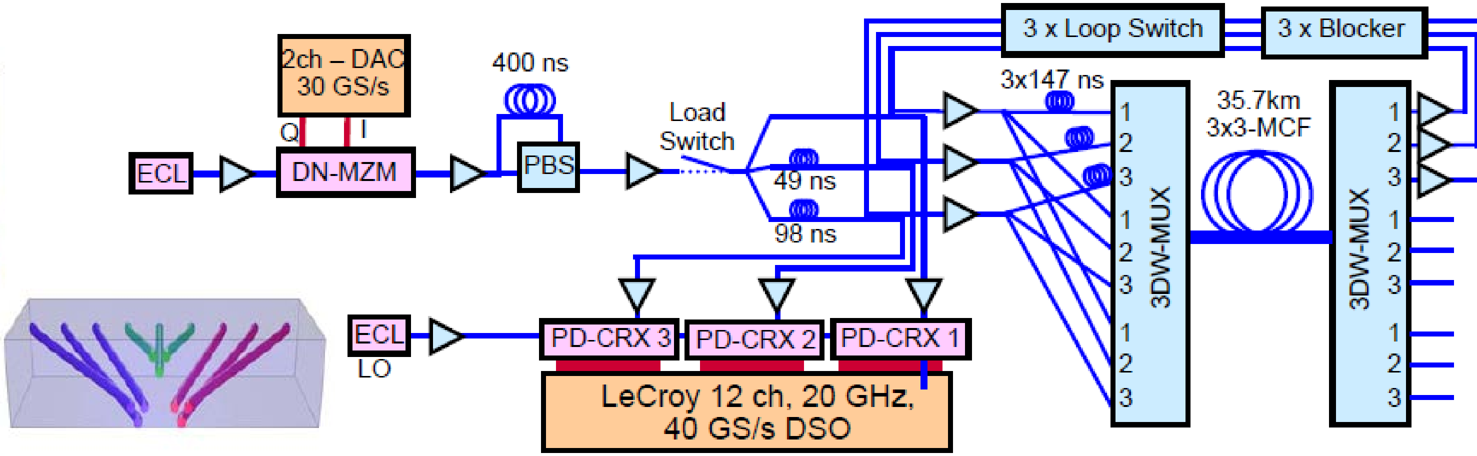


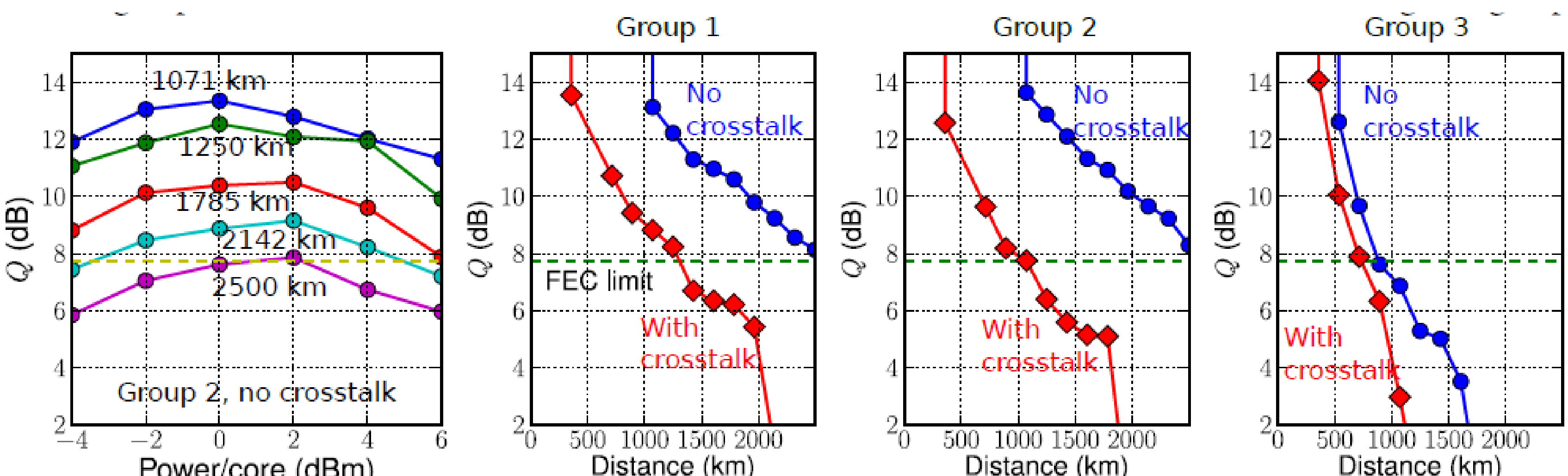


T. Mizuno et al. OFC 2014, PD Th5B.2.

Multi Channel CC Fiber







R. Ryf et al. OFC 2014, PD Tu2J.4.

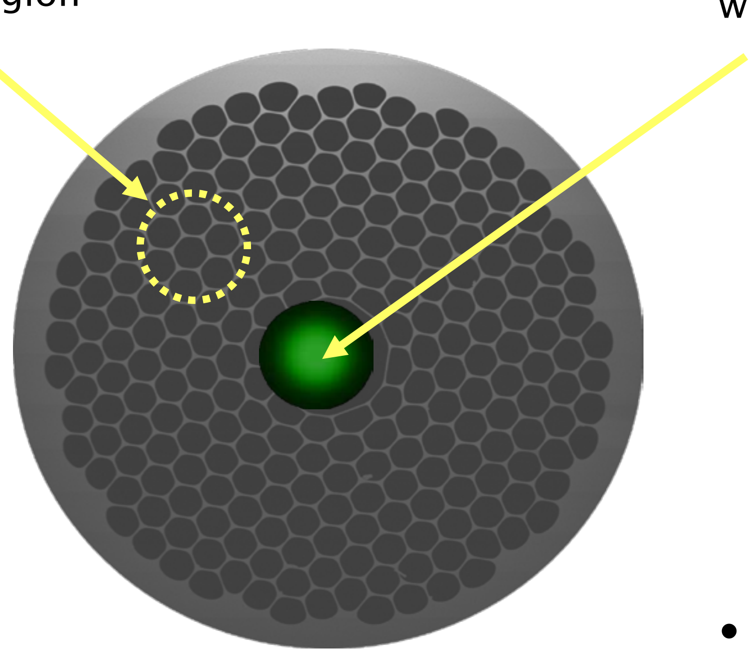
Even More Radical Solutions: Hollow Core PBGFs

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

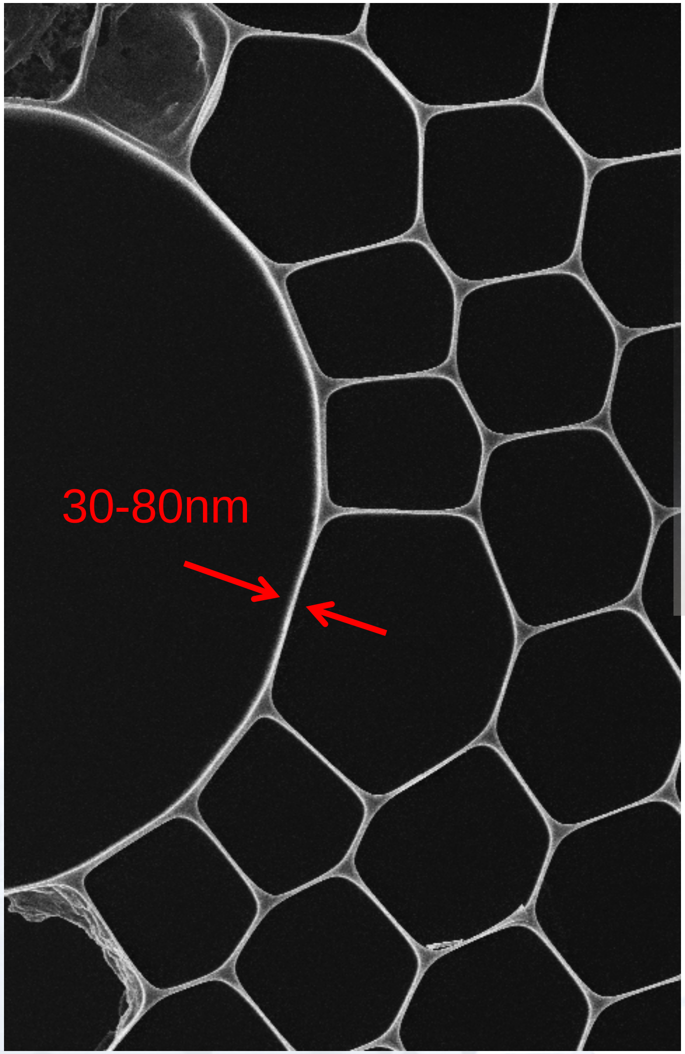


Key Attractions

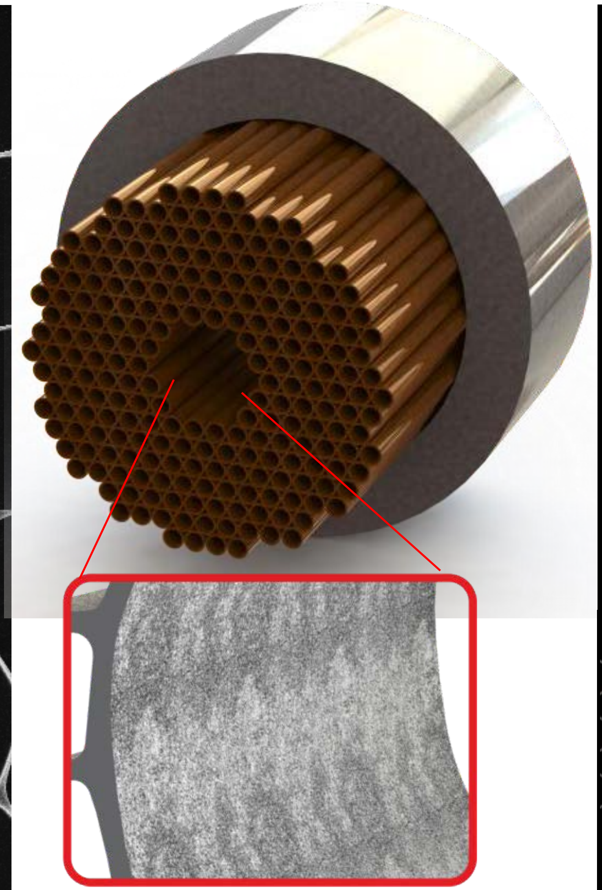
- Ultralow nonlinearity
- Potential for ultralow loss
- Minimum latency

Some of the Challenges…

Extreme aspect ratios

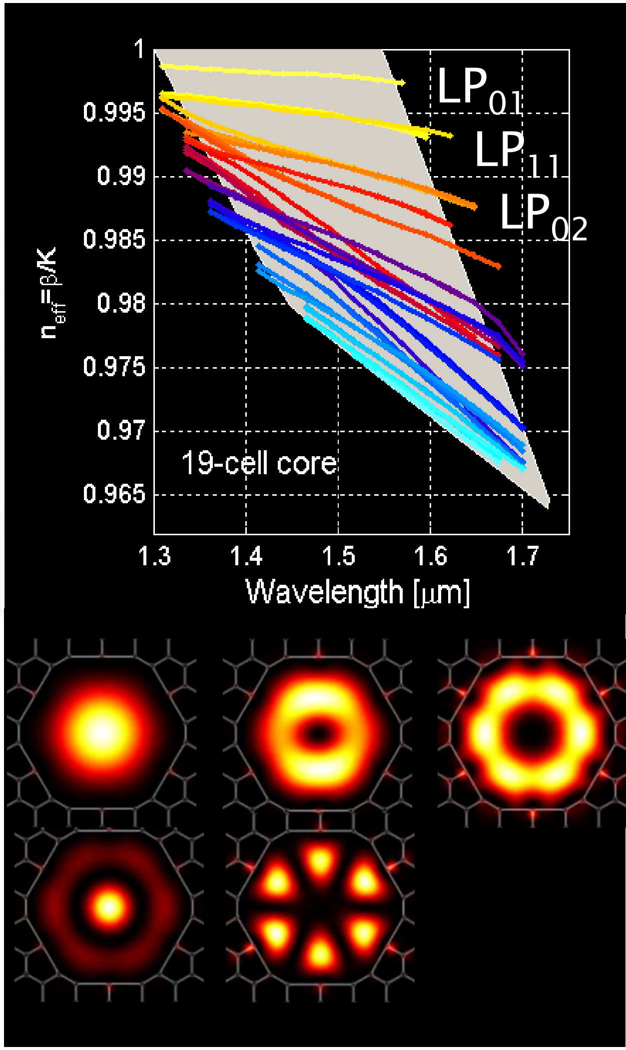


Ultra-smooth surfaces

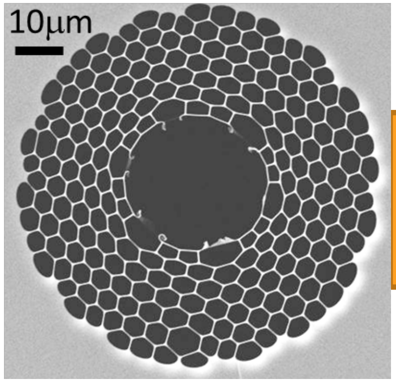


rms roughness
~2Å

Modal control

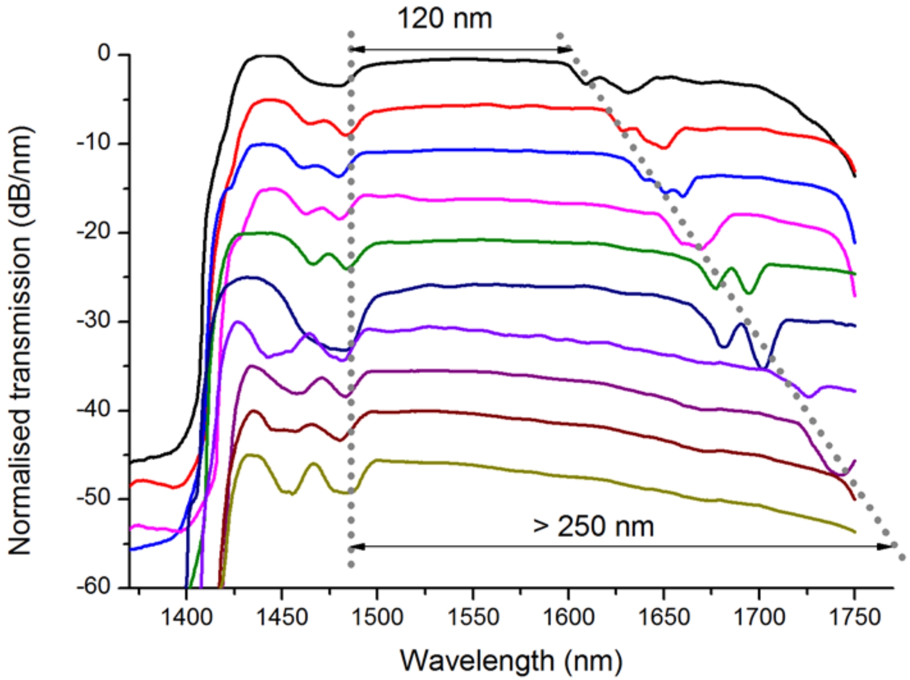


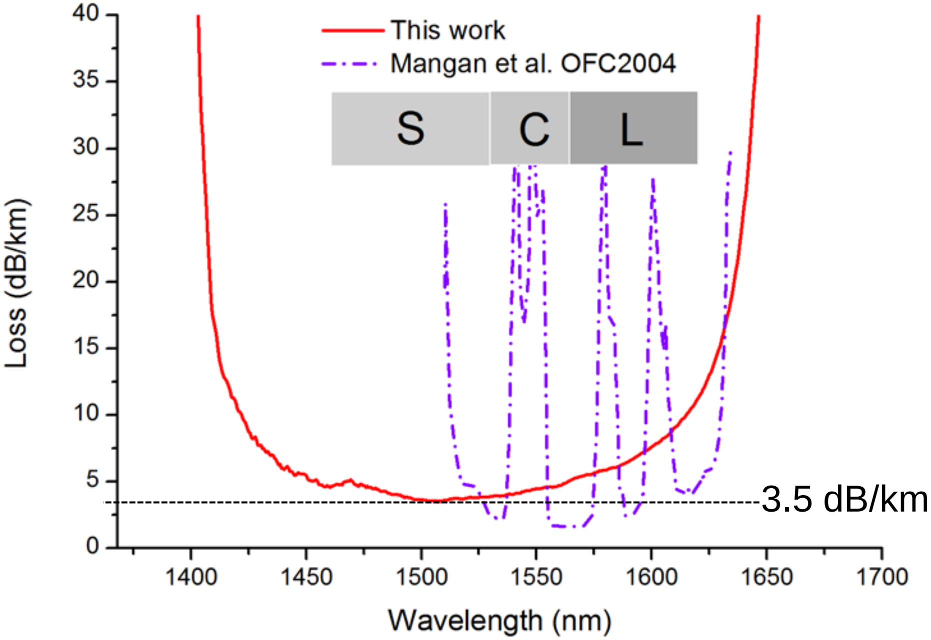
SM control in large core PBGFs



- 19 cell core
- Thin core surround
- Λ ~ 4.4 µm
- d/Λ~ 0.976
- Core diameter: 26 µm

First wide bandwidth 19cell HC-PBGF

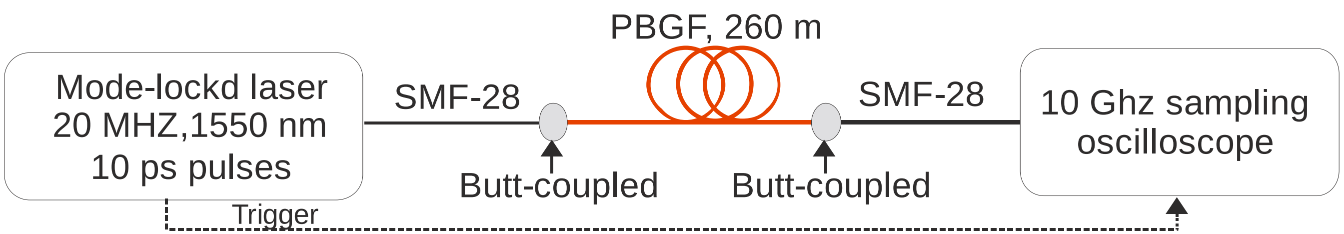


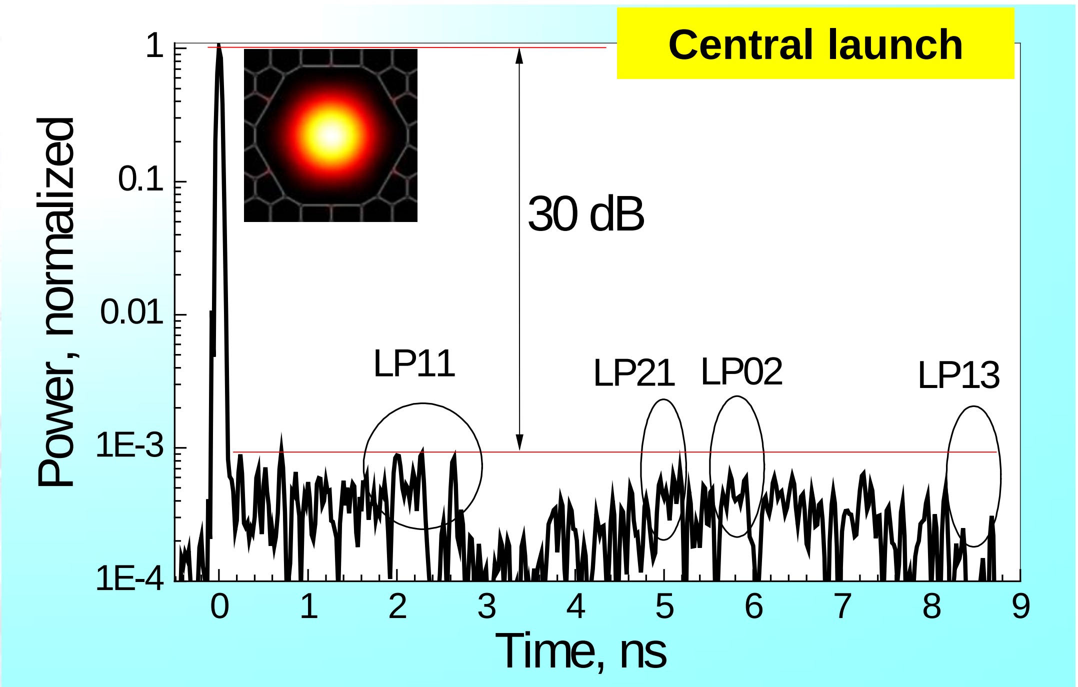


F. Poletti et al. Nature Photonics 7, 279–284 (2013)

Single-mode operation

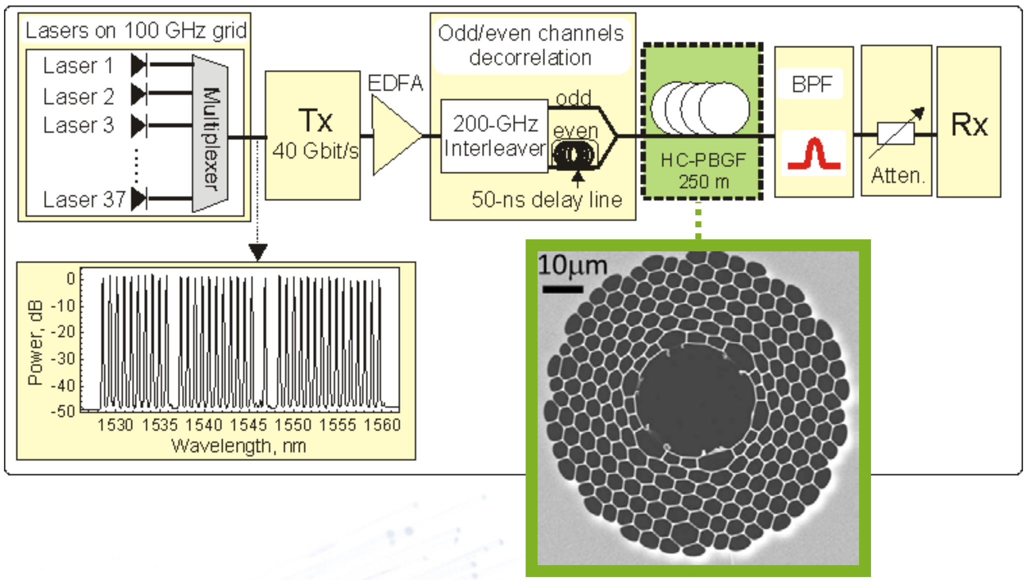
- The fibre can be made effectively single-mode through:
  - Selective launch
  - Spatial filtering at the output

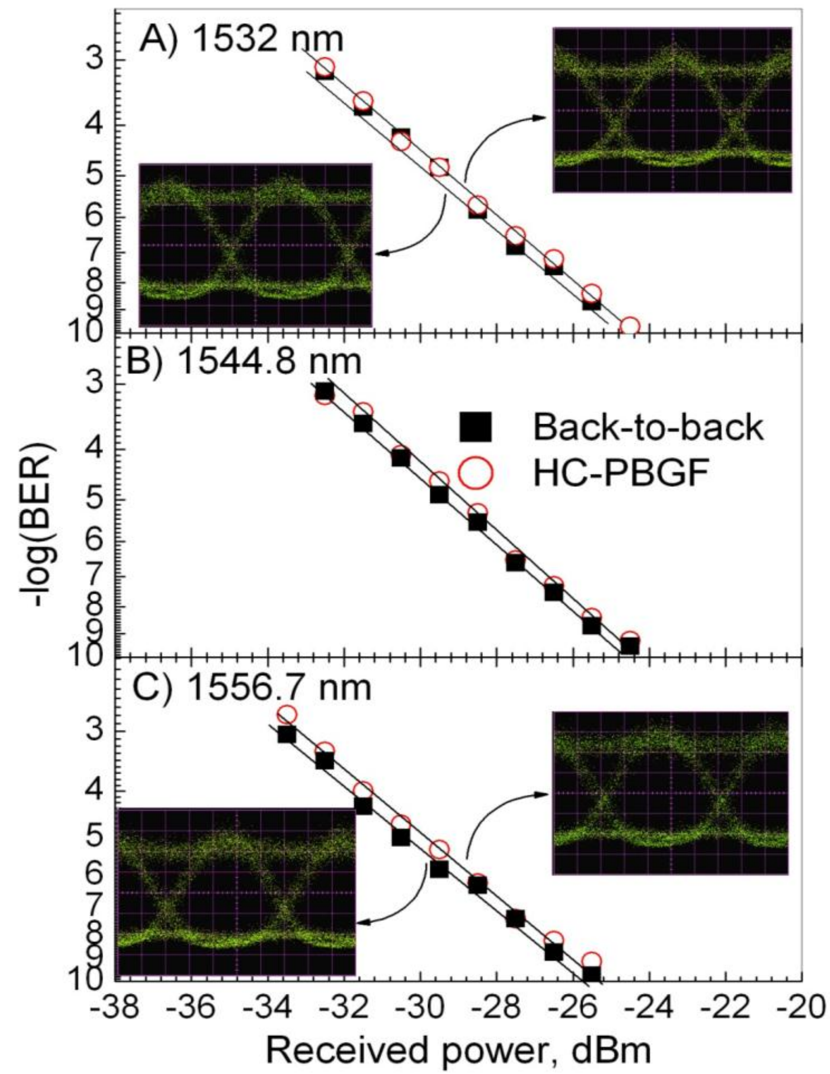




First DWDM Data Transmission

Transmission of 37 x 40 Gbit/s (1.45 Tbit/s) OOK data through 260 m of wide bandwidth PBGF (single polarisation)





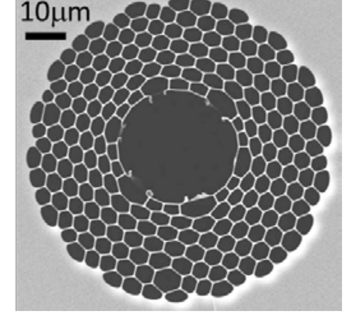
BER penalty (all channels):

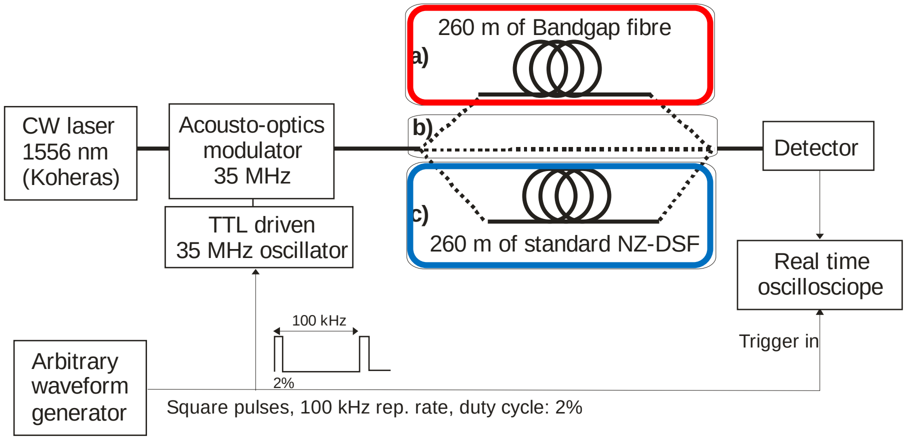
- To Back-to-back: < 1dB.
- Among channels: <1.5 dB.

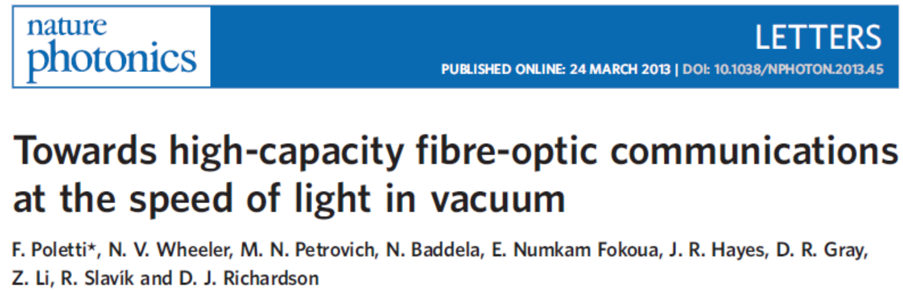
(First DWDM transmission in a PBGF)

Slavik et al., ECOC 2012,Mo.2.F.2.

Low Latency transmission





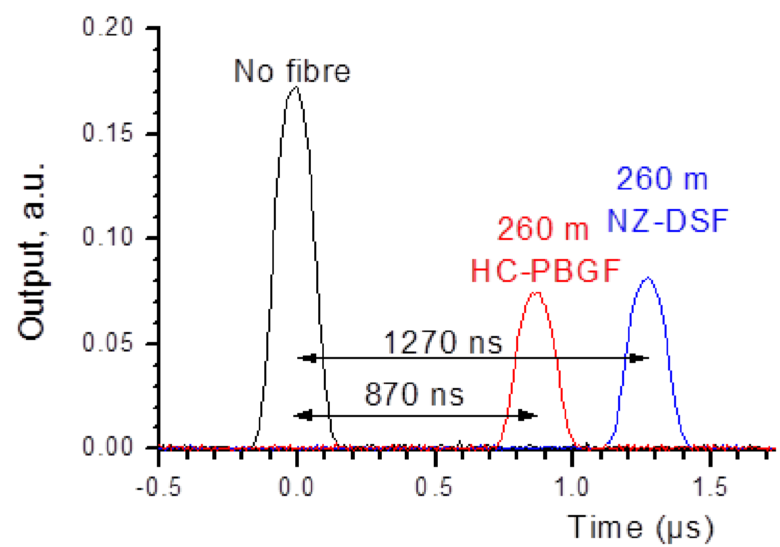


nature photonics
LETTERS
PUBLISHED ONLINE: 24 MARCH 2013 | DOI: 10.1038/NPHOTON.2013.45

Towards high-capacity fibre-optic communications at the speed of light in vacuum

F. Poletti*, N. V. Wheeler, M. N. Petrovich, N. Baddela, E. Numkam Fokoua, J. R. Hayes, D. R. Gray, Z. Li, R. Slavík and D. J. Richardson

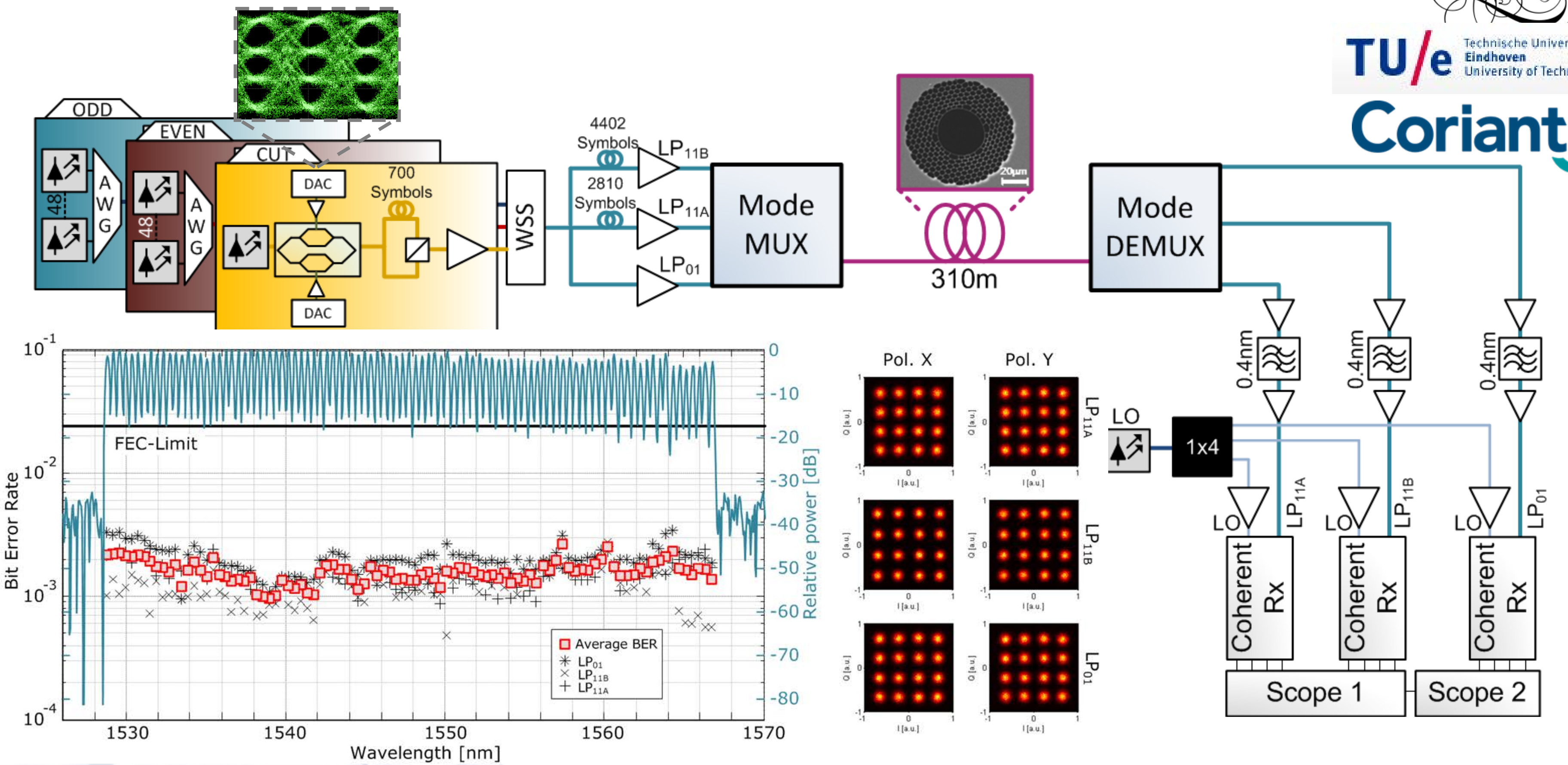
- Data transmission at 99.7% the speed of light in vacuum
- 1.46x faster propagation than in SMF
- 1.54 μs/km lower latency
- Promising for low-latency applications!!!



(First Low Latency transmission in a PBGF)

MODE GAP

MDM Transmission in a PBGF

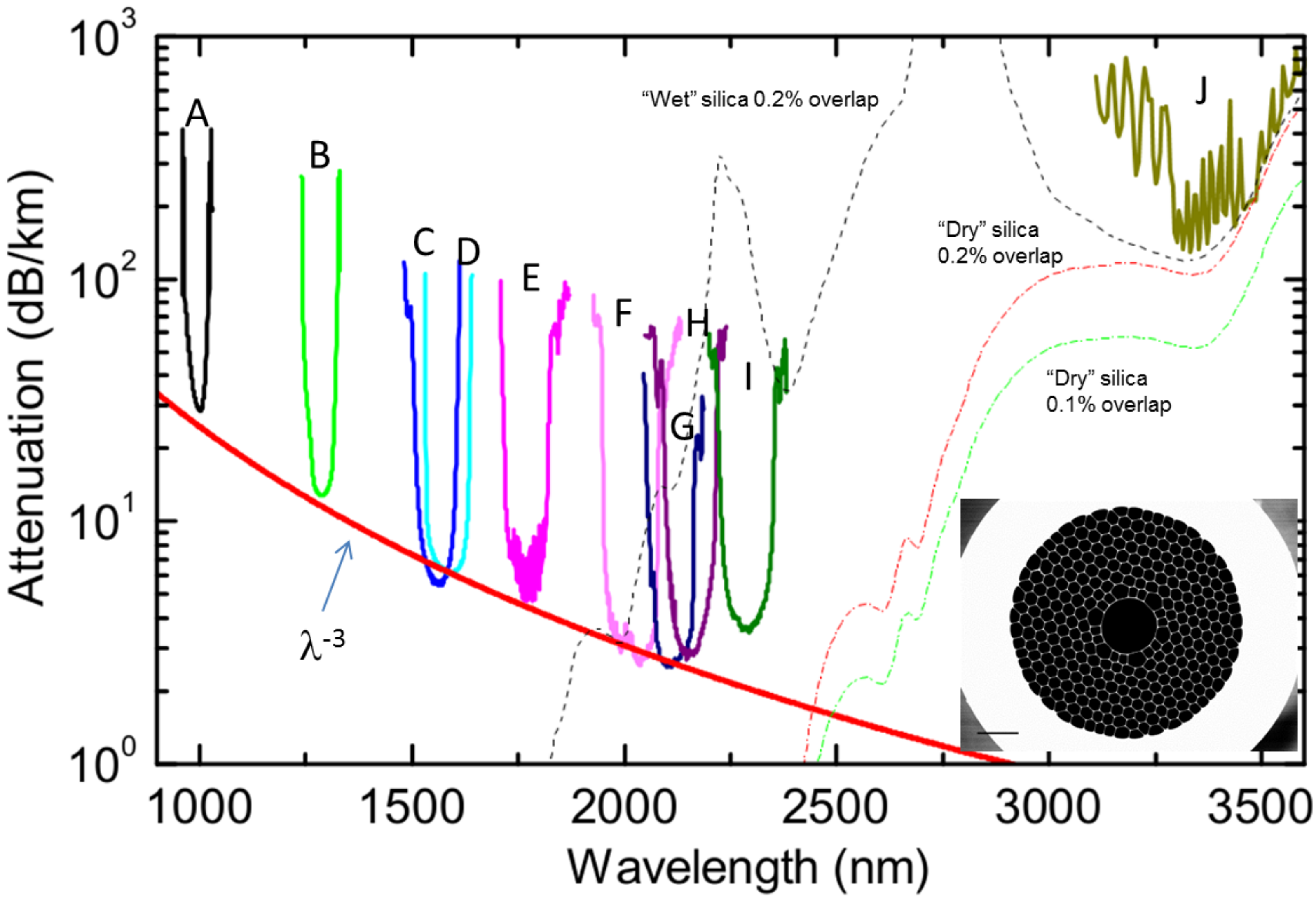


Tested the feasibility of large capacity transmission employing MDM:

- 96 WDM channels in extended C-band over LP_{01}, LP_{11a} and LP_{11b}
- Modulated with 256Gb/s **DP** 16QAM
- Total data capacity of 57.6 Tb/s (Gross rate 73.3 Tb/s)
- Well below FEC-limit at 2.4x10-2

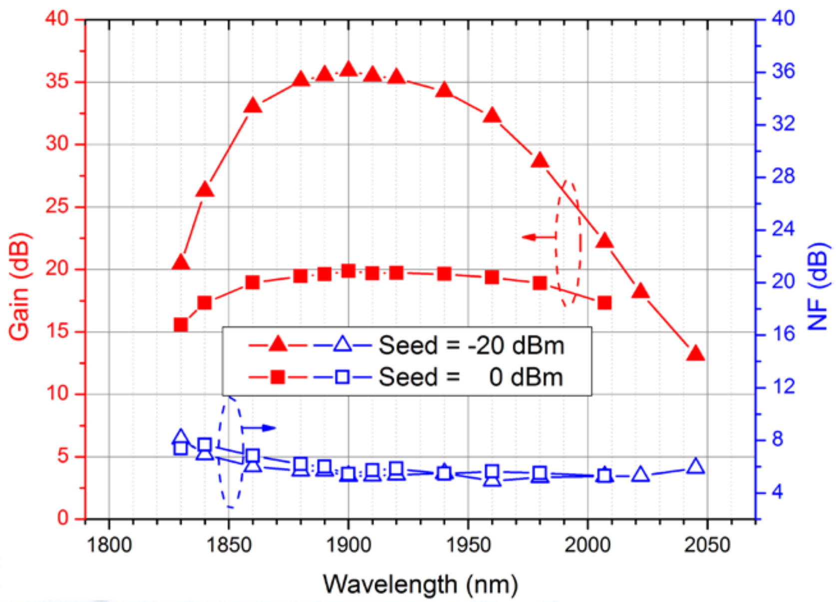
Jung et al., OFC 2013, PDP5A.3

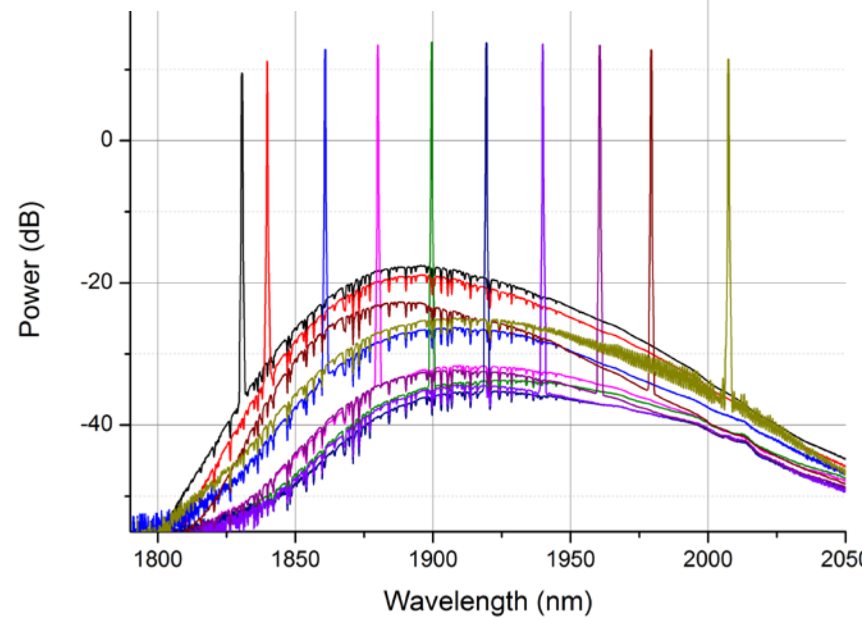
Confirming Origin of Loss in PBGF



Y Chen et al., Proc. OFC /NFOEC 2014, paper

The TDFA for Broadband Gain at 2µm

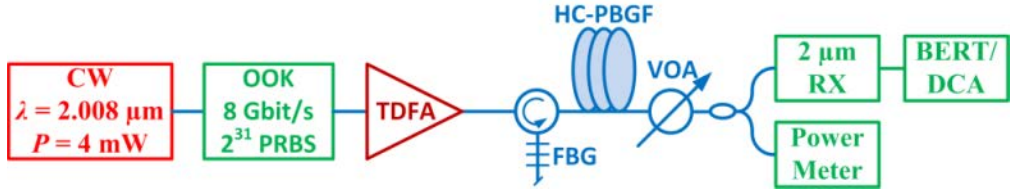


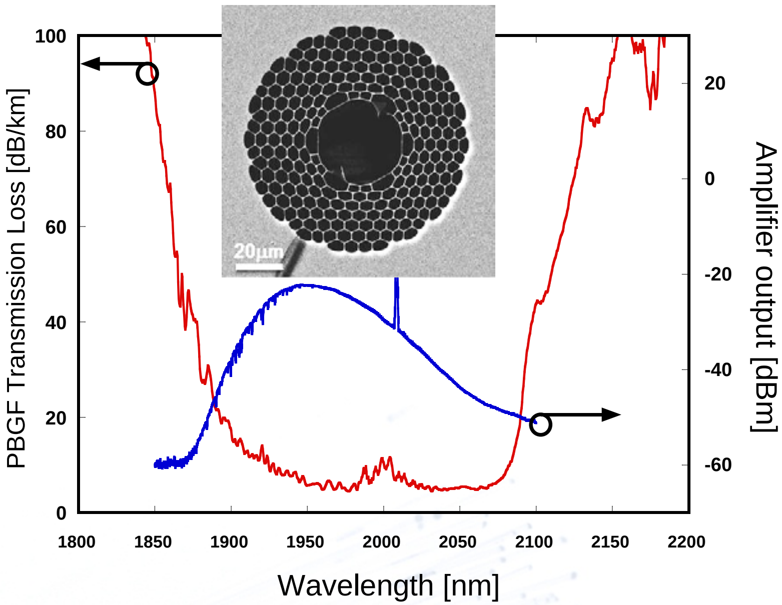


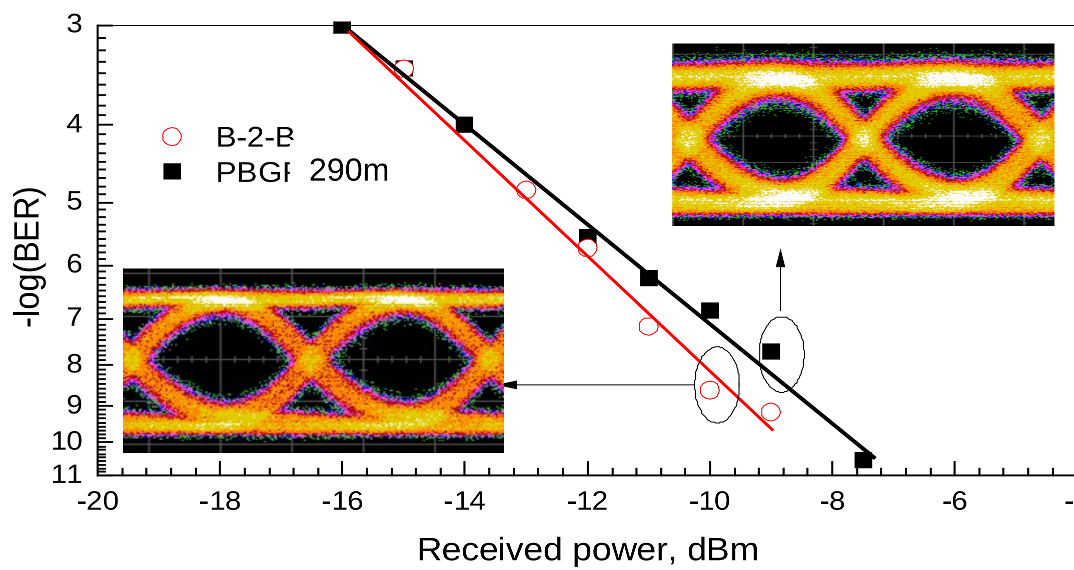
- 1560nm diode pumping
- More than 35dB small signal gain at the peak operating wavelength of 1900nm
- 100mW saturated output power, >40% conversion efficiency
- <5dB external
- >300nm BW now demonstrated (1730nm-2050nm)

Z. Li et al. Optics Express 2013

Amplified 2µm transmission in a PBGF





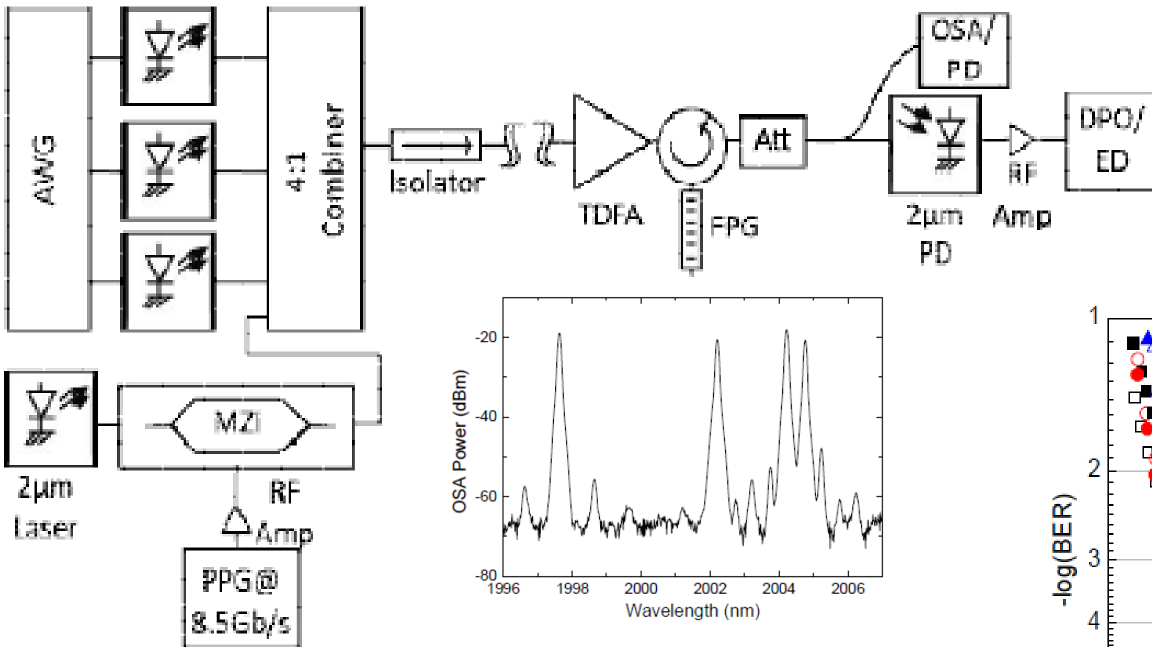


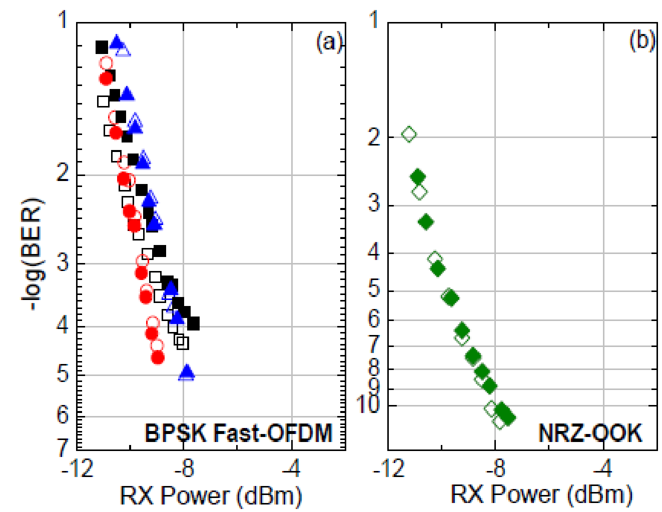
- Negligible penalty at BER 10^{-3}, ~1dB at 10^{-9}
- No BER floor observed
- Similar performances to earlier WDM experiment
- All components necessary for 2µm transmission developed in MG

(First Demonstration of 2µm transmission in a PBGF)

Petrovich et al., ECOC 2012, PDP Th3A.5

WDM Transmission at 2µm

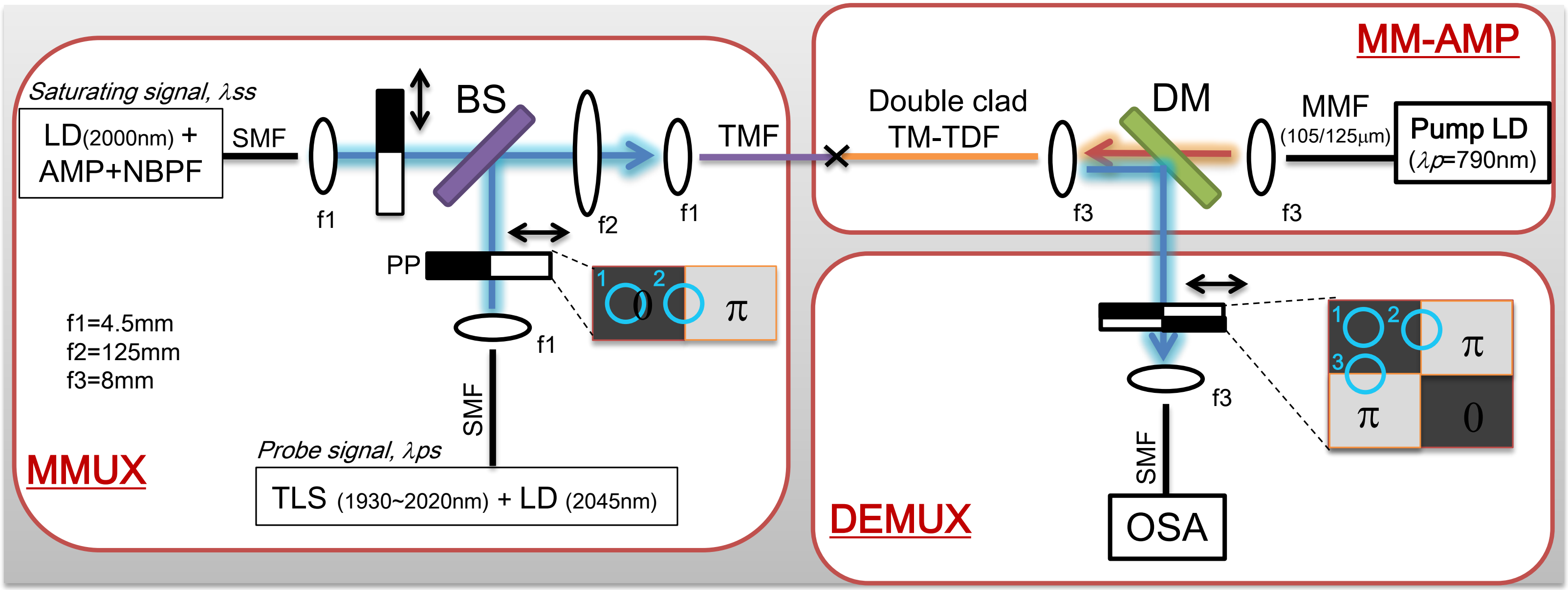


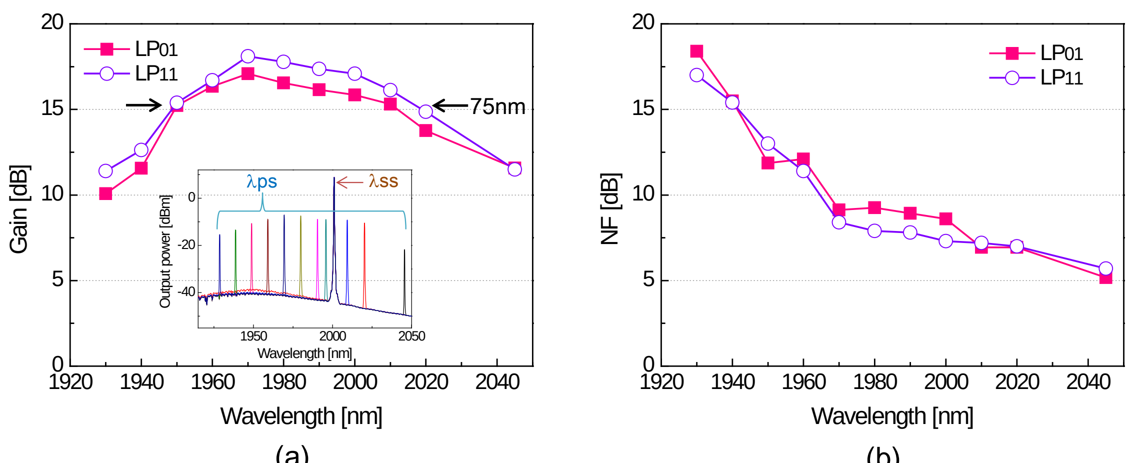


(First WDM transmission at 2µm)

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

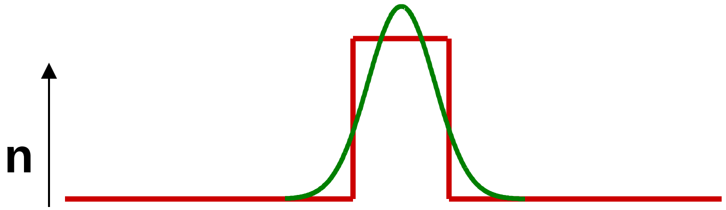
Cladding pumped 3-Mode TDFA





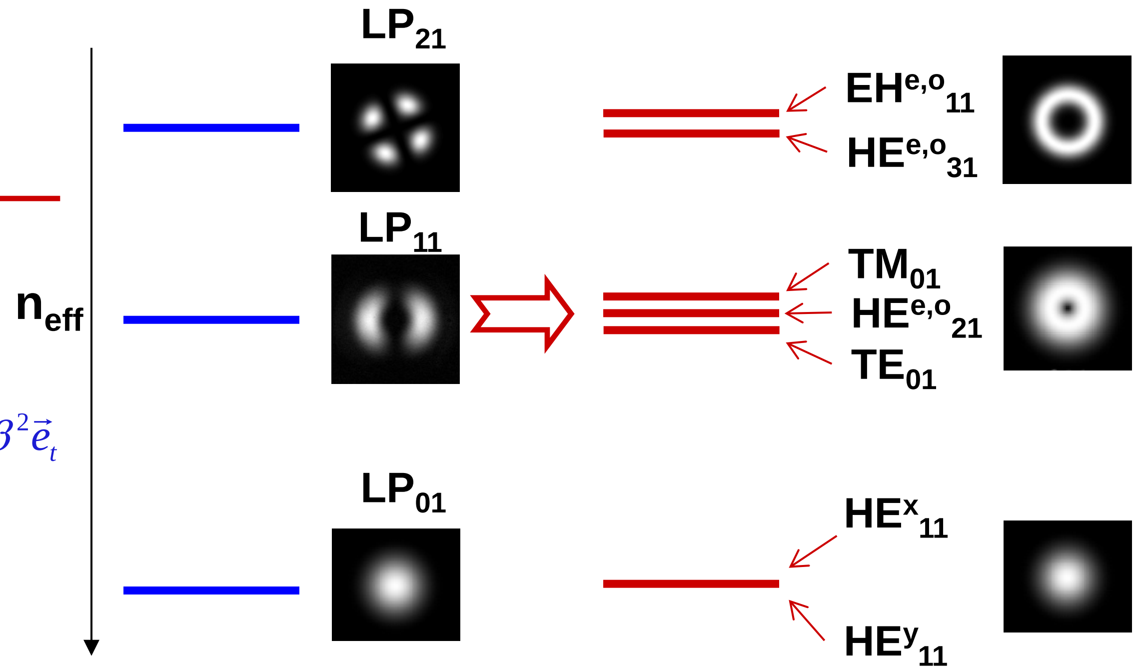
Y. Jung et al. Optics Express (2014).

Fiber modes: vector and scalar



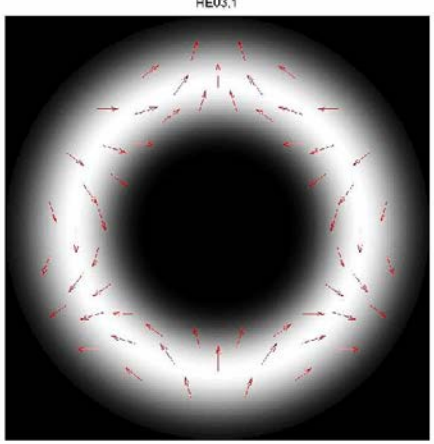
$$\left\{\nabla_t^2 + n^2k^2\right\}\vec{e}_t = \tilde{\beta}^2\,\vec{e}_t$$

$$\left\{\nabla_t^2 + n^2k^2\right\}\vec{e}_t + \nabla_T\left\{\vec{e}_t \cdot \nabla_T[\ln(n^2)]\right\} = \beta^2\vec{e}_t$$



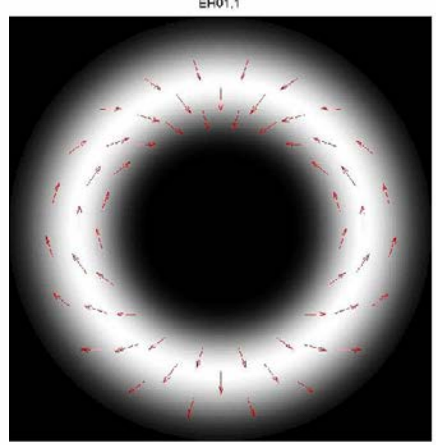
Same handedness of spin and twist

HE03,1



Opposite handedness of spin and twist

EH01,1



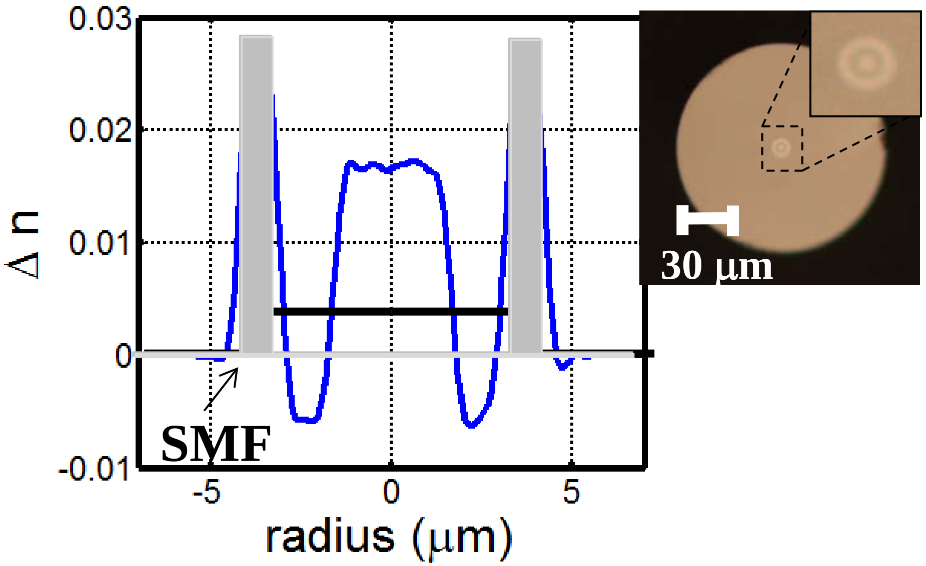
$$\mathrm{OAM}^{\pm}_{\pm\ell,m} = \mathrm{HE}^{\mathrm{even}}_{\ell+1,m} \pm j\,\mathrm{HE}^{\mathrm{odd}}_{\ell+1,m}$$

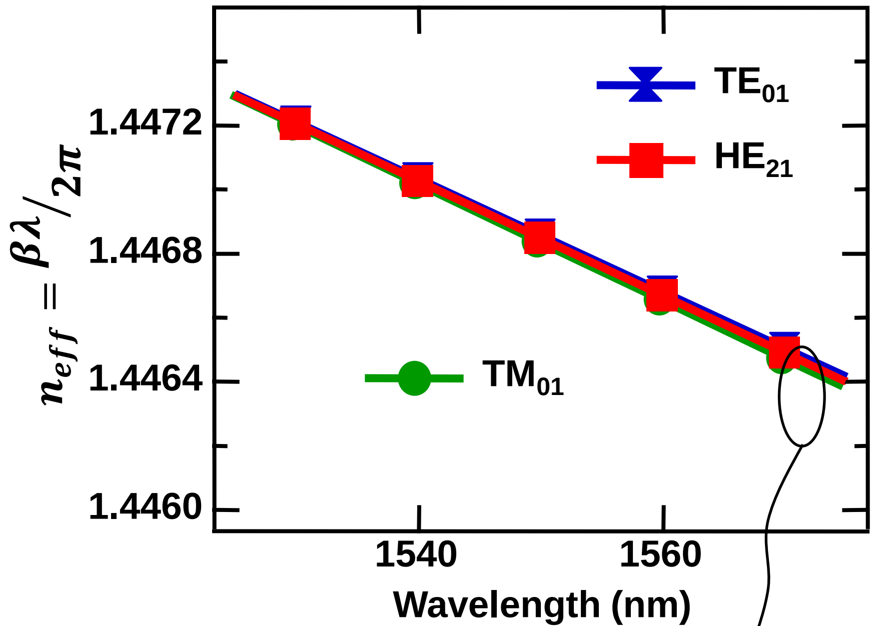
$$\mathrm{OAM}^{\mp}_{\pm\ell,m} = \mathrm{EH}^{\mathrm{even}}_{\ell-1,m} \pm j\,\mathrm{EH}^{\mathrm{odd}}_{\ell-1,m}$$

amachandran et al, OL, 34, 2525 (2009)

A.W. Snyder and J.D. Love, Optical Waveguide Theory, 1983

Gen I: vortex fiber





Splitting

$$= \int E^2(r) \cdot \frac{\partial F(r)}{\partial r} dr$$

Mode Intensity

Index Gradient

Δn ~ 1.8 x 10^{-4}

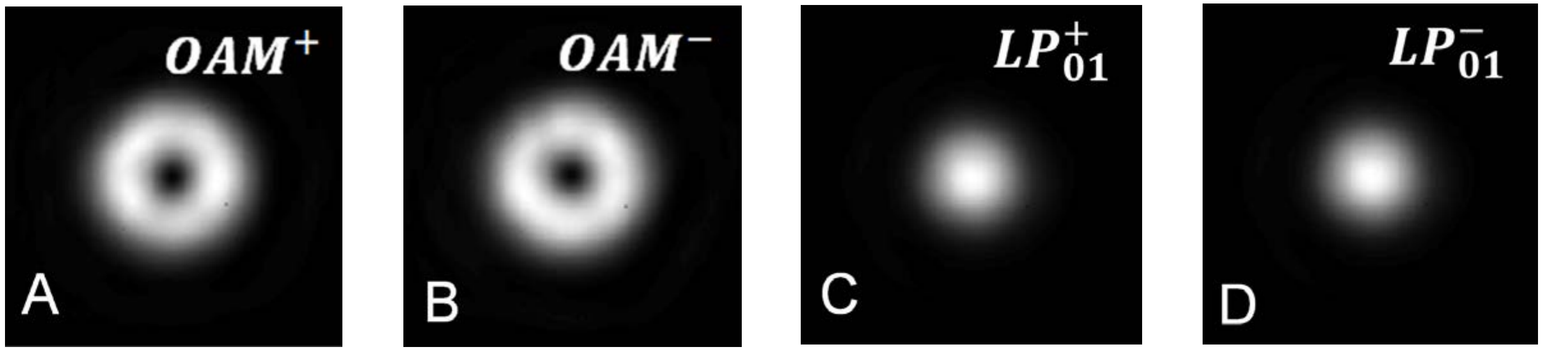
(Beat length ~ 8 mm)

Conventional PM fibers ~ 2–5 mm

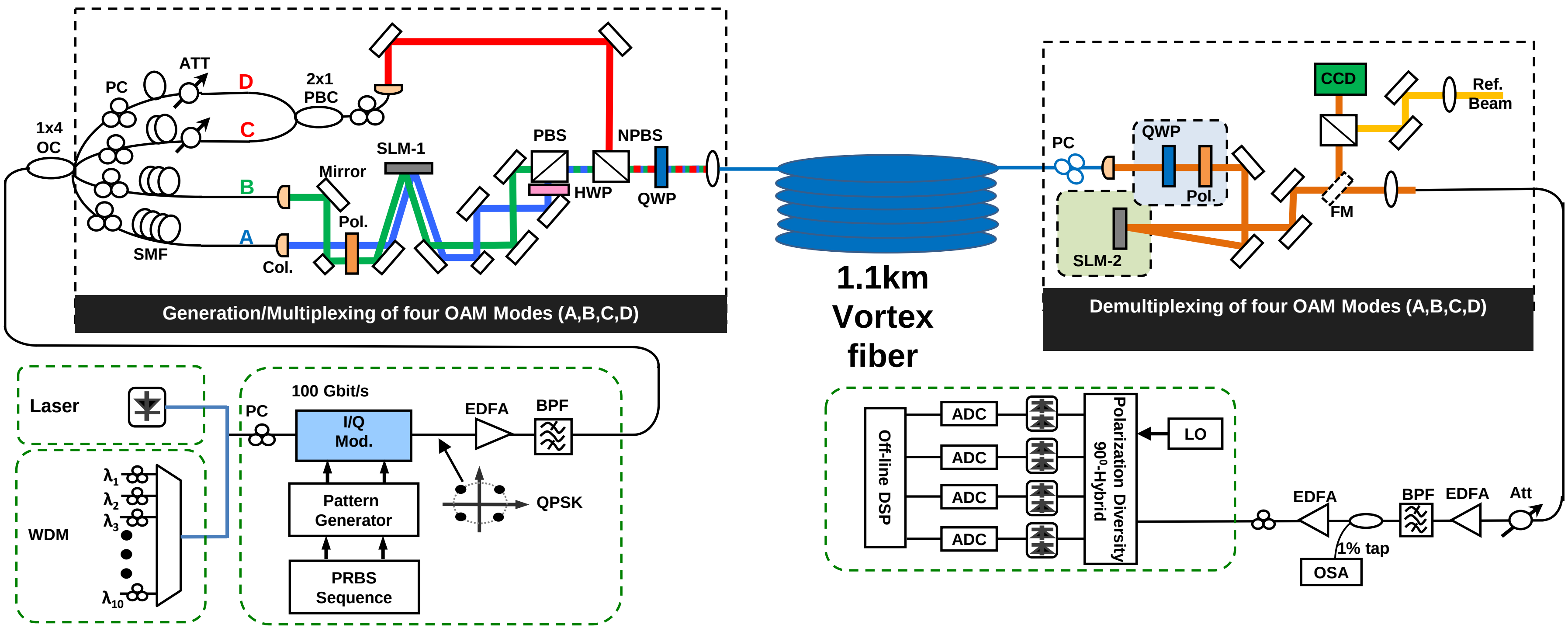
Δn_{eff} ↑ **Mode coupling** ↓↓

S. Ramachandran et al, OL, 34, 2525 (2009)

Data transmission experiment



ℓ = +1	ℓ = – 1	ℓ = 0	ℓ = 0
s = +1	s = – 1	s = +1	s = –1



N. Bozinovic et al, *Science vol. 340, p. 1545, 2013*

How large/many |L|s can we create in fiber?

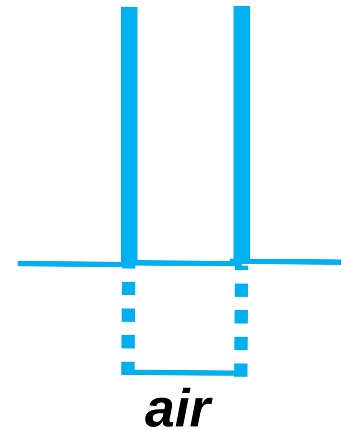
The Boston University photonics center
BOSTON UNIVERSITY
BU Department of Electrical & Computer Engineering

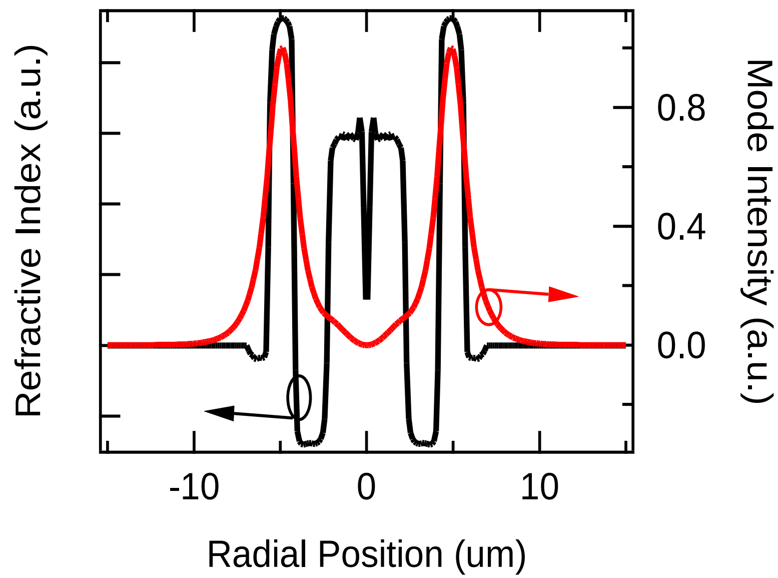
Splitting

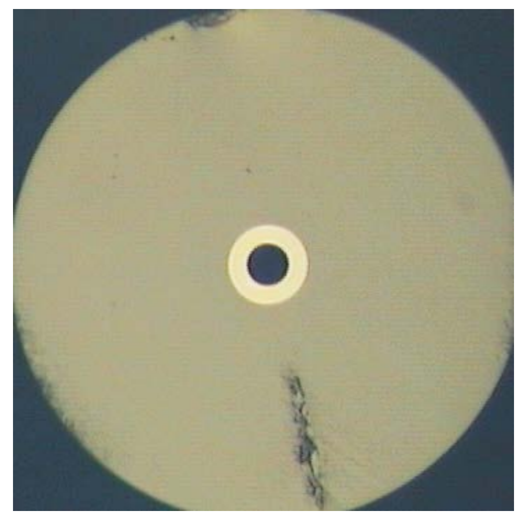
$$= \int E^2(r) \cdot \frac{\partial F(r)}{\partial r} dr$$

Mode Intensity

Index Gradient

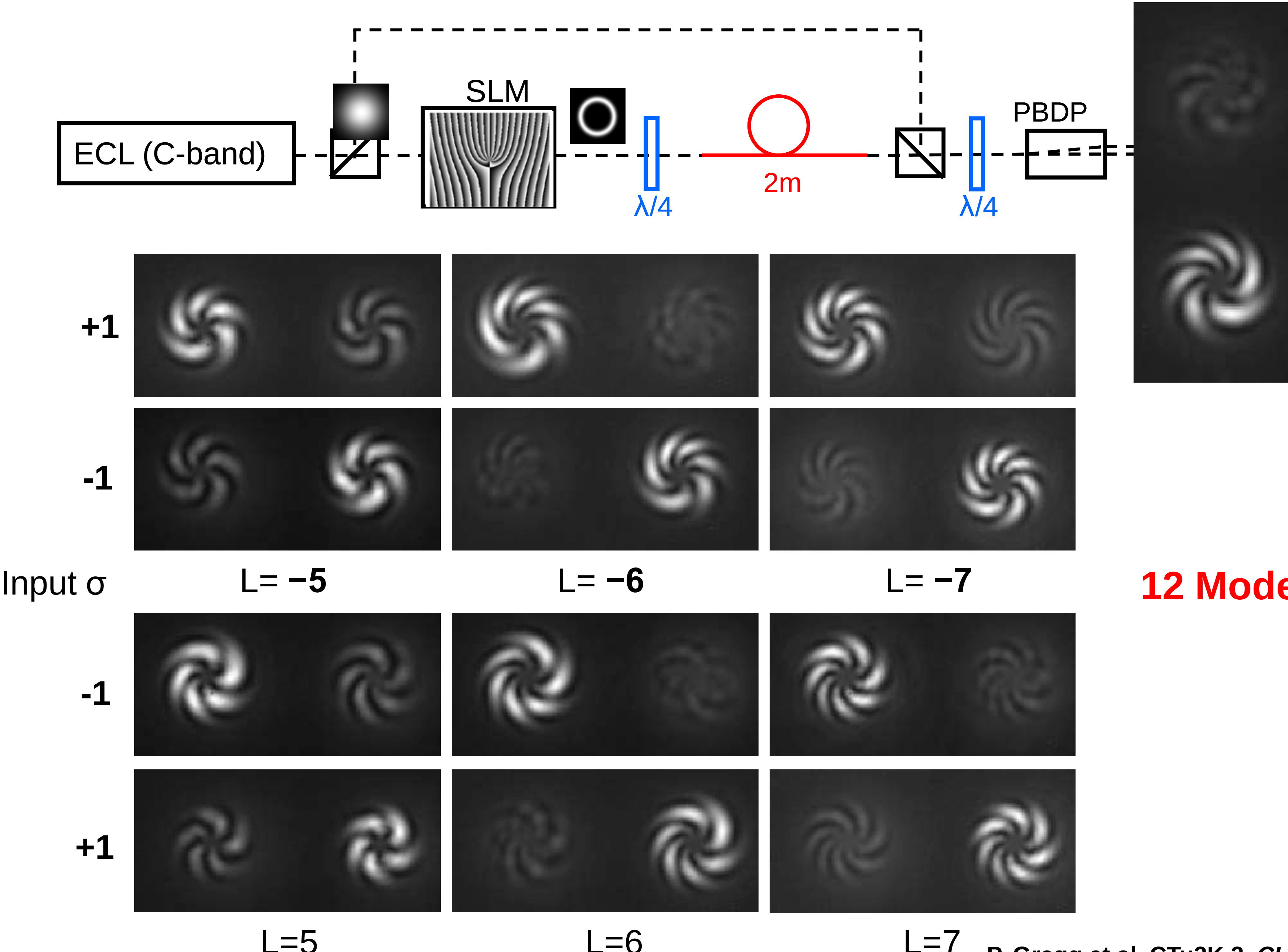






P. Gregg et al, CTu2K.2, *CLEO* 2013

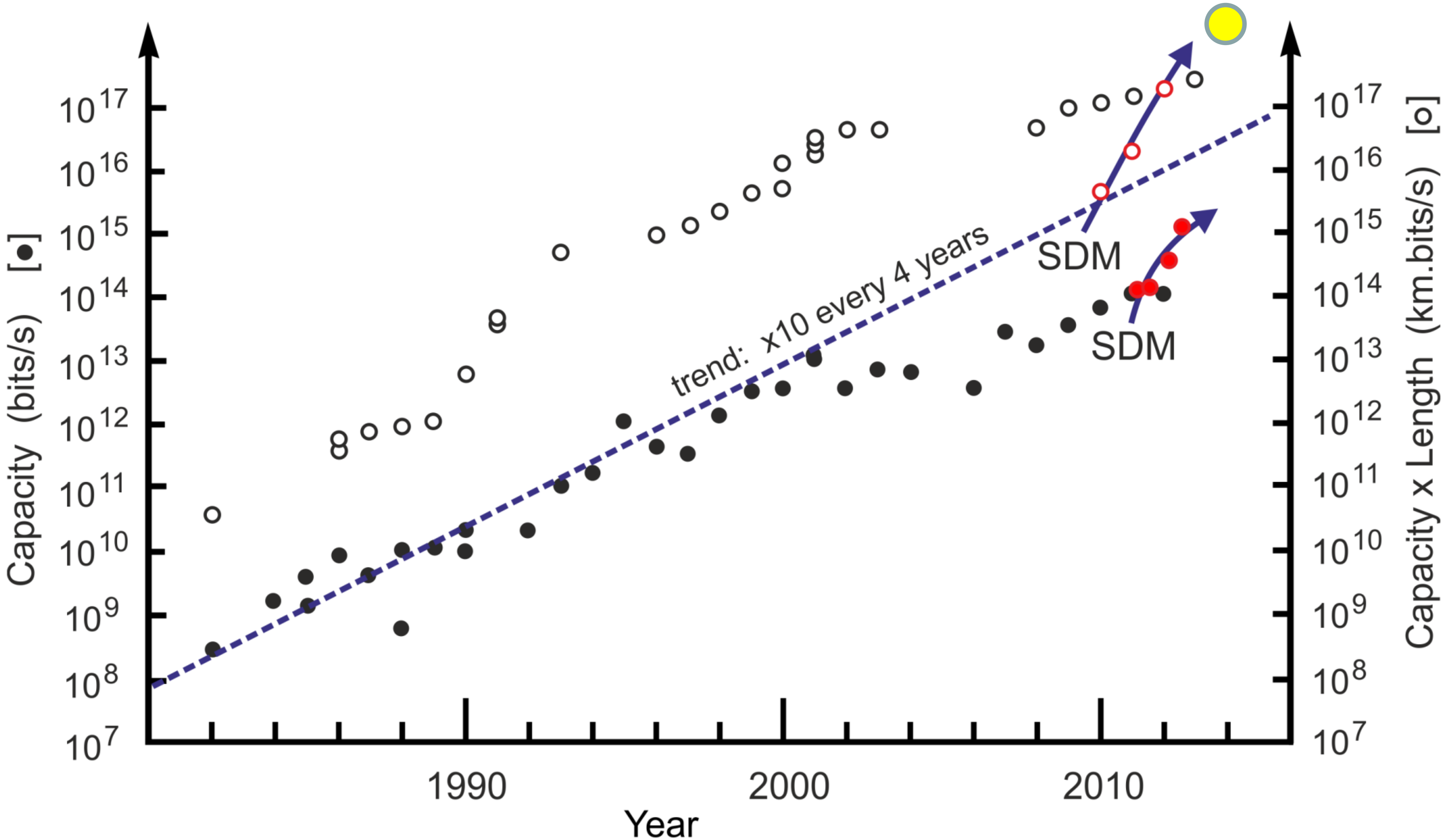
Mux and short length experiments



12 Modes

P. Gregg et al, CTu2K.2, *CLEO* 2013

SDM Progress to Date



- Transmission records as derived from OFC PDPs
- ECOC PDPs also included since 2010