High-rate/High-Speed Data Transmission Challenges and Solutions: Photonics Applied to Telecom

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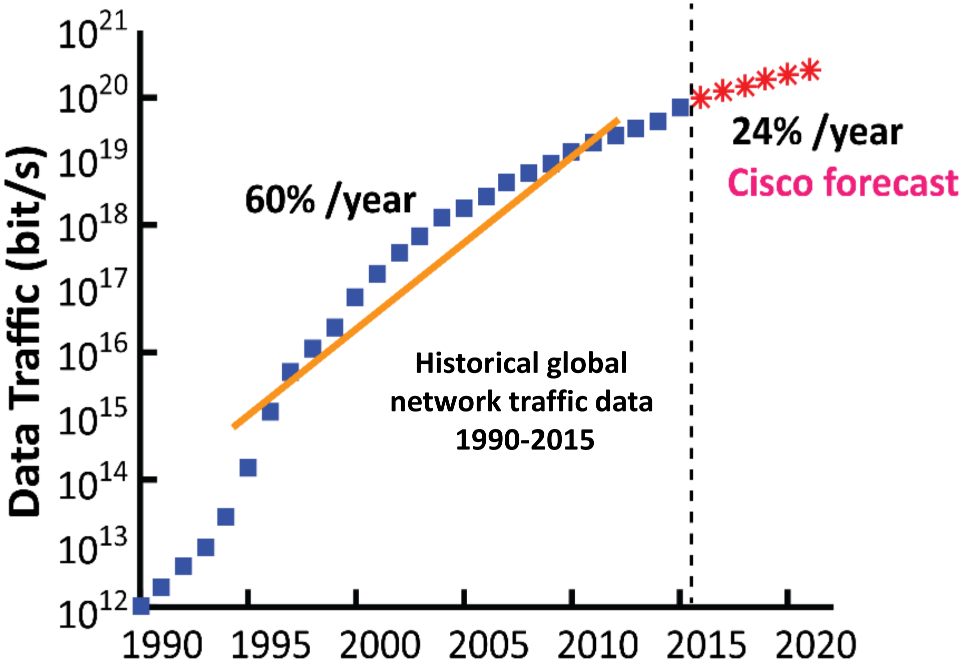
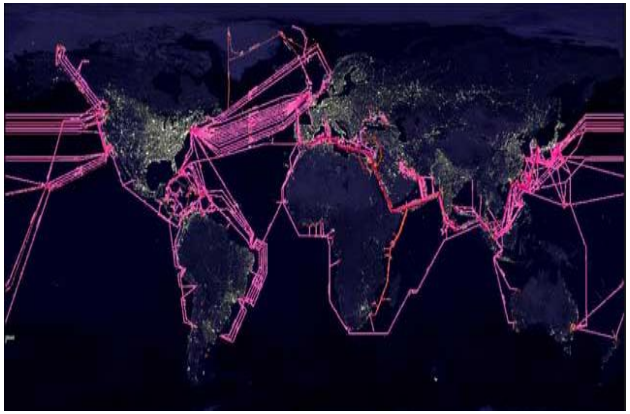
May 20, 2019, Wuhan, China

Global Traffic: economy and sustainable society





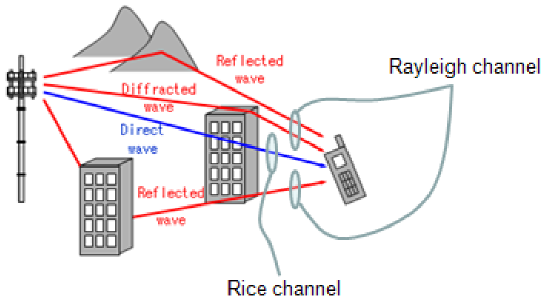
Fiber network connects the world

Big data

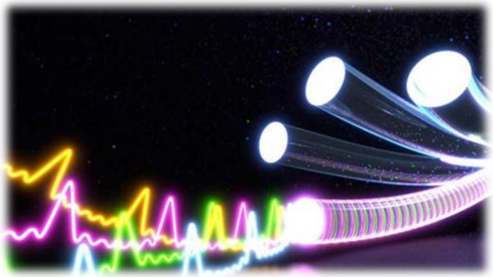
Cloud computing

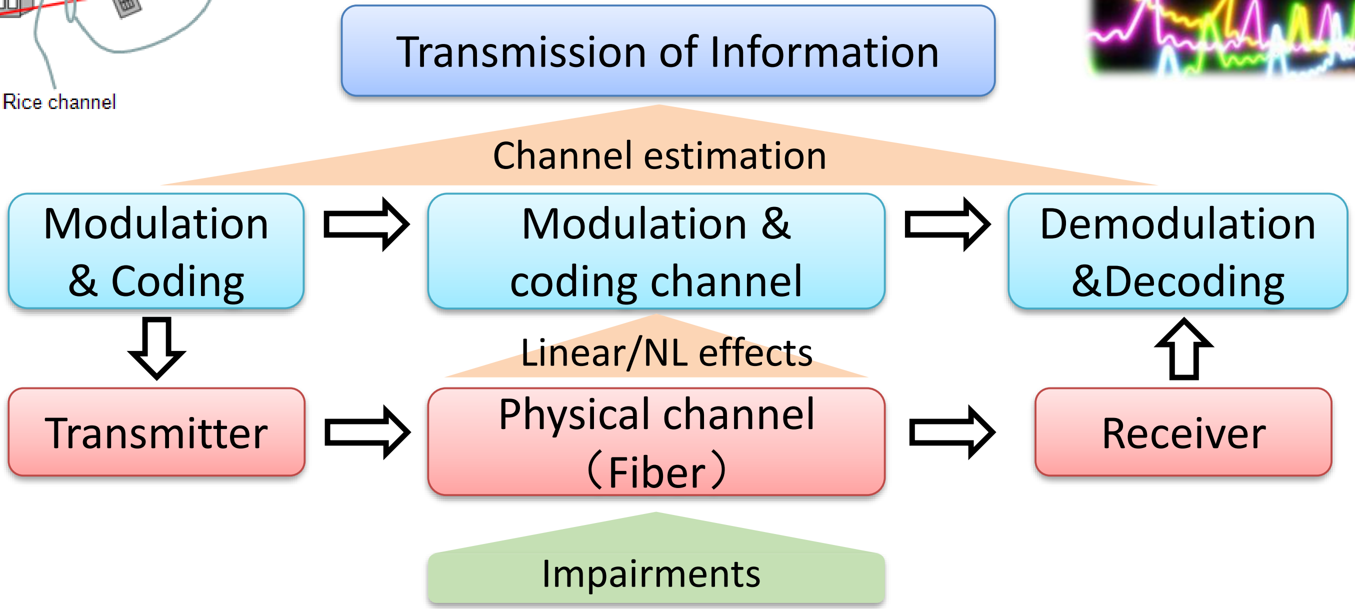
- The global traffic keeps increasing over the past 30 years with 60% annual growth rate;
- From China Telecom: the annual incremental rate in Chinese backbone network is 200%, the wideband subscriber increases 80% annually；
- Tremendous improvement of network capacity is demanding for applications like Big data, cloud computing, IoT, 5G, etc;
- **Photonic technologies are essential**

Artificial channel for telecom



Optical fiber: artificial channel





Transmission of Information

Channel estimation

Modulation & Coding ⇨ Modulation & coding channel ⇨ Demodulation &Decoding

Linear/NL effects

Transmitter ⇨ Physical channel （Fiber） ⇨ Receiver

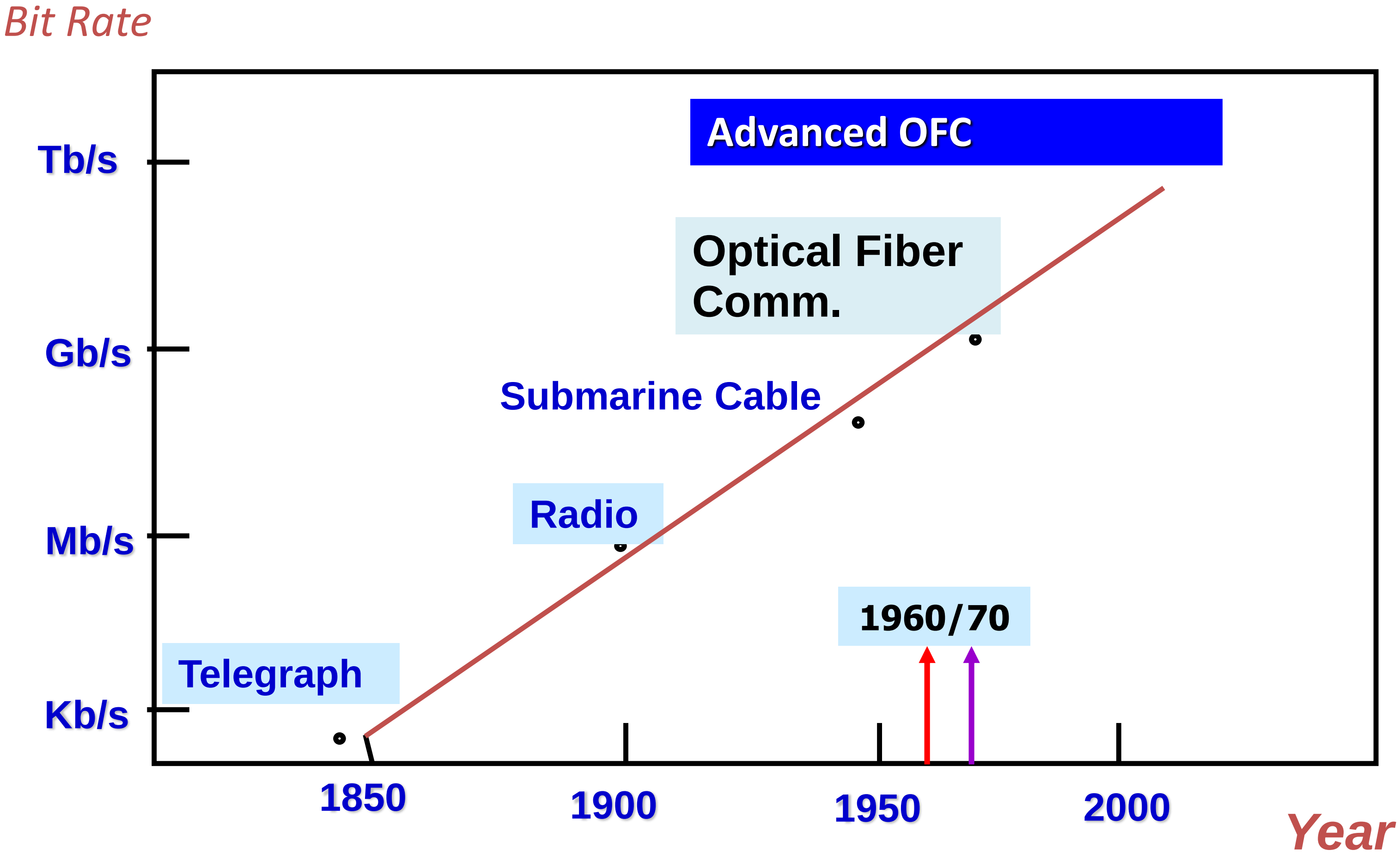
Impairments

- Optimized physical channel for better communication & sensing: high quality and long distance;
  Photonic solutions: medium, Tx/Rx, link component, etc.

Development of Digital Telecommunications

Optical Fiber Communications
1970-2010, 40 years

Charles K. Kao
1966

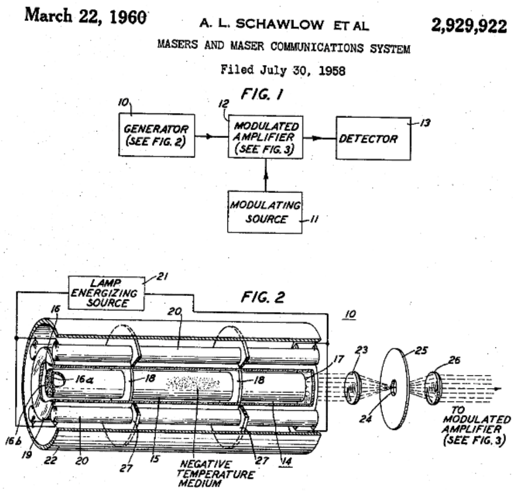


1960
Laser

1970
Low-Loss Optical Fiber

Laser and Communication

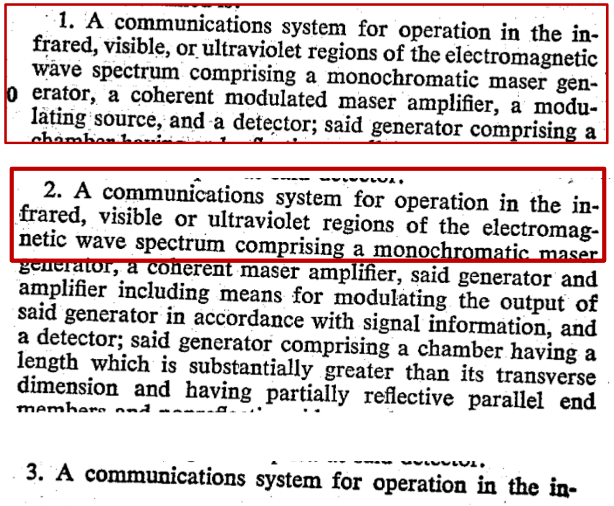
- A patent on laser was filed by Schawlow and Townes of Bell Lab in 1958 and awarded in 1960. 3 claims were on communication, 4 on laser and 4 on amplifiers.
- First laser was demonstrated by Maiman of Hughes Research Lab.
- One main intended application of laser was on communication



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

MASERS AND MASER COMMUNICATIONS SYSTEM

Filed July 30, 1958



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; said generator comprising a

2. A communications system for operation in the infrared, visible or ultraviolet regions of the electromagnetic wave spectrum comprising a monochromatic maser generator, a coherent maser amplifier, said generator and amplifier including means for modulating the output of said generator in accordance with signal information, and a detector; said generator comprising a chamber having a length which is substantially greater than its transverse dimension and having partially reflective parallel end

3. A communications system for operation in the in-

THIS DAY in PATENT HISTORY

March 22

On March 22, 1960, Schawlow and Townes were issued a patent for the **laser**.

Laser Technology Market is expected to be worth $17.06 Billion by 2020.

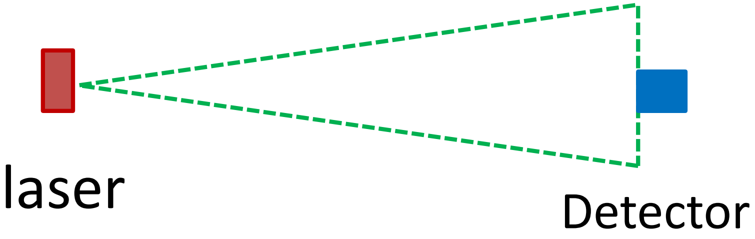
US 2929922 A
March 22, 1960

Image Credit - Wikipedia

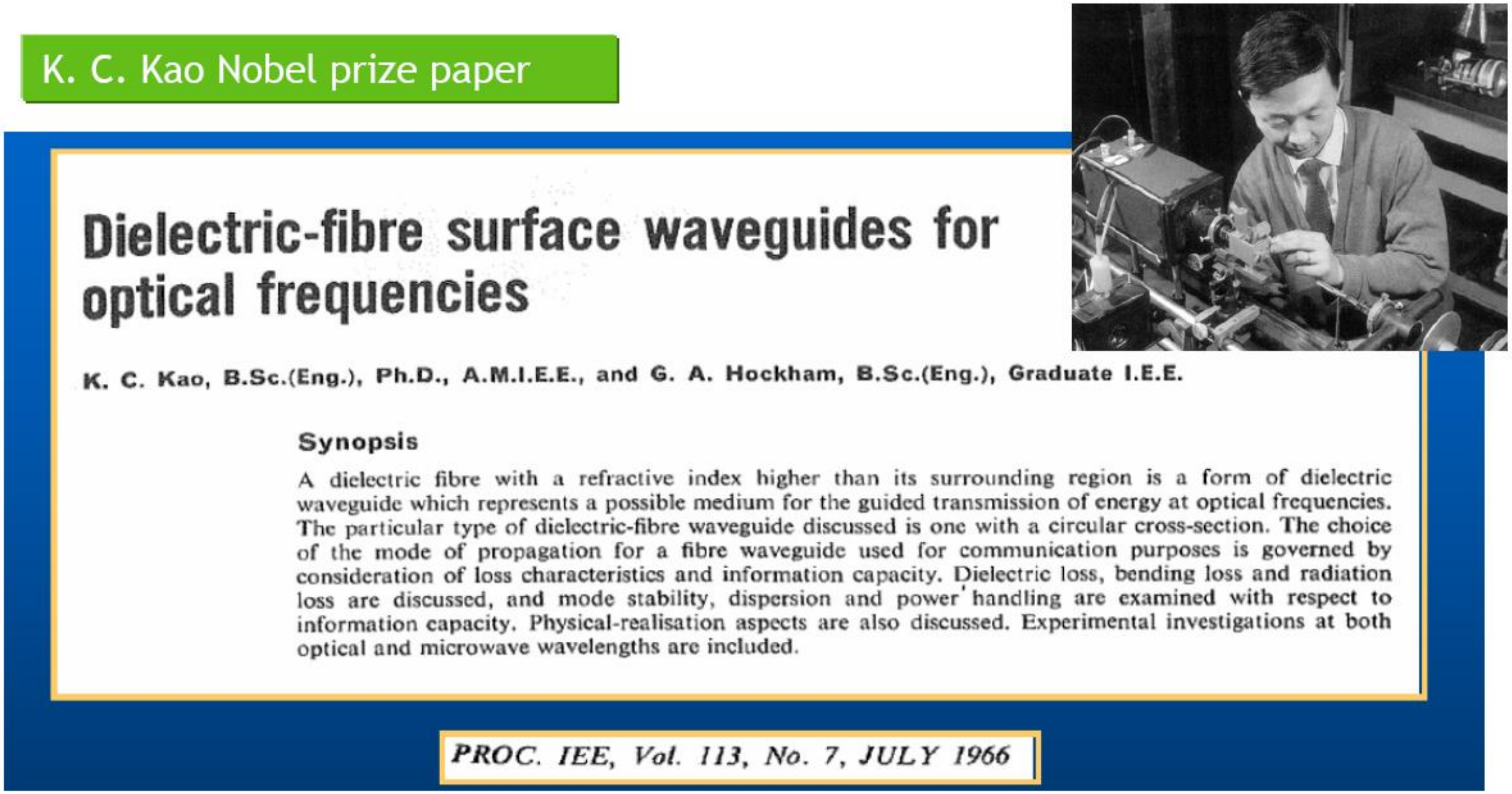
Think of all that bandwidth!

Optical fiber: perfect medium

- Challenge of laser communication:
  - Loss due to diverging beam
  - Loss due to environment
- Need a light guiding mechanism



K. C. Kao Nobel prize paper



Dielectric-fibre surface waveguides for optical frequencies

K. C. Kao, B.Sc.(Eng.), Ph.D., A.M.I.E.E., and G. A. Hockham, B.Sc.(Eng.), Graduate I.E.E.

Synopsis

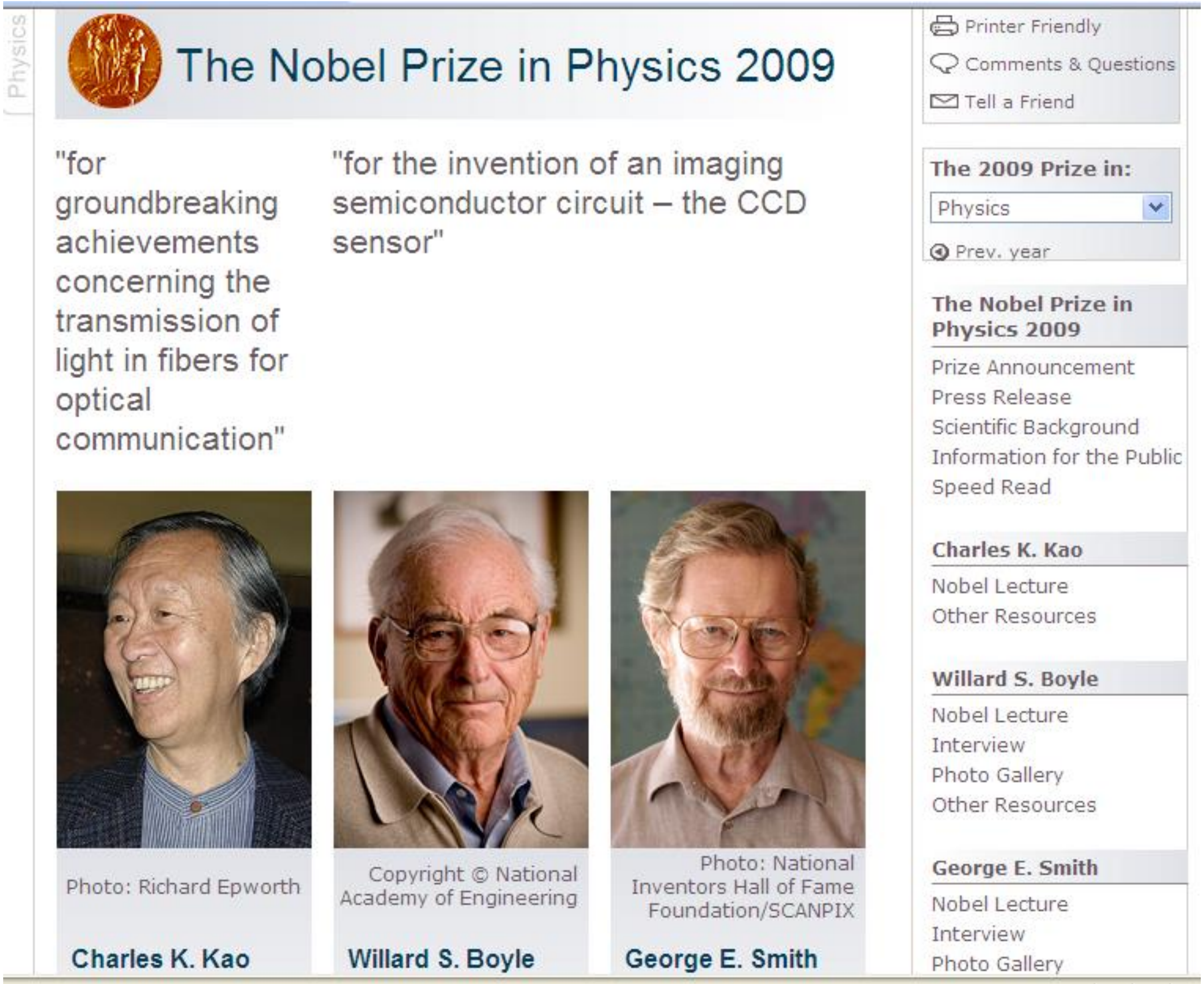
A dielectric fibre with a refractive index higher than its surrounding region is a form of dielectric waveguide which represents a possible medium for the guided transmission of energy at optical frequencies. The particular type of dielectric-fibre waveguide discussed is one with a circular cross-section. The choice of the mode of propagation for a fibre waveguide used for communication purposes is governed by consideration of loss characteristics and information capacity. Dielectric loss, bending loss and radiation loss are discussed, and mode stability, dispersion and power handling are examined with respect to information capacity. Physical-realisation aspects are also discussed. Experimental investigations at both optical and microwave wavelengths are included.

PROC. IEE, Vol. 113, No. 7, JULY 1966

loss of the best fiber was ***1000 dB/km***!

1966 K. C. Kao and G. A. Hocker of STC labs proposed loss reduction to ***20 dB/km*** by removal of impurities

G. MW Kao, Nobel Prize speech, Dec 2009



The Nobel Prize in Physics 2009

"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

"for the invention of an imaging semiconductor circuit – the CCD sensor"

Photo: Richard Epworth

Charles K. Kao

Copyright © National Academy of Engineering

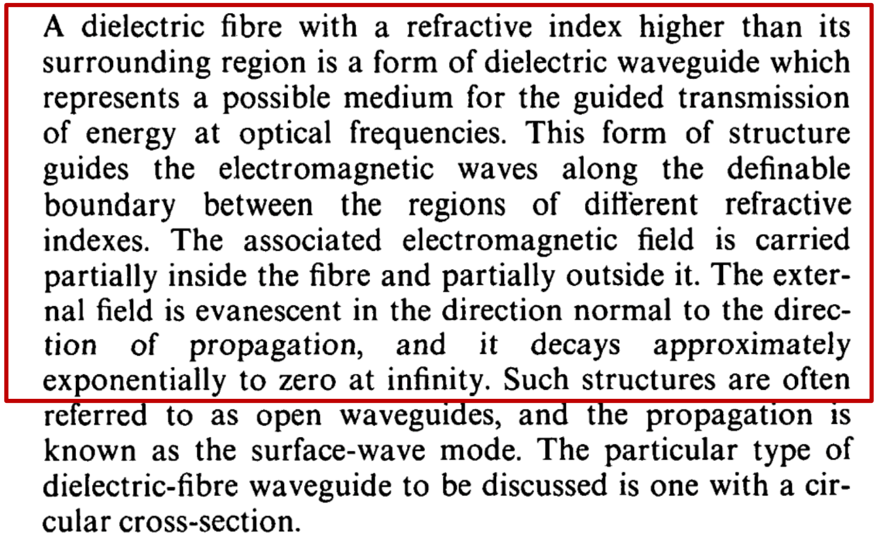
Willard S. Boyle

Photo: National Inventors Hall of Fame Foundation/SCANPIX

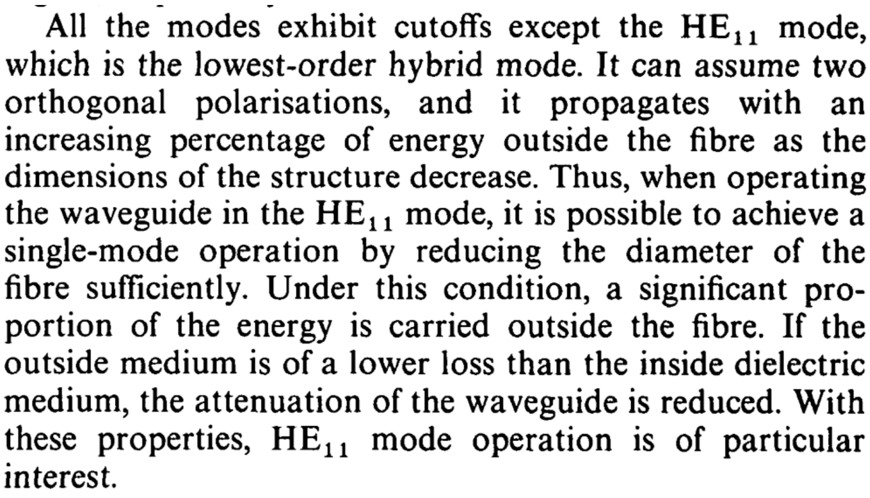
George E. Smith

Charles Kao(高錕)

- Optical fiber with core and cladding
- Single mode operation with very low guiding loss



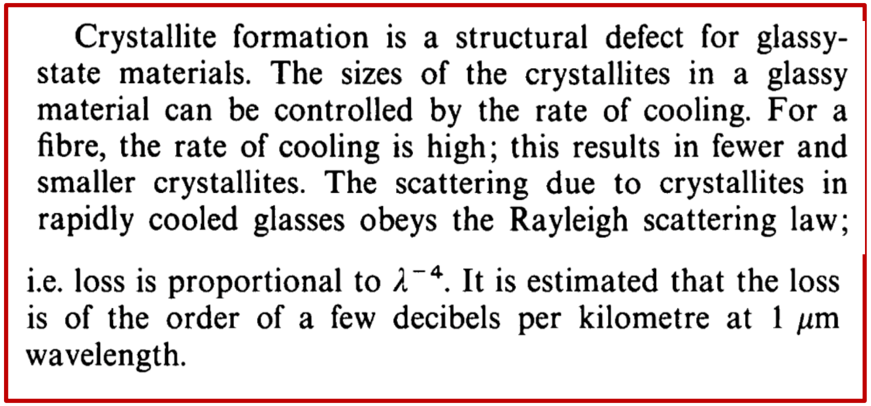
A dielectric fibre with a refractive index higher than its surrounding region is a form of dielectric waveguide which represents a possible medium for the guided transmission of energy at optical frequencies. This form of structure guides the electromagnetic waves along the definable boundary between the regions of different refractive indexes. The associated electromagnetic field is carried partially inside the fibre and partially outside it. The external field is evanescent in the direction normal to the direction of propagation, and it decays approximately exponentially to zero at infinity. Such structures are often referred to as open waveguides, and the propagation is known as the surface-wave mode. The particular type of dielectric-fibre waveguide to be discussed is one with a circular cross-section.



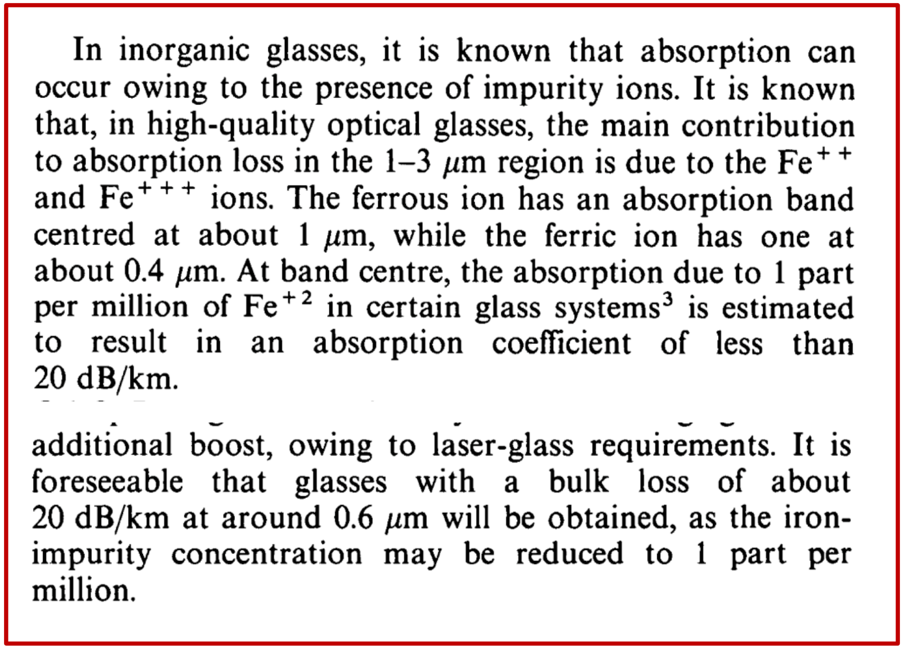
All the modes exhibit cutoffs except the HE_{11} mode, which is the lowest-order hybrid mode. It can assume two orthogonal polarisations, and it propagates with an increasing percentage of energy outside the fibre as the dimensions of the structure decrease. Thus, when operating the waveguide in the HE_{11} mode, it is possible to achieve a single-mode operation by reducing the diameter of the fibre sufficiently. Under this condition, a significant proportion of the energy is carried outside the fibre. If the outside medium is of a lower loss than the inside dielectric medium, the attenuation of the waveguide is reduced. With these properties, HE_{11} mode operation is of particular interest.

Charles Kao(高錕)

- Loss due to Rayleigh scattering loss can be small for glass fiber
- Loss is mainly due to impurity and can be reduced to less than 20dB/km



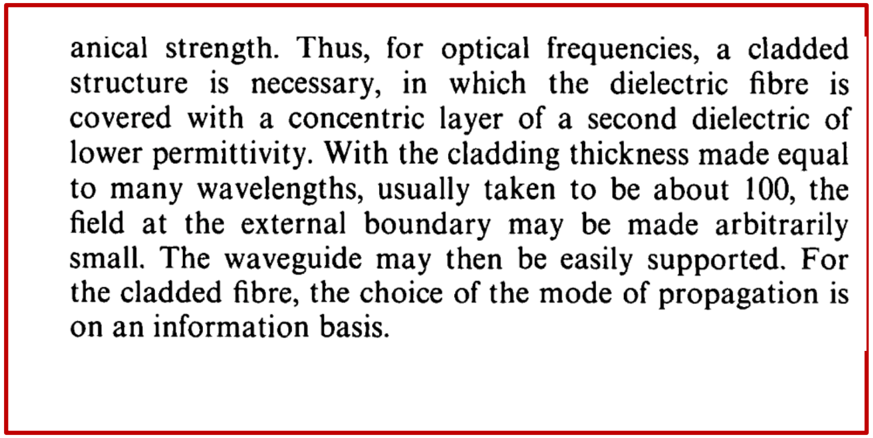
Crystallite formation is a structural defect for glassy-state materials. The sizes of the crystallites in a glassy material can be controlled by the rate of cooling. For a fibre, the rate of cooling is high; this results in fewer and smaller crystallites. The scattering due to crystallites in rapidly cooled glasses obeys the Rayleigh scattering law; i.e. loss is proportional to λ^{-4}. It is estimated that the loss is of the order of a few decibels per kilometre at 1 μm wavelength.



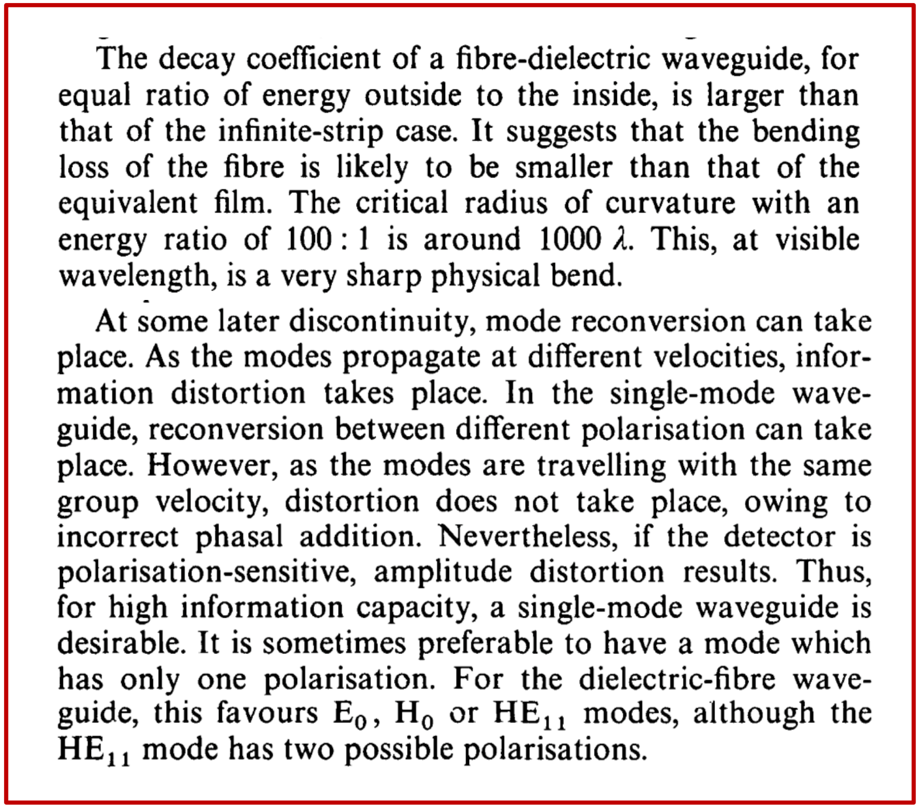
In inorganic glasses, it is known that absorption can occur owing to the presence of impurity ions. It is known that, in high-quality optical glasses, the main contribution to absorption loss in the 1–3 μm region is due to the Fe^{++} and Fe^{+++} ions. The ferrous ion has an absorption band centred at about 1 μm, while the ferric ion has one at about 0.4 μm. At band centre, the absorption due to 1 part per million of Fe^{+2} in certain glass systems[3] is estimated to result in an absorption coefficient of less than 20 dB/km.

additional boost, owing to laser-glass requirements. It is foreseeable that glasses with a bulk loss of about 20 dB/km at around 0.6 μm will be obtained, as the iron-impurity concentration may be reduced to 1 part per million.

- With cladding size 100 times of wavelength, mechanical strength is good
- Bending radius can be 1000 times of the wavelength.
- Single mode is important for good transmission performance



anical strength. Thus, for optical frequencies, a cladded structure is necessary, in which the dielectric fibre is covered with a concentric layer of a second dielectric of lower permittivity. With the cladding thickness made equal to many wavelengths, usually taken to be about 100, the field at the external boundary may be made arbitrarily small. The waveguide may then be easily supported. For the cladded fibre, the choice of the mode of propagation is on an information basis.

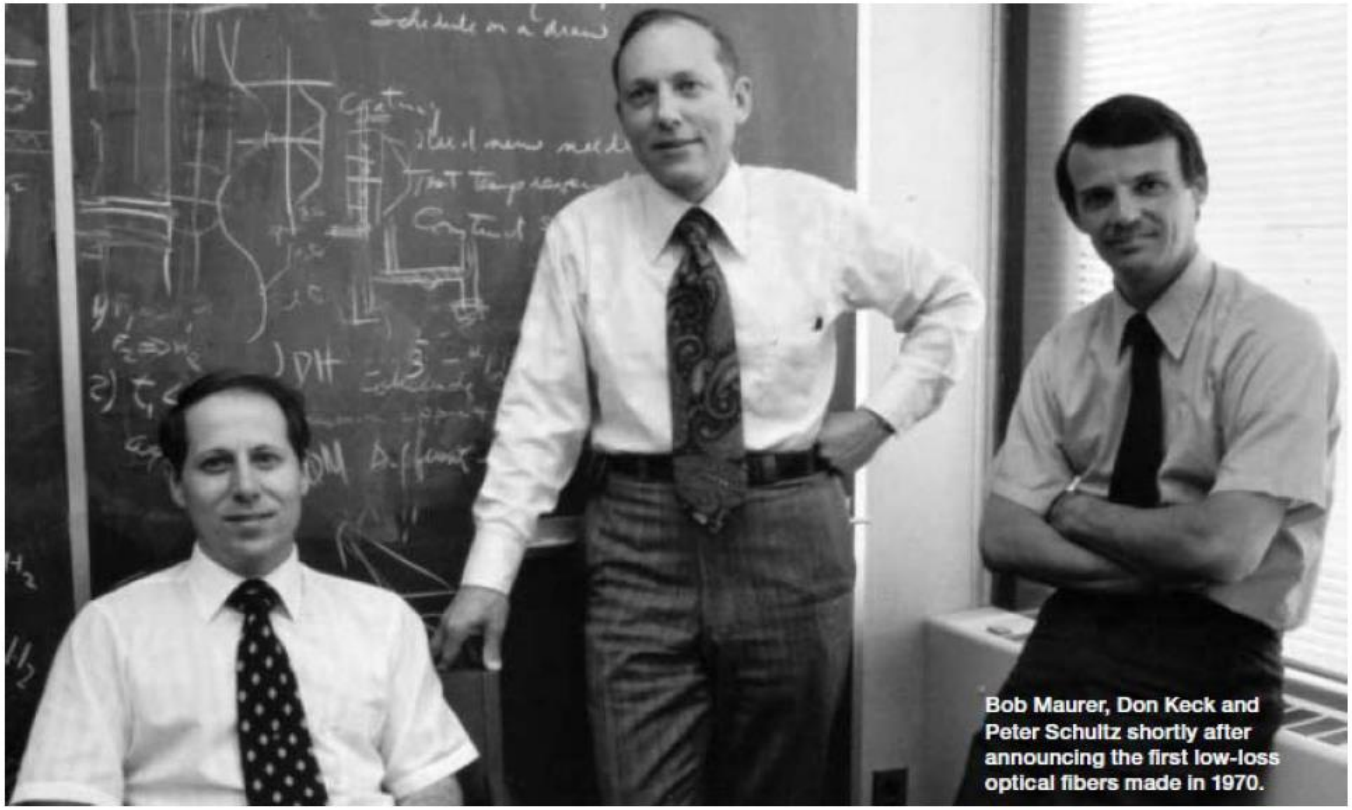


The decay coefficient of a fibre-dielectric waveguide, for equal ratio of energy outside to the inside, is larger than that of the infinite-strip case. It suggests that the bending loss of the fibre is likely to be smaller than that of the equivalent film. The critical radius of curvature with an energy ratio of 100 : 1 is around 1000 λ. This, at visible wavelength, is a very sharp physical bend.

At some later discontinuity, mode reconversion can take place. As the modes propagate at different velocities, information distortion takes place. In the single-mode waveguide, reconversion between different polarisation can take place. However, as the modes are travelling with the same group velocity, distortion does not take place, owing to incorrect phasal addition. Nevertheless, if the detector is polarisation-sensitive, amplitude distortion results. Thus, for high information capacity, a single-mode waveguide is desirable. It is sometimes preferable to have a mode which has only one polarisation. For the dielectric-fibre waveguide, this favours E_0, H_0 or HE_{11} modes, although the HE_{11} mode has two possible polarisations.

Pioneers of Low Loss Silica Glass Optical Fibers —Corning (1970) and Bell Labs (1971) (later also NTT)

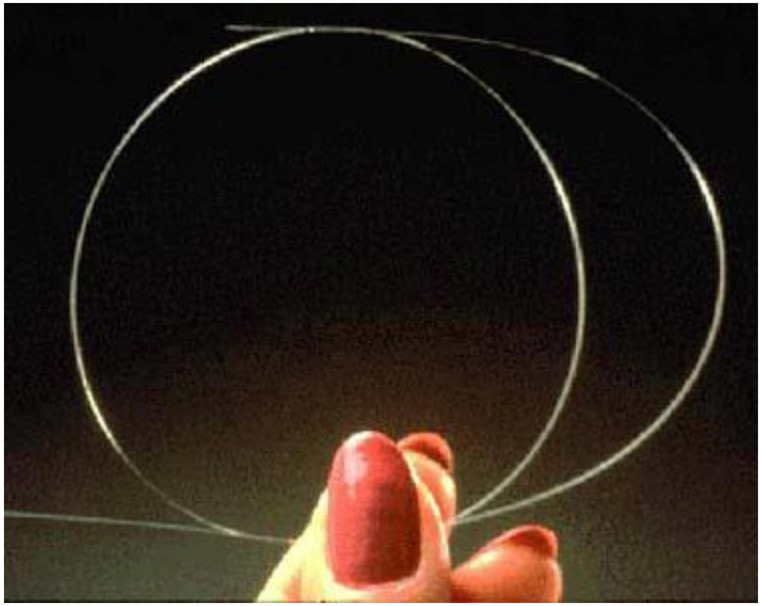
In 1970, Corning made the first low loss fibers with attenuation of ***17 dB/km***!



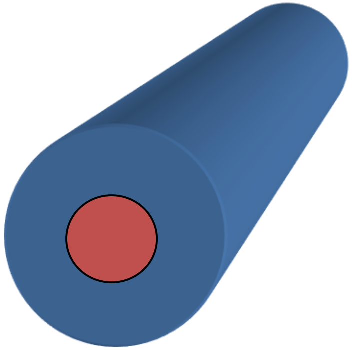
Bob Maurer, Don Keck and Peter Schultz shortly after announcing the first low-loss optical fibers made in 1970.

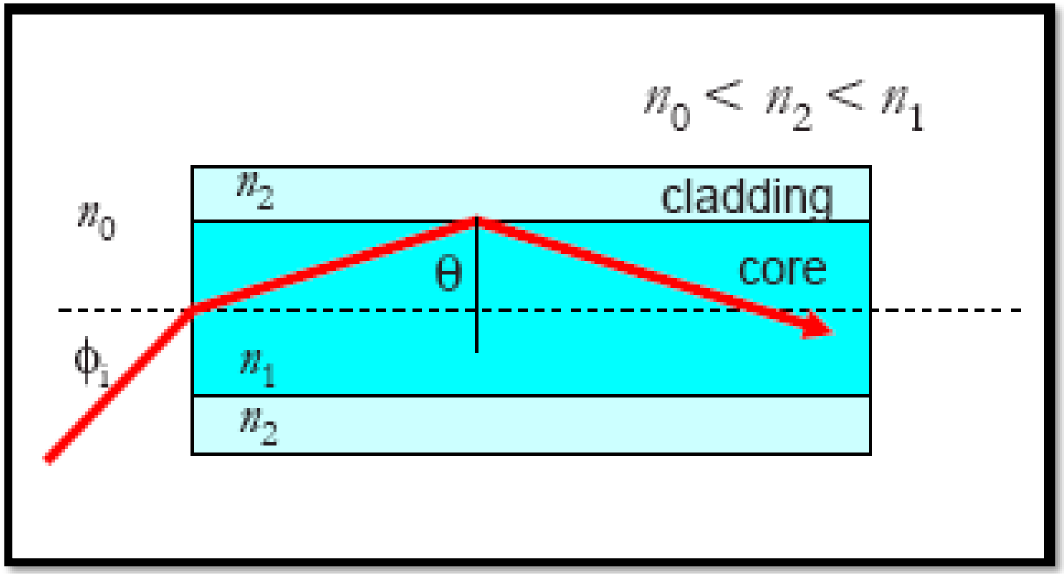
P. C. Schultz, OPN, Oct 2010

- Lightweight / non-obtrusive
- Passive / low power
- EMI resistant
- High sensitivity and bandwidth
- Environmental ruggedness
- **Complementary to telecom / optoelectronics**



Conventional optical fiber

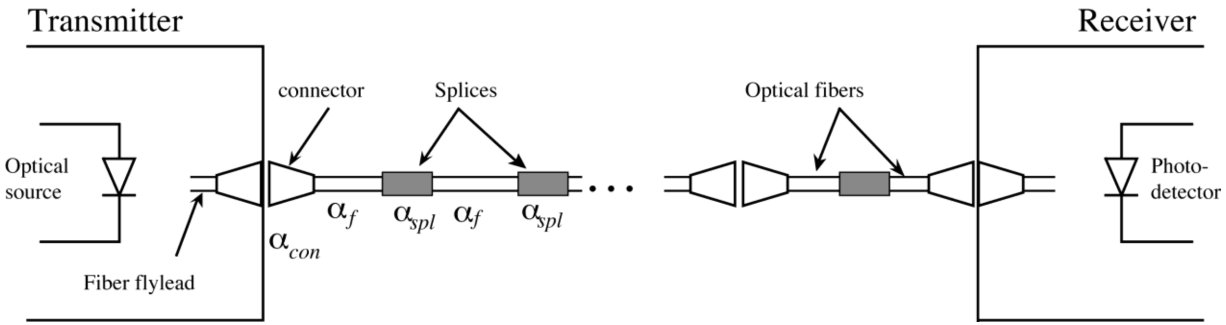




Guiding mechanism: TIR (Total Internal Reflection)

Optical Communications

- Early optical communication systems used direct detection



- Photodetector is a square law detector and only intensity can be detected. Minimum received average power(**sensitivity**) for a given Bit Error rate(**BER**)

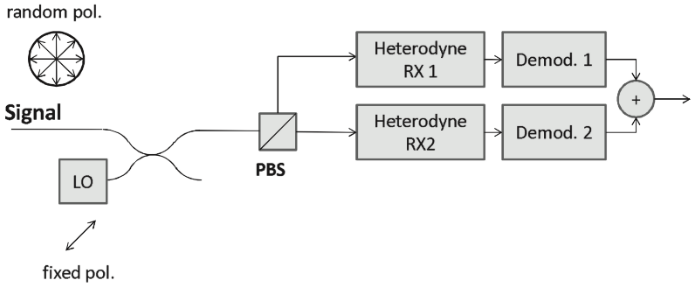
$$P_{rec} = \frac{QN_{TIA}\sqrt{B}}{R}$$

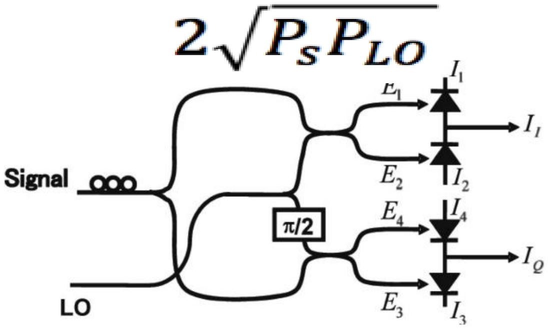
Q=7, BER=10^{-12} , R: responsivity, B: bandwidth

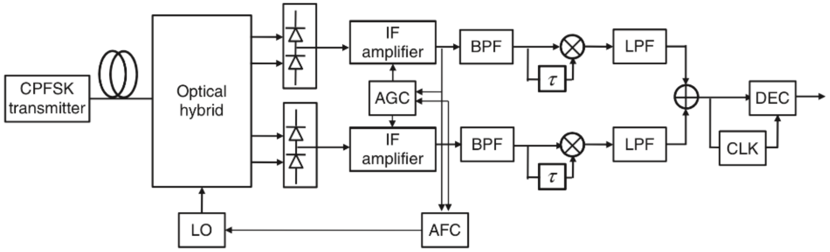
- Receiver sensitivity is decided by data rate. Transmission distance is limited by data rate and thermal noise of the receiver transimpedance amplifier (**TIA**).
- From first generation optical communication system operating at 0.8 µm with GaAs semiconductor lasers at 45 Mbit/s with repeater spacing of up to 10 km in 1970’s to 2.5Gbit/s at 1.5 µm with repeater spacing of 100km in the early 1990’s

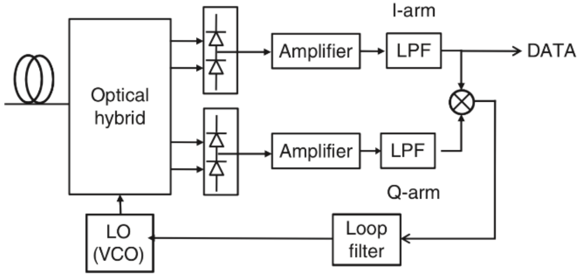
Coherent Detection-First Generation

- ◆ Best sensitivity can be achieved with shot noise limited detection
- ◆ This can be realized using coherent detection with a local oscillator with large power. Instead of detecting P_s as in direct detection system, $2\sqrt{P_S P_{LO}}$ is detected.
- ◆ Need frequency and phase diversity (Homodyne) and polarization diversity.
- ◆ Significantly improved receiver sensitivity can be realized.





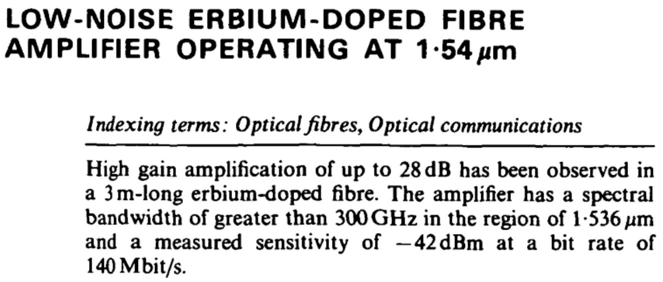




K Kikuchi: Fundamental of Coherent Optical fiber Communications, Journal of Lightwave Technology, Vol. 34, No.1, pp. 157-179, January 2016.

Optical Amplifier

- The use of optical amplifier will also allow achieving shot noise limited detection and will also allow the removal of electronic regenerator.
- The concept is not new but suggested in the first laser patent.
- First demonstrated in 1987 by ORC of university of Southampton and Bell Lab.



LOW-NOISE ERBIUM-DOPED FIBRE AMPLIFIER OPERATING AT 1·54 μm

Indexing terms: Optical fibres, Optical communications

High gain amplification of up to 28 dB has been observed in a 3 m-long erbium-doped fibre. The amplifier has a spectral bandwidth of greater than 300 GHz in the region of 1·536 μm and a measured sensitivity of −42 dBm at a bit rate of 140 Mbit/s.

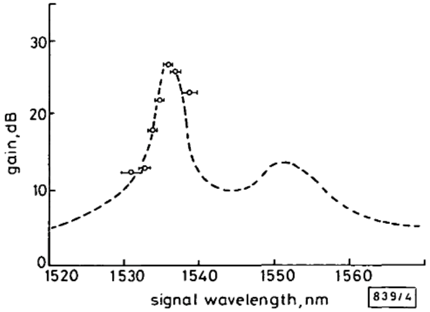


Fig. 4 *Gain spectrum and spontaneous emission*

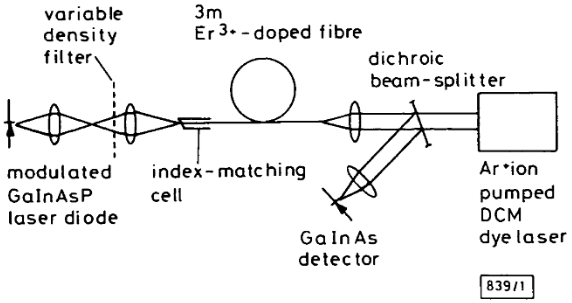


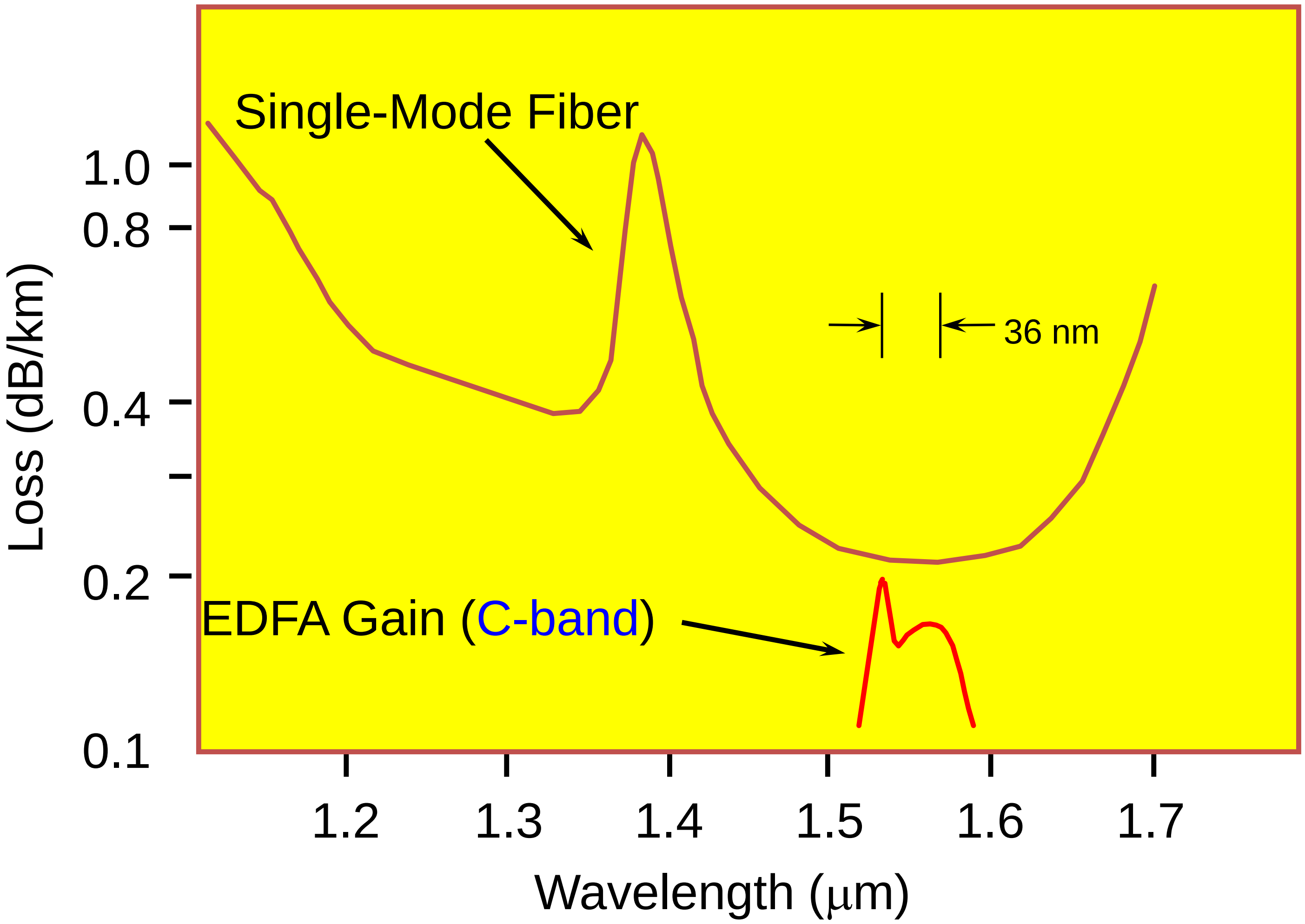
Fig. 1 *Experimental configuration for fibre amplifier*

Poole, S. B., Payne, D. N., and Fermann, M. E.: 'Fabrication of low-loss optical fibres containing rare-earth ions', Electron. Lett.,1985, 21, pp. 737-738, August 1985.

R. J. Mears, L. Reekie, I.M. Jauncey, D. N. Payne, "Low-Noise Erbium-Doped Fibre Amplifier Operating at 1.54um," Electronics Letters, Vol 23, No. 19, September 1987

E. Desurvire, J. Simpson, and P.C. Becker, High-gain erbium-doped traveling-wave fiber amplifier," Optics Letters, vol. 12, No. 11, 1987, pp. 888–890

Single-Mode Fiber Loss Spectrum vs. EDFA Amplifier Gain Spectrum



C Band (1530-1566 nm)

L Band (1570-1610 nm)

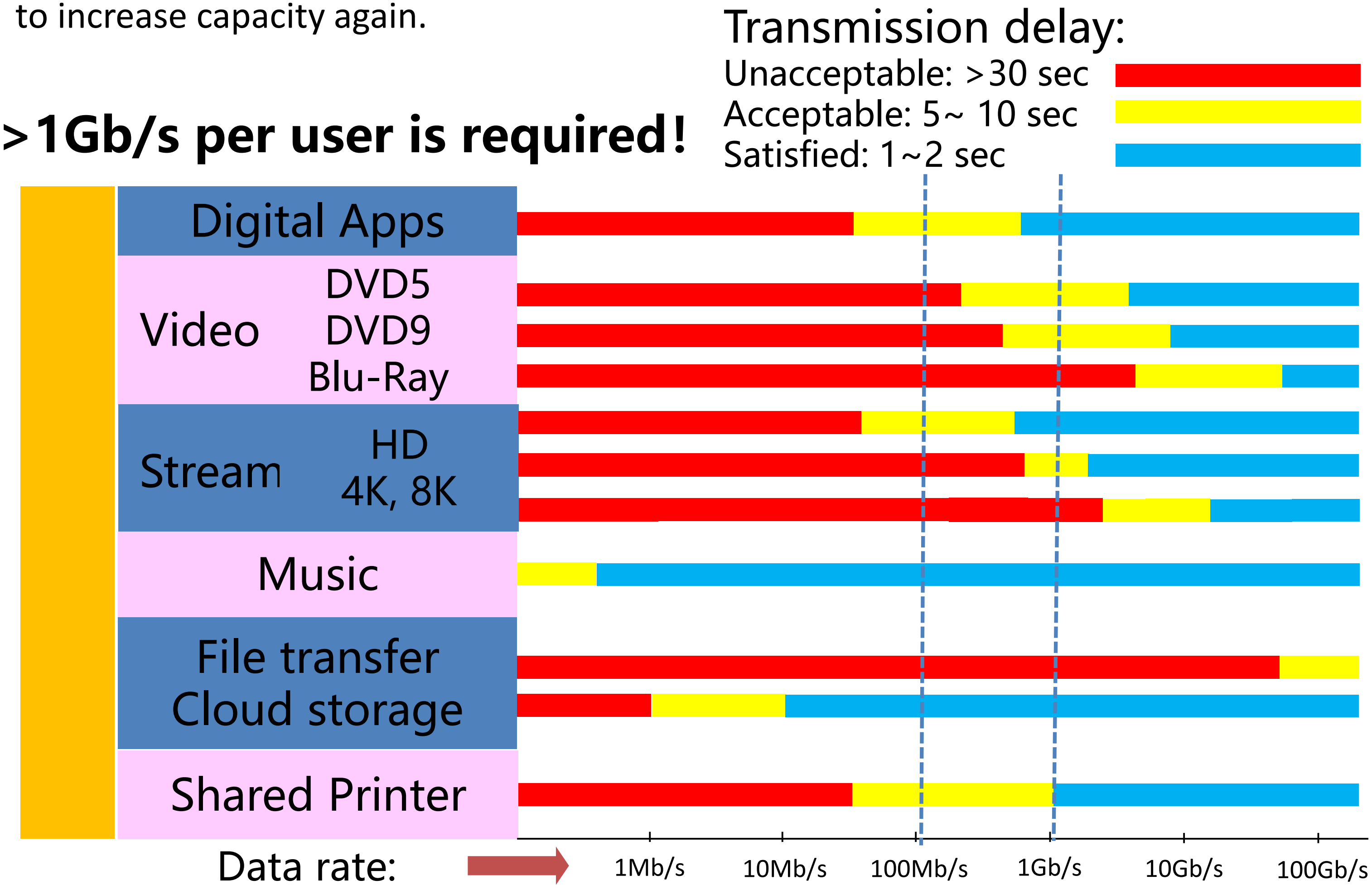
Need for Capacity

◆ The internet developed rapidly in 1990’s after the release of the first Web Browser **Netscape Navigator.** The internet traffic demand has since increased rapidly

◆ The need for transmission capacity on optical fiber has since increased rapidly.

◆ At one time, people think 2.5Gbps will last us for generations. Soon there is an urgent need to increase capacity again.

>1Gb/s per user is required!



Ultra-high speed OFC

- **Shannon Capacity**

$$C=B\log_2(1+S/N)$$

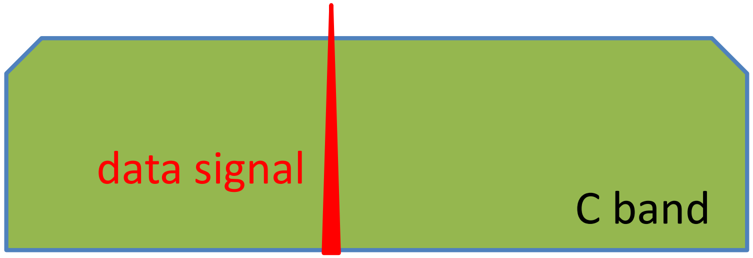
Single fiber capacity

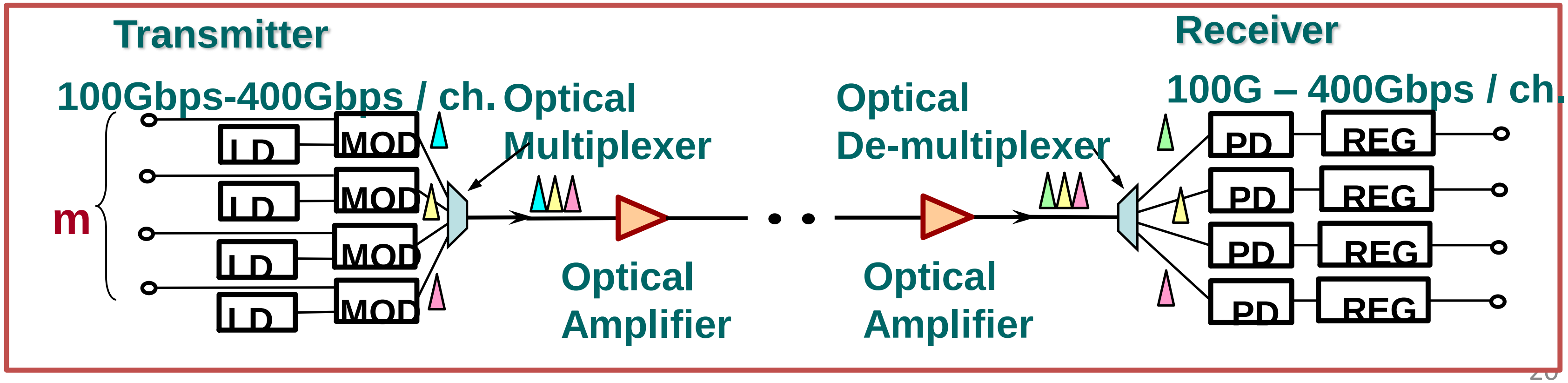
Bandwidth: determined by EDFA, C+L=95nm

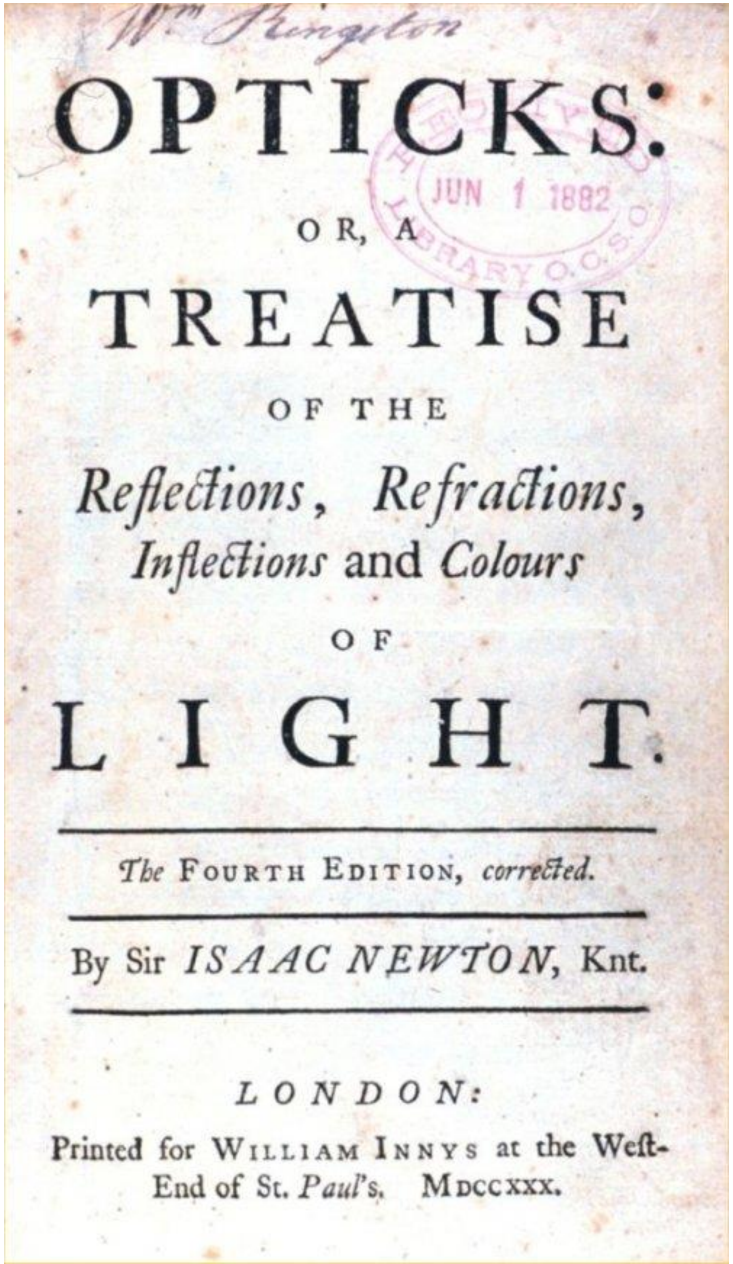
Power: limited by NL

Noise of EDFA, PD, TIA

- Typical C band EDFA has a bandwidth of 35nm. Roughly 4375GHz.
- How to utilize the available bandwidth to increase system capacity – wavelength division multiplexing







Wm Pengilton

OPTICKS:

OR, A

TREATISE

OF THE

Reflections, *Refractions*,
Inflections and *Colours*

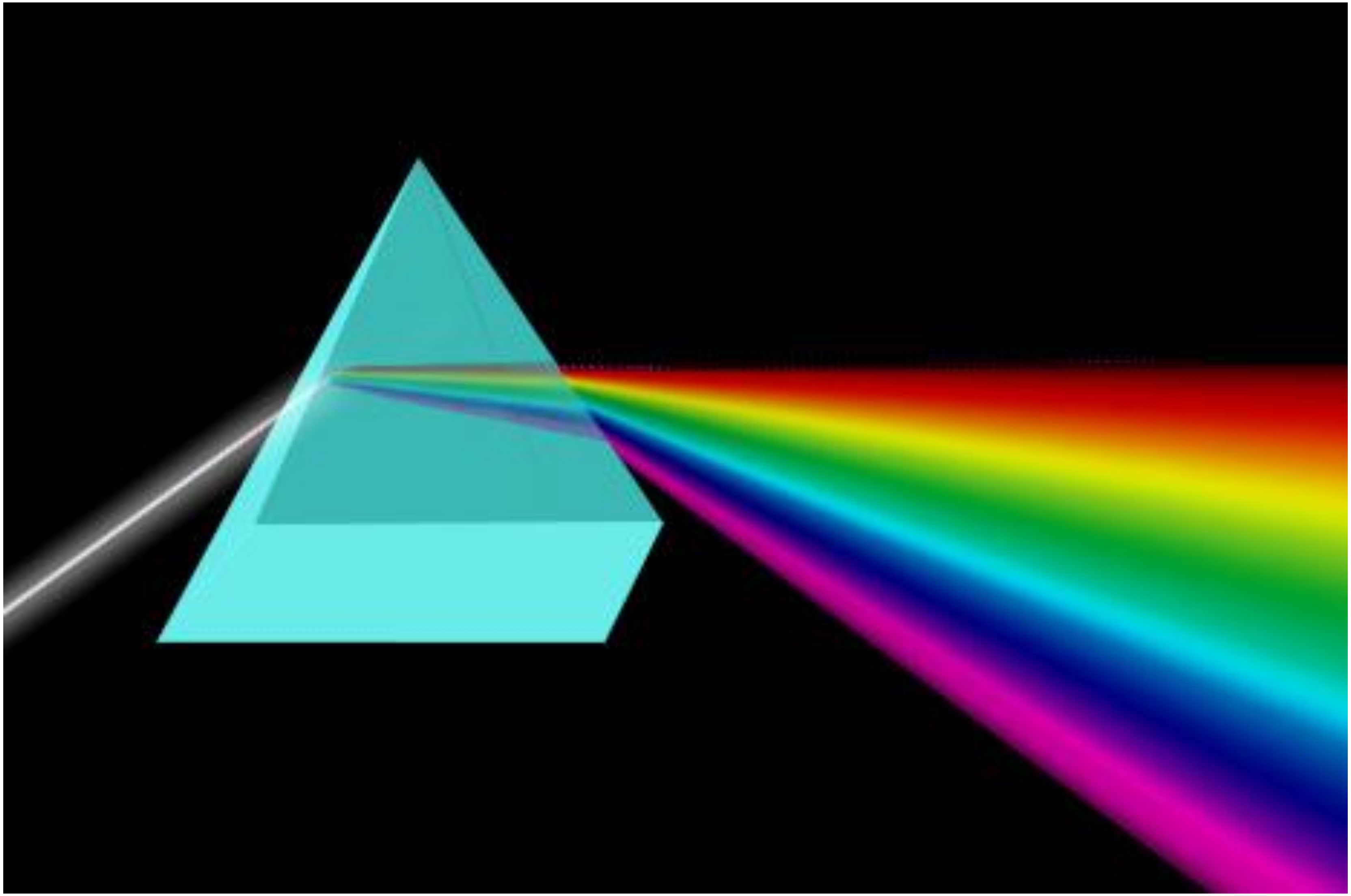
OF

LIGHT.

The FOURTH EDITION, *corrected.*

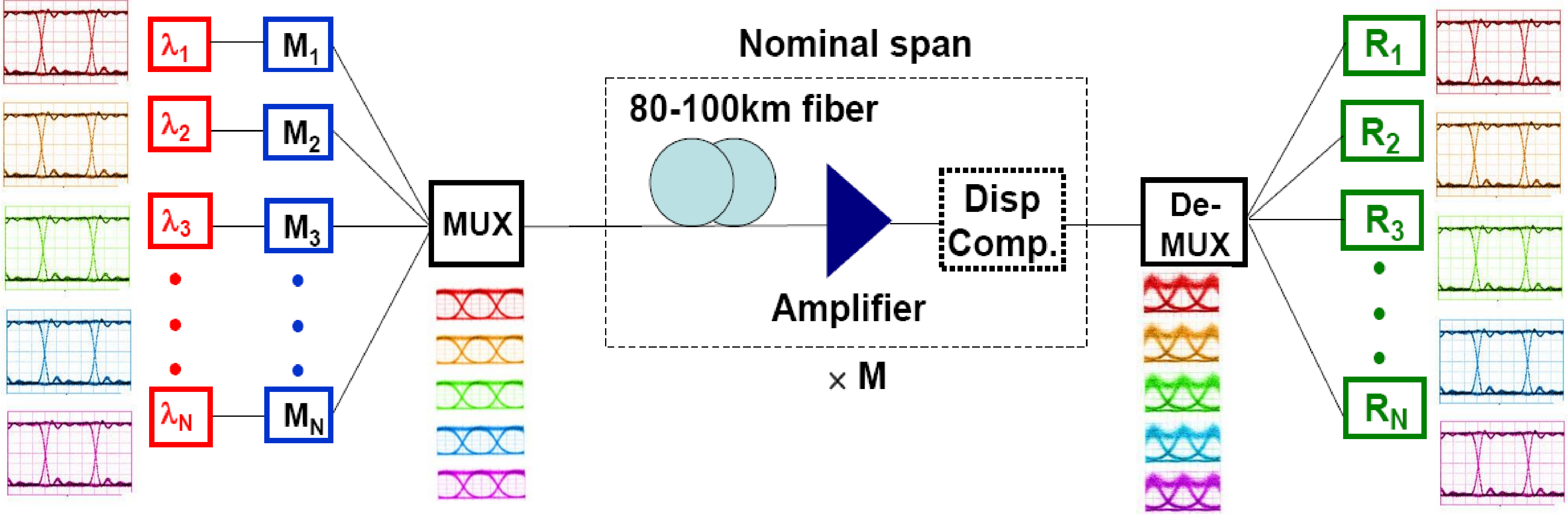
By Sir *ISAAC NEWTON*, Knt.

LONDON:
Printed for WILLIAM INNYS at the Weſt-
End of St. *Paul's*. MDCCXXX.



WDM transmission system

Inventor of WDM: Tingye Li



System design choices:

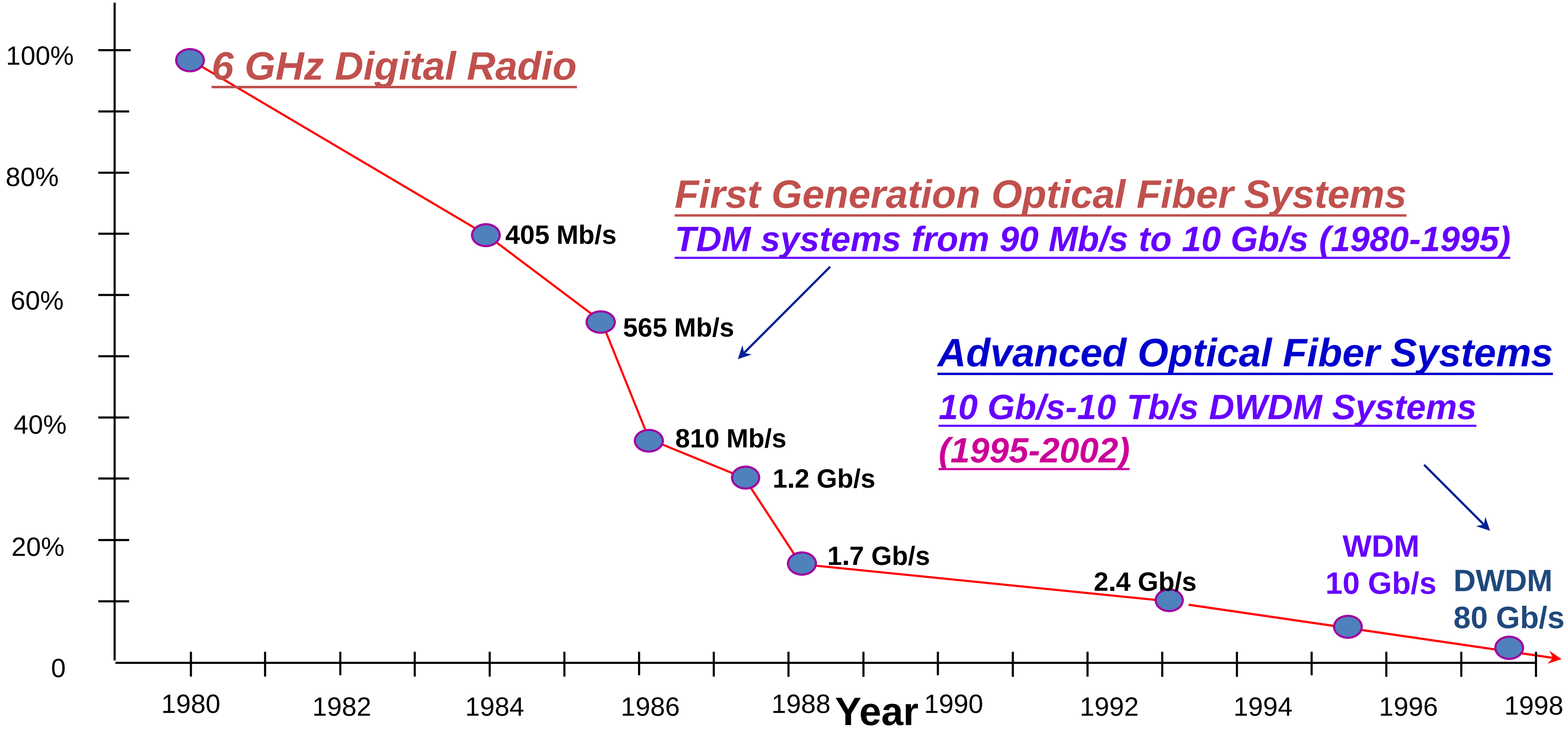
- Method of encoding the data on the optical channel (i.e. modulation format)
- Type of receiver (direct-detection or coherent)
- Loss compensation method (discrete EDFA or distributed Raman)
- Dispersion compensation strategies (optical or electrical)

Rainbow in Great Falls, Montana, USA

Beauty of DWDM in Nature

Optical Fiber Communication Systems Greatly Reduced Cost of Digital Transmission

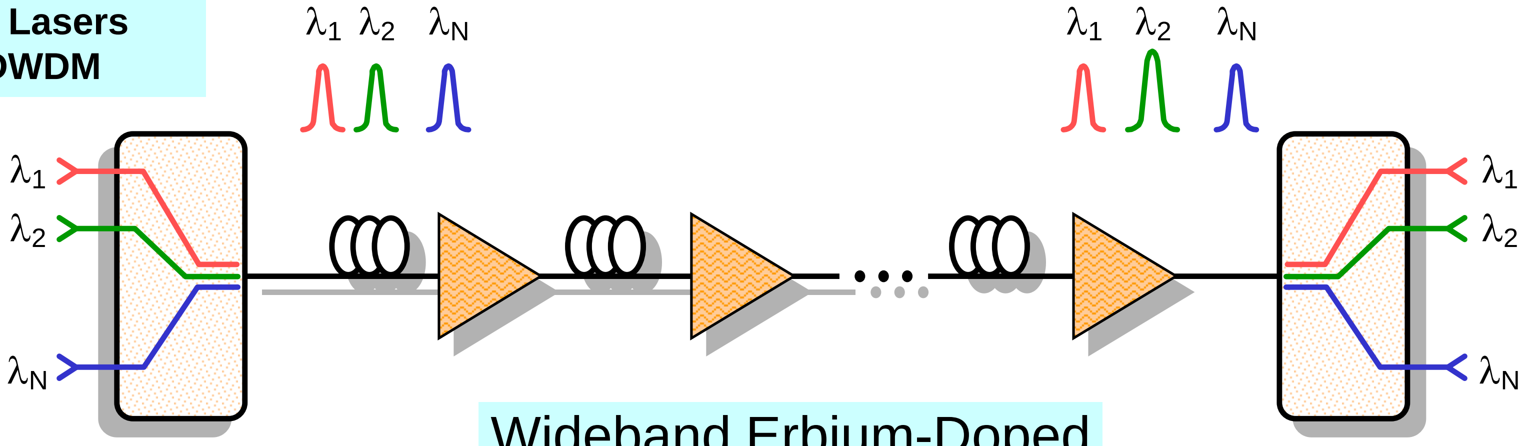
Relative Costs / DS-3 Mile (or 45 Mb/s x 1.6 km)



DWDM Transmission: "Rainbow Principle"
Wideband Optical Amplifiers (EDFAs) are essential

$$SNR_{opt}(dB) = 58 + P_{in}(dBm) - NF(dB) - L_{span}(dB) - 10\log_{10}(N)$$

DFB Lasers for DWDM

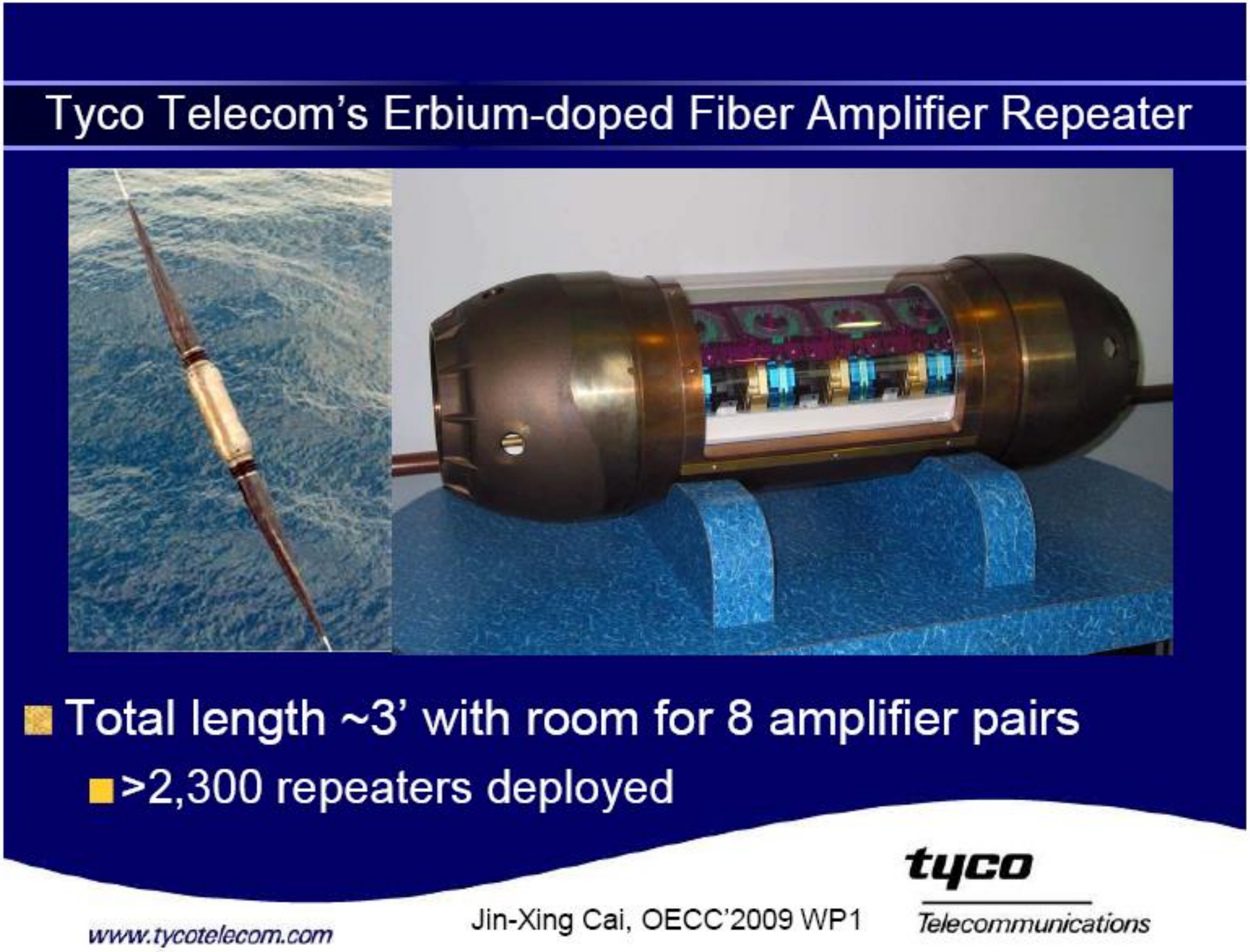


Wavelength Multiplexer (WDM-MUX)

Wideband Erbium-Doped Optical Fiber Amplifiers (EDFA)

Wavelength Demultiplexer (WDM-DMUX)

- *Multiplex Several Optical Channels (Colors of Light) on the Same Fiber for e.g., 8, 16, 40, or 160 Times in Transmission Capacity*
- *Use Wideband EDFA (Erbium-Doped Optical Fiber Amplifier) for simultaneous amplification of all optical channels* ***C+L+S Bands***



Tyco Telecom's Erbium-doped Fiber Amplifier Repeater

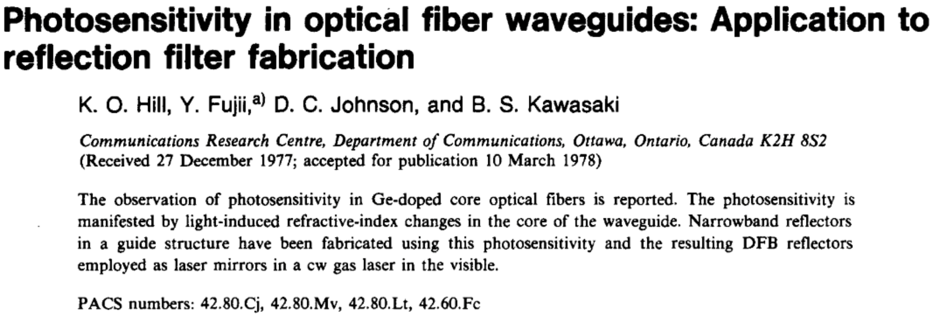
- Total length ~3' with room for 8 amplifier pairs
  - >2,300 repeaters deployed

www.tycotelecom.com

Jin-Xing Cai, OECC'2009 WP1

tyco
Telecommunications

- **Invention of fiber Bragg grating:**
  - By K Hill of CRC Canada
  - DWDM filter, add/drop multiplexer, EDFA gain equalizer



Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication

K. O. Hill, Y. Fujii,[a] D. C. Johnson, and B. S. Kawasaki

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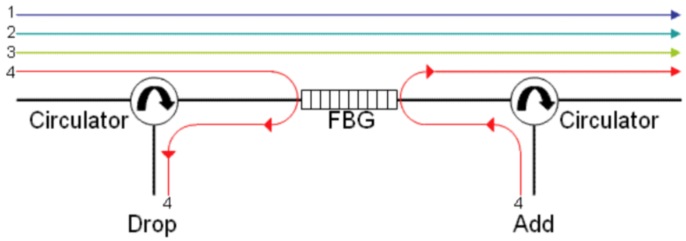
The observation of photosensitivity in Ge-doped core optical fibers is reported. The photosensitivity is manifested by light-induced refractive-index changes in the core of the waveguide. Narrowband reflectors in a guide structure have been fabricated using this photosensitivity and the resulting DFB reflectors employed as laser mirrors in a cw gas laser in the visible.

PACS numbers: 42.80.Cj, 42.80.Mv, 42.80.Lt, 42.60.Fc



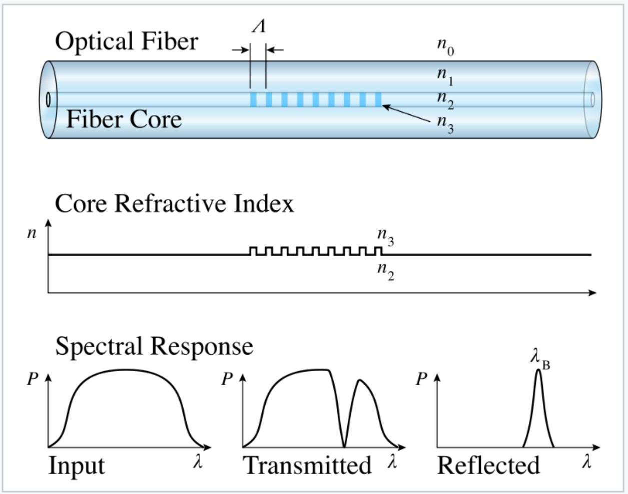


Figure 1: A Fiber Bragg Grating structure, with refractive index profile and spectral response

Hill, K.O.; Fujii, Y.; Johnson, D. C.; Kawasaki, B. S. (1978). "Photosensitivity in optical fiber waveguides: application to reflection fiber fabrication". *Appl. Phys. Lett*. **32** (10): 647

Meltz, G.; et al. (1989). "Formation of Bragg gratings in optical fibers by a transverse holographic method". *Opt. Lett*. **14** (15): 823–5

Ultra-high efficient OFC

◆ **Shannon Capacity**

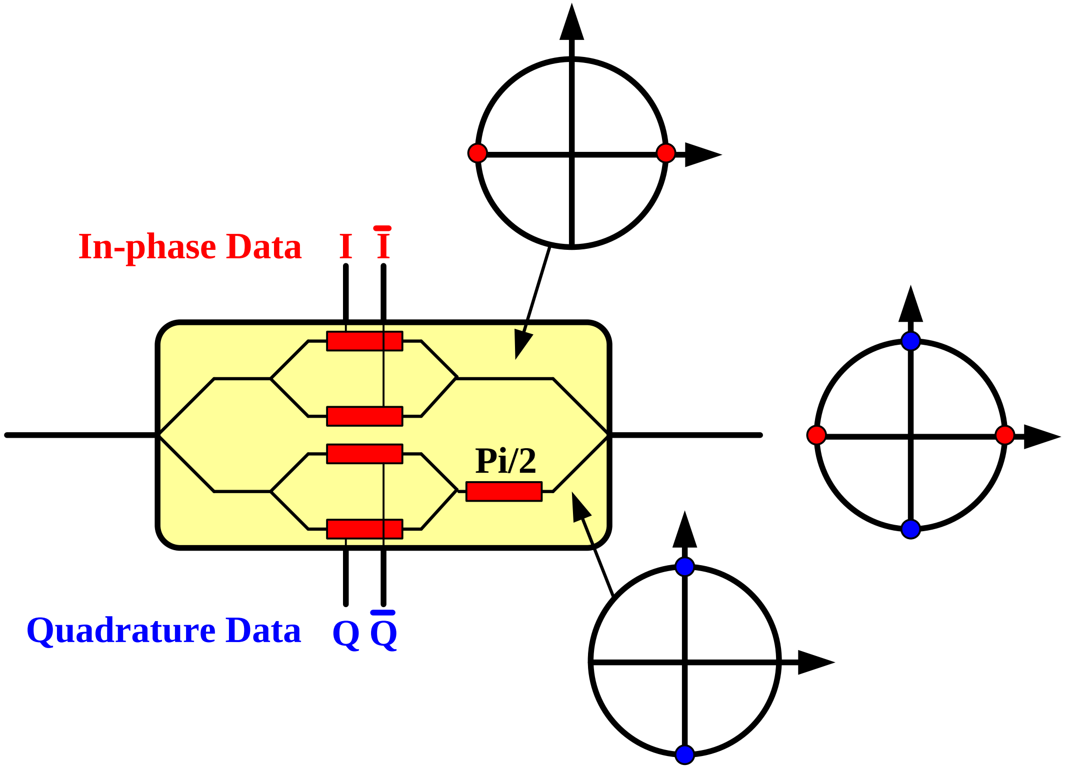
$$(C/B)=\log_2(1+S/N)$$

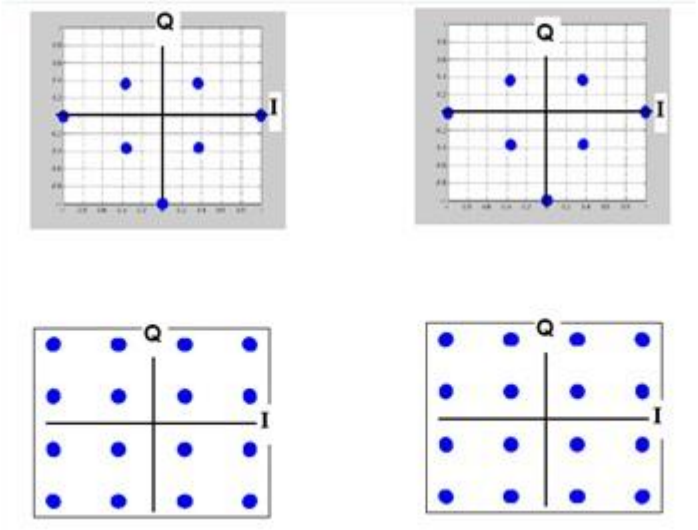
Spectral efficiency： Bit/Hz

Signal to noise ratio in E-domain

- Since bandwidth is decided by EDFA bandwidth, we can increase the spectral efficiency – bit/Hz.
- Improve the bandwidth utilization and efficiency：
  - Multilevel modulation, Nyquist shaping, Superchannel, SEFDM 和 FTN to further increase bandwidth utilization
  - Need detection of phase and polarization – second generation of coherent optical communication systems.

Advanced modulation format





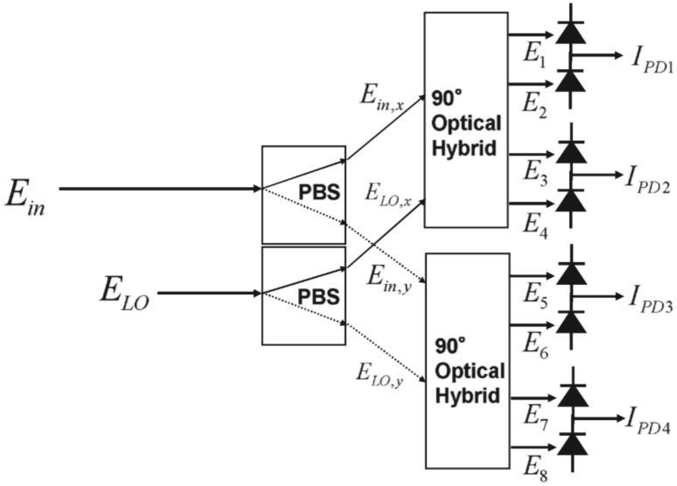
PM-QPSK: 2 bits/symbol – for the same amplifier bandwidth data rate is doubled

PM-QAM8: 6 bits/symbol

PM-QAM16: 8 bits/symbol

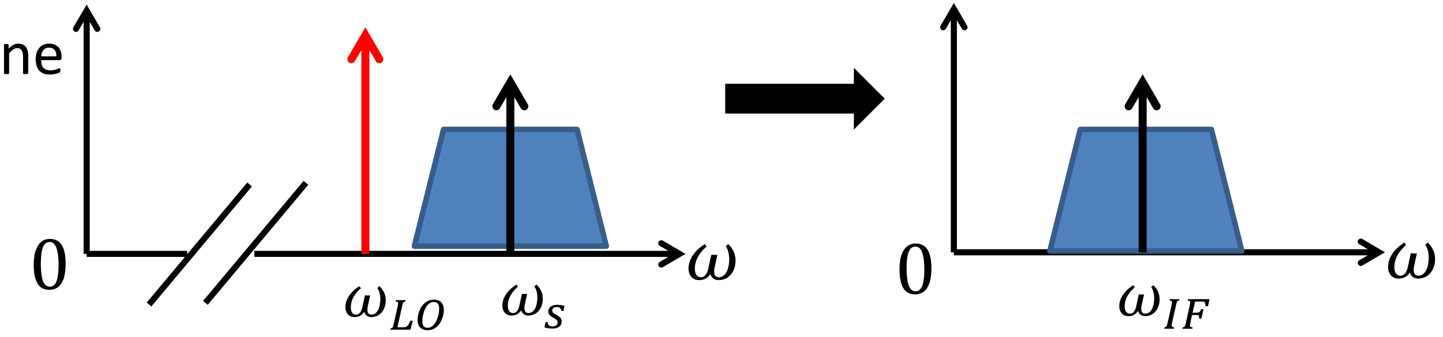
Coherent System – second generation

- Second generation coherent system
  - Intradyne detection using optical hybrid and polarization diversity
  - Frequency tracking, carrier phase recovery, equalization, synchronization, polarization tracking and demultiplexing are all done using DSP



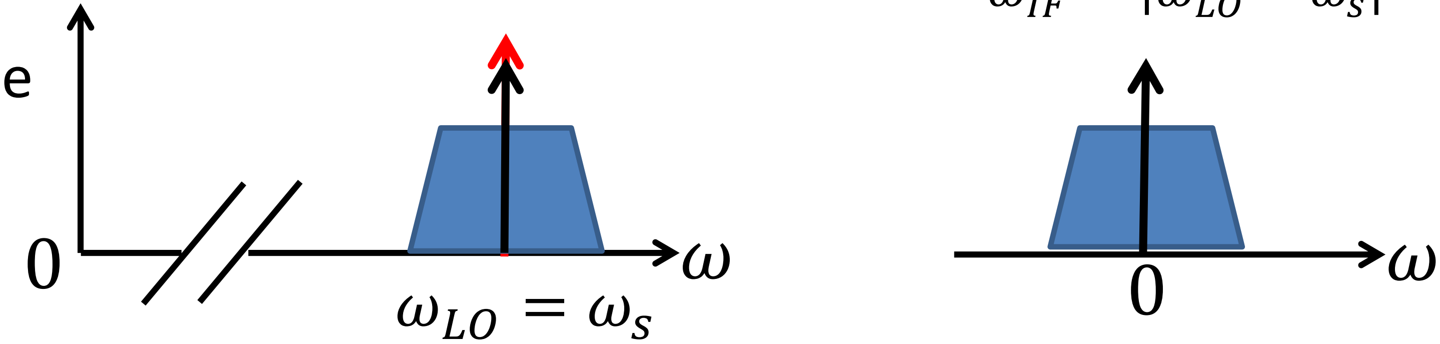
K Kikuchi: Fundamental of Coherent Optical fiber Communications, Journal of Lightwave Technology, Vol. 34, No.1, pp. 157-179, January 2016.

A. Heterodyne

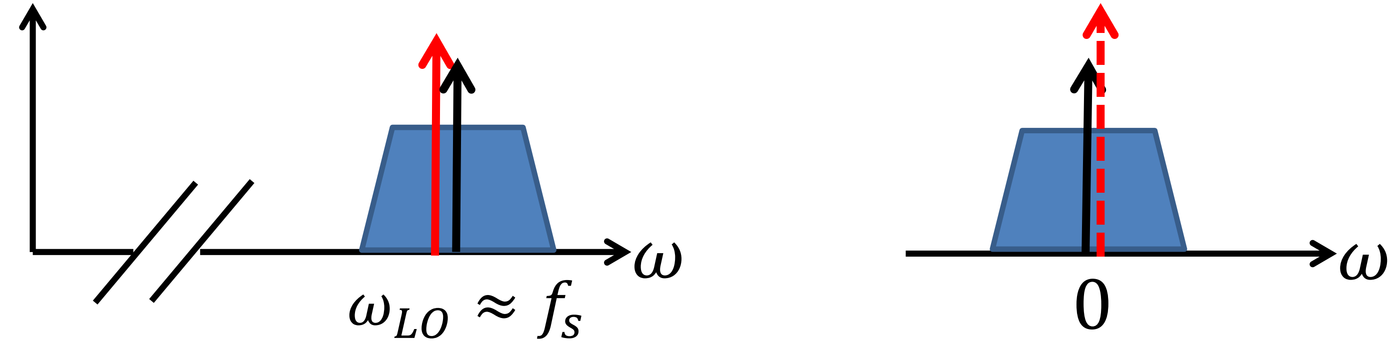


$\omega_{IF} = |\omega_{LO} - \omega_s|$

B. Homodyne



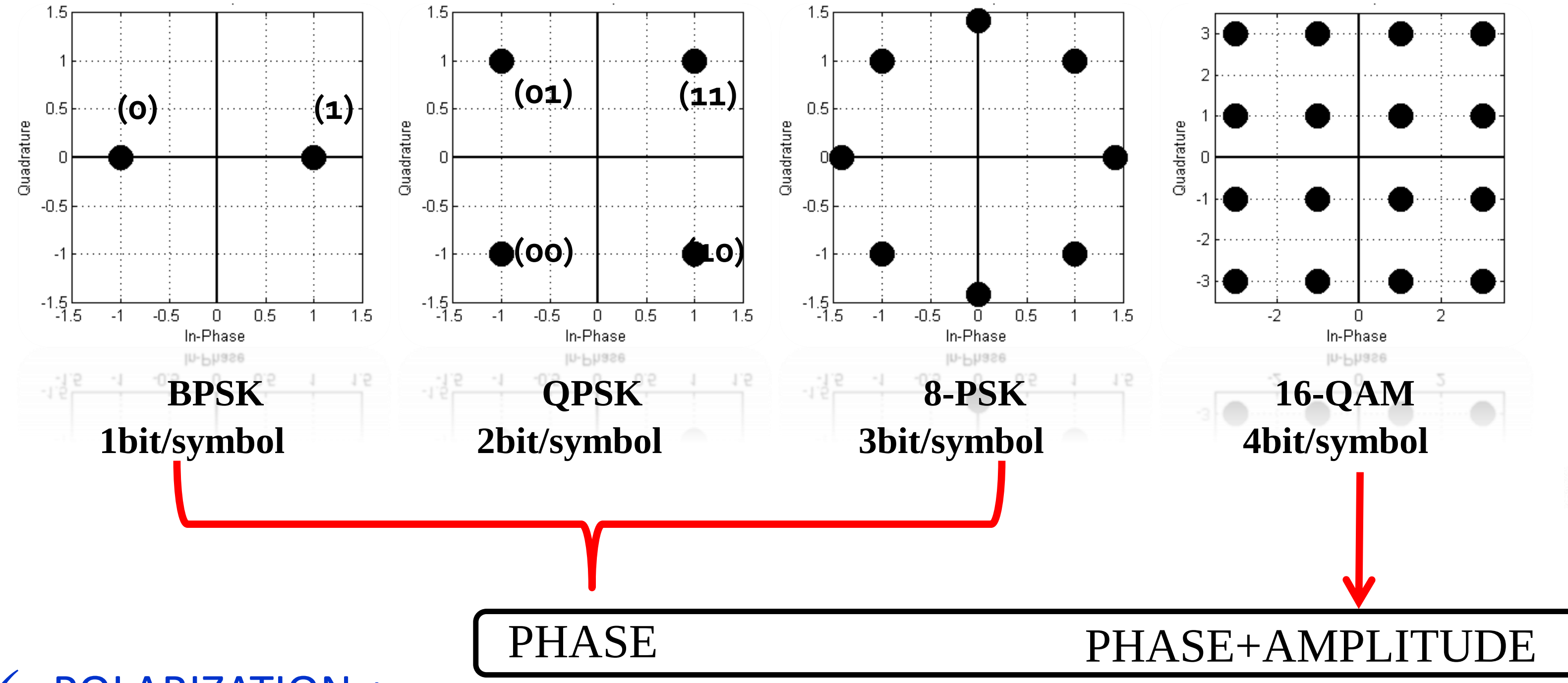
C. Intradyne



$\Delta\omega = |\omega_{LO} - \omega_s|$

Coherent System- second generation

- Degree of freedom



BPSK
1bit/symbol

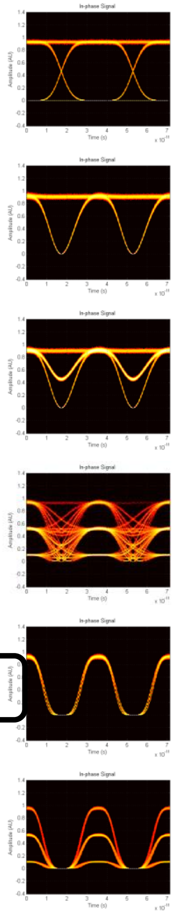
QPSK
2bit/symbol

8-PSK
3bit/symbol

16-QAM
4bit/symbol

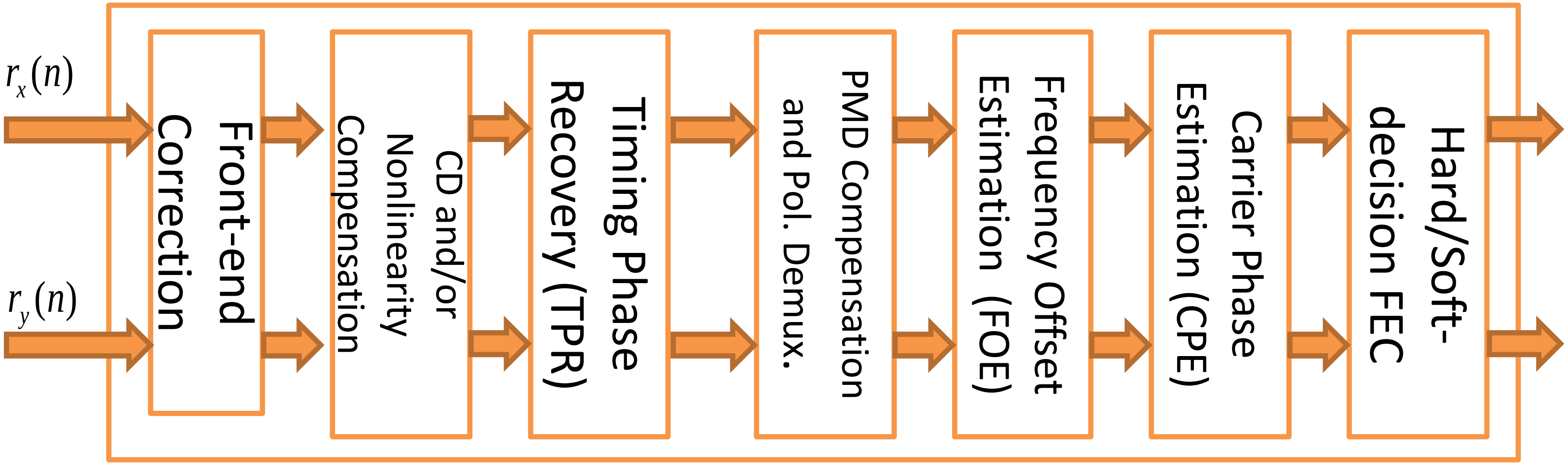
PHASE

PHASE+AMPLITUDE



- ✓ POLARIZATION +
- ✓ Polarization division multiplexing (PDM) – using two orthogonal polarizations to double the transmission rate

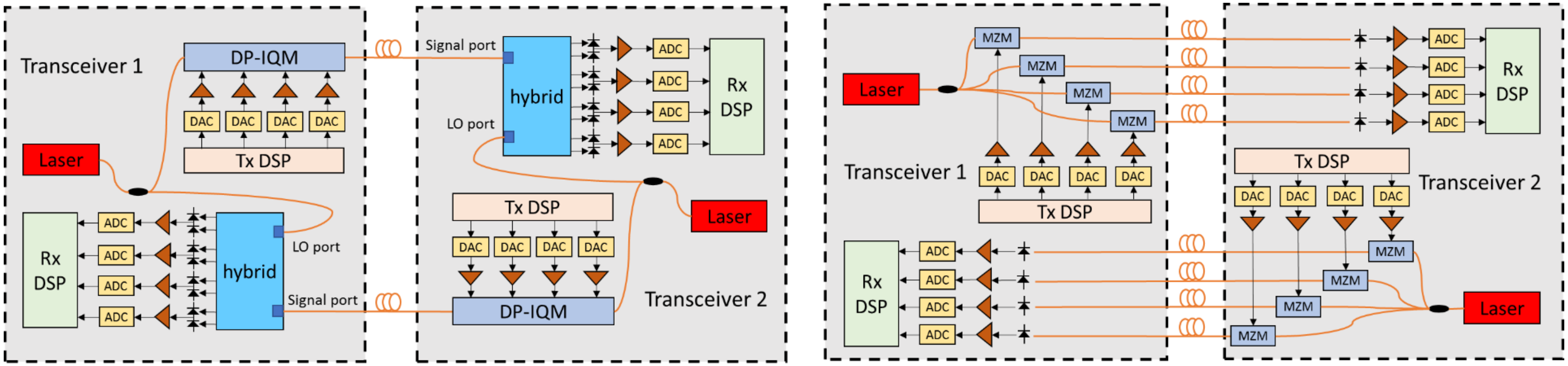
Coherent System- second generation



S J Savory"Digital Coherent Optical Receivers: Algorithms and Subsystems". *IEEE J SEL TOP QUANT, 16 (5)*, 2010

A.P.T. Lau, et al, "Advanced DSP Techniques Enabling High Spectral Efficiency and Flexible Transmissions: Toward Elastic Optical Networks," *IEEE Signal Processing Magazine*, 31, (2), pp. 82–92, March 2014.

Coherent Vs IM/DD



(a) Coherent transceiver

(b) IMDD transceiver

<table>
<tr><th></th><th colspan="6">TX DSP</th><th colspan="8">RX DSP</th></tr>
<tr><td>Coherent</td><td rowspan="4">FEC encoding</td><td rowspan="4">Bit-to-symbol mapping</td><td rowspan="2">Resample</td><td rowspan="3" colspan="2">Pulse shaping</td><td rowspan="4">Pre-emphasis</td><td rowspan="4">Resample</td><td rowspan="2" colspan="2">Timing recovery</td><td>Adaptive Equalization</td><td colspan="2">Carrier recovery</td><td rowspan="4">Symbol-to-bit mapping</td><td rowspan="4">FEC decoding</td></tr>
<tr><td>PAM</td><td colspan="3">Feedforward equalization</td></tr>
<tr><td>CAP</td><td>Upsample</td><td colspan="2">Matched filter</td><td>Downsample</td><td colspan="2">Equalization</td></tr>
<tr><td>DMT</td><td>Add TS</td><td>IFFT</td><td>Add CP</td><td>Synchronization</td><td>Remove CP</td><td>FFT</td><td>Channel estimation</td><td>One-tap equalization</td></tr>
</table>

☐ Coherent detection + DSP (ASIC): Golden combination

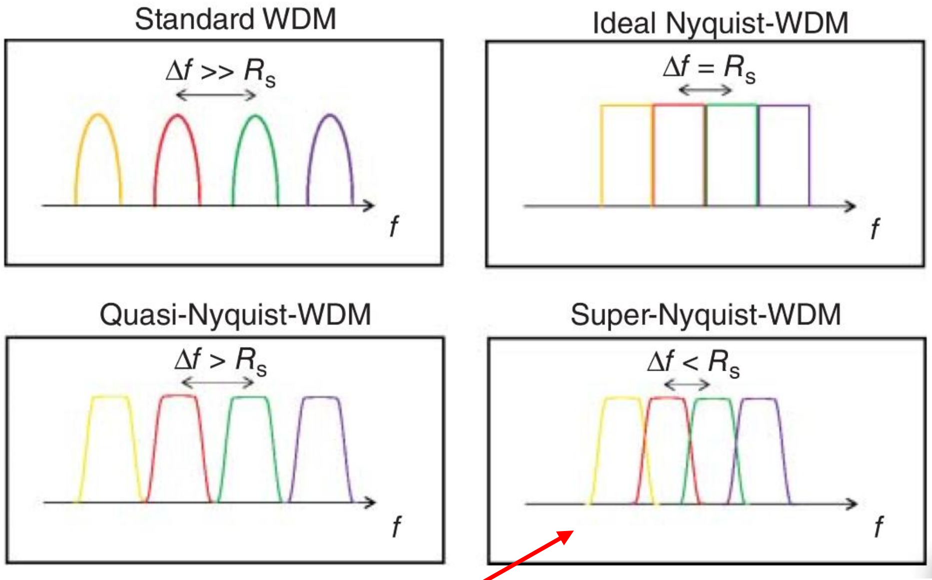
◆ Shannon Capacity

$$(C/B)=\log_2(1+S/N)$$

Spectral efficiency： Bit/Hz

Signal to noise ratio in E-domain

- Bandwidth efficiency
  - Nyquist WDM, Superchannel, SEFDM, FTN to further increase bandwidth utilization



Standard WDM

Ideal Nyquist-WDM

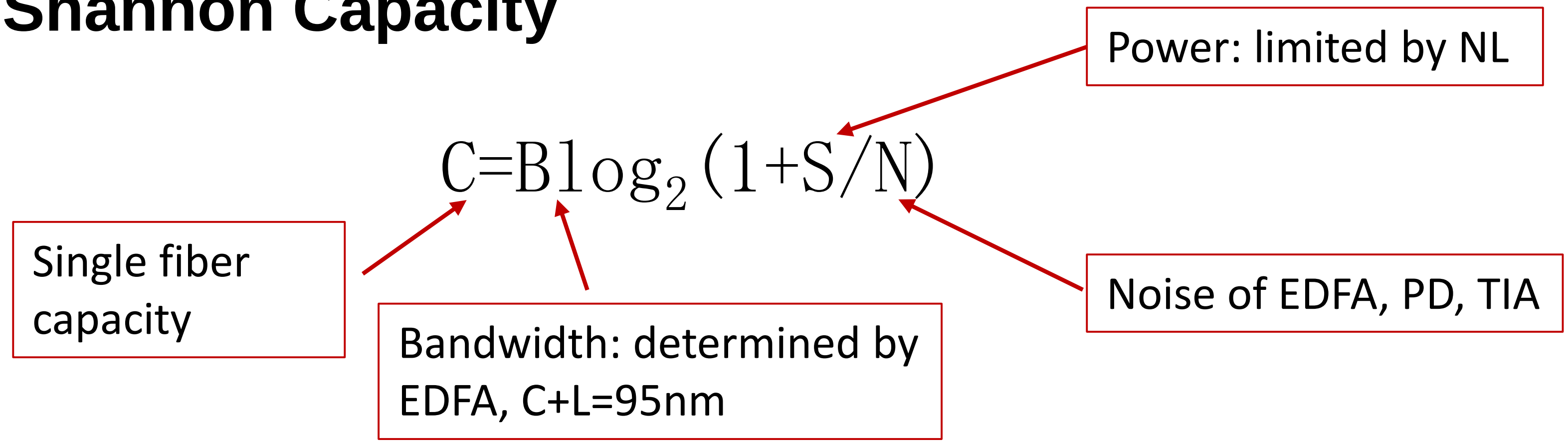
Quasi-Nyquist-WDM

Super-Nyquist-WDM

Detection using Maximum-likelihood sequence estimation (MLSE) or maximum-a-posteriori probability (MAP) algorithms

How to further enhance the data rate?

- **Shannon Capacity**



$$C=B\log_2(1+S/N)$$

Power: limited by NL

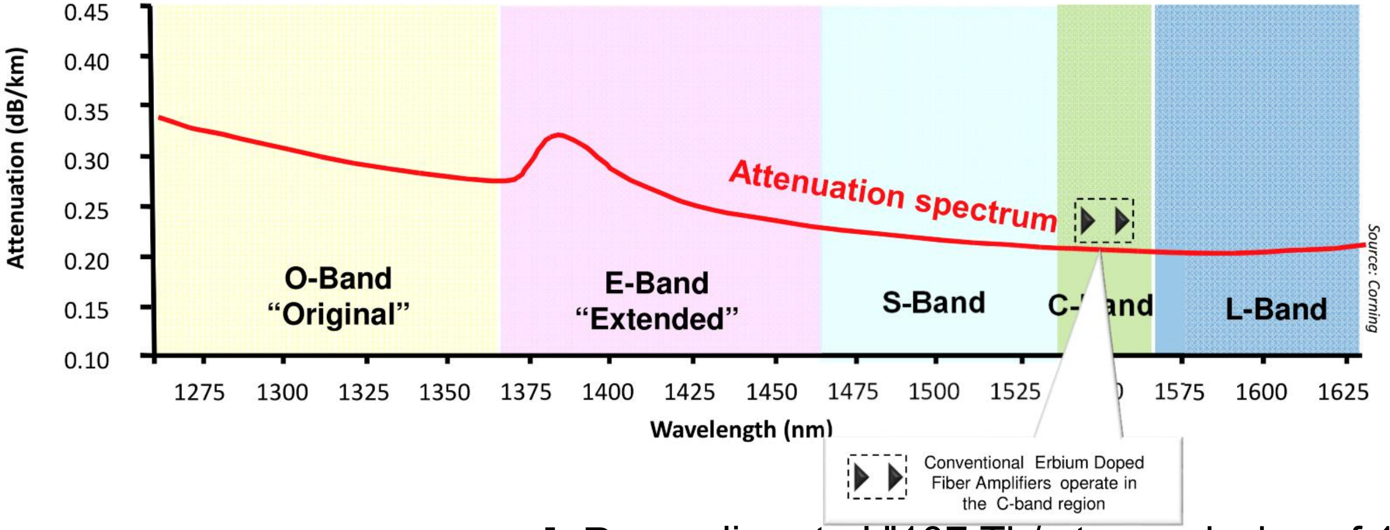
Single fiber capacity

Bandwidth: determined by EDFA, C+L=95nm

Noise of EDFA, PD, TIA

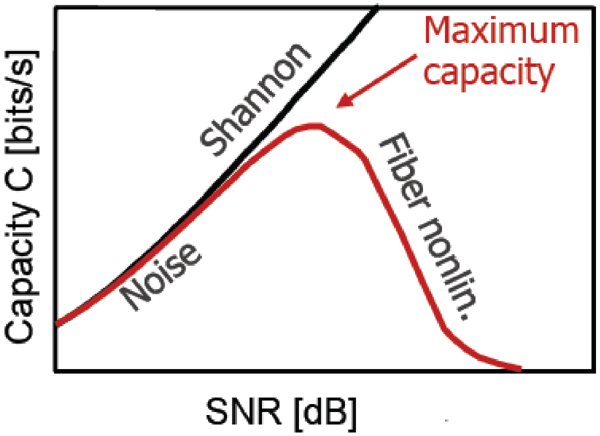
Since we have reached the spectral efficiency limit of quasi linear transmission, further increase in transmission capacity will involve either increase **B (linear increase)** or increase SNR**(increase power: Log increase)**

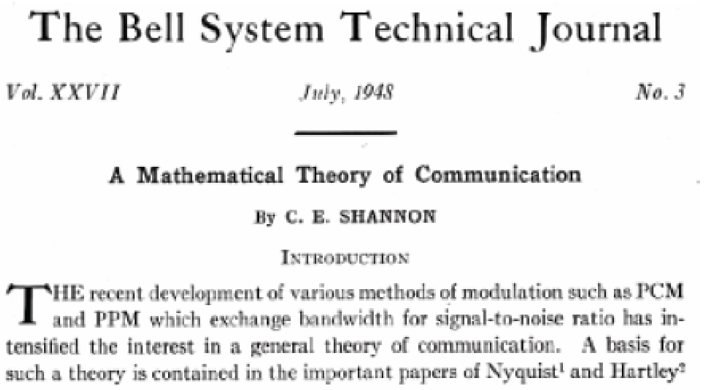
- Adding additional B (linear increase of capacity)：
  - S+C+L
  - SOA， Raman amplifier
- Reduce the fiber loss to have smaller L_{span} (0.145dB/km, limited by Rayleigh scattering）



J. Renaudier et al,"107 Tb/s transmission of 103 nm bandwidth over 3x100 km SSMF using ultra-wideband hybrid Raman/SOA repeaters", ECOC 2018 PDP paper.

Noise and nonlinearity-limited system





The Bell System Technical Journal

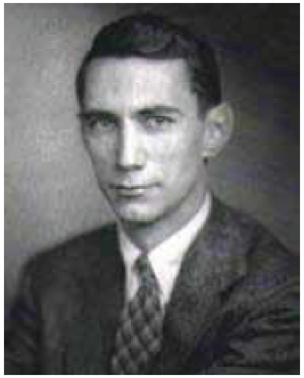
Vol. XXVII *July, 1948* *No. 3*

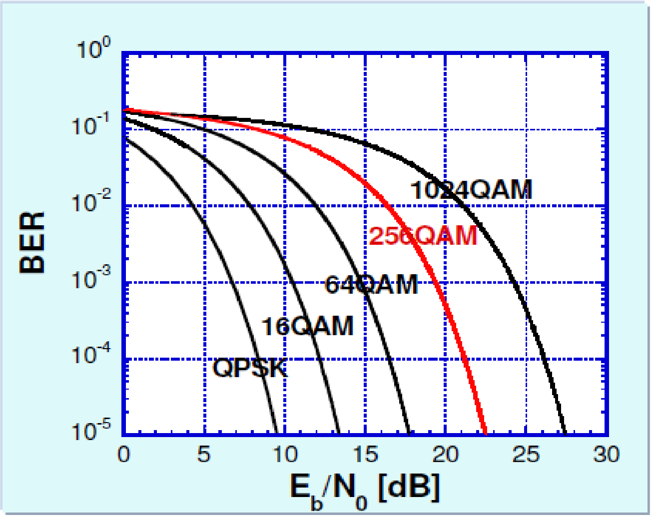
A Mathematical Theory of Communication

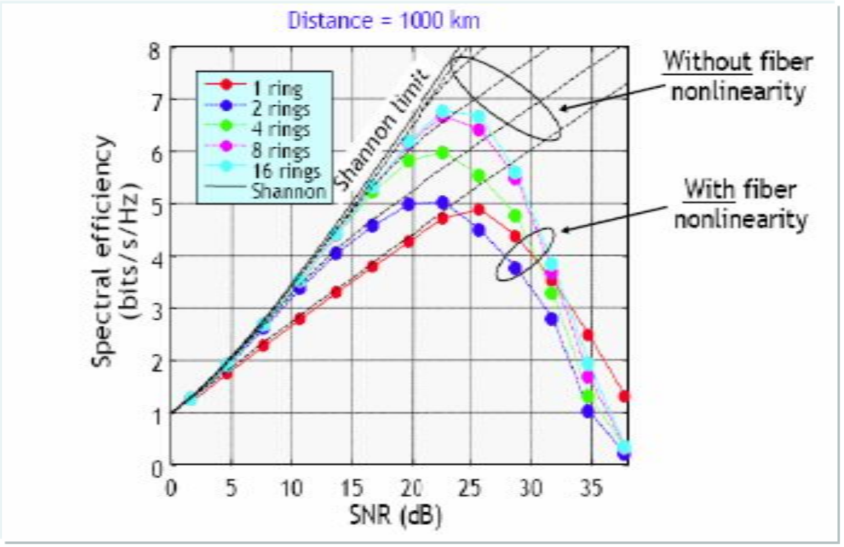
By C. E. SHANNON

INTRODUCTION

THE recent development of various methods of modulation such as PCM and PPM which exchange bandwidth for signal-to-noise ratio has intensified the interest in a general theory of communication. A basis for such a theory is contained in the important papers of Nyquist[1] and Hartley[2]







SE is not free, more signal energy is required for a higher SE.

R.-J. Essiambre et al., Phys. Rev. Lett. (2008) or J. Lightwave Technol. (2010)

Fiber Nonlinearity-Digital Backpropagation

- Digital back-propagation(DBP):

$$\frac{\partial E}{\partial z} + j\frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2} + \frac{\alpha}{2}E = j\gamma |E|^2 E$$

- Use the received waveform, insert it as an input for NLSE, swaps the sign of z, and then solves the NLSE in the backward direction to the transmitter z=0 using split step Fourier method. This has effectively removed the effect of fiber nonlinearity.
- A few dB improvement. In order to realize its effectiveness, need to increase the number of steps per span(up to 10 steps per span). However, complexity can be prohibitive.
- Only intrachnnel nonlinearity.
- Interchannel nonlinearity can be compensated through joint processing of multiple WDM channels
- Machine learning may help in the system design.

Fiber Nonlinearity Mitigation

- Using machine learning techniques such as Support Vector Machine(SVM) at the receiver to create nonlinear detection boundaries

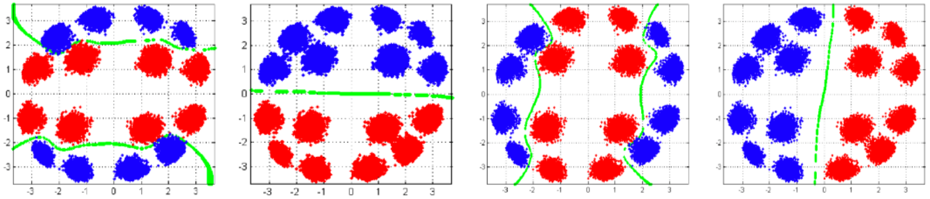
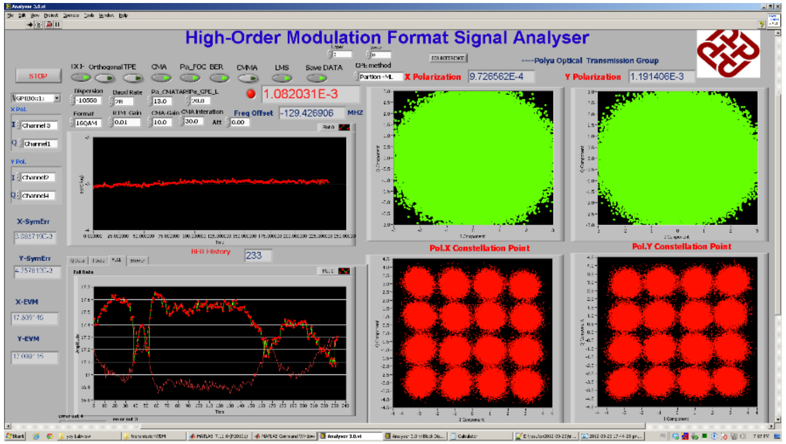


Fig. 8



Dispersion -10560
Baud Rate 28
Format 16QAM
RTM Gain 0.01
CMA-Gain 10.0
CMA Interation 30.0
Att 0.00
Freq Offset -129.426906 MHZ
X Polarization 9.726562E-4
Y Polarization 1.191406E-3
1.082031E-3

Yue Cui, Min Zhang, Danshi Wang, Siming Liu, Ze Li, and Gee-Kung Chang, "Bit-based support vector machine nonlinear detector for millimeter-wave radio-over-fiber mobile fronthaul systems," Opt. Express 25, 26186-26197 (2017)

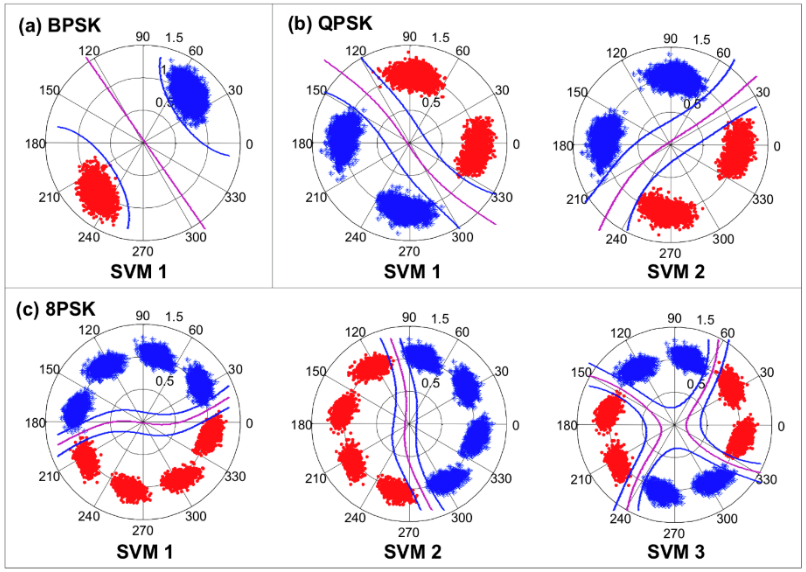
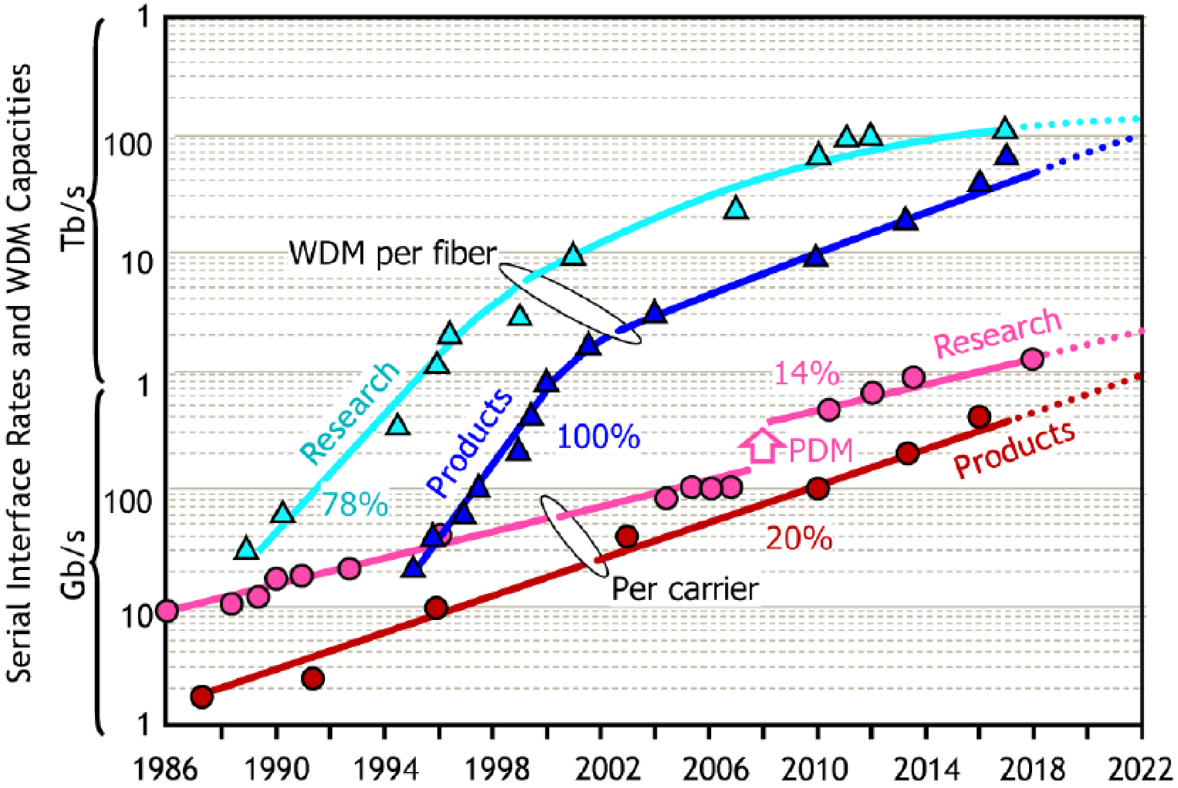


Fig. 4: The nonlinear decision boundaries created by SVM-based classifiers: (a) BPSK by one SVM; (b) QPSK by two SVMs; (c) 8PSK by three SVMs.

D. Wang, M. Zhang, Z. Li, Y. Cui, J. Liu, Y. Yang, H. Wang, Nonlinear decision boundary created by a machine learning-based classifier to mitigate non- linear phase noise, in: Optical Communication (ECOC), 2015 European Con- ference, IEEE, 2015, pp. 1–3.

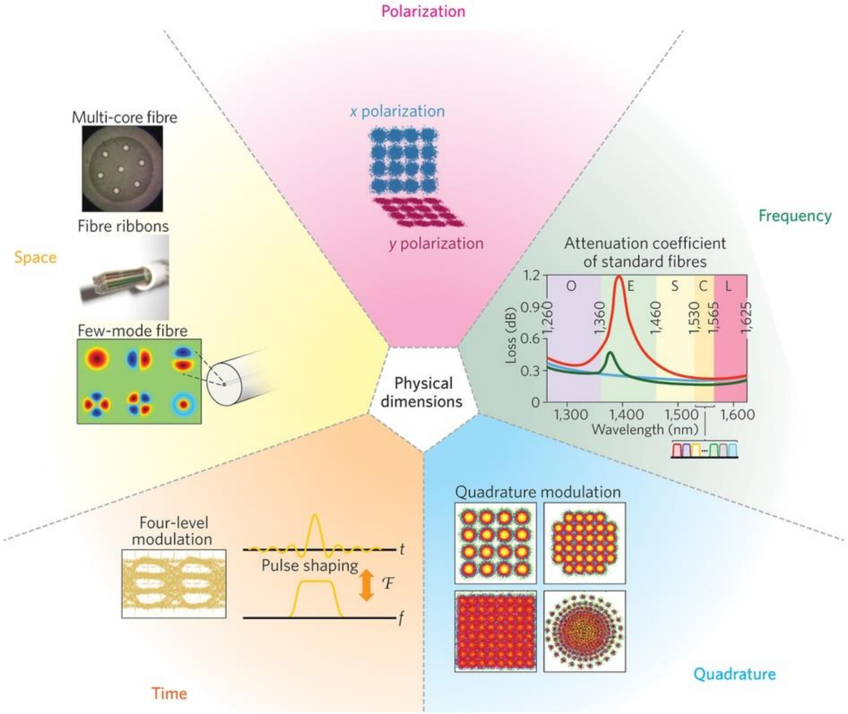
Demand from the market



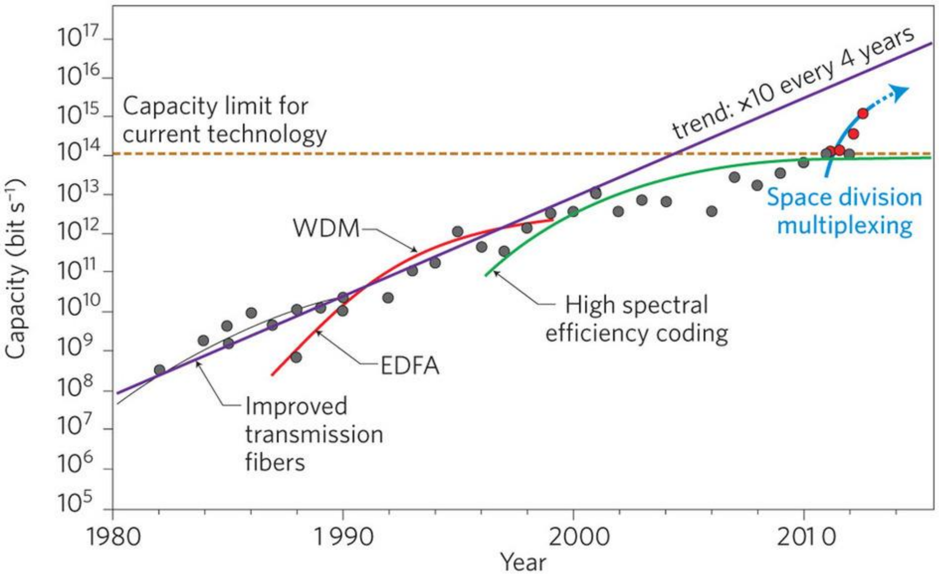
- The growth of telecom market is even faster than research

SDM technology in telecommunication

Spatial division multiplexing (SDM) technique has been intensively investigated for expanding the transmission capacity in telecommunication.

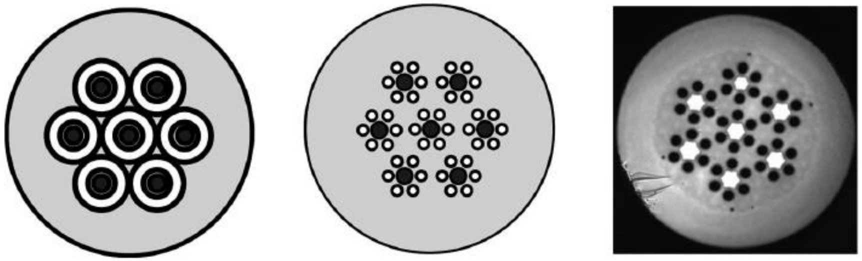


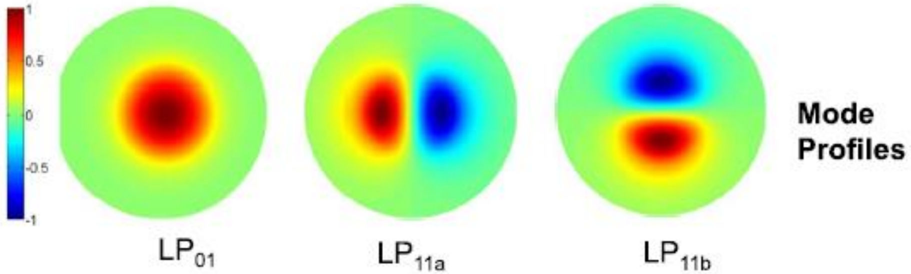
Physical dimensions for modulation and multiplexing of electromagnetic waves [1].

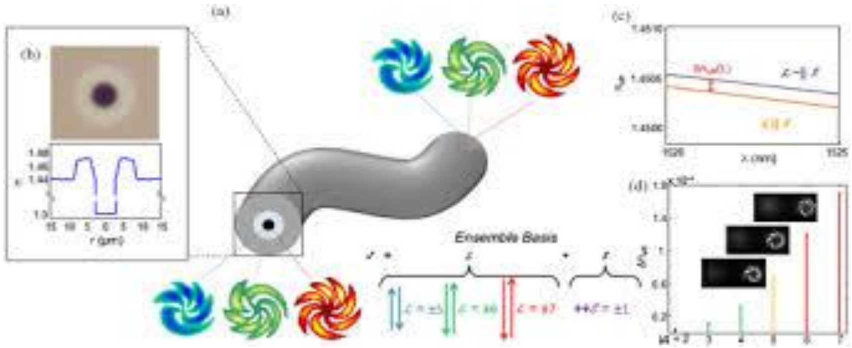


The evolution of transmission capacity in optical fibres as evidenced by state-of-the-art laboratory transmission demonstrations [2].

[1] P. Winzer, “Making spatial multiplexing a reality,” Nat. Photonics 8(5), 345–348 (2014).
[2] D. J. Richardson, J. M. Fini, and L. E. Nelson, “Space-division multiplexing in optical fibres,” Nat. Photon. 7, 354–362 (2013).

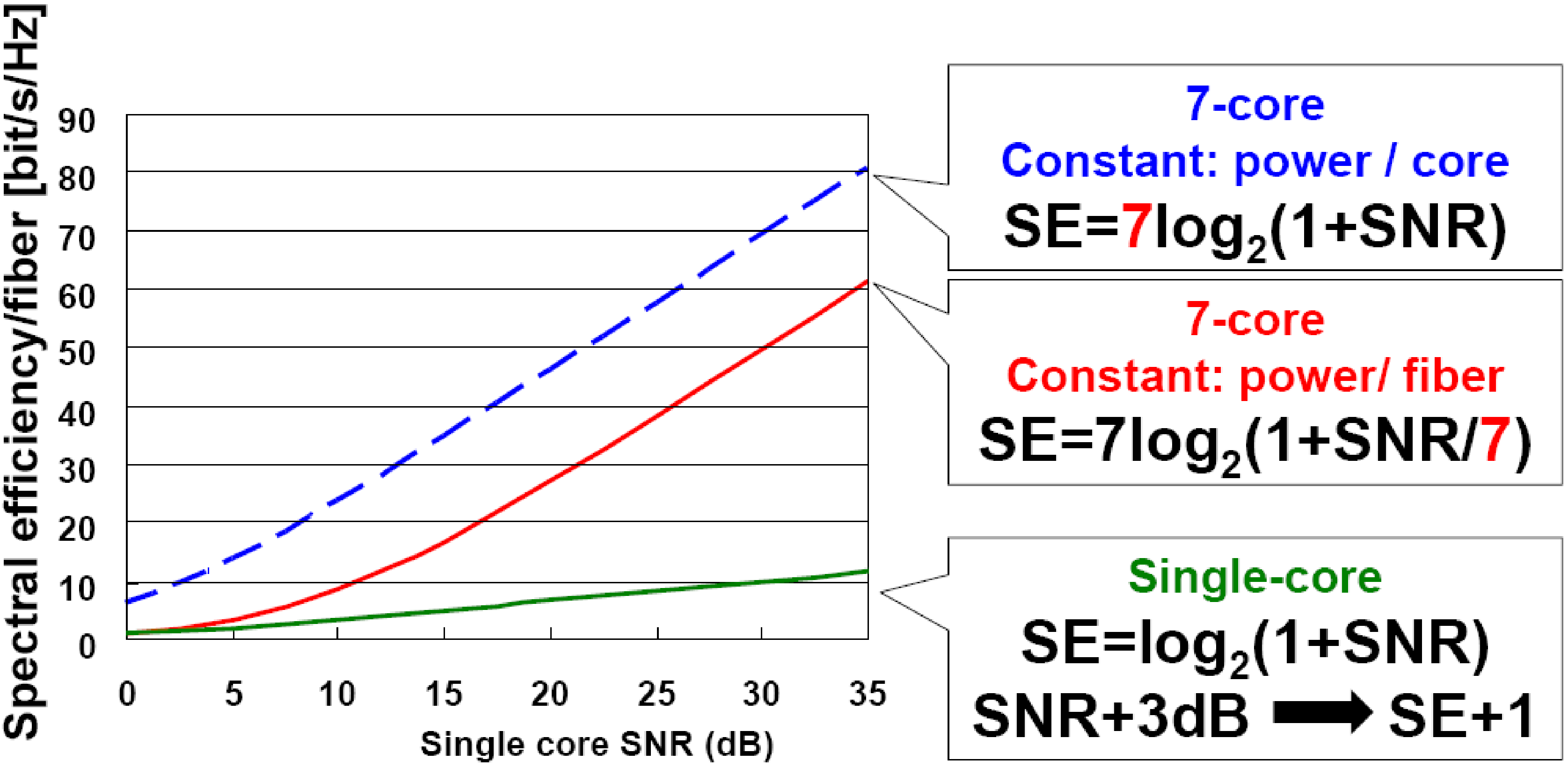






Advances in Optics and Photonics 6, 413–487 (2014)

Why MCF is promising



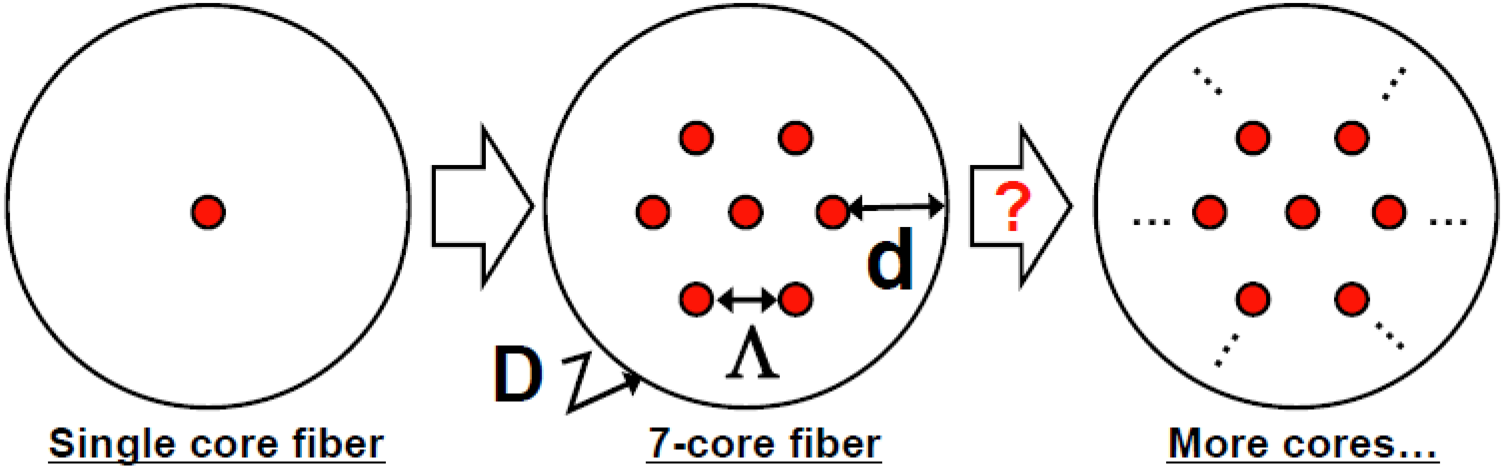
7-core
Constant: power / core
$SE=7\log_2(1+SNR)$

7-core
Constant: power/ fiber
$SE=7\log_2(1+SNR/7)$

Single-core
$SE=\log_2(1+SNR)$
SNR+3dB ➡ SE+1

Merit of improving SE using SDM (Shannon limit)

Challenge of MCF



Fiber structure:

1) Core pitch; 2)Cladding diameter;
3)Core-outer cladding distance; 4)Optical confinement

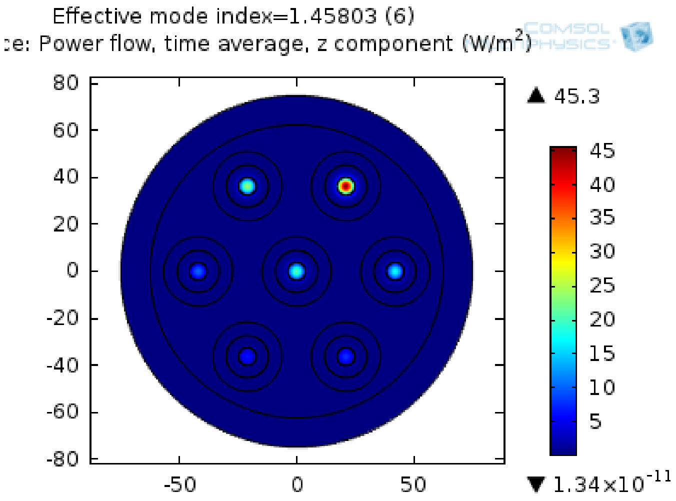
Fiber application:

1) Fiber bend & twist; 2) Larger effective area;
2) Low Loss; 4) Crosstalk

MCF design

Multicore fiber design using COMSOL environment and Matlab

Simulation model:



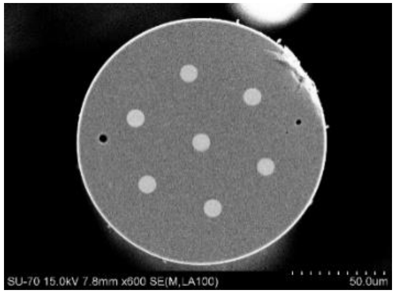
Design procedures

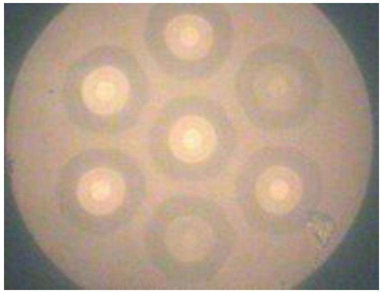
1 refractive index profile map to satisfy MFD, bending loss, cutoff wavelength

2 core pitch to suppress crosstalk and cutoff wavelength of inner core

3 out cladding thickness to suppress excess loss of outer cores.

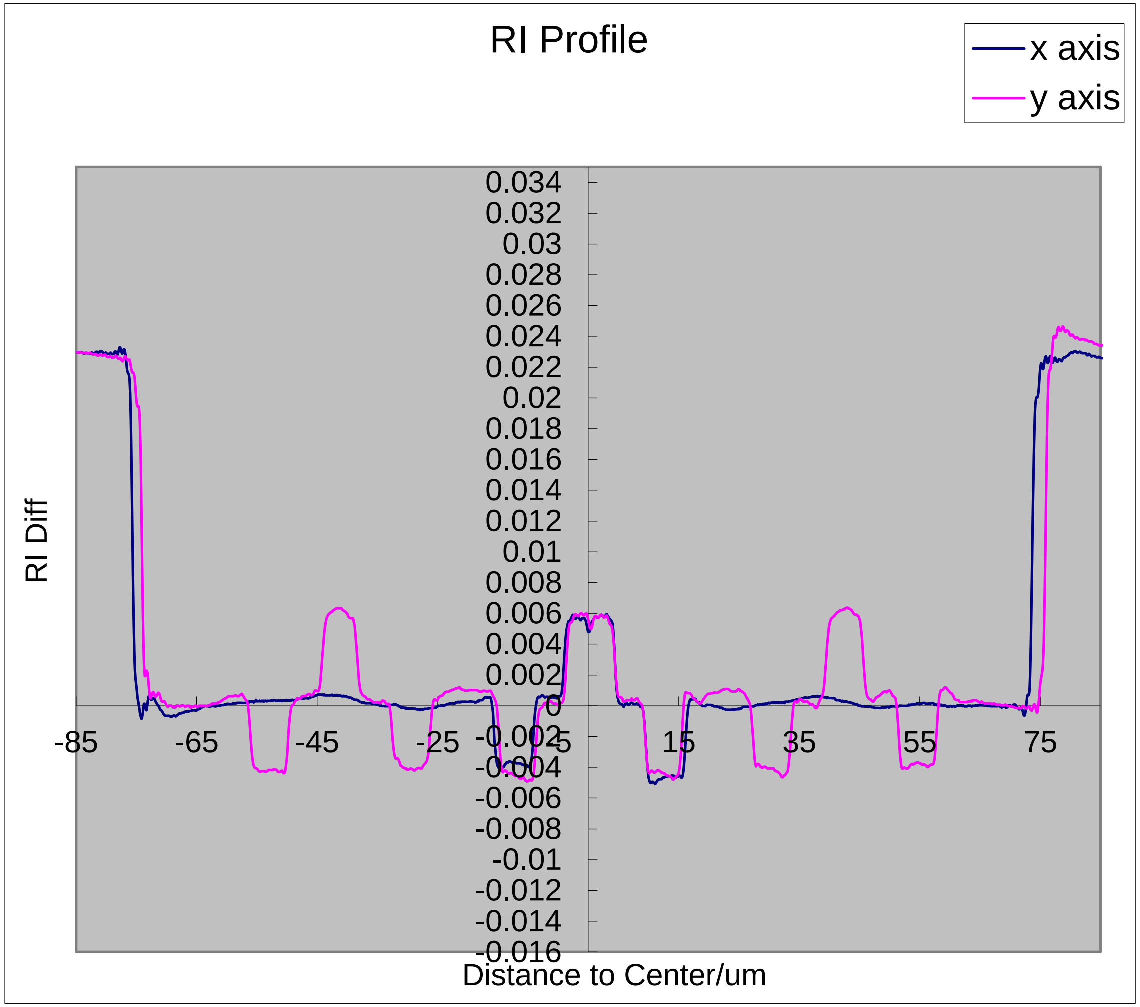
MCF fabrication





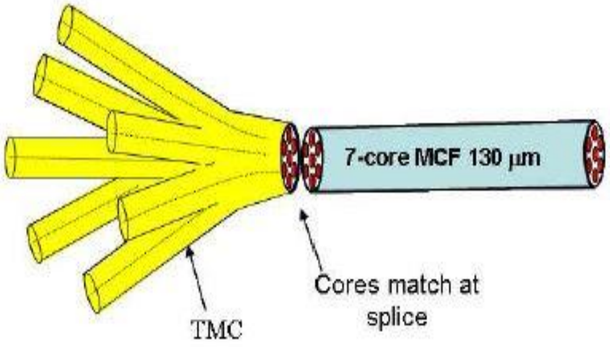
Two kinds of MCF have been fabricated: Homogeneous step-index 7-core fiber; Homogeneous trench-assisted (TA) 7-core fiber

Optical Properties Characteristics		
	Value	Typical
Cross Talk（Adjacent Core）	**<-40dB/100km**	**-50dB/100km**
Attenuation@1310nm (dB/km)	< 0.45	0.3
Attenuation@1550nm (dB/km)	**< 0.25**	**0.18**
Zero Dispersion Wavelength (nm)	1290～1320	1308
Dispersion@1550nm (ps/nm/km)	17±1.0	17.1
PMD ps/sqrt(km)	< 0.2	< 0.2
Cable Cutoff Wavelength λcc (nm)	< 1350	1300
Mode Field Diameter@1310nm(μm)	8.5±0.5	8.4
Mode Field Diameter @1550nm(μm)	9.5±0.5	**9.5**


RI Profile
x axis
y axis
RI Diff
0.034
0.032
0.03
0.028
0.026
0.024
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
-85
-65
-45
-25
-5
15
35
55
75
Distance to Center/um

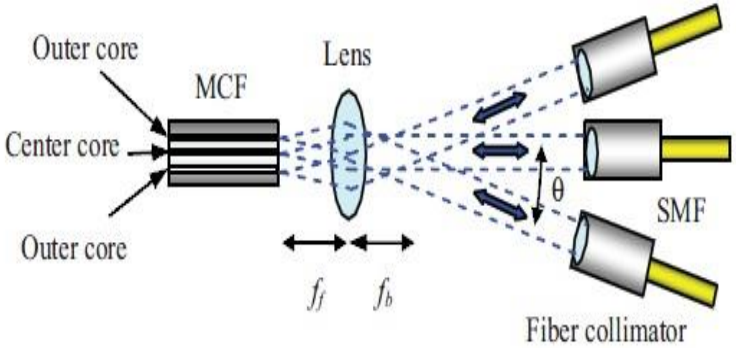
MCF SDM MUX/DEMUX methods

Tapered MCF Connector



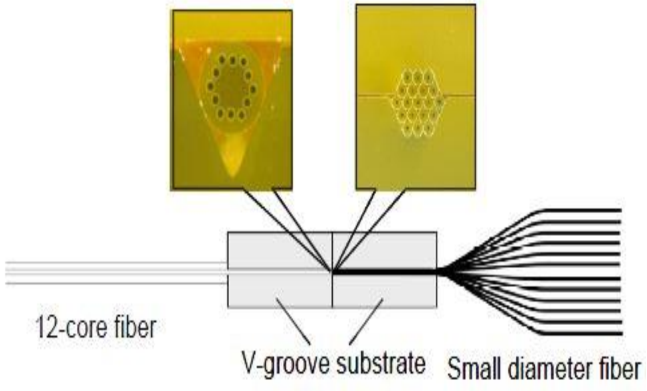
B. Zhu et al. *Opt. Express, 18, pp* 117-122.

Lens Coupling



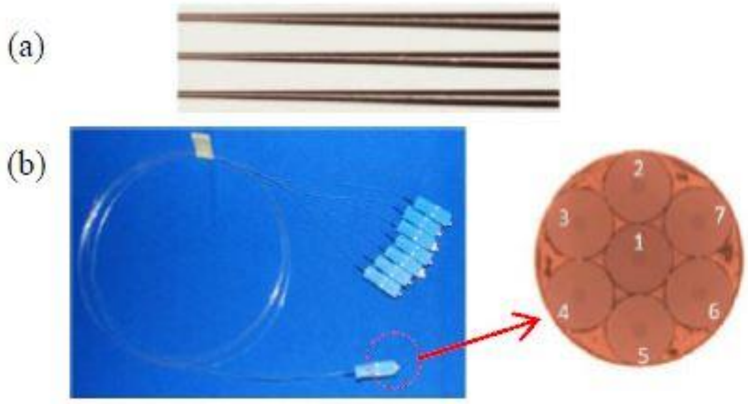
Yusaku Tottori et al. *Photonics Technology Letters, 24*.

Fiber Bundle with V-groove



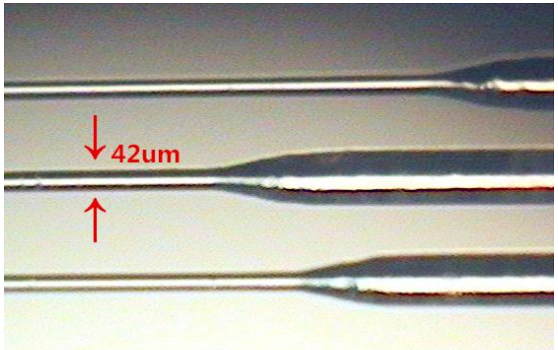
H. Takara et al. *ECOC Postdeadline Papers 2012*

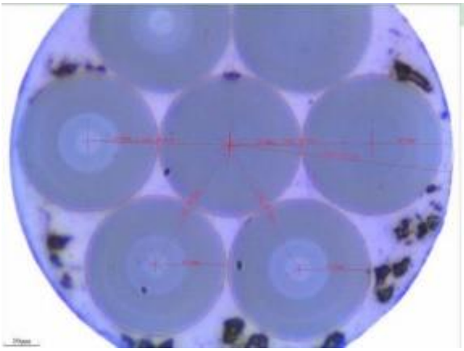
Fiber Bundle Method



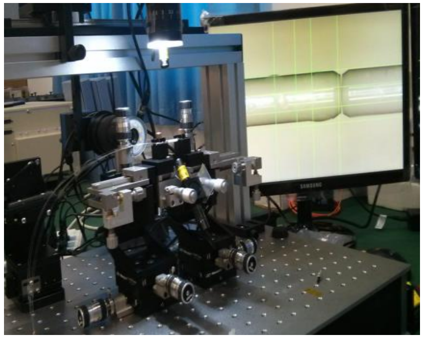
Osamu Shimakawa et al. *OFC/NFOEC OM3I.2 2013*

Fiber bundles preparations

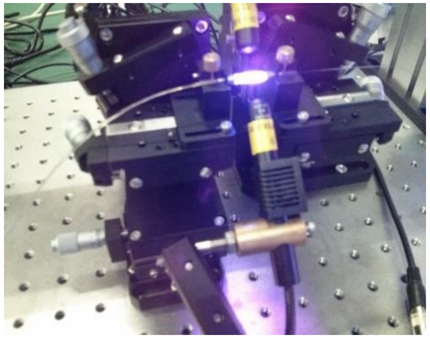




Free space alignment



UV curing



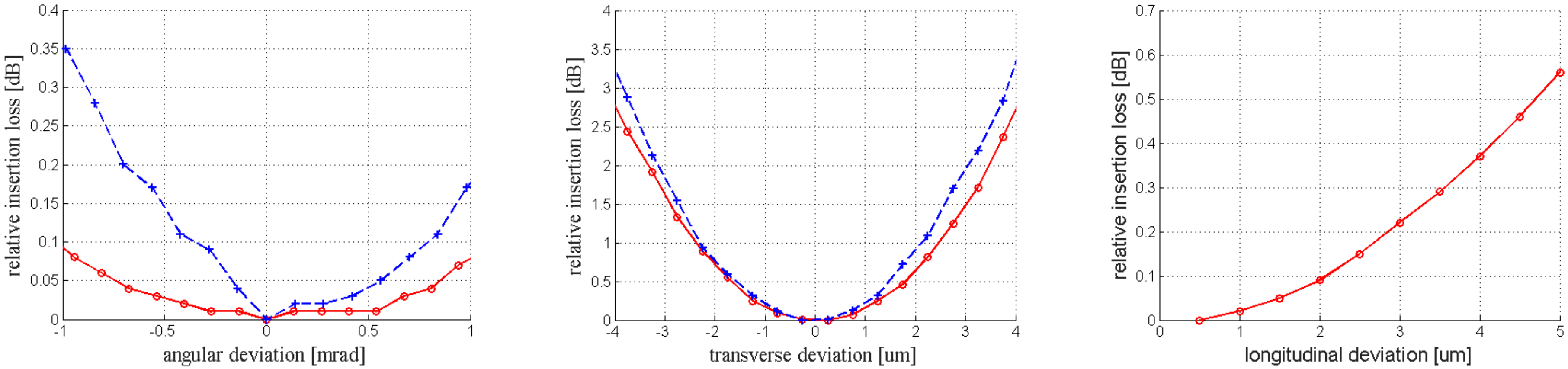
in-house product

Chinese patent pending, 201510691273.x

Chinese patent licensed, ZL201310069346.2

Properties of fan-in/fan-out device

loss analysis



Characterization of fan-in/fan-out device

Core	1	2	3	4	5	6	7	**AVE**
IL(dB)	0.3	1.0	0.8	1.0	1.2	1.0	1.0	**<1.0**
RL(dB)	-54	-55	-56	-55	-53	-57	-55	**-55**

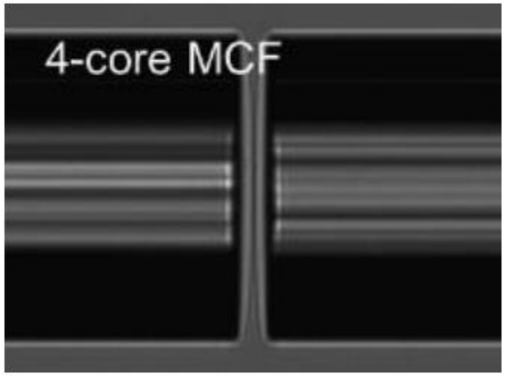
Crosstalk between channels is less than -50 dB

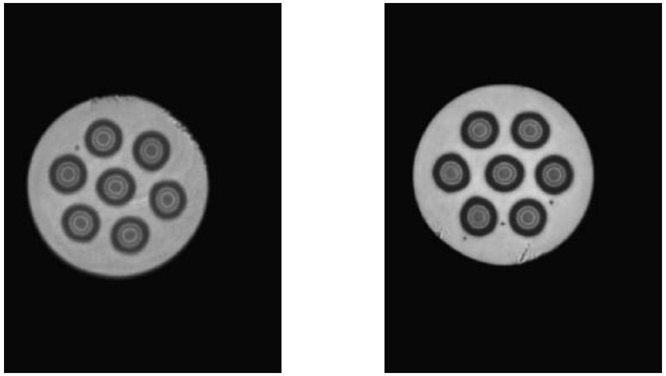
Borui Li, et al., Opt. Express 23, 10997-11006 (2015)

Low loss MCF splicing : angle rotation alignment

Side-view based alignment method

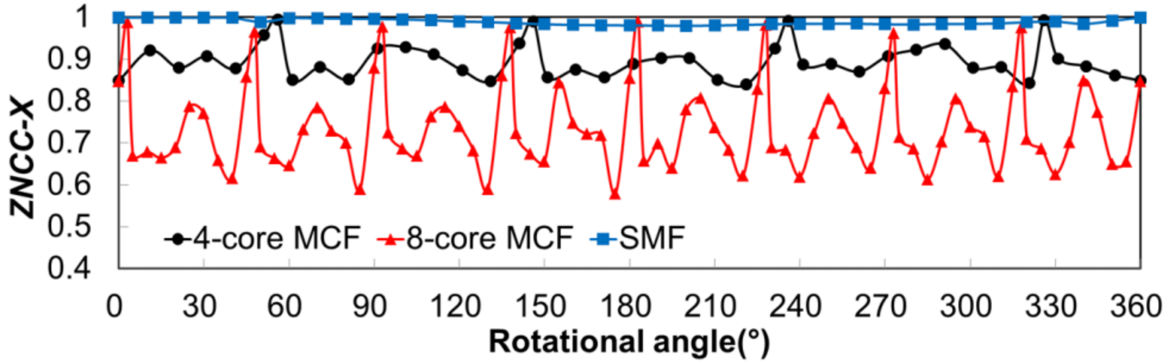
End-view based alignment method





K.Saito et al. OFC(2016),paper M3F.3.

Results of side-view based method



Lack of accuracy:

need to rotate fiber to different angle when splicing, accuracy is less than 4° .

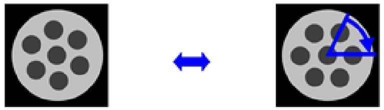
K. Saito et al. OFC(2016),paper M3F.3.

Alignment procedure: cross-correlation method

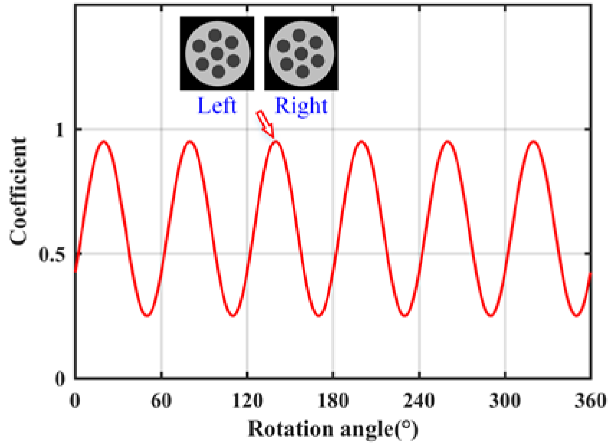
Step 1: Acquire the image

Step 2: Extract the cladding edge

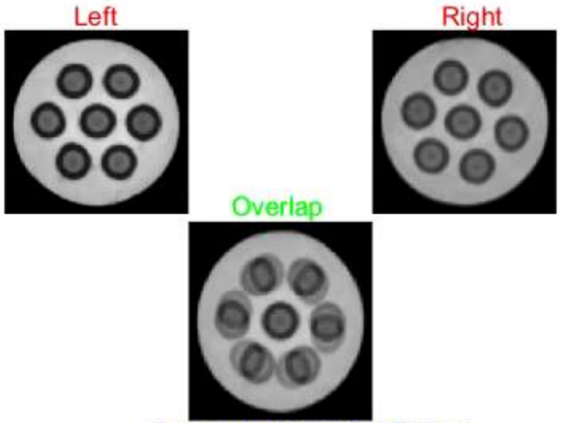
Step 3: Resize the image

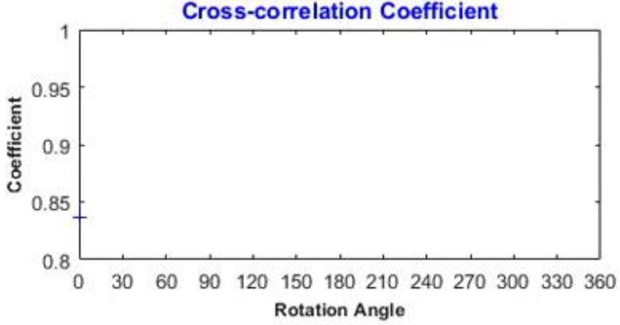


Step 4: Rotate the image and calculate the cross-correlation coefficient



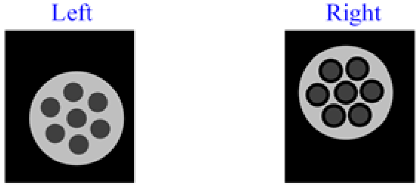
$$coefficient = \frac{\sum_{m}\sum_{n}\left(A_{mn}-\bar{A}\right)\left(B_{mn}-\bar{B}\right)}{\sqrt{\left(\sum_{m}\sum_{n}\left(A_{mn}-\bar{A}\right)^{2}\right)\left(\sum_{m}\sum_{n}\left(B_{mn}-\bar{B}\right)^{2}\right)}}$$





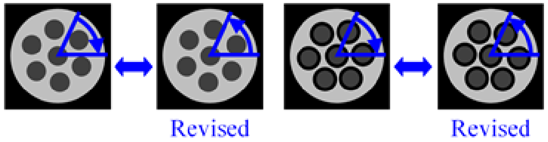
Alignment procedure: self-correlation method

Step 1: Acquire the image

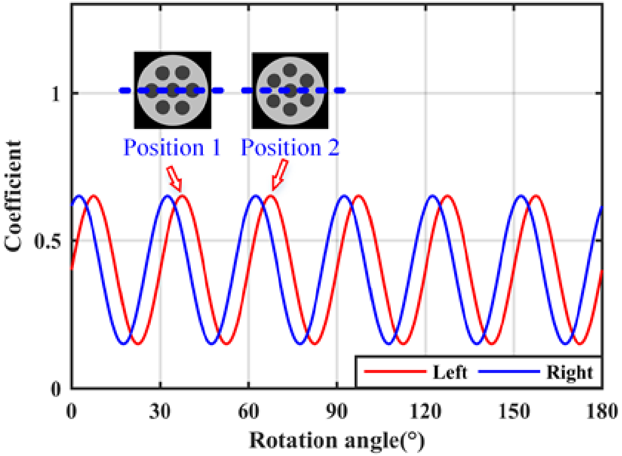


Step 2: Extract the cladding edge

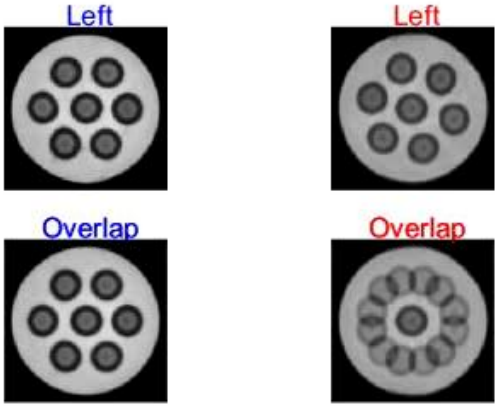
Step 3: Resize and revise the image

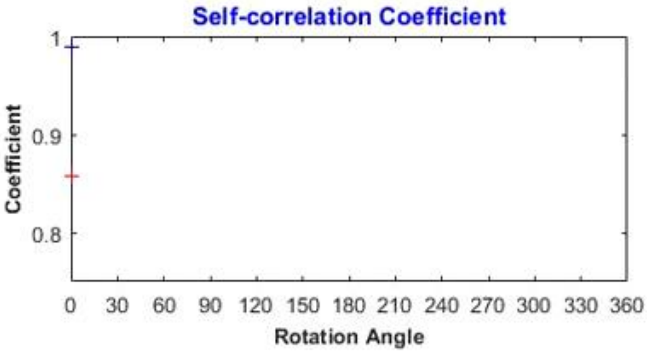


Step 4: Rotate and revise the image to calculate the self-correlation coefficient



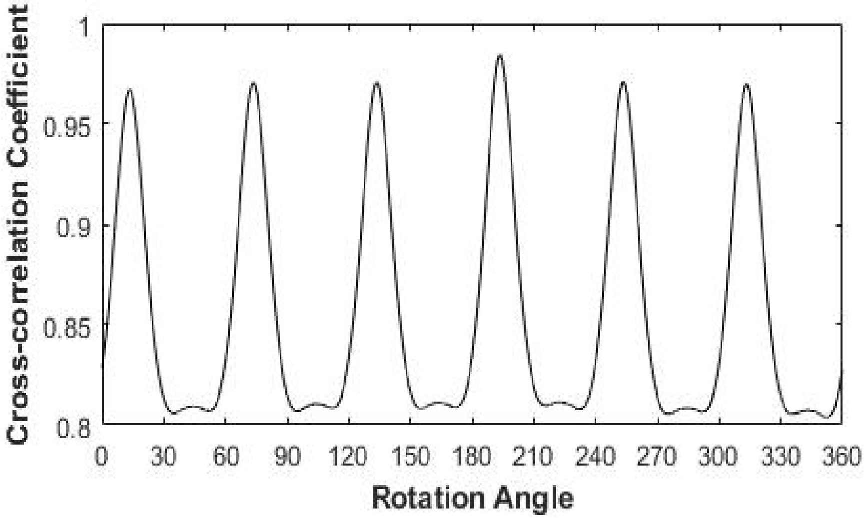
$$coefficient = \frac{\sum_{m}\sum_{n}\left(A_{mn}-\bar{A}\right)\left(B_{mn}-\bar{B}\right)}{\sqrt{\left(\sum_{m}\sum_{n}\left(A_{mn}-\bar{A}\right)^{2}\right)\left(\sum_{m}\sum_{n}\left(B_{mn}-\bar{B}\right)^{2}\right)}}$$





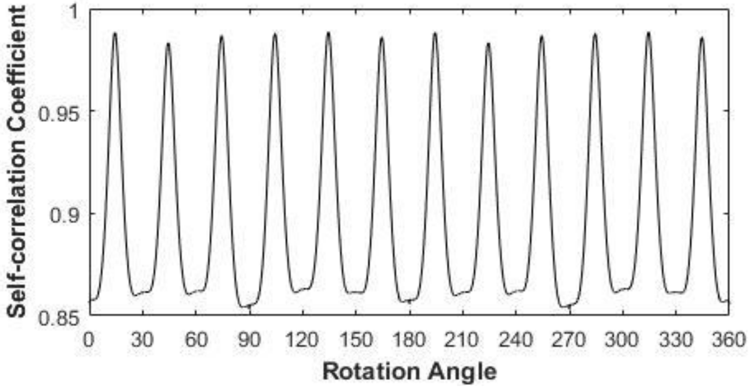
7-core MCF Splicing results

Cross-correlation

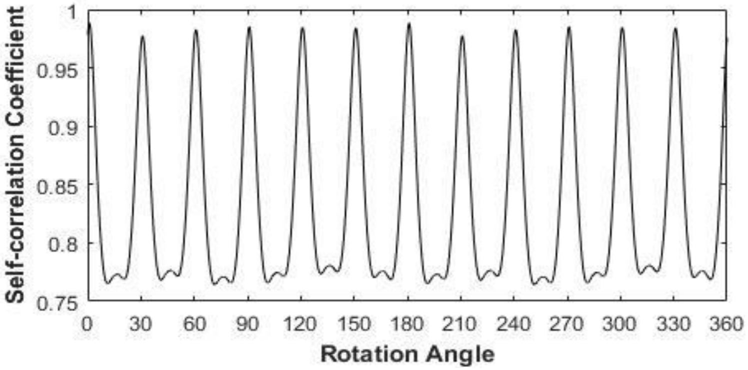


Self-correlation

Right

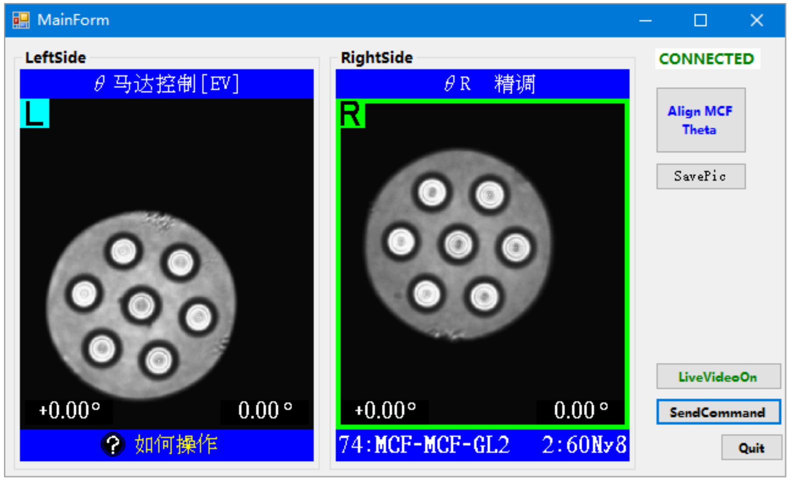


Left

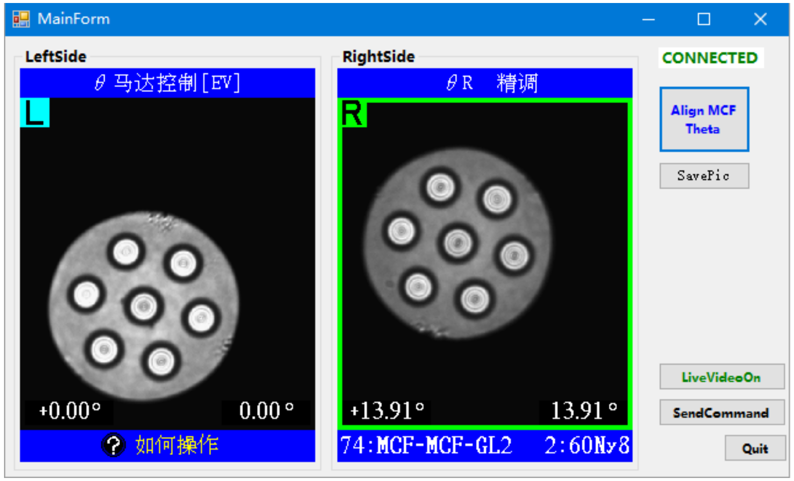


Peak angle number		**1**	**2**	**3**	**4**	**5**	**6**
Cross-correlation		13.4°	73.5°	133.5°	193.4°	253.4°	313.4°
Self-correlation	Right	14.5°	74.4°	135.4°	194.5°	254.4°	314.5°
	Left	1.0°	61.0°	121.0°	181.0°	241.0°	301.0°

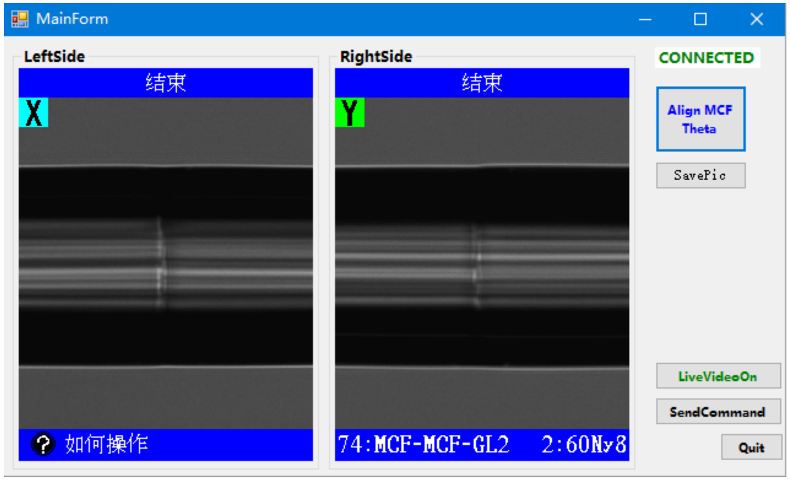
Software panel:



Before alignment



After alignment

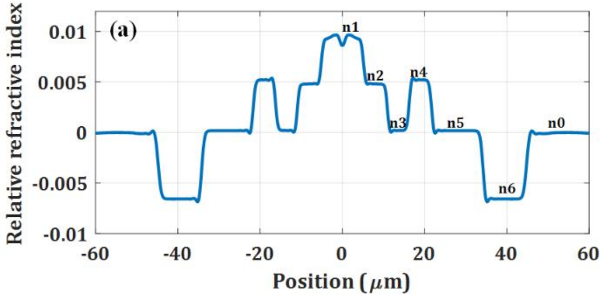


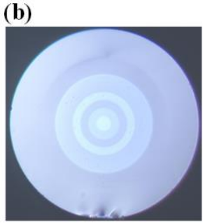
Result

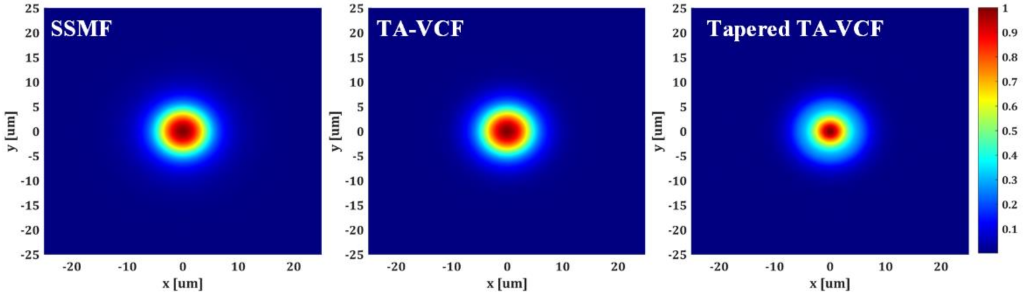
Core	1	2	3	4	5	6	7	Mean(dB)	Max(dB)
1	0.520	0.460	0.260	0.064	0.541	0.365	0.432	0.377	0.541
2	0.211	0.086	0.176	0.120	0.235	0.357	0.363	0.221	0.363
3	0.743	0.037	0.196	0.355	0.370	0.677	0.770	0.450	0.770
4	0.180	0.224	0.161	0.012	0.288	0.204	0.211	0.183	0.288
Ave	0.414	0.202	0.198	0.138	0.359	0.401	0.444	**0.308**	**0.491**

Ultra-Low Crosstalk Fused Taper Type Fan-in/Fan-out

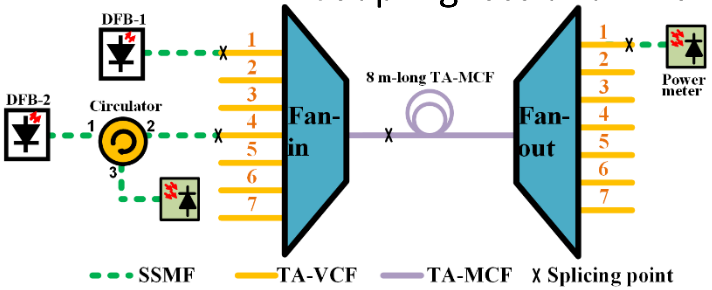
Vanishing core fiber as bridge fiber for tapering process

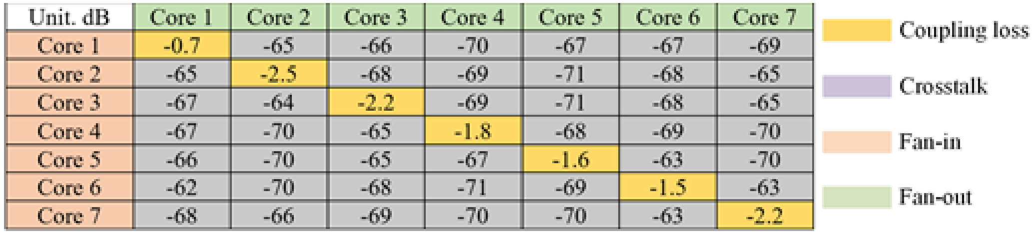






Coupling loss and XT of the fabricated Fi/Fo with 8 m-long 7-core TA-MCF



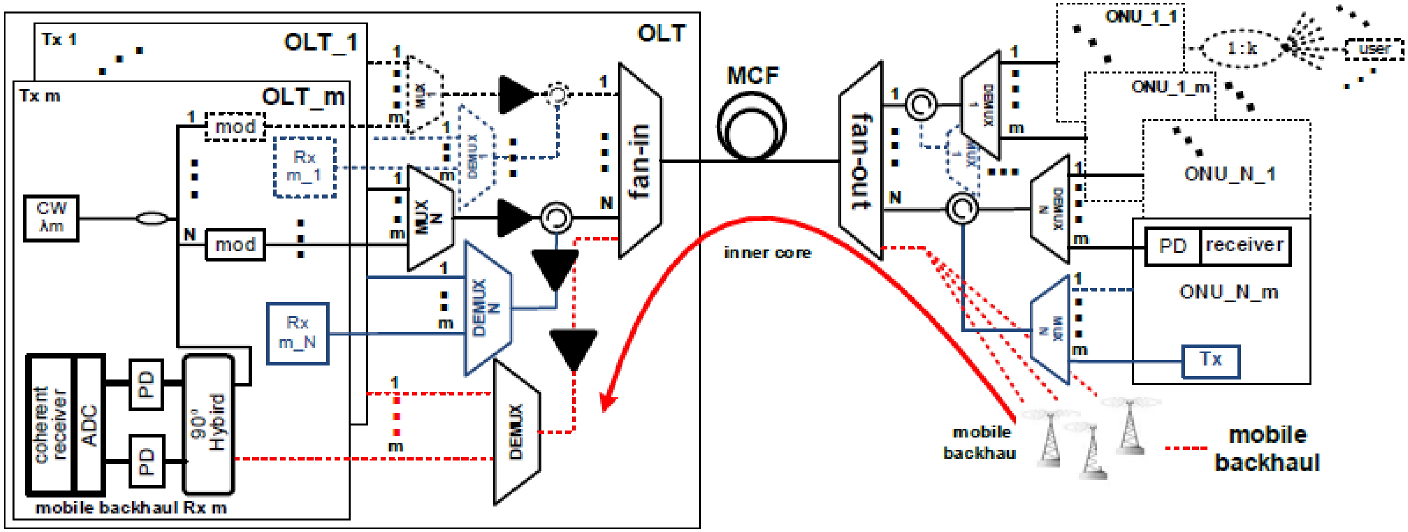


Unit. dB	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7
Core 1	-0.7	-65	-66	-70	-67	-67	-69
Core 2	-65	-2.5	-68	-69	-71	-68	-65
Core 3	-67	-64	-2.2	-69	-71	-68	-65
Core 4	-67	-70	-65	-1.8	-68	-69	-70
Core 5	-66	-70	-65	-67	-1.6	-63	-70
Core 6	-62	-70	-68	-71	-69	-1.5	-63
Core 7	-68	-66	-69	-70	-70	-63	-2.2

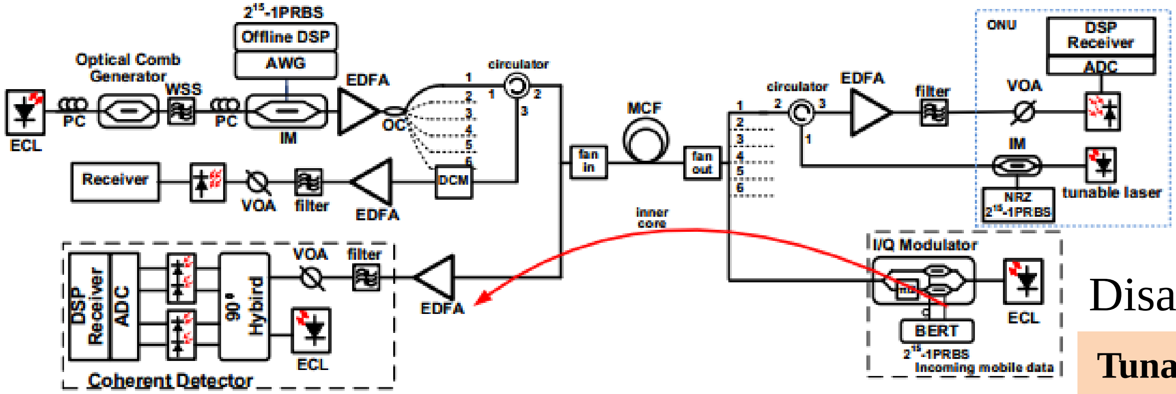
🟨 Coupling loss
🟪 Crosstalk
🟧 Fan-in
🟩 Fan-out

Ultra-low crosstalk under -63 dB, insertion loss about 0.2 dB.
L. Gan, M. Tang et al., OFC 2019.

SDM/WDM hybrid optical access network



DS: 6 outer cores
IM/DD;
US: Tunable laser;
MB: inner core
coherent Rx;



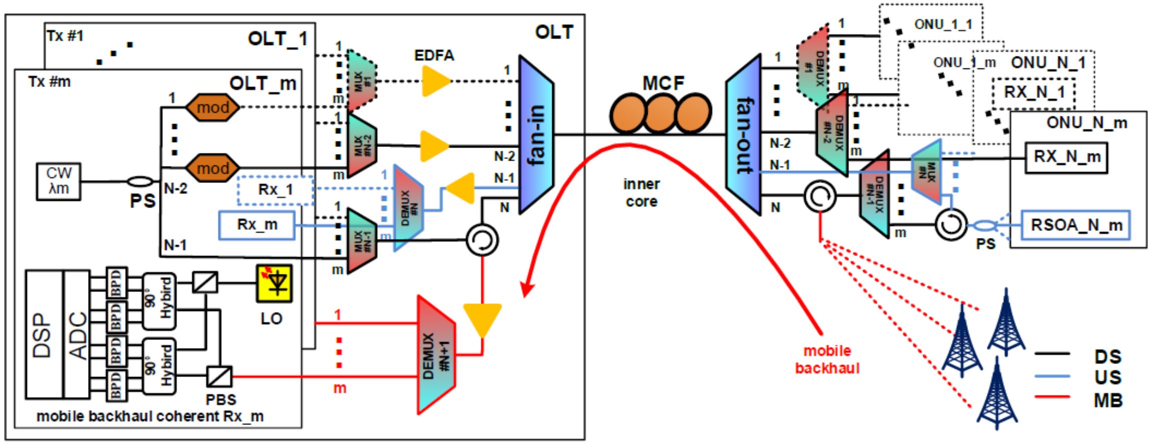
58.7km MCF;10 wavelength;
DS: **300 Gb/s QPSK-OFDM**;
US: 5 Gb/s OOK;
MB: 20 Gb/s QPSK;

Disadvantages:

Tunable lasers are used in the ONU side, Relatively simple modulation formats with limited capacity.

Borui Li, Zhenhua Feng, Ming Tang, et al., CLEO-EURO, CI_2_3, 2015.
Borui Li, Zhenhua Feng, Ming Tang, et al., Opt. Express 23, 10997-11006 (2015)

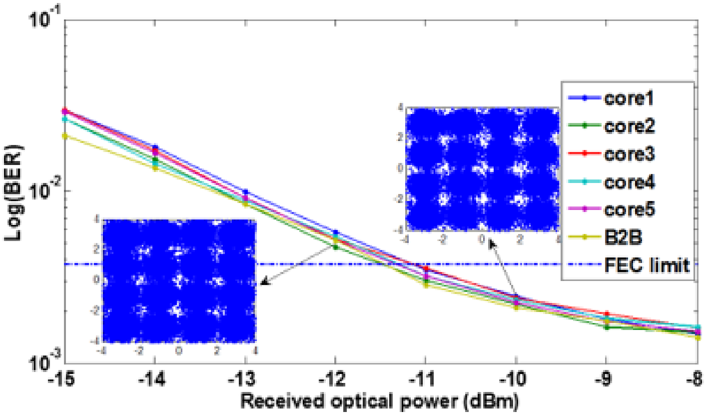
WSDM PON with adaptive modulation Using RSOA

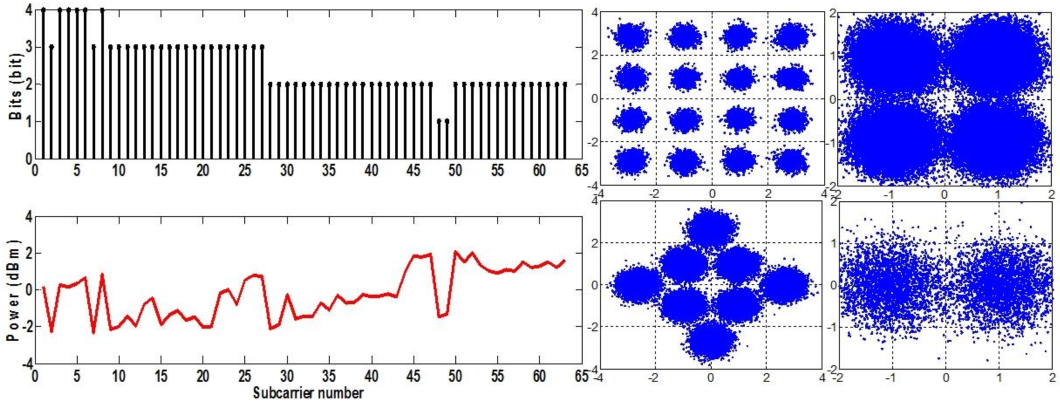


US: Adaptive Modulation

DS:16QAM-OFDM

MB: PDM-QPSK

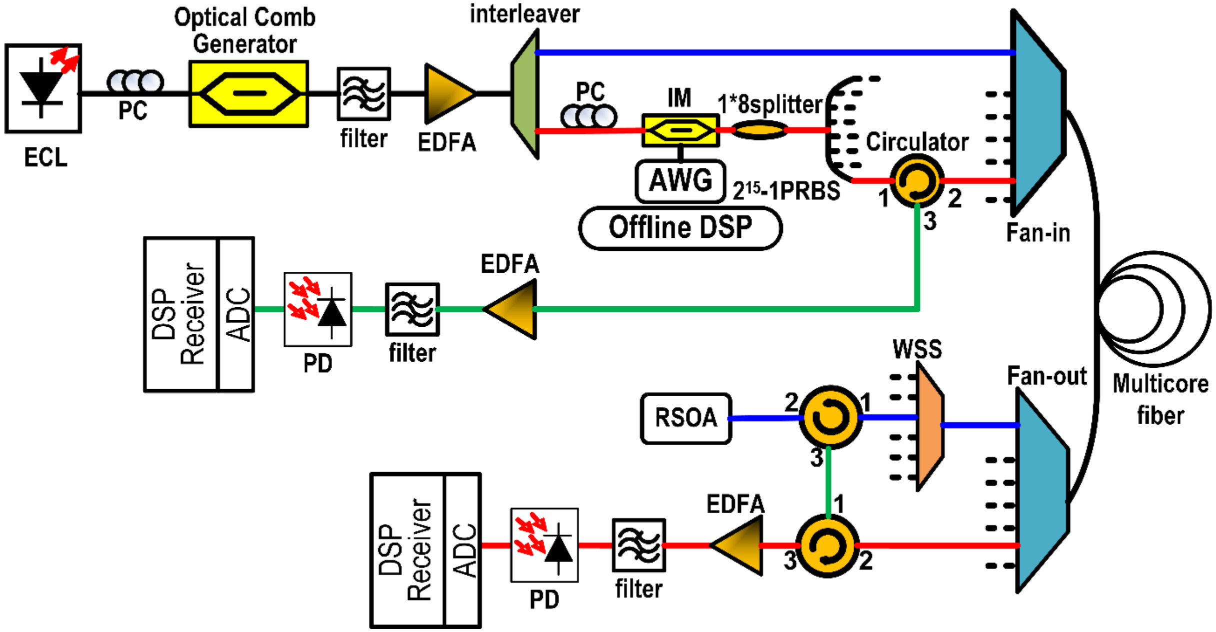




Zhenhua Feng, Borui Li, Ming Tang, et al., PIERS 2015.
Zhenhua Feng, Borui Li, Ming Tang, et al., IEEE Photonics Journal, 2015, 7(4):1-9.

All the ONUs served by the same subset OLT must share the same wavelength for US transmission, in a TDMA or OFDMA manner.

Bidirectional symmetric WDM-SDM access network



- **16 wavelengths** with 25GHz channel spacing from the optical frequency comb generator (OFCG) seeded by an **ECL** centered at **1549.59nm** are selected by a **WDM 400GHz** de-multiplexer.
- the carriers are split into the **even** and **odd** channels by a **25/50GHz inter-leaver**.

DS transmission

- Odd channels are intensity modulated by **1.25GBaud/s OFDM-QPSK signals** (the real rate is 1.0286Gbit/s), split by 1:8 and injected into one of the MCF’s outer cores.

US transmission

- Even channels are injected into the MCF’s inner core. After the MCF transmission, one wavelength is filtered by a WSS and launched into the **RSOA for US modulation and amplification**.

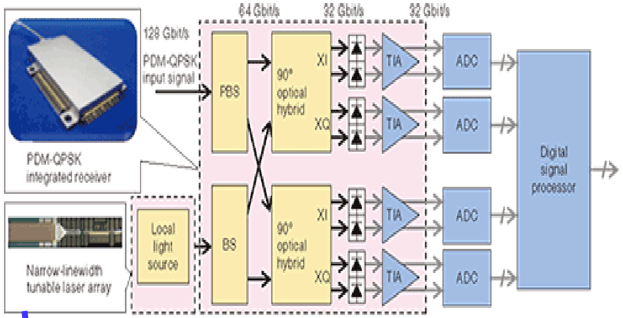
1Gb/s per ONU bidirectional symmetric WDM-SDM optical access network over 20-km MCF!

SHCD: Tradeoff between cost and performance

Direct detection

Access/Metro Network

Cost-efficient, high sensitivity and 20~100 km reach

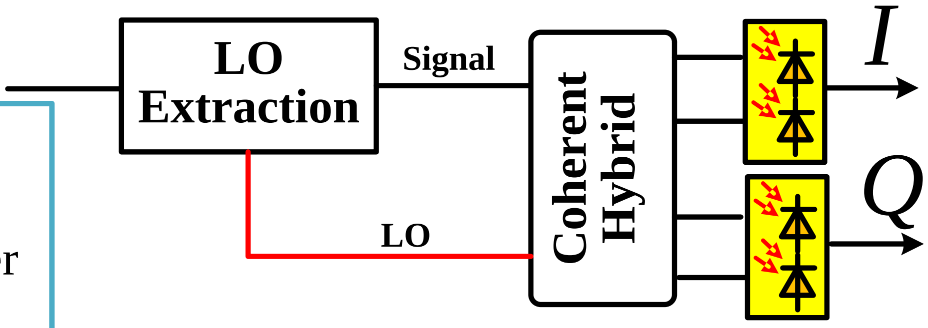


Coherent detection

Reach, Data Rate, Receiver Sensitivity

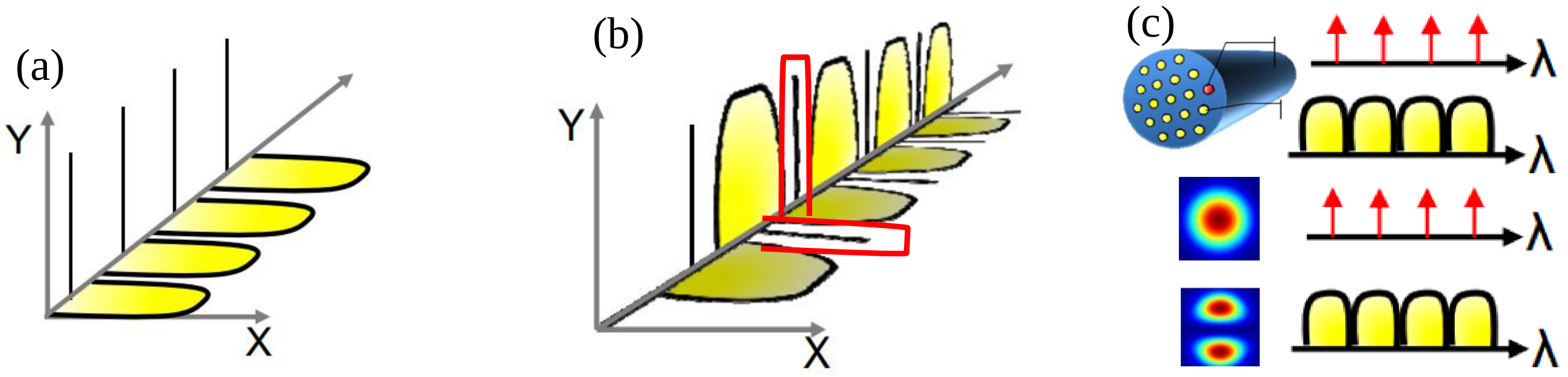
Complexity, Latency, Power consumption

- ✓ Lower cost without using tunable LO laser
- ✓ Simplified RX DSP without frequency offset and phase noise compensation (lower latency and power consumption)
- ✓ Relaxation on the requirement of expensive narrow-linewidth lasers



Self-homodyne coherent detection

Implementation of SHCD

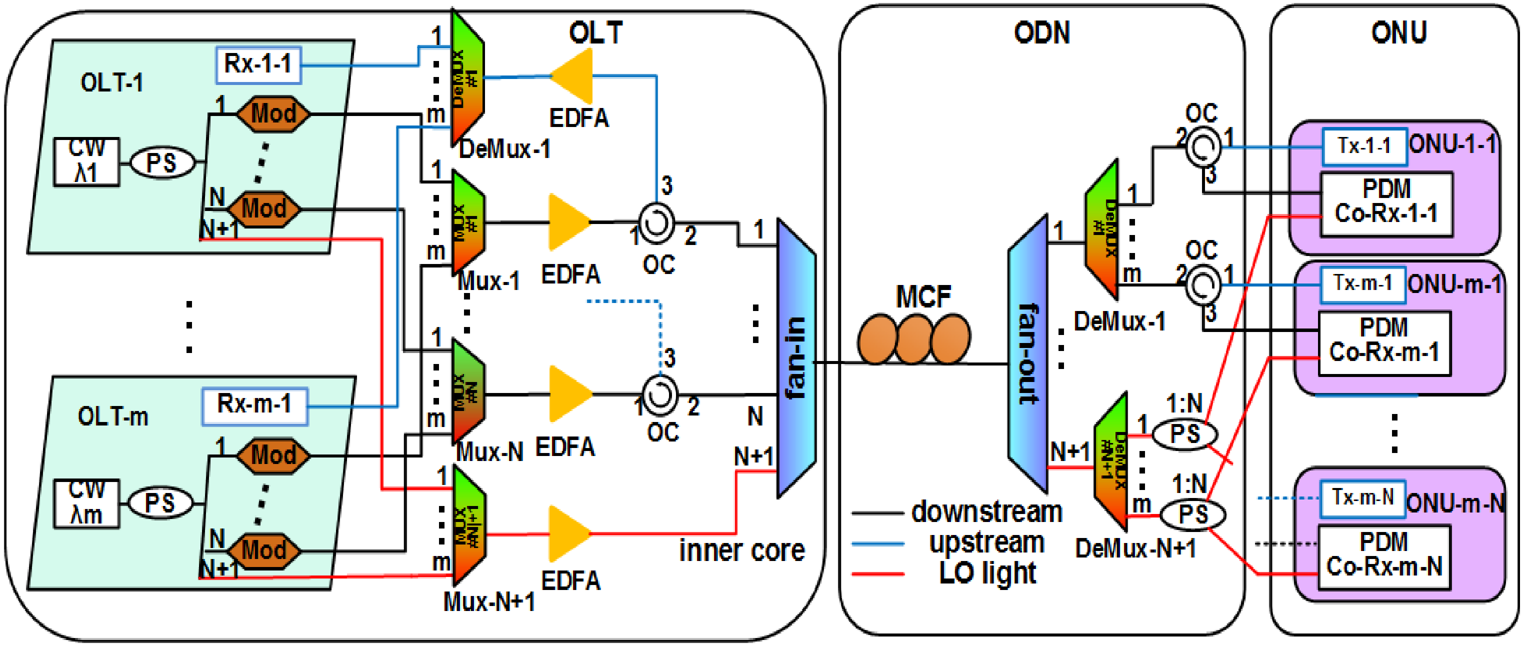


- (a) Polarization interleaving method:
  - ☐ half of spectral efficiency
- (b) Optical carrier extraction technique:
  - ☐ Narrow band optical filter
  - ☐ Poor performance due to noisy LO
- (c) LO delivery via SDM channels:
  - ☺ Large channel counts
  - ☺ Negligible spectral efficiency penalty
  - ☺ Easier LO seperation
  - ☺ Perfect uniformity between spatial channels
  - ☺ Controllable delay between signals and LO

Fiber Type	**Reach (km)**	**Data rate per λ (Gb/s)**	**Signal**	**REF**
19 core-fiber	10.1	10	SP-QPSK	Opt. Exp. 21(2),2013
2-mode fiber	55	40	DP OFDM-QPSK	Opt. Exp. 23(25),2015

MCF based scheme is suitable for large capacity optical access network!

Proposed architecture for SDM-SHCD access



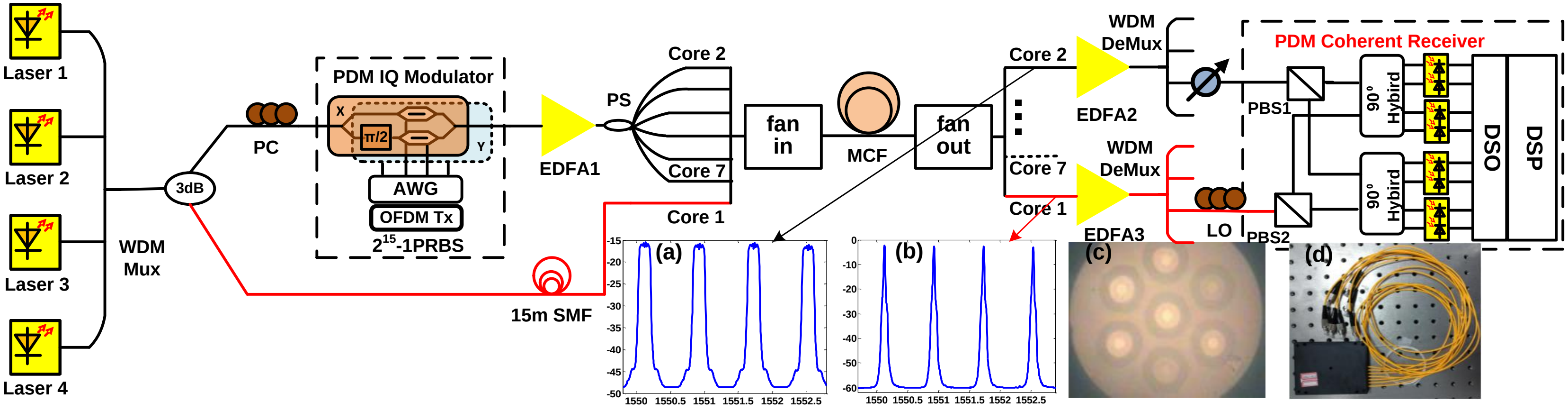
◆ Inner core for LO delivery, the other N cores for signals transmission

◆ M wavelengths to support mxN ONUs

◆ SHCD is implemented in the ONUs for downstream transmission

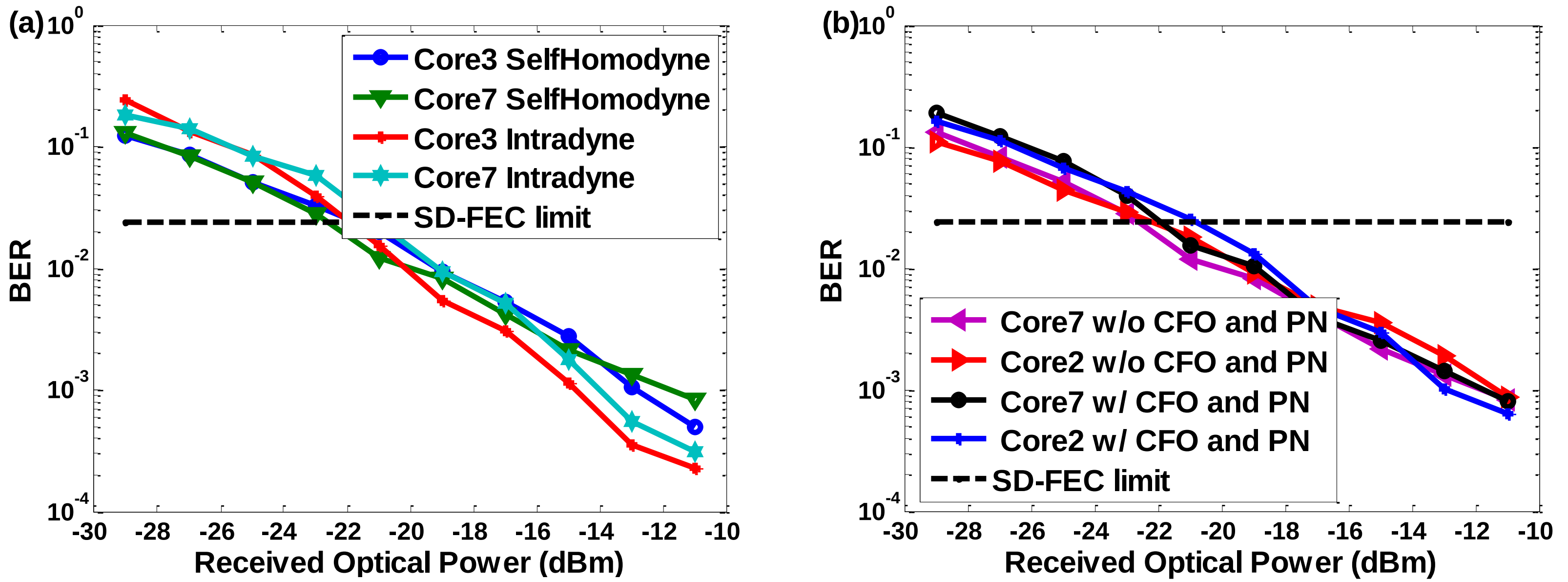
◆ Bidirectional transmission is possible, but we only demonstrated downstream experiment in this work

Experimental Setup



- ◆ Four wavelength channels with 100-GHz spacing
- ◆ 25Gbaud PDM-OFDM-16QAM singles per wavelength
- ◆ Constant amplitude zero auto-correlation (CAZAC) precoding is used for baseband OFDM generation and demodulation
- ◆ Conventional ICR typically for 100Gb/s PDM-QPSK
- ◆ PC is used before the ICR on the LO path for polarization alignment
- ◆ Two types of lasers are used. ECL with linewidth of ~100 kHz, and DFB with linewidth of ~10 MHz
- ◆ 15-m SMF for optical path equalization on LO tributary only in case of 10 MHz linewidth DFB laser

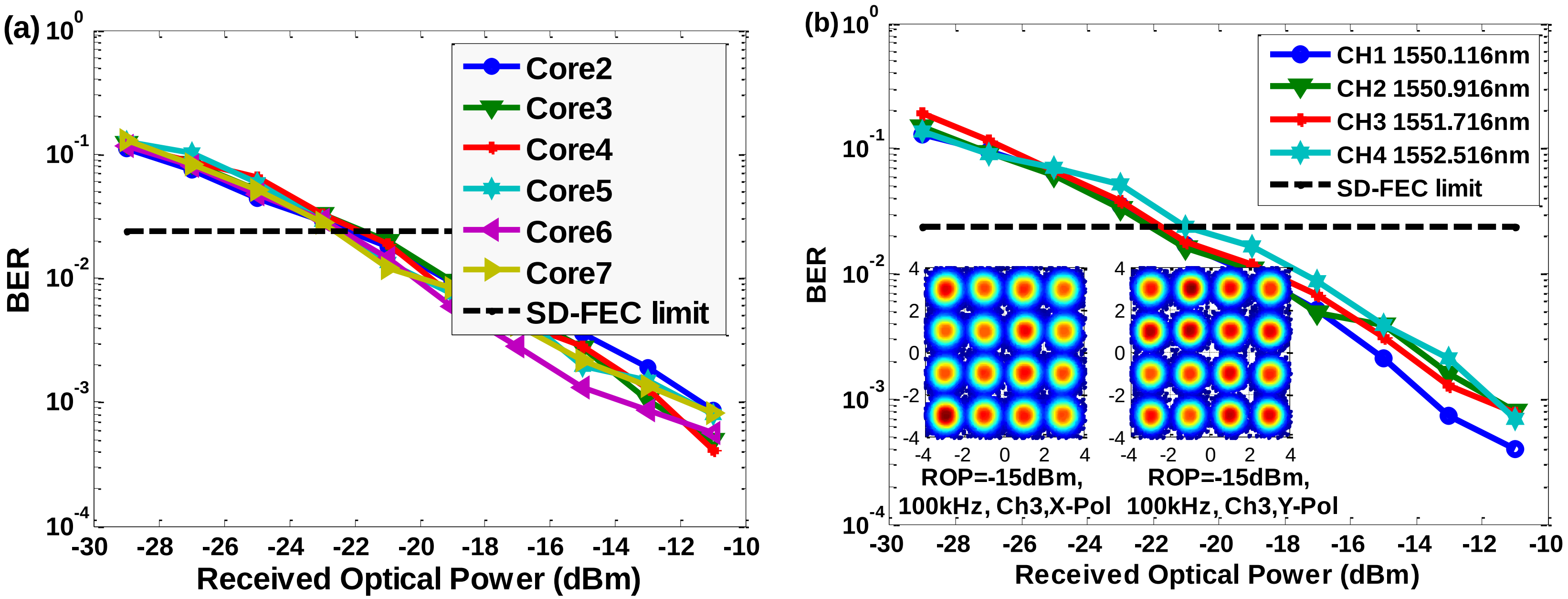
Performance comparison



(a) comparison between traditional intradyne detection and SHCD, (b) influence of carrier frequency offset and phase noise compensation in SHCD

- Single channel of 100kHz linewidth ECL transmission;
- Negligible performance degradation compared with Intradyne detection;
- CFO and PN compensation DSP can be eliminated in SHCD!

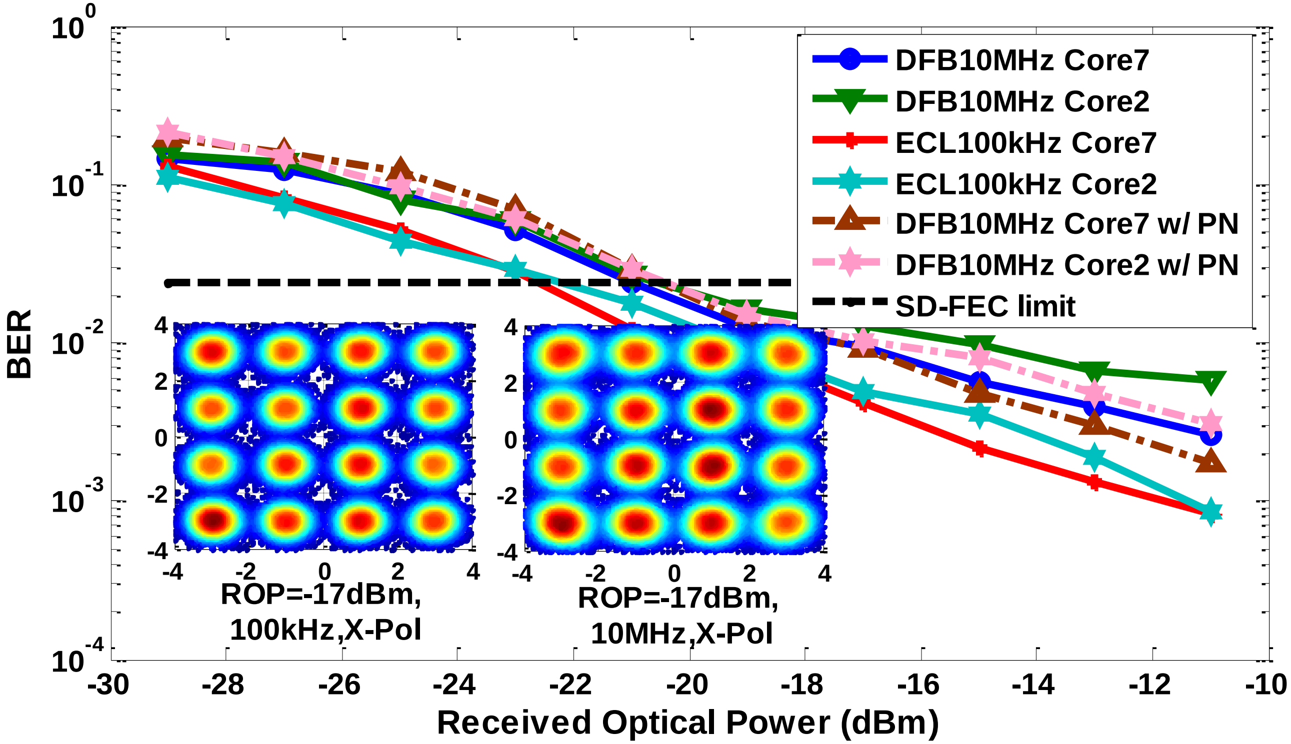
Transmission performance of SHCD



(a) Single wavelength SHCD transmission over 7-core fiber, (b) 4 wavelength WDM SHCD transmission over core 7.

- Single channel and 4 channels of 100kHz linewidth ECLs transmission;
- Negligible BER performance variation among different fiber cores and wavelength channels;
- Receiver sensitivity of 200Gb/s per wavelength CO-OFDM-16QAM is about -22 dBm.
- Total downstream capacity is **4.8 Tb/s** (200Gb/s/λ × 4λ × 6 core).

SHCD using 10MHz linewidth DFB



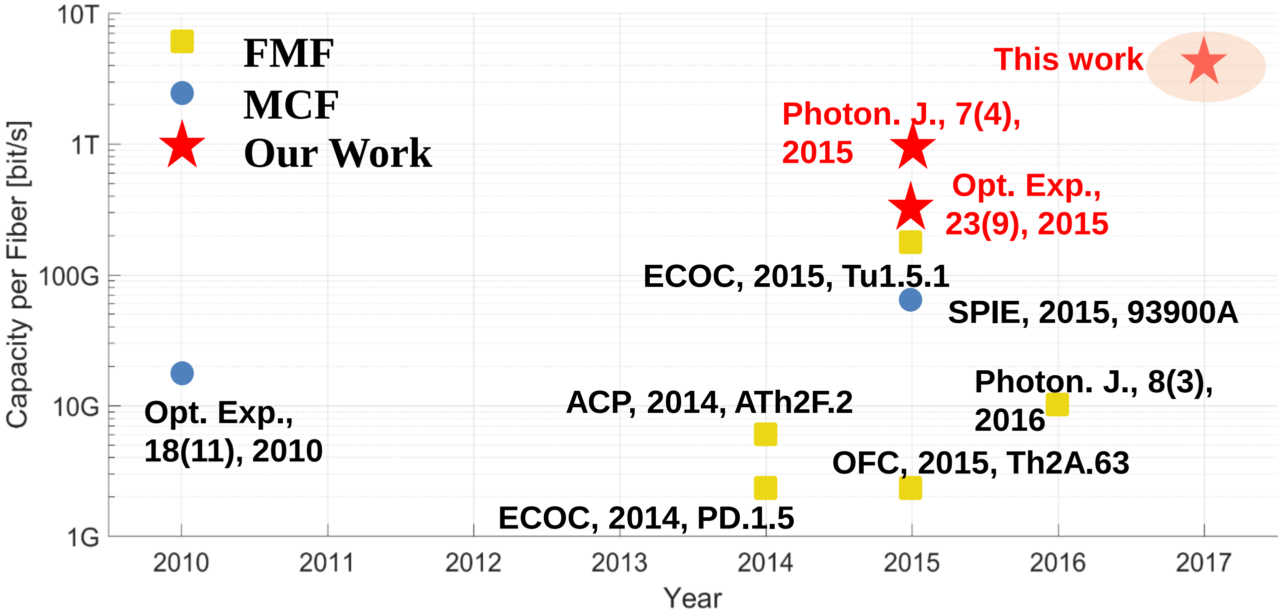
Tolerance to laser linewidth in single wavelength SDM based SHCD system

Less than 2dB power penalty using DFB!

Phase noise compensation further reduces this penalty

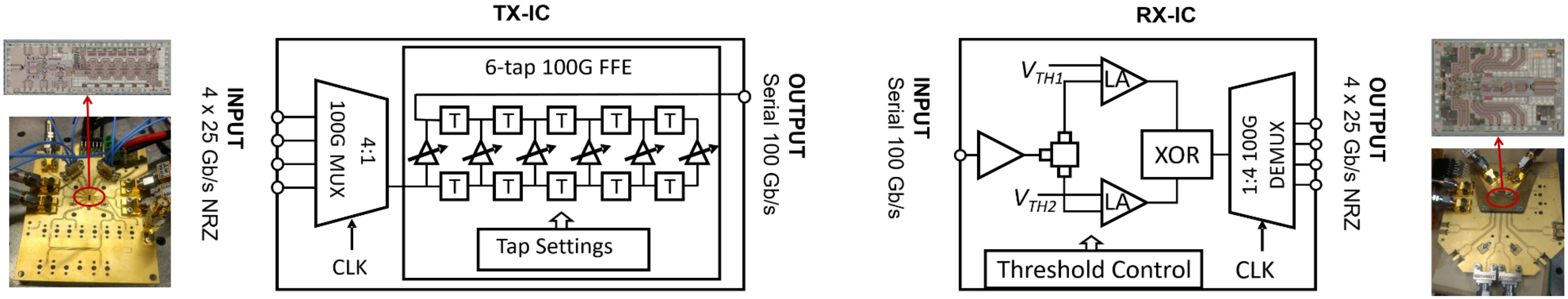
It is feasible to employ cost-efficient ~10MHz linewidth DFB lasers in 200Gb/s/λ transmission system, suitable for cost sensitive access scenarios.

Research Progress on SDM based Access Network

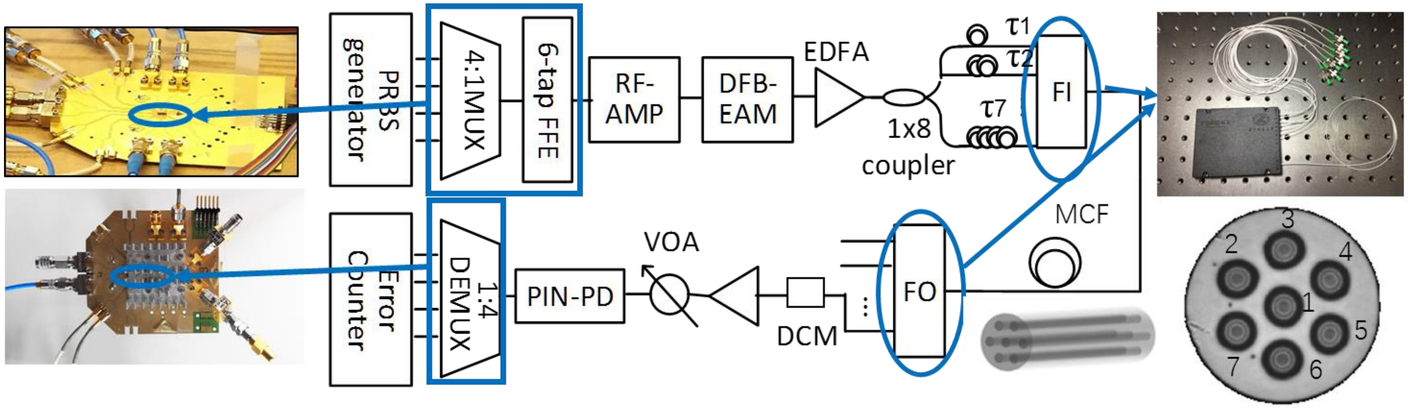


- ☐ Overveiew of our previous work on MCF based **IM/DD** access network.
- ☐ Proposal and experimental demonstration of self-homodyne coherent detection based WDM-SDM optical access.
- ☐ Ultra-large downstream capacity (4.8 Tb/s) is realized with good compromise between transmission performance and system cost/complexity.

Real time large capacity MCF based Intra--Datacenter Communication Networks

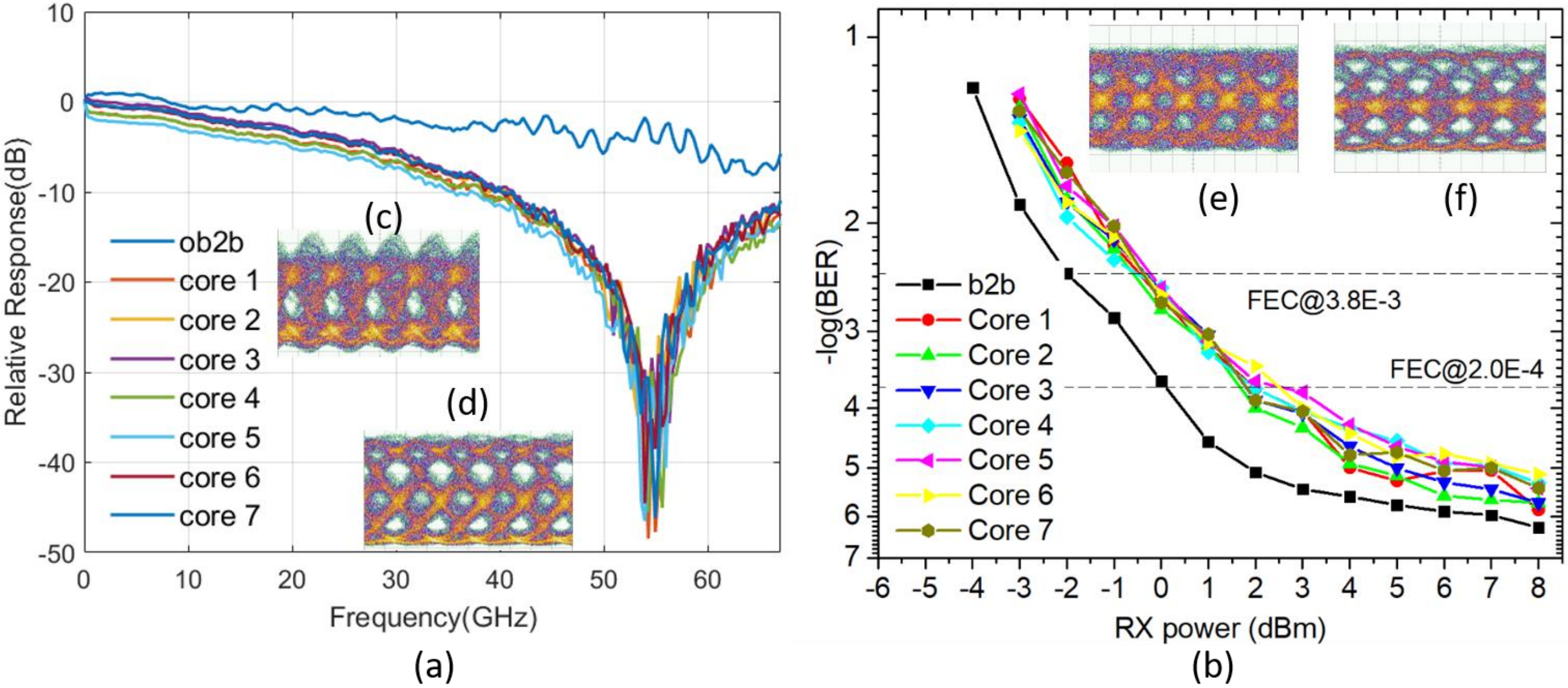


0.13 μm BiCMOS technology, multiplexing 4 lanes up to 25 Gbps signals into a serial 100 Gbps 6-tap analog feedforward equalizer (FFE)



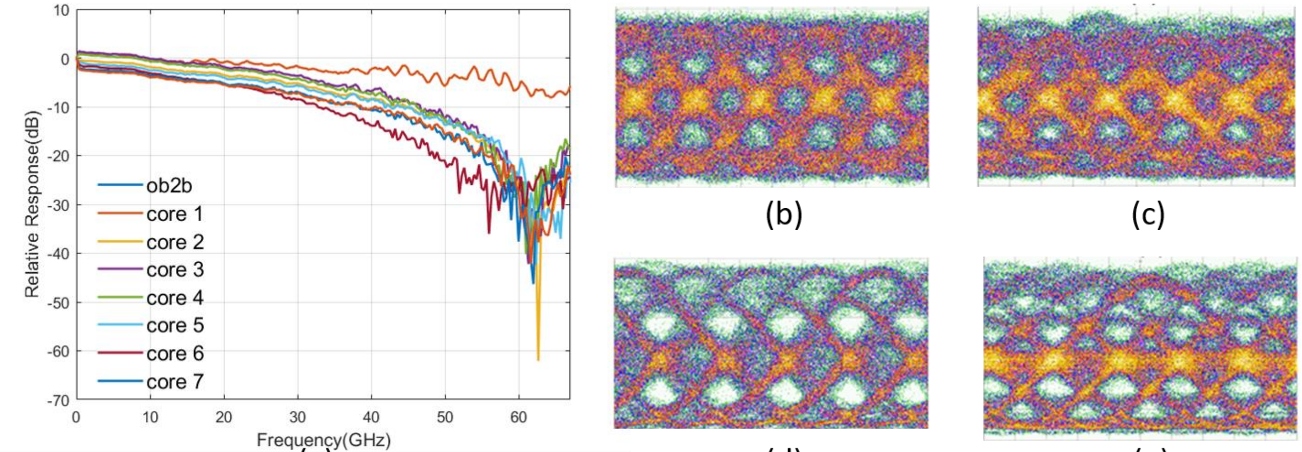
R. Lin, J. M. Tang, and J. Chen, "Real-time 100 Gbps/λ/core NRZ and EDB IM/DD transmission over multicore fiber for intra-datacenter communication networks," *Opt. Express*, vol. 26, pp. 10519-10526, 2018.

NRZ&EDB transmissions over all the 7 cores of the 1 km MCF

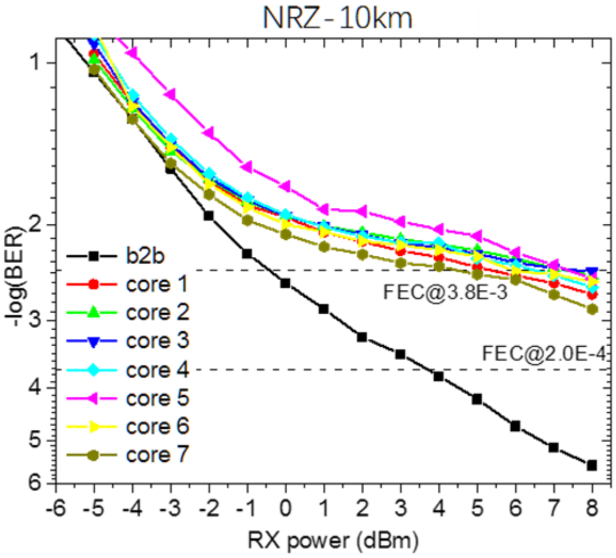


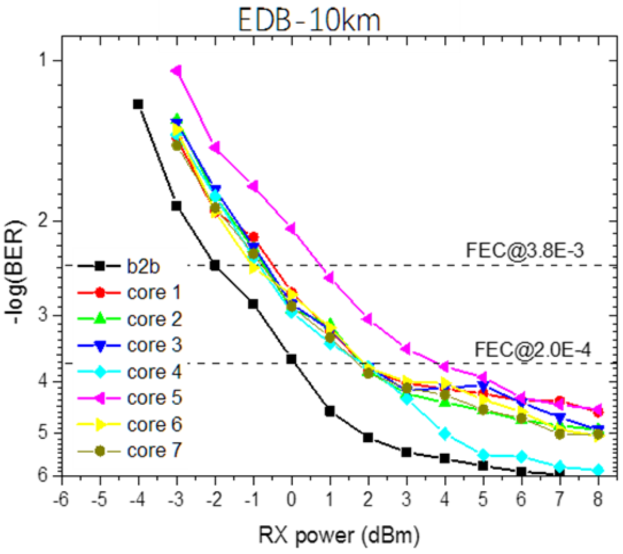
(a) Frequency response of the b2b optical link and different cores of 1 km MCF, (b) BER of real-time 100 Gbps EDB signal measurement for b2b and different cores after 1 km MCF transmission, eye diagrams of b2b (c) NRZ signal and (d) EDB signal measured for optical b2b, eye diagram of (e) NRZ signal and (f) EDB signals measured at core 7 after 1 km MCF transmission.

NRZ&EDB transmissions over all the 7 cores of the 10 km MCF



(a) (b) (c) (d) (e)

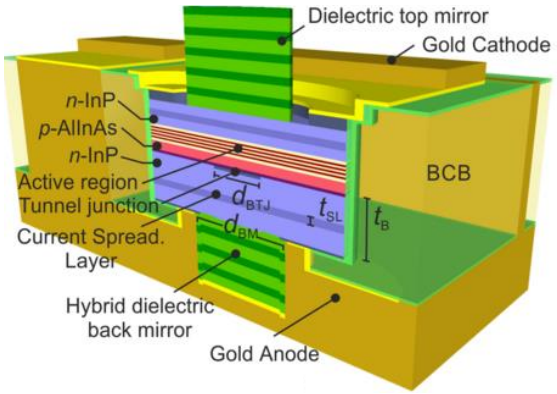




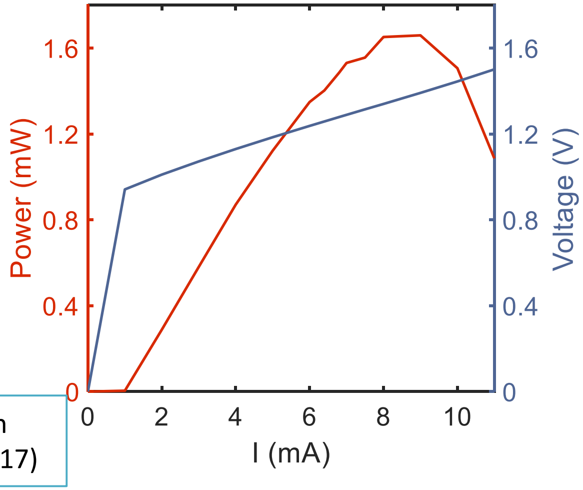
The real-time and DSP-free SDM system covers the short-to-medium reach optical communication, indicating its potential for providing high-speed intra-DCI.

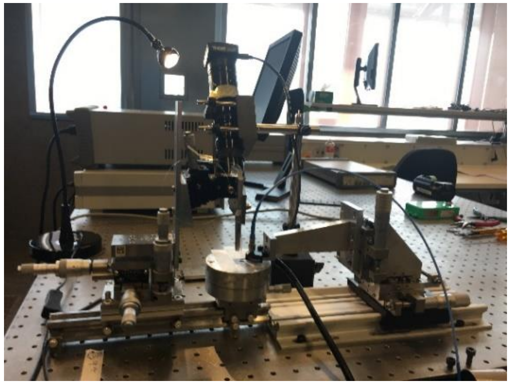
Long wavelength SM-VCSEL + MCF

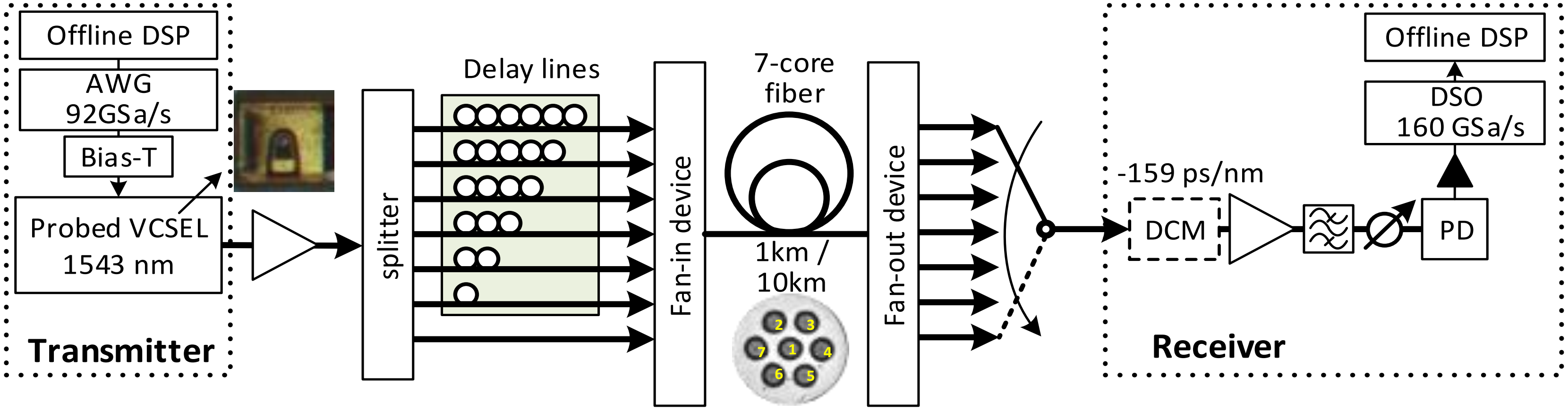
PAM-4 Transmission over Single Mode 7-core Fiber using 1.5-µm SM-VCSEL



S. Spiga et al., "Single-Mode High-Speed 1.5-µm VCSELs," J. Lightwave Technol. 35(4), 727-733 (2017)

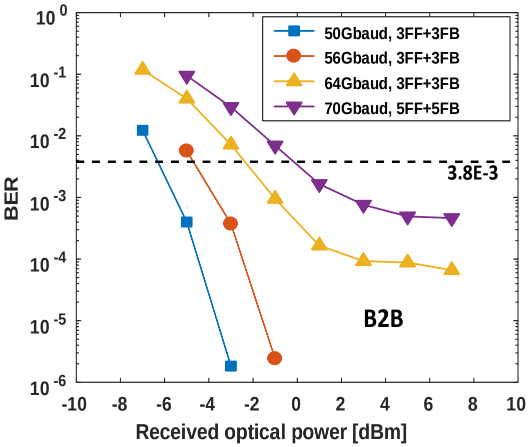


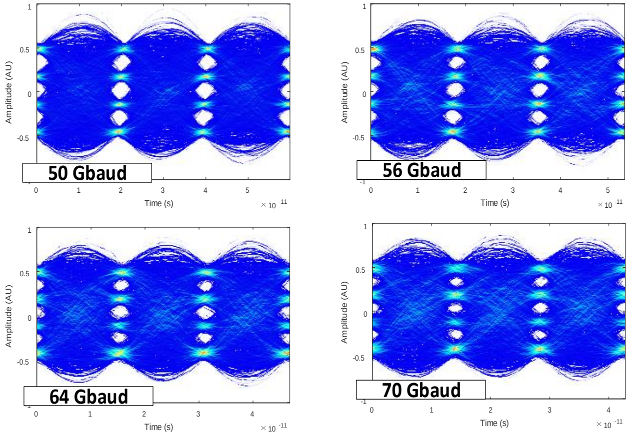




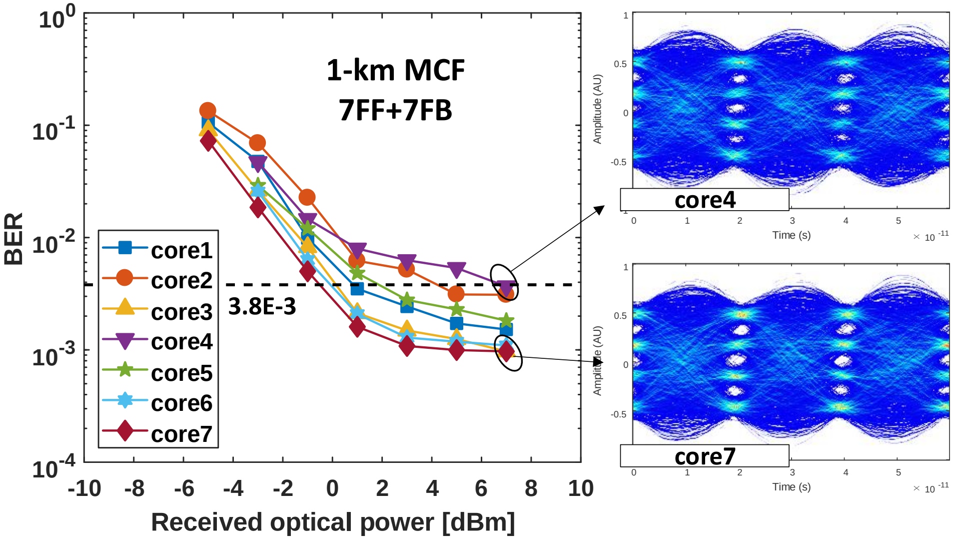
Pang, Xiaodan, et al. "7× 100 Gbps PAM-4 Transmission over 1-km and 10-km Single Mode 7-core Fiber using 1.5-µm SM-VCSEL." *OFC 2018, M1I.4.*

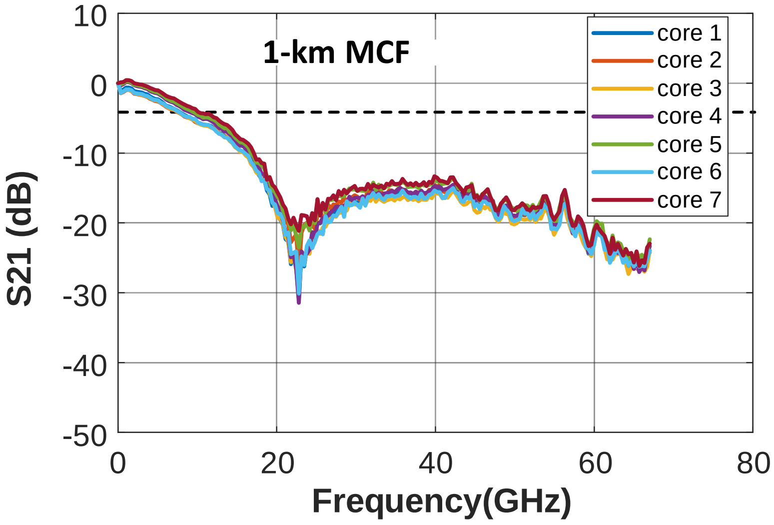
PAM4 B2B & transmissions over all the 7 cores of the 1 km MCF





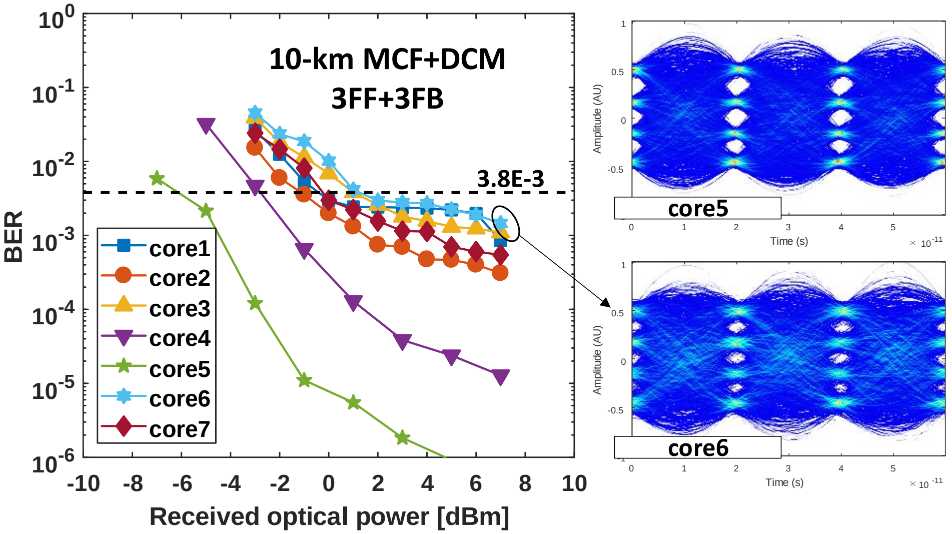
- Pre-equalization up to 30GHz at Tx
- Post equalization with 3 FF + 3 FB taps symbol-spaced DFE for 50Gbd, 56Gbd and 64Gbd
- 5 FF + 5 FB taps for 70Gbd

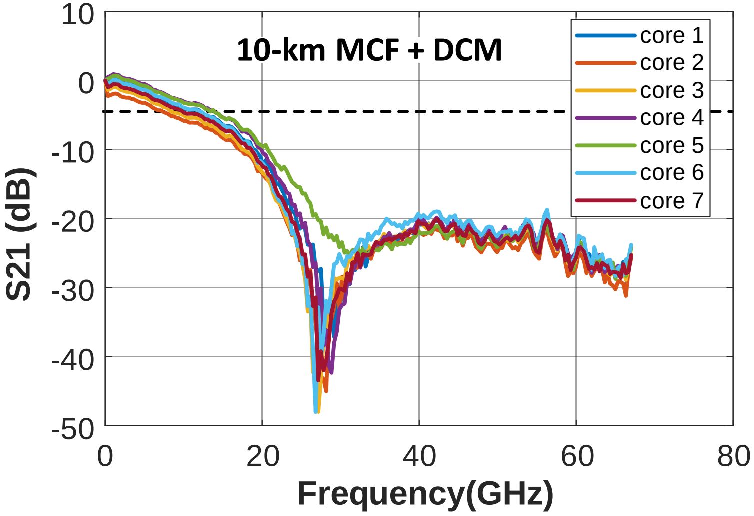




- 3 dB bandwidths for all cores are ~10GHz, 10 dB BWs are <17GHz
- Pre-equalization up to 26GHz at Tx
- Post equalization with 7 FF + 7 FB tap DFE required

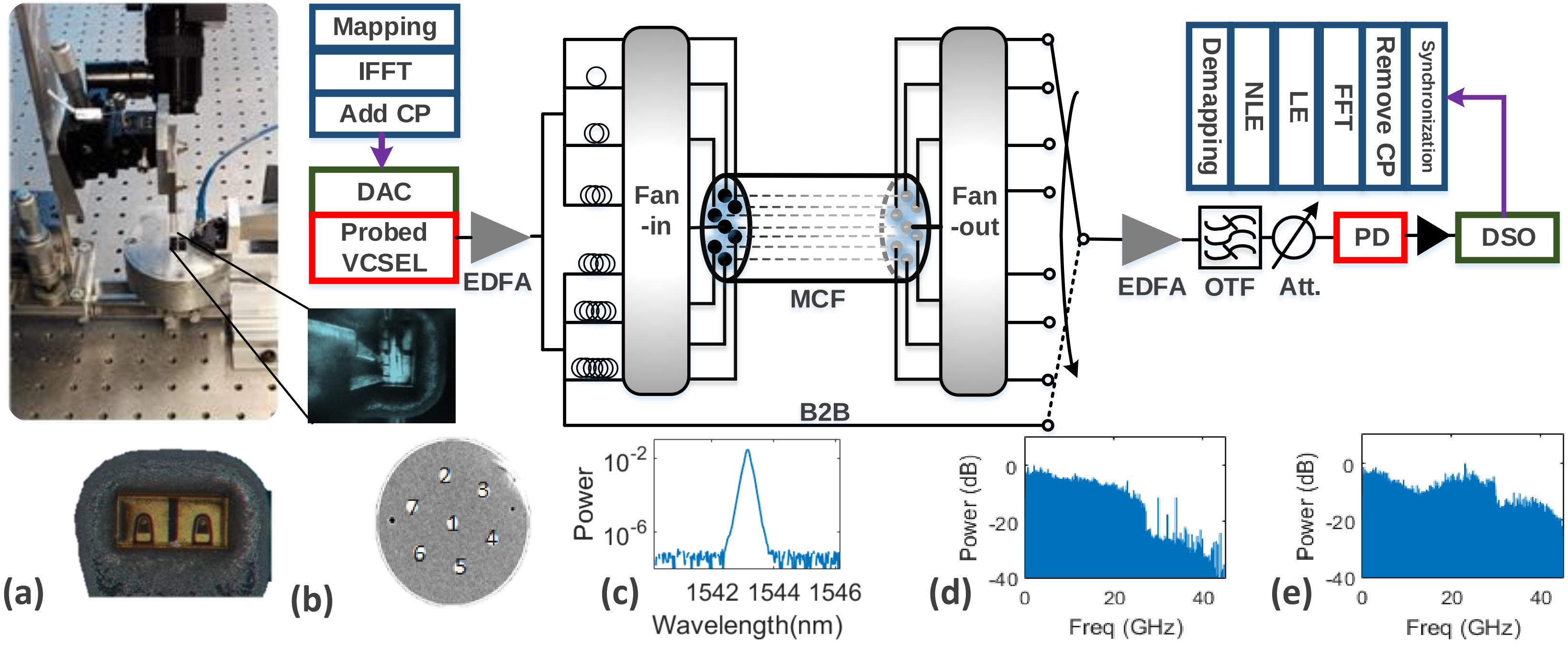
PAM4 transmissions over all the 7 cores of the 10 km MCF + DCM





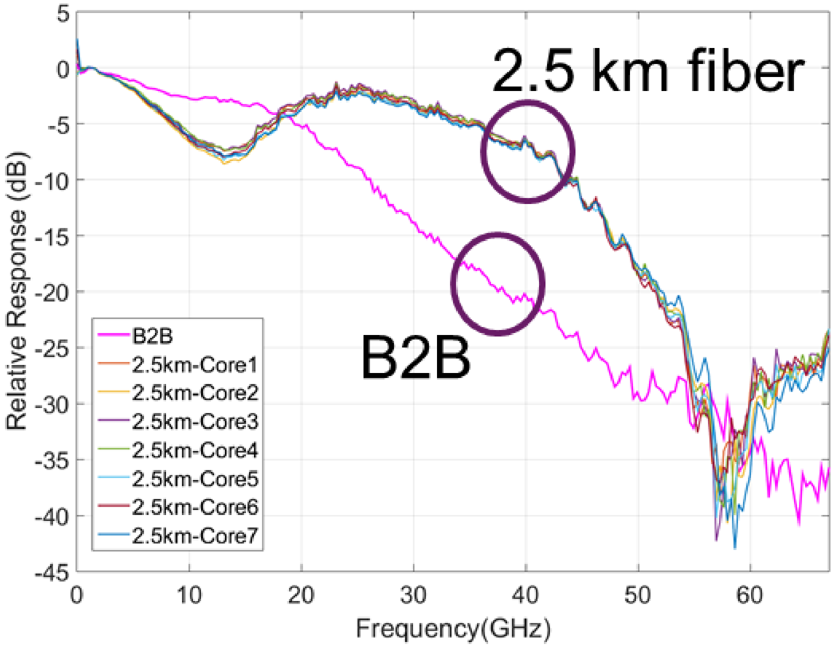
- 3 dB bandwidths for all cores varie between 10GHz and 15GHz
- 10 dB BWs are >18GHz
- Pre-equalization up to 26GHz at Tx
- Post equalization with 3 FF + 3 FB tap DFE

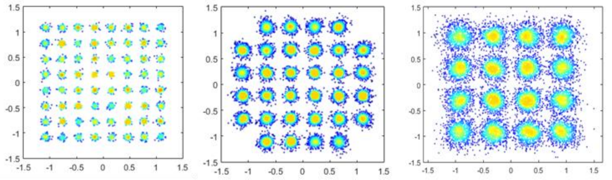
1.5-µm Single-Mode VCSEL Discrete Multi-Tone Transmission

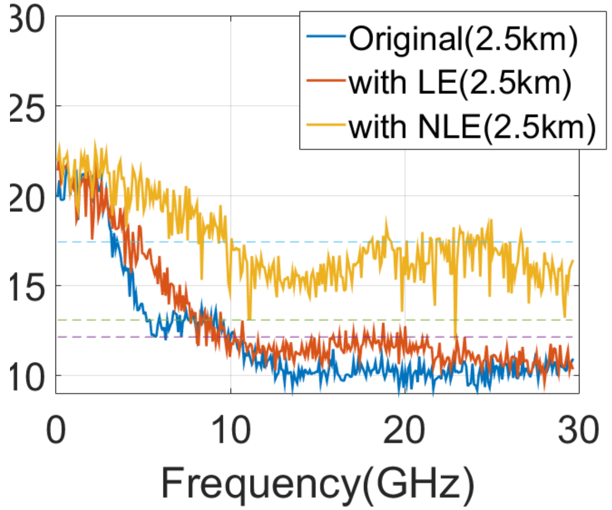


Van Kerrebrouck J, Zhang L, Lin R, et al. 726.7-Gb/s 1.5-µm Single-Mode VCSEL Discrete Multi-Tone Transmission over 2.5-km Multicore Fiber", OFC, 2018: M1I. 2.

Linear and Non-linear equalization for the link







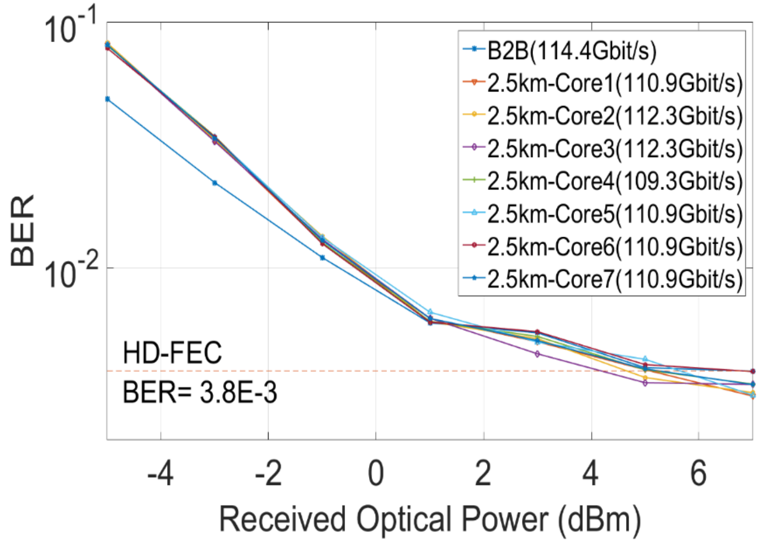
Nonlinear effects in link

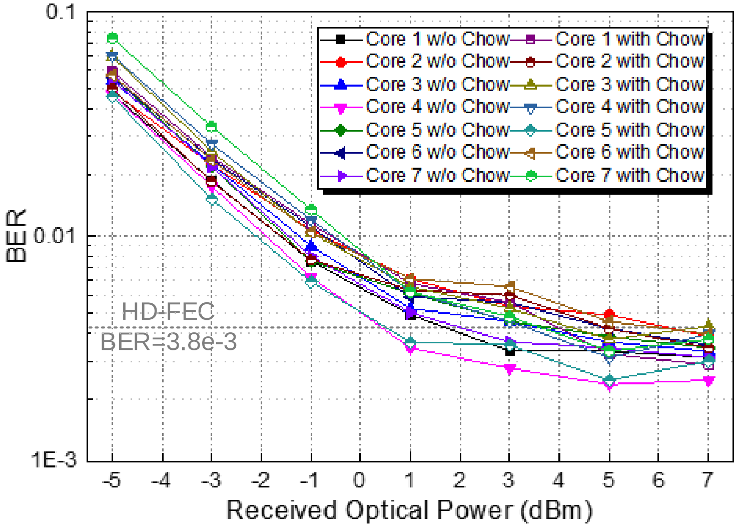
- VCSEL nonlinear behaviors
- DMT large peak-to-average ratio (PAPR)
- Inter-subcarrier mixing in square-law photodiode

Equalization

- Linear equalization
- Non-Linear equalization (NLE)
- Volterra series
- 2nd and partially 3rd-order terms
- Recursive least square (RLS)

DMT over 2.5/10km 7-core MCF



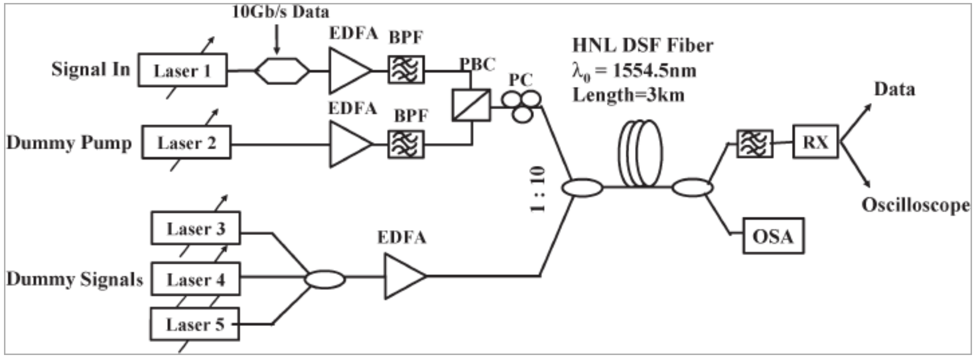


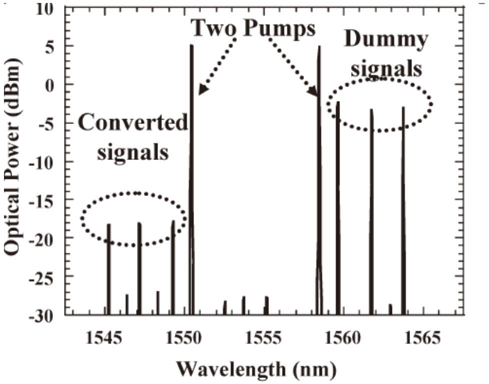
Achieved net data rates with 2.5-km/10-km 7-core MCFs.

	Core Nr.	Net Data Rate (Gbit/s)							
		#1	#2	#3	#4	#5	#6	#7	Total
2.5-km MCF		103.7	105.0	105.0	102.1	103.6	103.6	103.6	**726.6**
10-km MCF	w/o Chow	70.9	70.9	68.5	70.7	72.3	68.5	68.5	**490.3**
	with Chow	82.5	72.1	71.4	83.1	74.9	70.1	79.0	**533.1**

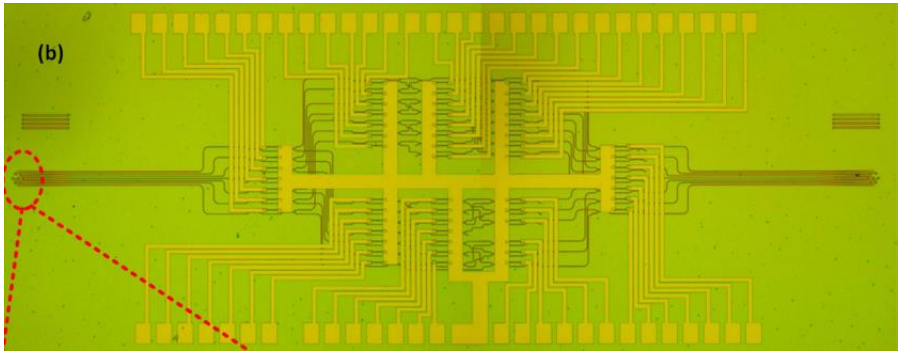
MCF LPG Array enabled SDM signal switching and multicasting

WDM wavelength multicasting

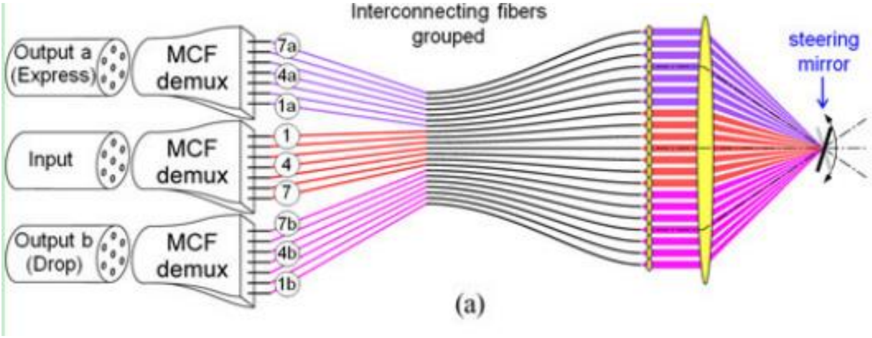




SDM core-to-core switch and multicasting



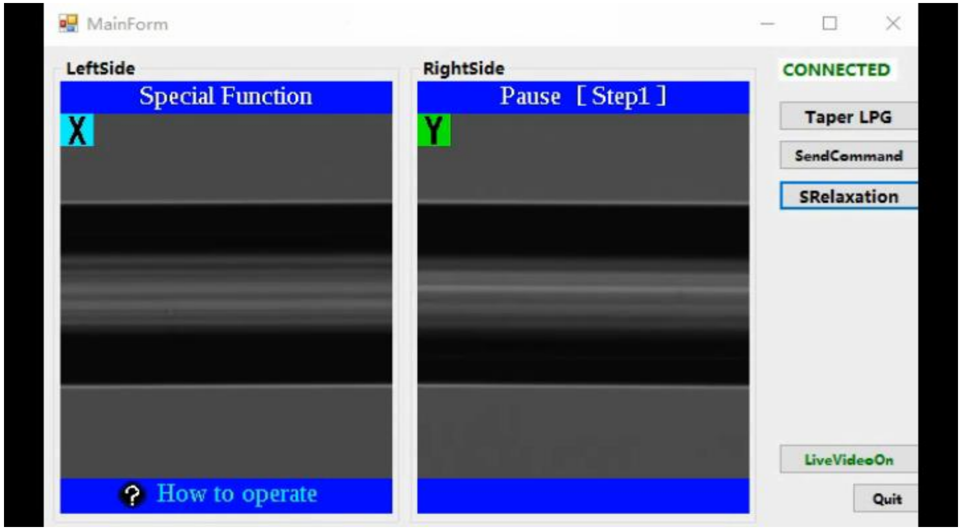
Silicon-based switch

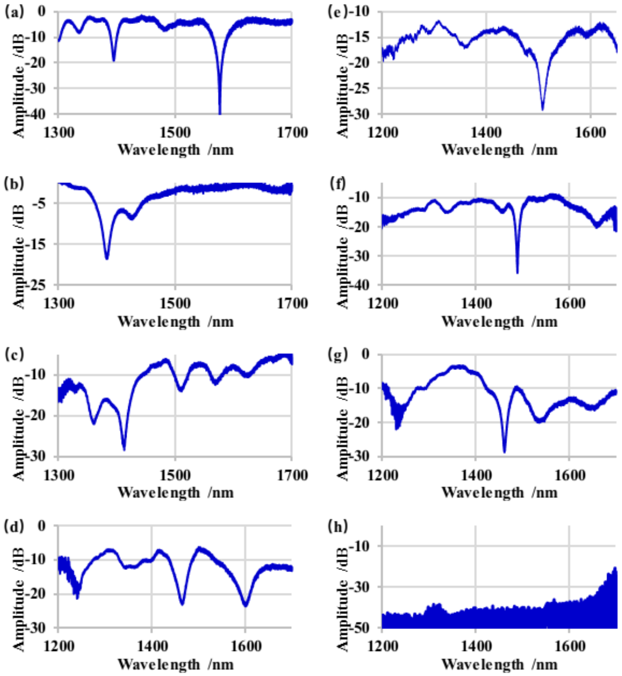


MEMS based coupling

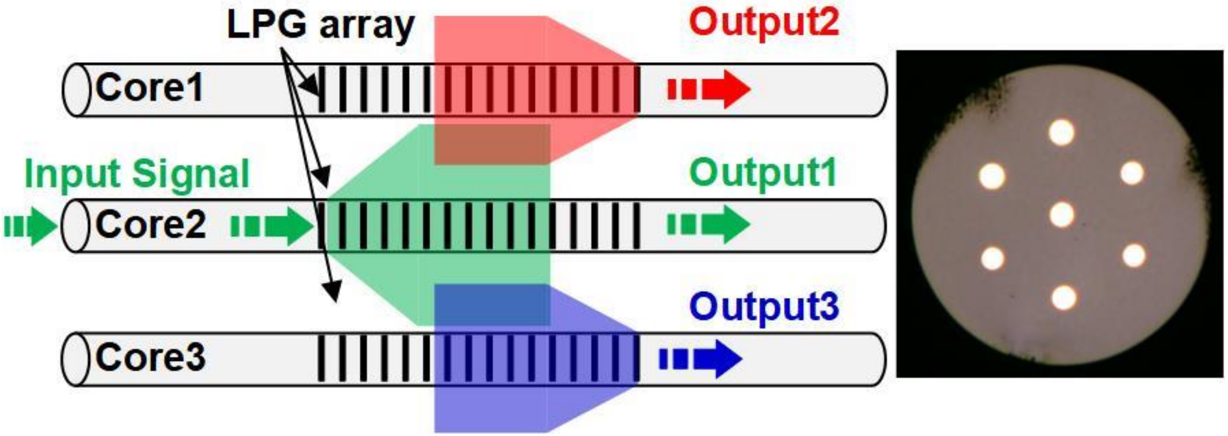
- Yan Wang, et al. JLT 2005
- Yunhong Ding, et,al, Scientific Reports, 2016
- L. E. Nelson, et al, JLT 2014

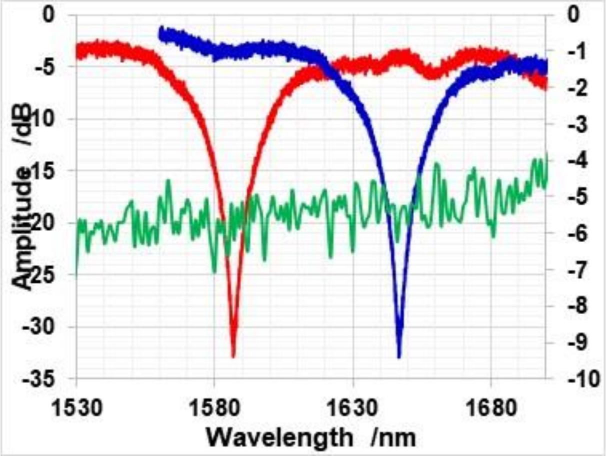
MCF-long period gratings (LPG) by strain relaxation: programmable





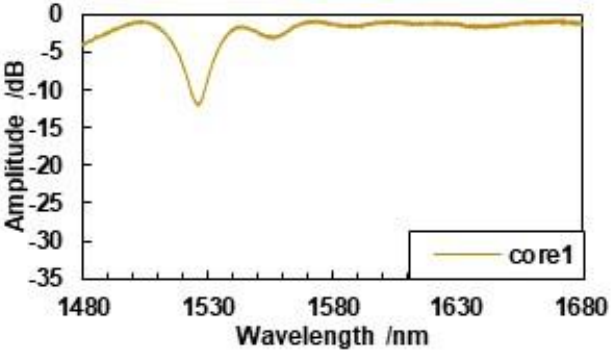
Transmission spectrums of long period grating group in seven cores with grating pitch equals to 510μm. (a) center core transmission spectrum; (b)-(g) outer 6 cores transmission spectrums; (h) supercontinuum light injected into the center core and measured in one of the outer cores.

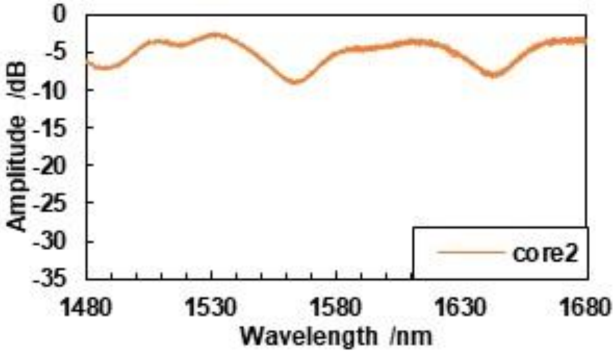


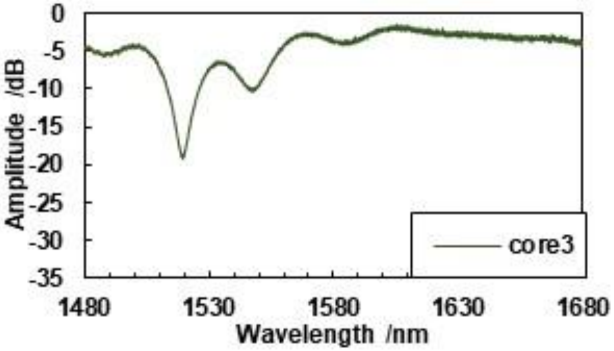


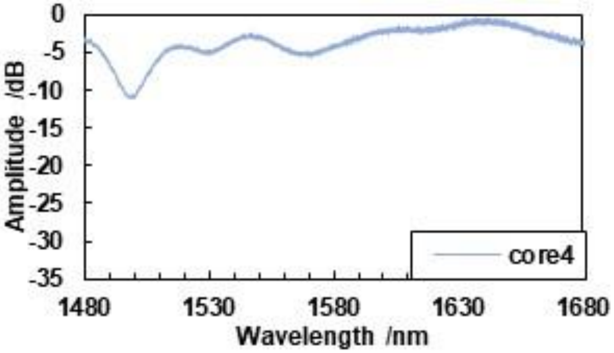
- LPGs in MCF as an competitive approach to implement the power coupling between cores with low loss;
- The broadband transmission spectra of LPGs enable the signal coupling between selective cores

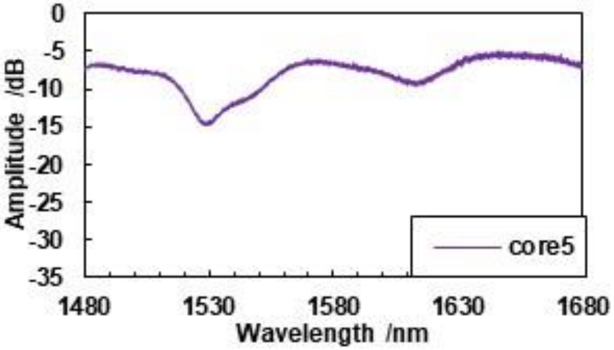
LPG array fabricated

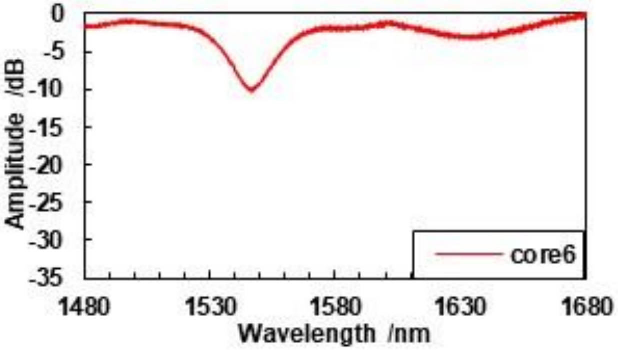


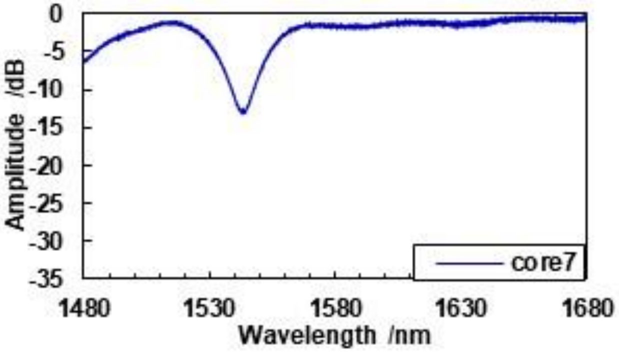


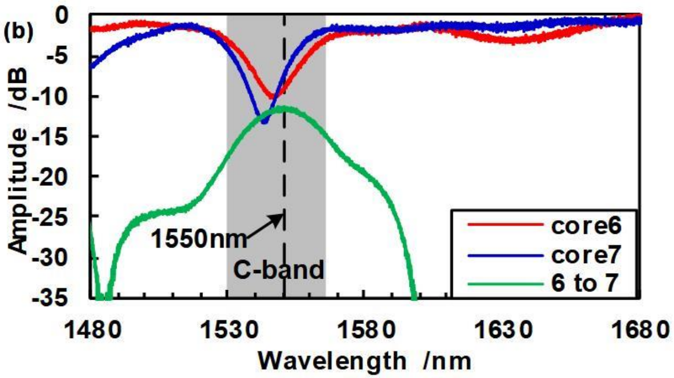


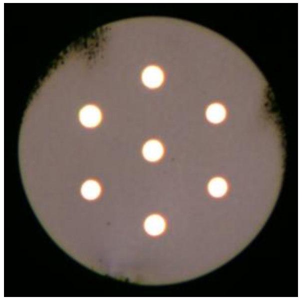




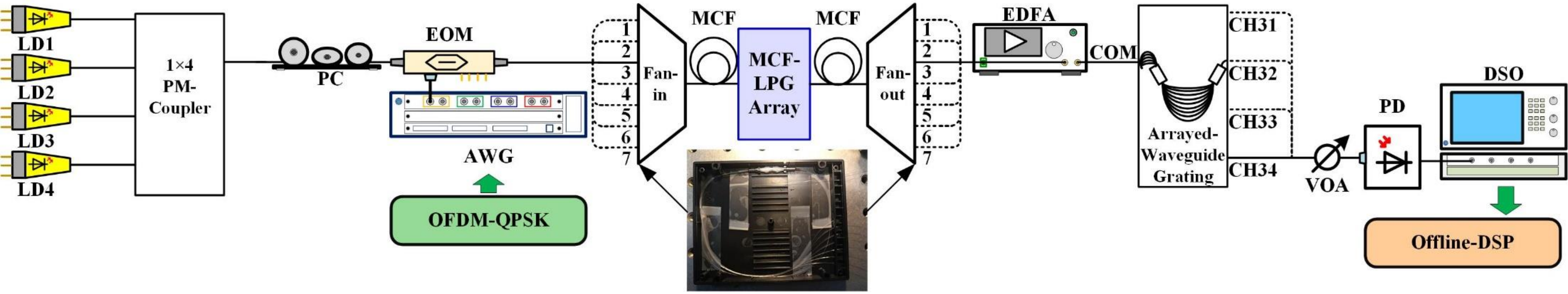




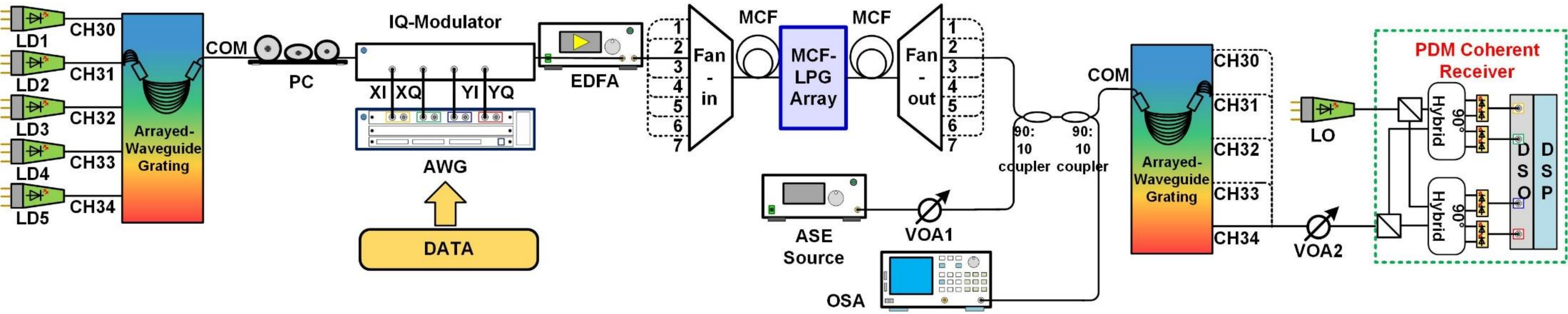




IMDD transmission system：

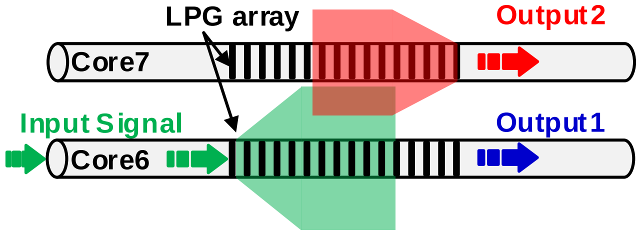


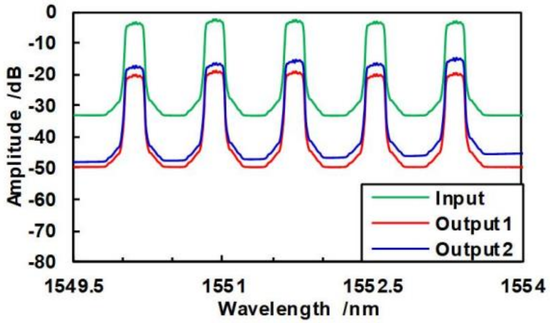
CO-OFDM transmission system：

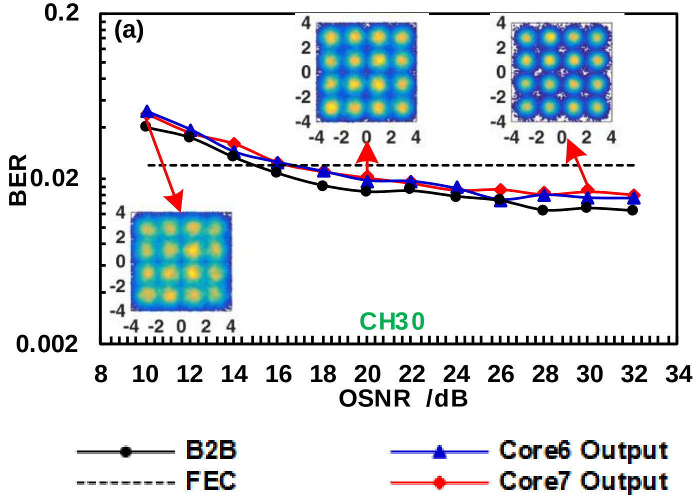


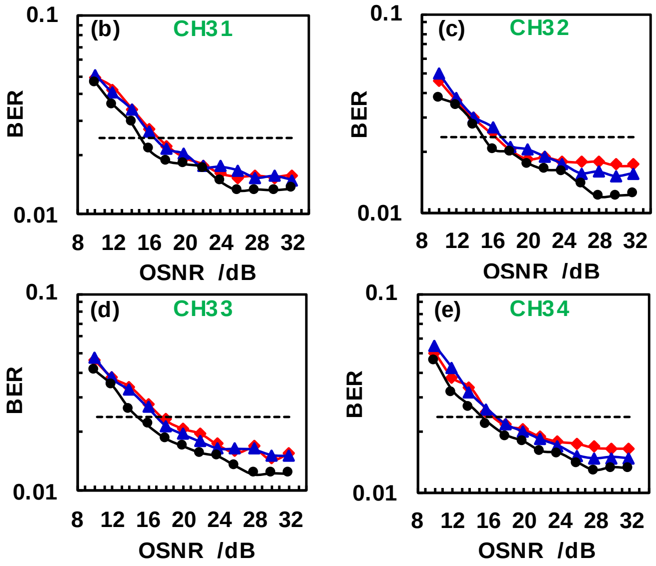
28GSam/s×4×2=224Gb/s for single wavelength, and 1.12Tb/s for 5 WDM channels

CO-OFDM inter-core casting：





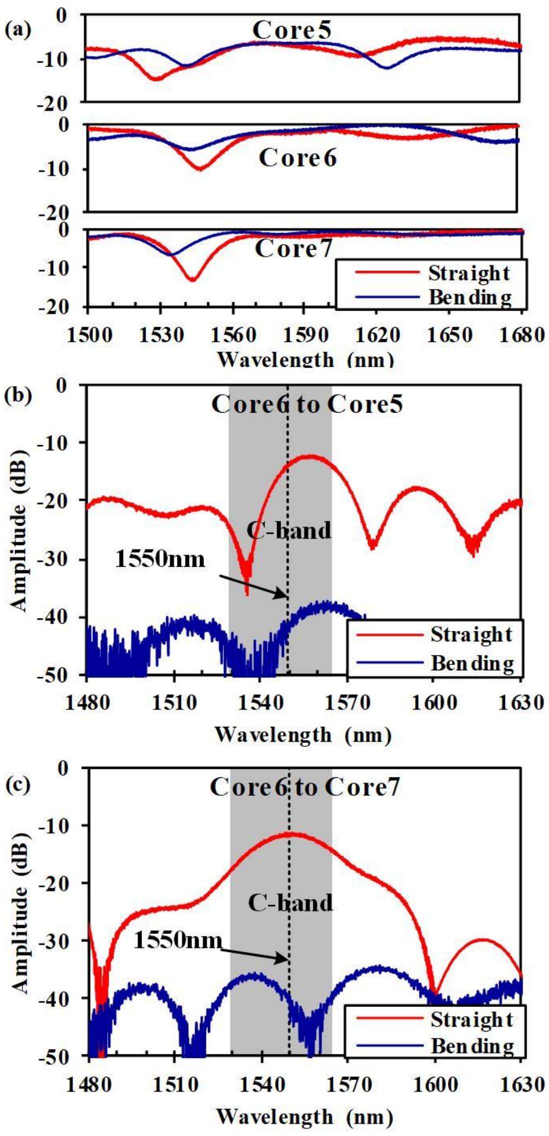


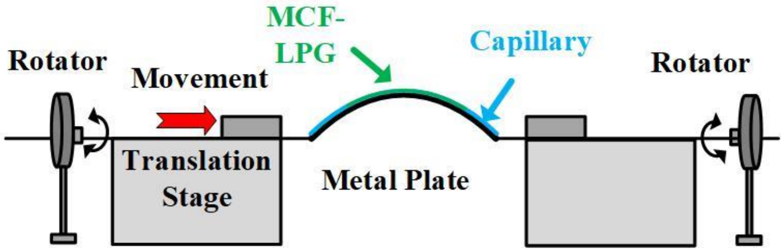


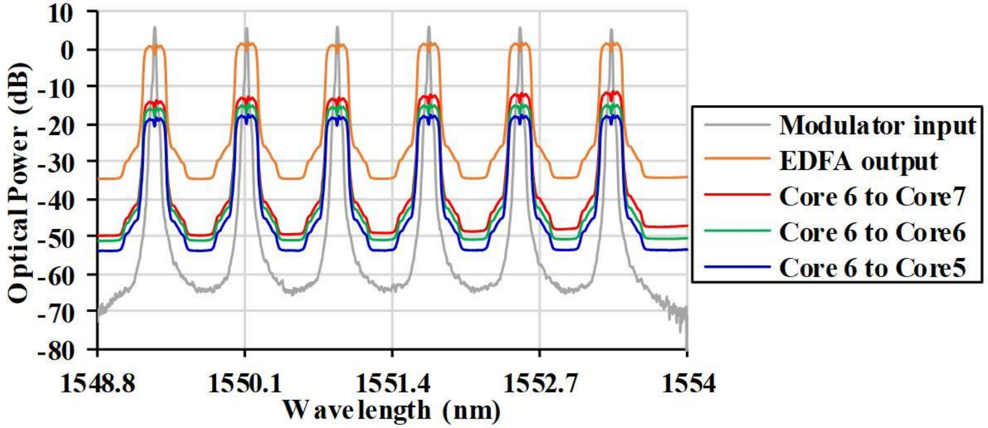
1. C-band 5 wavelength Tb/s signal, 1:2 inter core multicasting；
2. No signal degradation after inter-core coupling

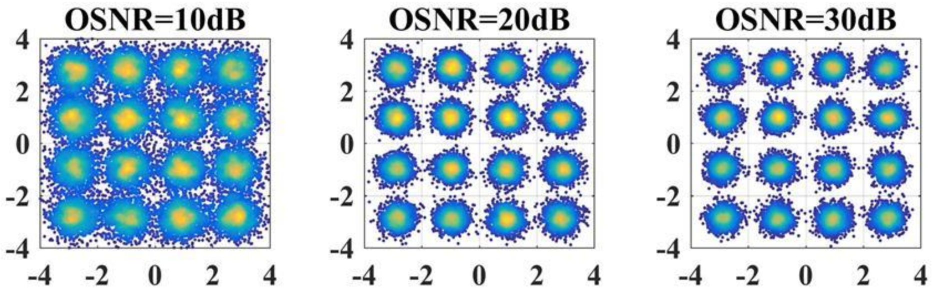
R. Wang, M. Tang. Et al., ECOC 2017, Sweden

Reconfigurable Inter-Core Switching Within the Multicore Fiber



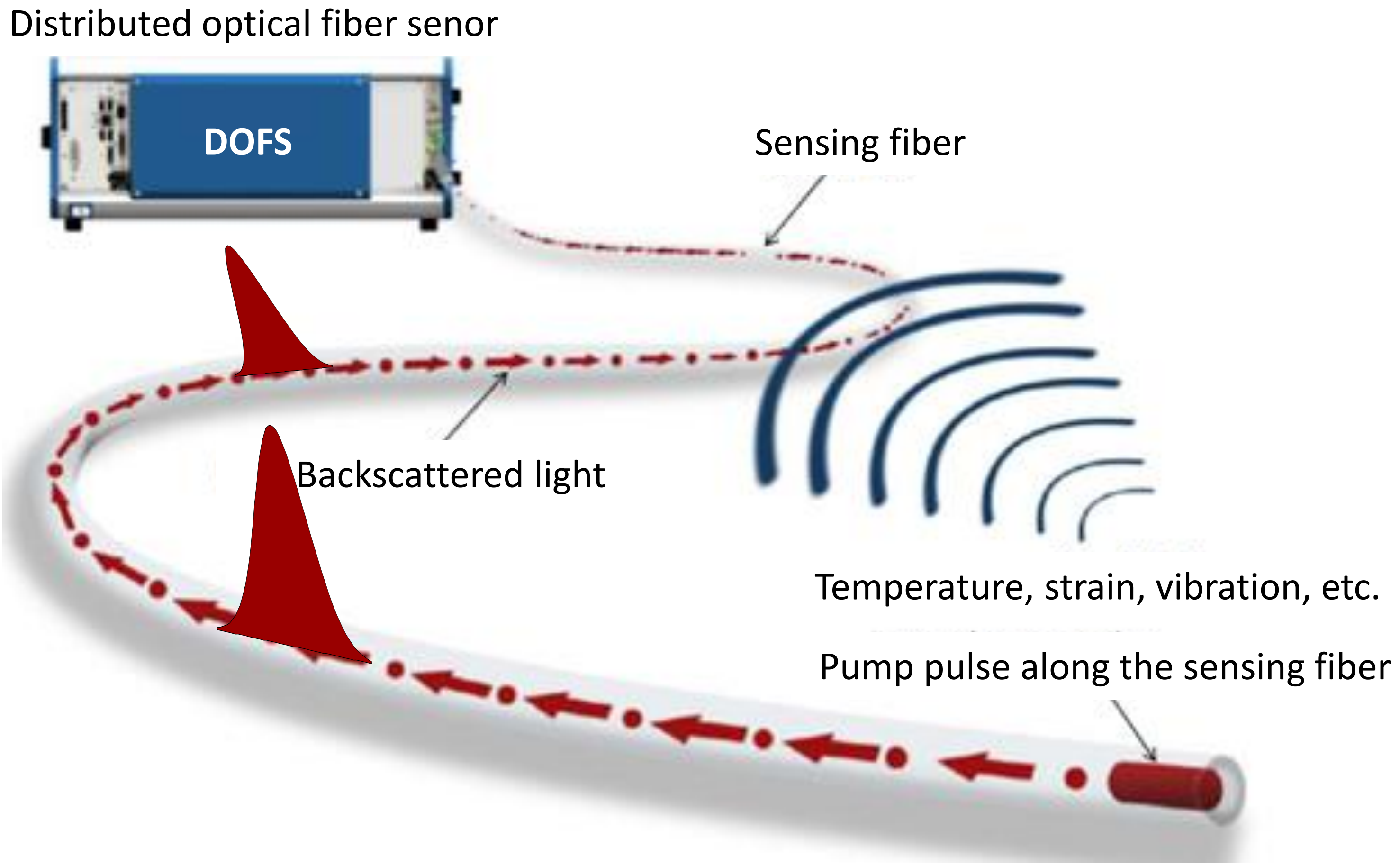






Wang Ruoxu, Wu Qiong, Tang Ming, OFC 2018: W2A.38. (top scored paper)

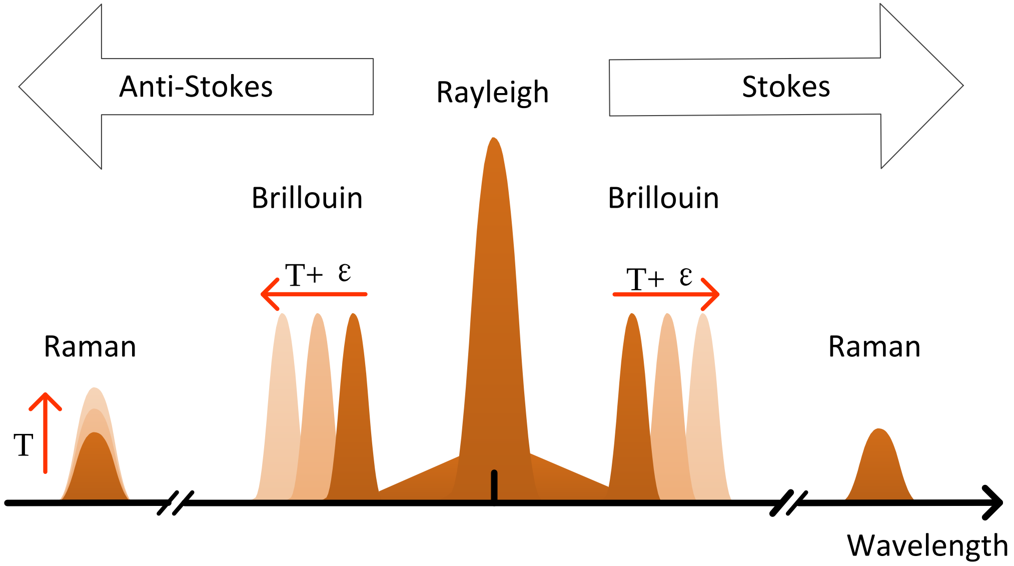
Background: distributed optical fiber sensing



☺ **Meter or even sub-meter scale spatial resolution；**

☺ **Tens or even hundreds of kilometers sensing range.**

Distributed optical fiber sensing techniques



Rayleigh scattering

- Phase sensitive optical time-domain reflectometry (Φ-OTDR)
- Optical frequency-domain reflectometry (OFDR)
- Polarization optical time-domain reflectometry (P-OTDR)

Brillouin scattering

- Brillouin optical time-domain reflectometry/ analyzer (BOTDR/A)
- Brillouin optical correlation-domain reflectometry /analysis (BOCDR/A)

Raman scattering

- Raman optical time-domain reflectometry (ROTDR)

Challenges and difficulties of traditional DFS

- Cross sensitivity issue;
- Multi-parameter measurement;
- Dynamic and static measurement;
- Signal processing technique

SDM：Artificial physical channel

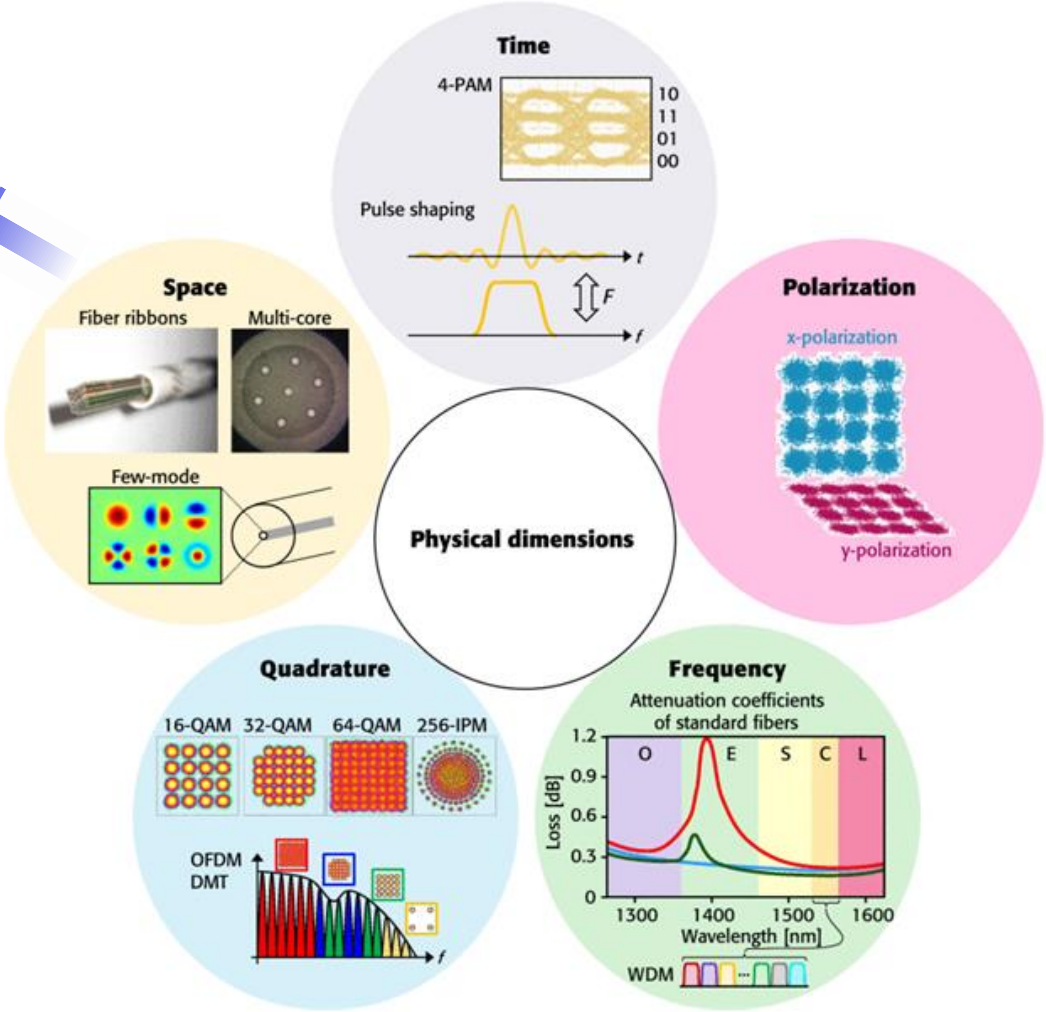
Space-division multiplexing：
- Different spatial cores of multi-core fiber;
- Different spatial modes of few-mode fiber

Space-division multiplexing

+

Distributed fiber sensing

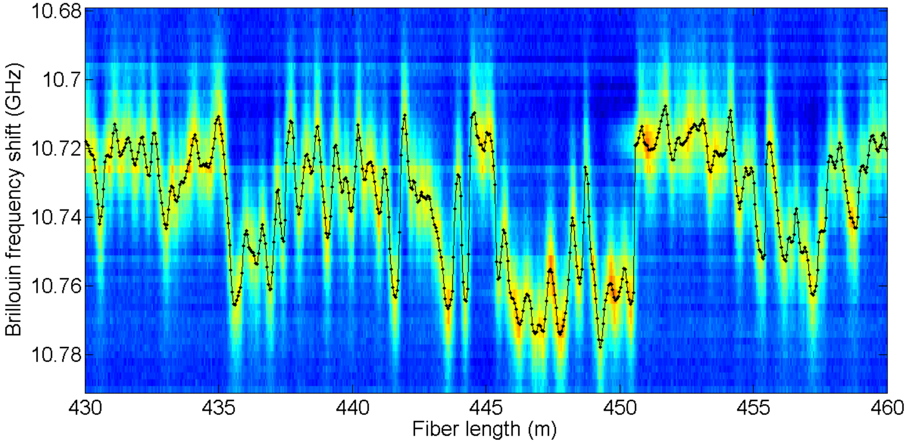
New implementation methods,
new solutions and new applications

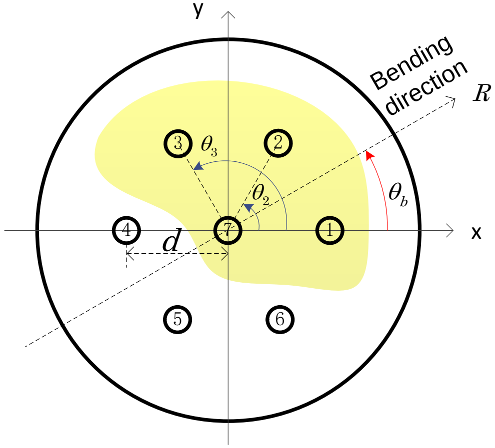


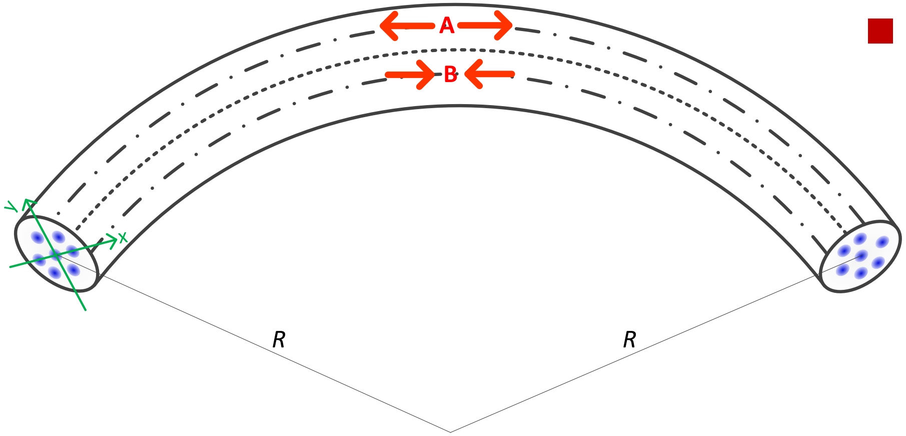
Winzer, Peter J. "Spatial multiplexing in fiber optics: the 10x scaling of metro/core capacities." Bell Labs Technical Journal, 2014, 19: 22-30.

MCF based distributed optical fiber sensors

- Long range and distributed bending and 3-D shape sensing







- Bending induced strain at any point is determined by:

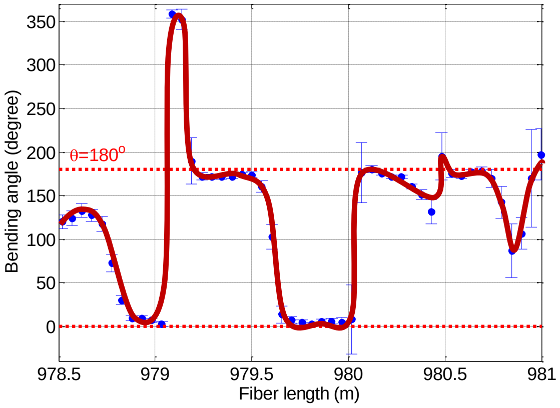
$$\varepsilon_i = -\frac{d_i}{R}\cos(\theta_b - \theta_i)$$

- The strain along the tangential direction at the bending point leads to BFS shift:

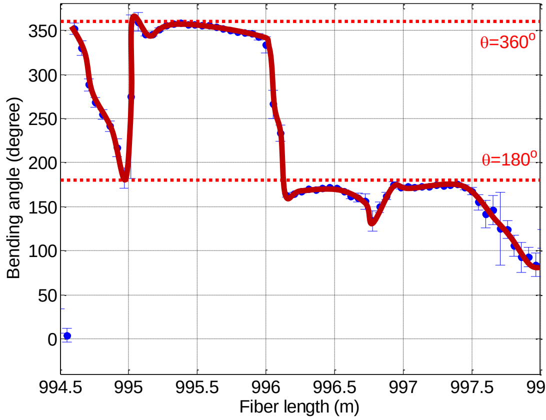
$$\Delta\nu_{Bi} = -\frac{\alpha \cdot d_i \cdot \nu_B}{R}\cos(\theta_b - \theta_i)$$

Zhiyong Zhao, Marcelo A. Soto, Ming Tang, and Luc Thévenaz, "Distributed shape sensing using Brillouin scattering in multi-core fibers," Opt. Express 24, 25211-25223 (2016)

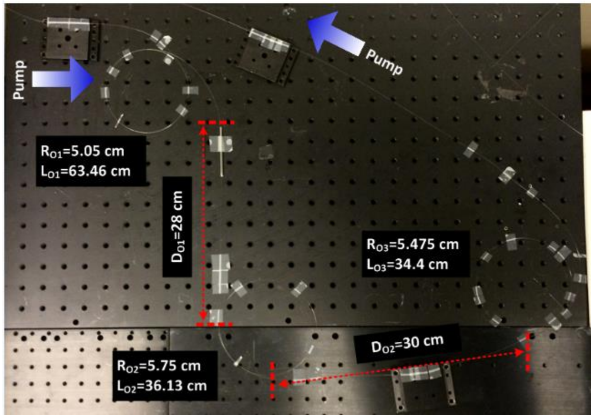
- Distributed bending sensing with long sensing range has been demonstrated;
- Fully 3-D shape sensing is validated by using BOTDA in MCF.

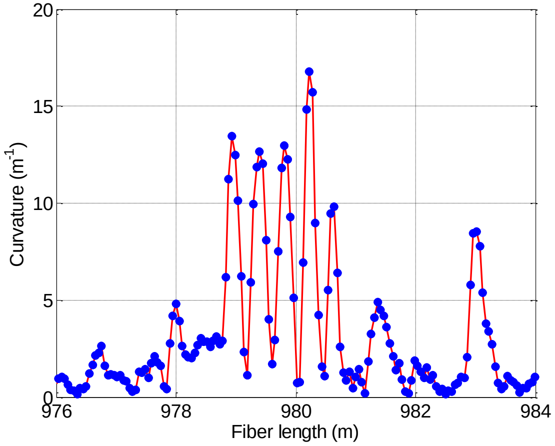


(a)

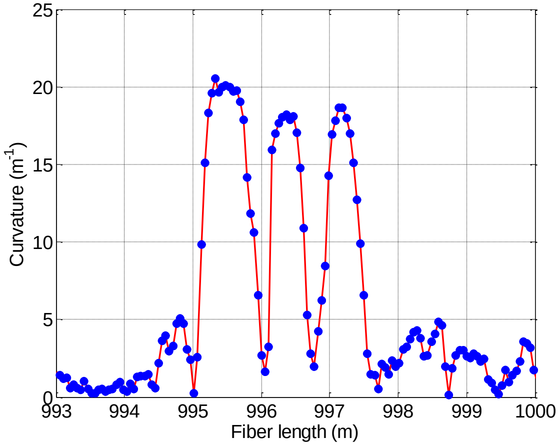


(b)





(c)



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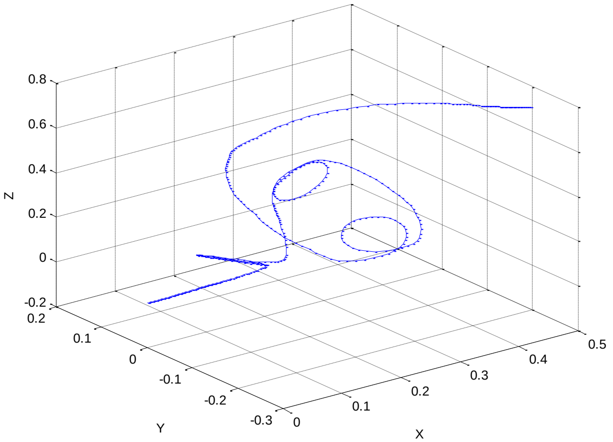


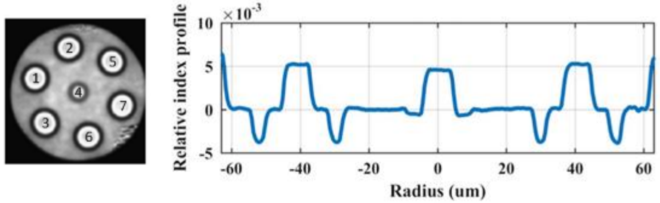
Fiber length: 1 km

Frenet-Serret formulas

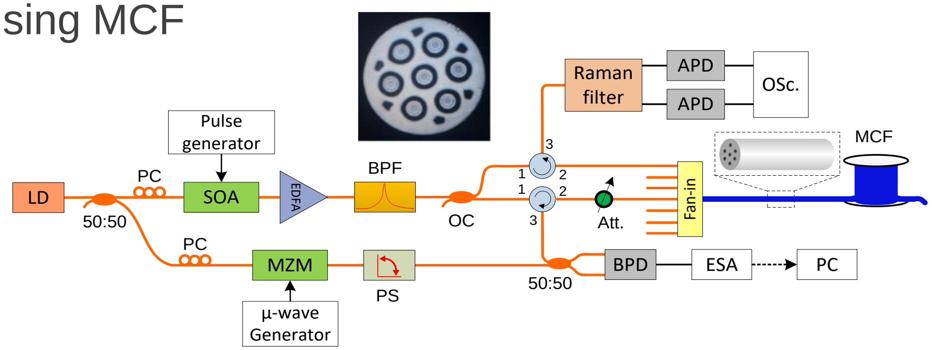
Zhiyong Zhao, Marcelo A. Soto, Ming Tang, and Luc Thévenaz, "Distributed shape sensing using Brillouin scattering in multi-core fibers," Opt. Express 24, 25211-25223 (2016)

MCF based distributed optical fiber sensors

- Temperature and strain discriminative measurement by using
  - BOTDA in a heterogeneous MCF
  - SDM hybrid ROTDR and BOTDR using MCF

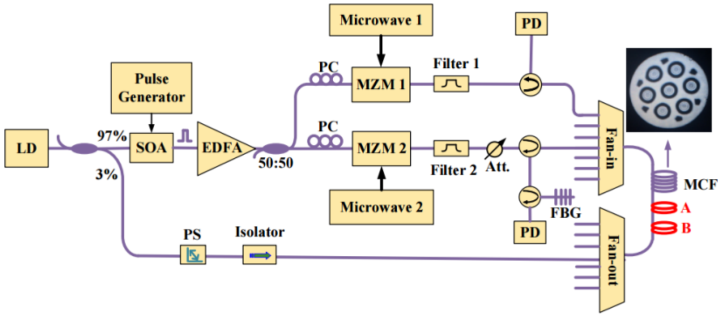


Opt. Lett. 42, 171-174 (2017)



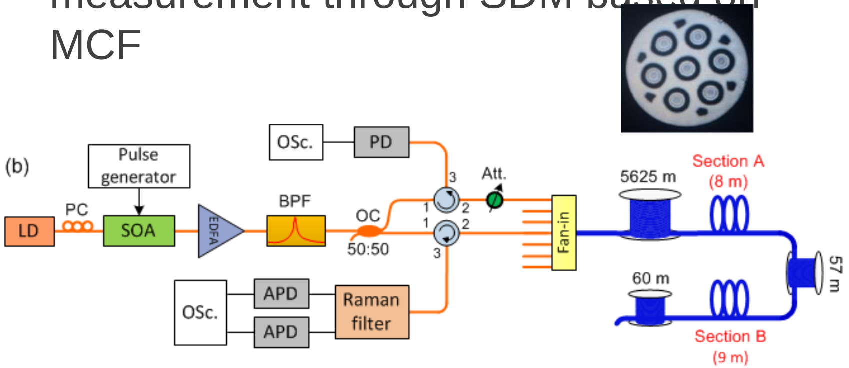
Opt. Express 24, 25111-25118 (2016)

- Large dynamic range and high measurement resolution by using hybrid BOTDA and φ-OTDR in MCF



Opt. Express 25, 20183-20193 (2017)

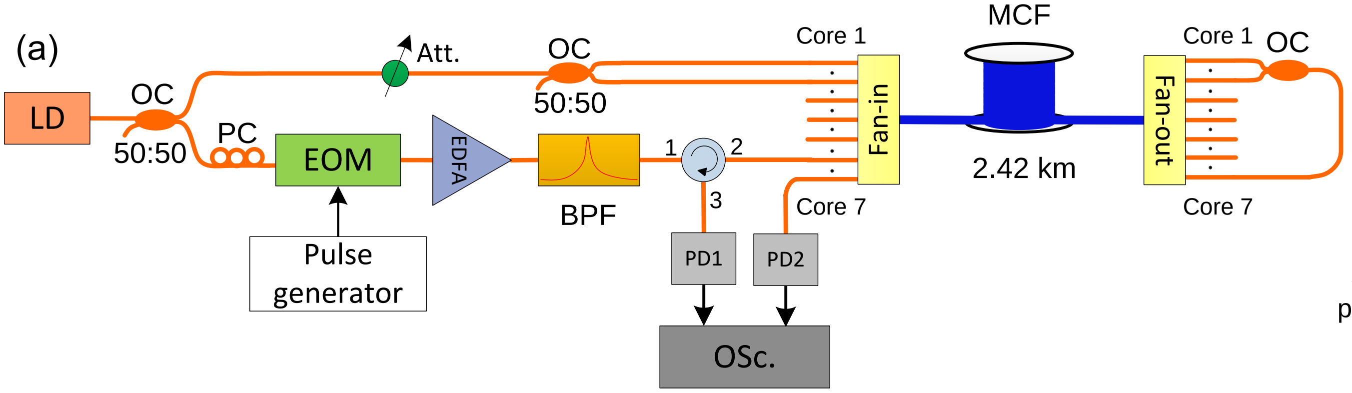
- Simultaneous DAS and DTS measurement through SDM based on MCF



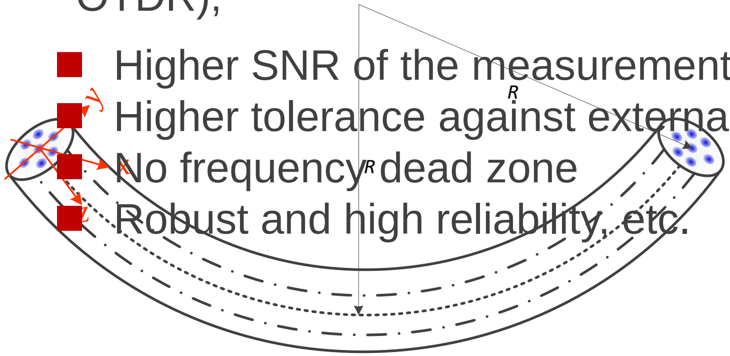
OFC, paper W2A.7, 2018.

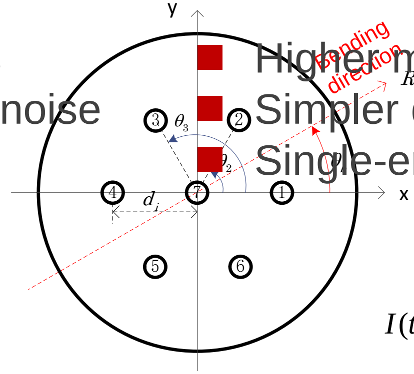
MCF SDM φ-OTDR and MZI for vibration sensing

- The φ-OTDR is used to locate the vibration and the vibration frequency is retrieved by the interferometer, which enables high spatial resolution and large frequency response range.



- Interferometer: Mach-Zehnder interferometer (MZI);
- Reflectometer: phase-sensitive optical time-domain reflectometer (φ-OTDR);
  - Higher SNR of the measurements
  - Higher tolerance against external noise
  - No frequency dead zone
  - Robust and high reliability, etc.
  - Higher measurement accuracy
  - Simpler data processing procedure
  - Single-end access





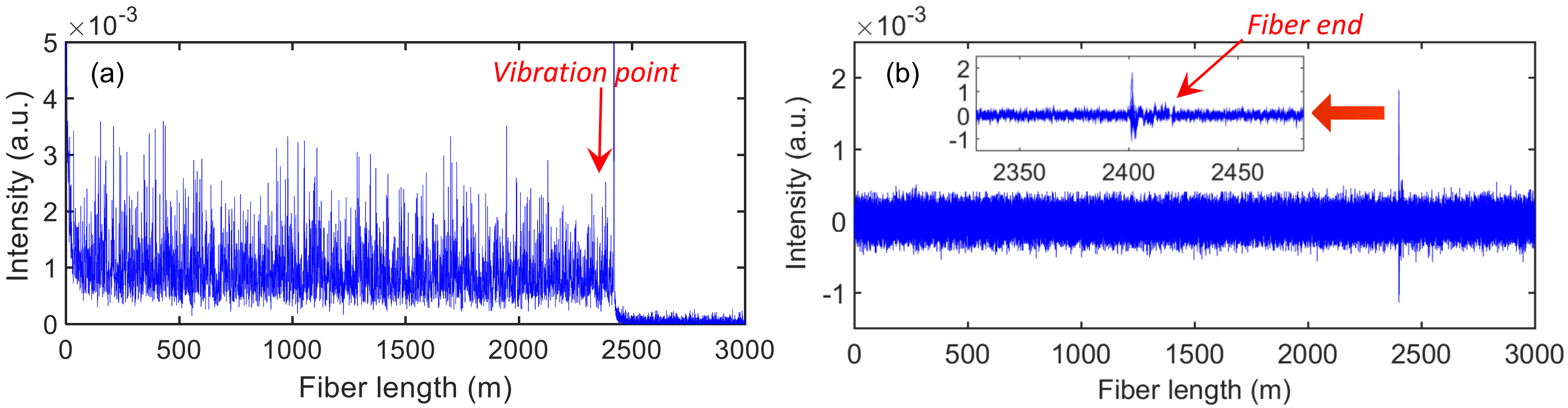
- Bending induced strain at any point is determined by:

$$\varepsilon_i = -\frac{d_i}{R}\cos(\theta_b - \theta_i)$$

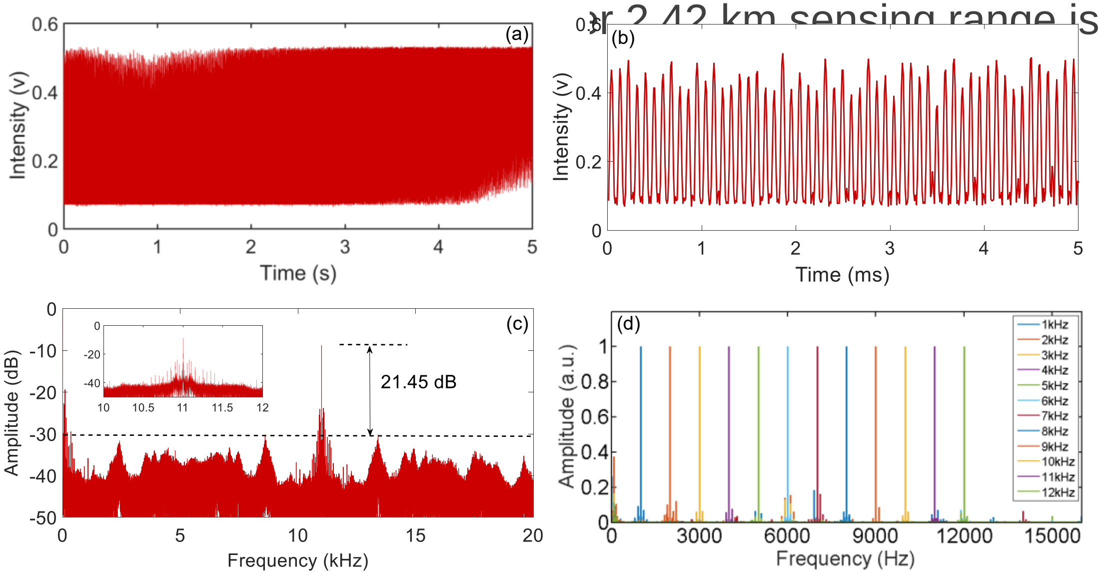
- The MZI output:

$$I(t) \propto E_1^2(t) + E_2^2(t) + 2E_1(t)E_2(t)\cos(\theta_P)\cos[\varphi_1(t) - \varphi_2(t)]$$

Z. Zhao, M. A. Soto, M. Tang, and L. Thévenaz, Opt. Express 24, 25211-25223 (2016)



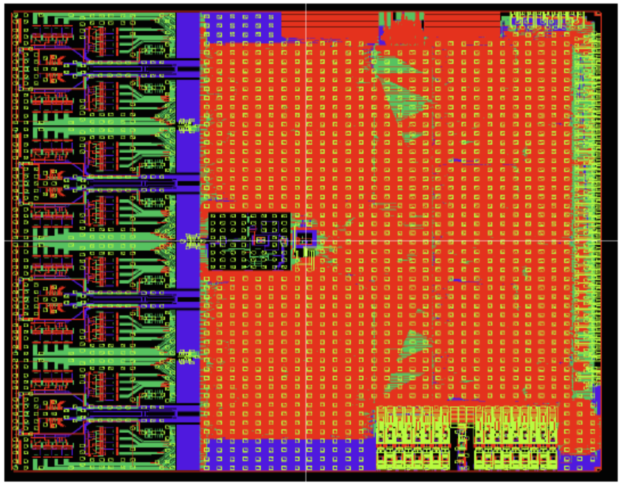
- To locate the vibration, consecutive traces are measured and then subtracted from an undisturbed reference trace;
- In order to increase the SNR of measurement, the trace has been averaged by 256 times;
- r 2.42 km sensing range is achieved.

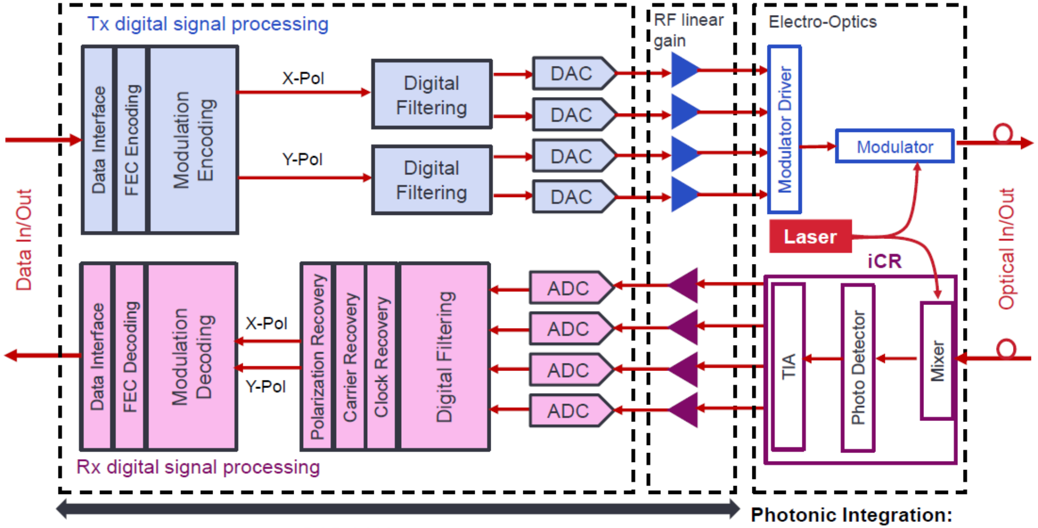


- The frequency spectrum measured by the MZI of the SDM hybrid sensing system has high SNR;
- Repeated vibration measurements is performed, which verifies the excellent reliability of the proposed SDM MZI vibration sensor.

OEIC for optical communications

- Coherent receiver: CMOS ASIC





Tx digital signal processing

Data Interface

FEC Encoding

Modulation Encoding

X-Pol

Y-Pol

Digital Filtering

Digital Filtering

DAC

DAC

DAC

DAC

RF linear gain

Electro-Optics

Modulator Driver

Modulator

Laser

iCR

Data In/Out

Optical In/Out

Data Interface

FEC Decoding

Modulation Decoding

X-Pol

Y-Pol

Polarization Recovery

Carrier Recovery

Clock Recovery

Digital Filtering

ADC

ADC

ADC

ADC

TIA

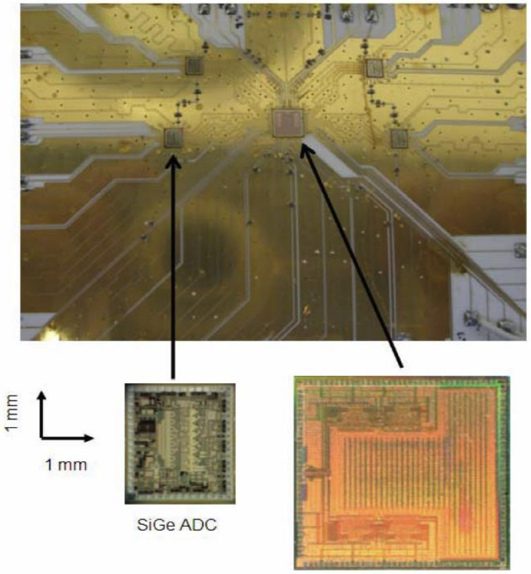
Photo Detector

Mixer

Rx digital signal processing

DSP ASIC

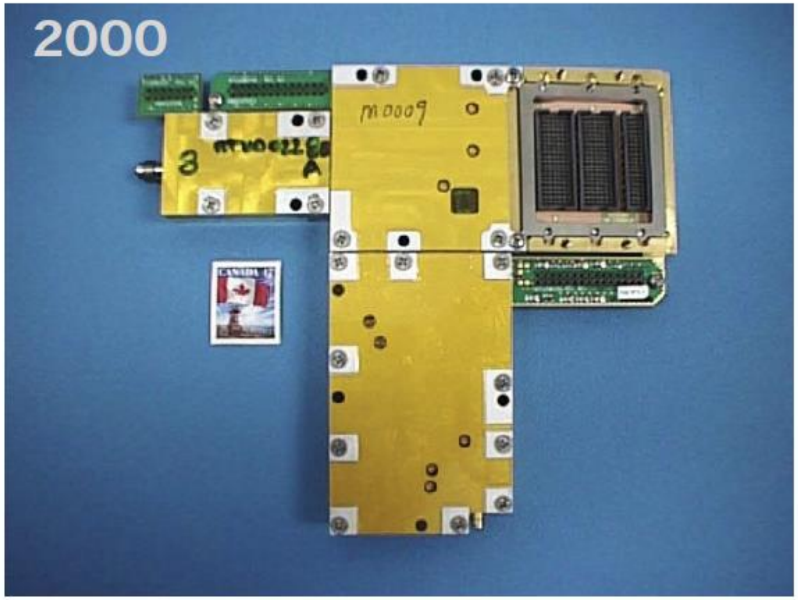
Photonic Integration: Integration of electro-optic functions



SiGe ADC

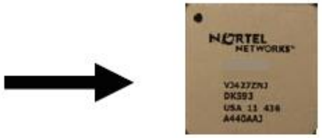
CMOS chip

OEIC for optical communications



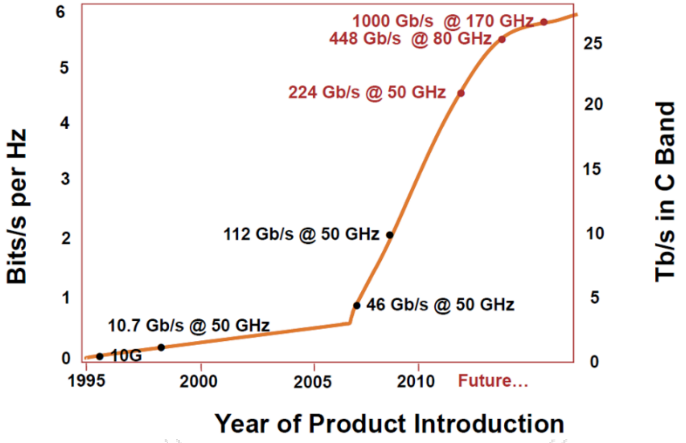
40G IM-DD Rx Electronics

2008

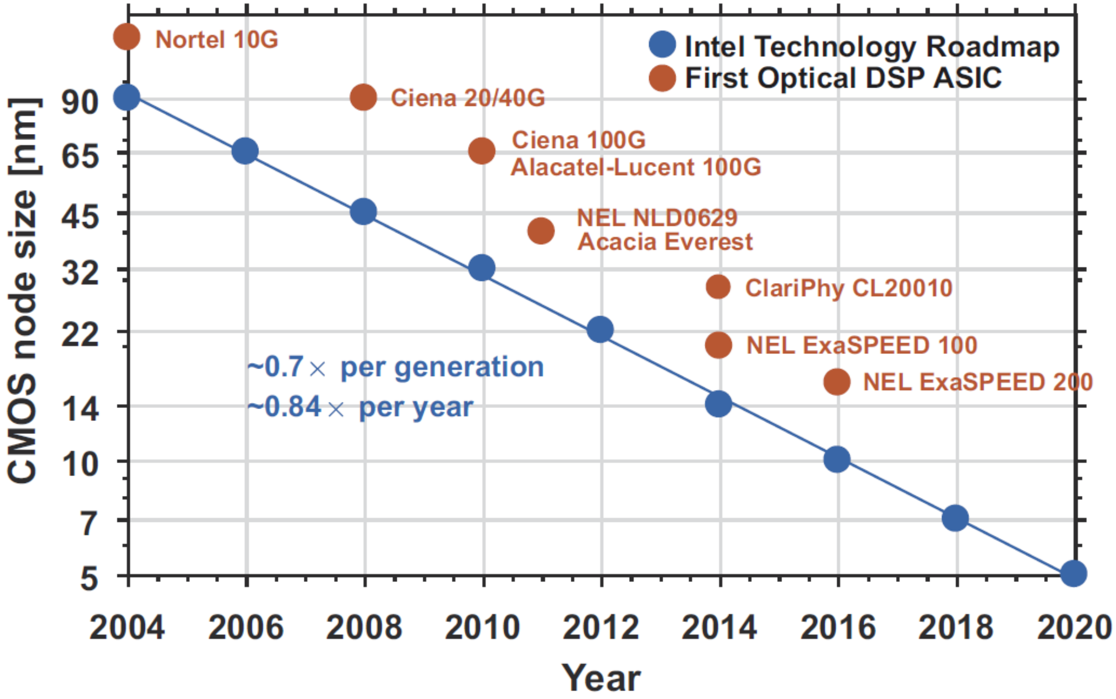


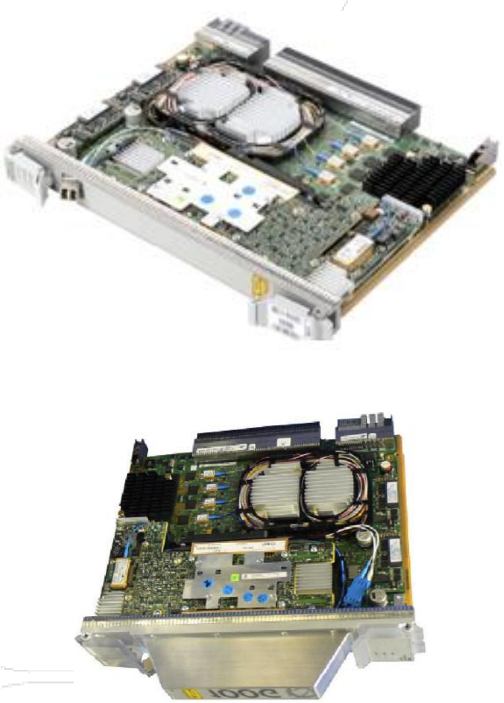
40G DP-QPSK Rx Electronics

- ☐ Faster A/D→11, 28, 56, … Gbaud
- ☐ More gates of DSP
- ☐ CMOS riding Moore’s Law


Capacity Trend

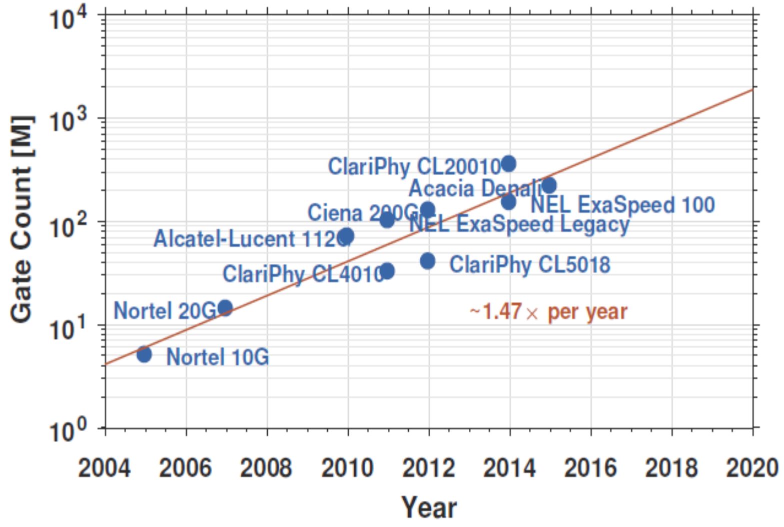
OEIC for optical communications



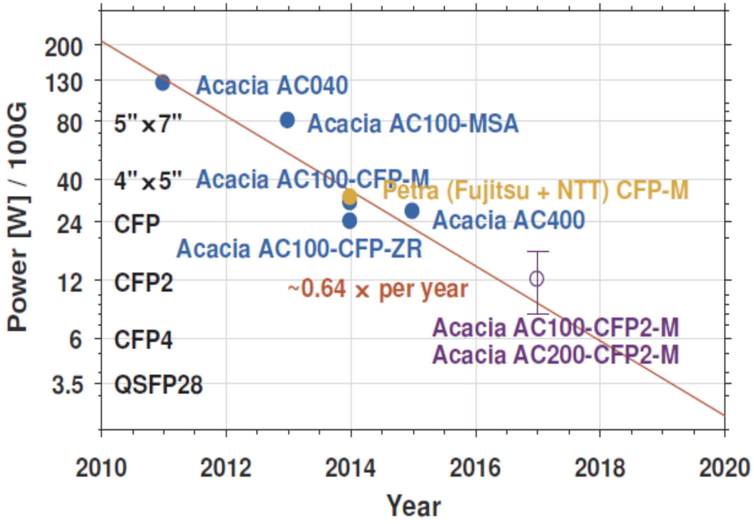


- Optical DSP ASICs follow current CMOS generations with a delay of about 2-3years
- The CMOS power consumptions scales approximately with its node size, thus each process step allows a power reduction of roughly ~30%
- Power consumption of 16nm node size is less than 10-watt per 100Gb/s for data-center interconnects

OEIC for optical communications



Reported gate counts for various optical DSP ASICs



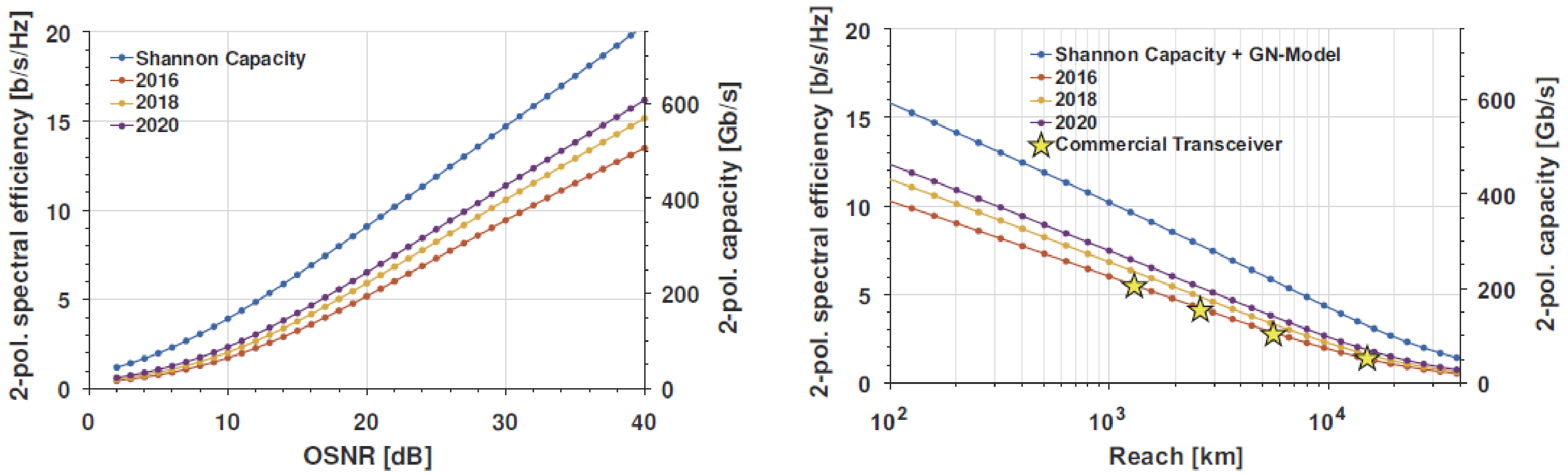
Required power per 100G for recent transponders and DCOs

- The complexity of current optical DSP ASICs for long-haul applications is in the order of 200 million gates and beyond
- the power required to transmit 100G shows a constant decrease with a rate of about 0.64× per year

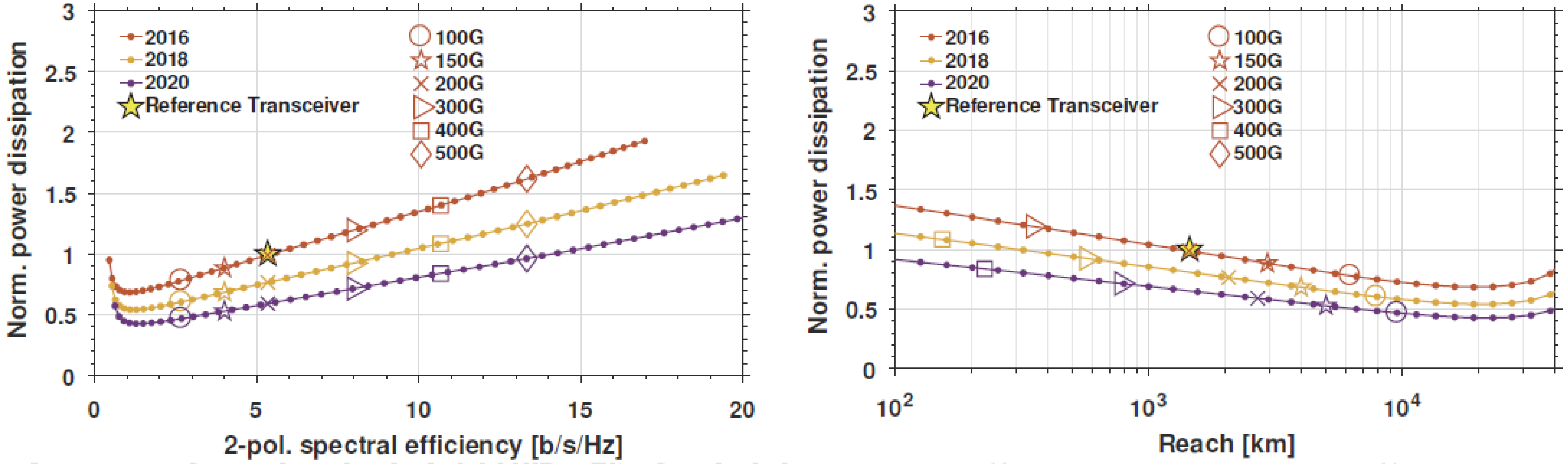
[1] Frey F, Elschner R, Fischer J K. Estimation of Trends for Coherent DSP ASIC Power Dissipation for different bitrates and transmission reaches[C]// Photonic Networks; 18. ITG-Symposium; Proceedings of. VDE, 2017.

OEIC for optical communications

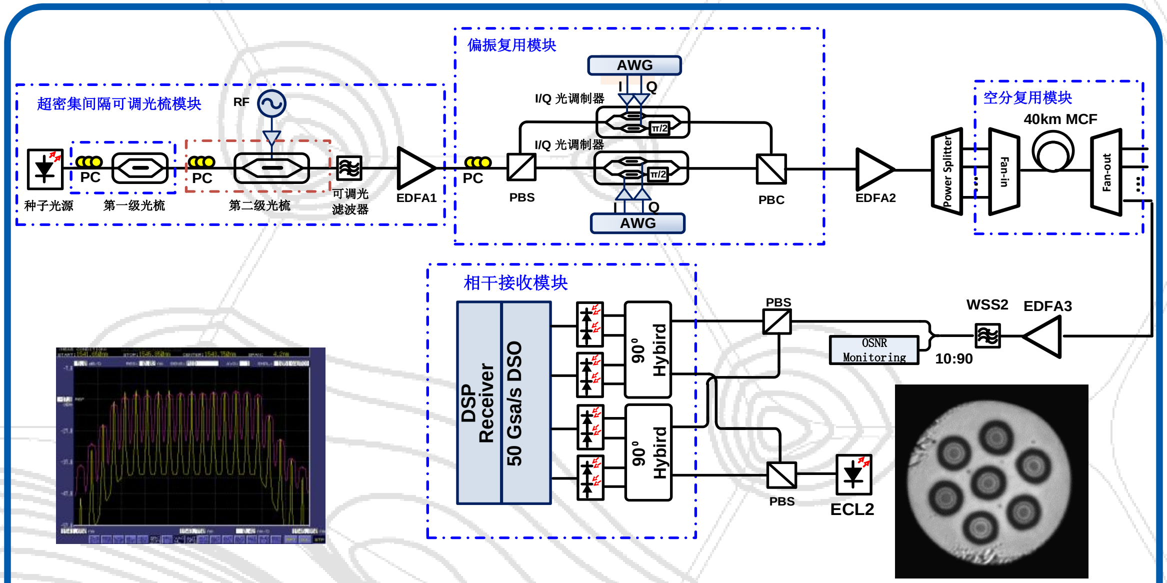
Spectral efficiency and capacity (for a symbol rate of 32 GBd)

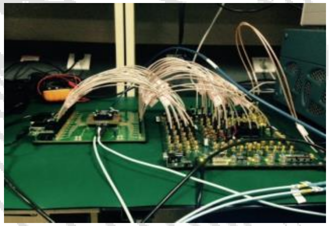


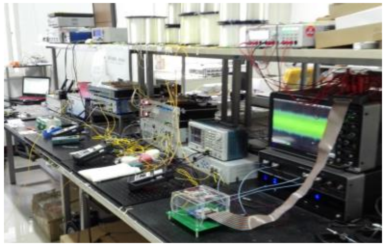
Normalized power dissipation of a 32 GBd ASIC



High speed OFC R&D platform in HUST





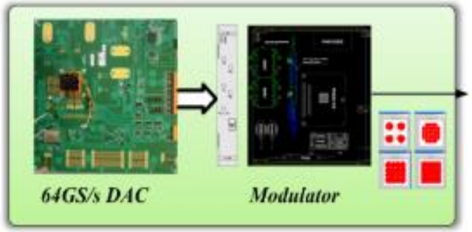


Ultra-High Capacity: 33.6Tb/s

Spectral Efficiency :44.8b/s/Hz

Fiber Distance:5000km

Our research on DSP algorithm



Huawei released world first 200/400 Gbps ASIC for optical communication in OFC 2016 (partial contribution from our work)

Conclusion

Power of High-Speed

Worldwide Internet Access

Depends on *the Global*

Broadband Optical Fiber Telecom Networks;

Communications at

@

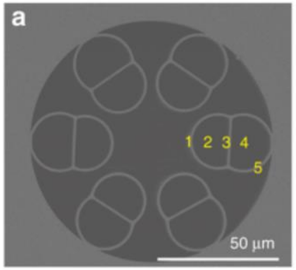
The Speed of Light C

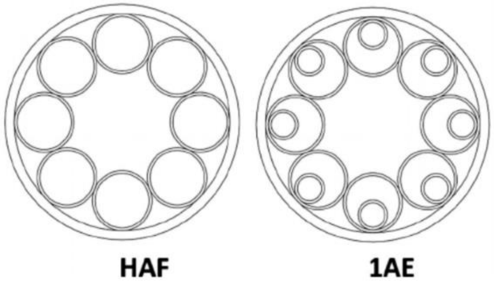
What's in the Future?

Emerging Photonics Technologies beyond Broadband

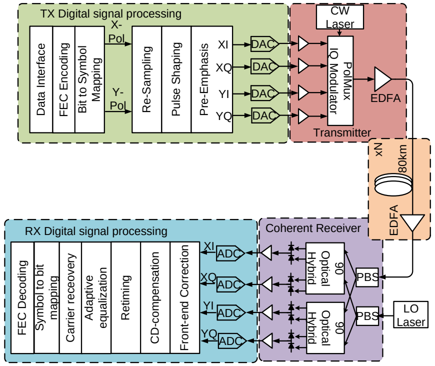
Emerging Photonics Technologies beyond Broadband

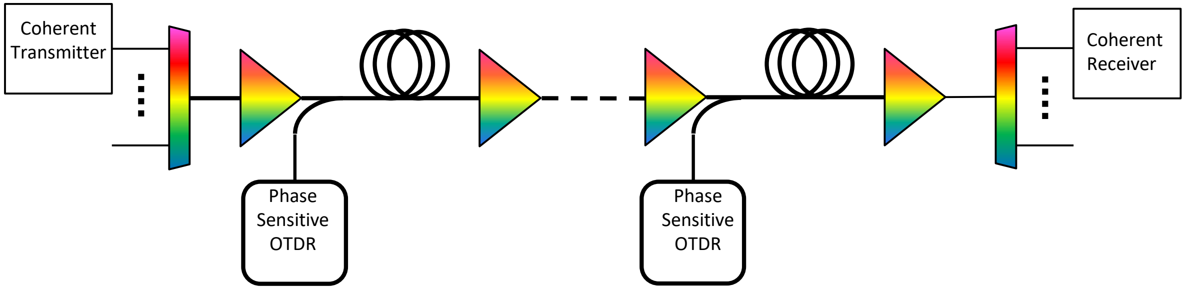
- Smart Optical Network:
  - AI+ optical network
  - Monitoring of global fiber network
  - Smart city

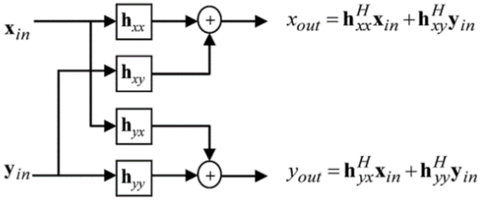




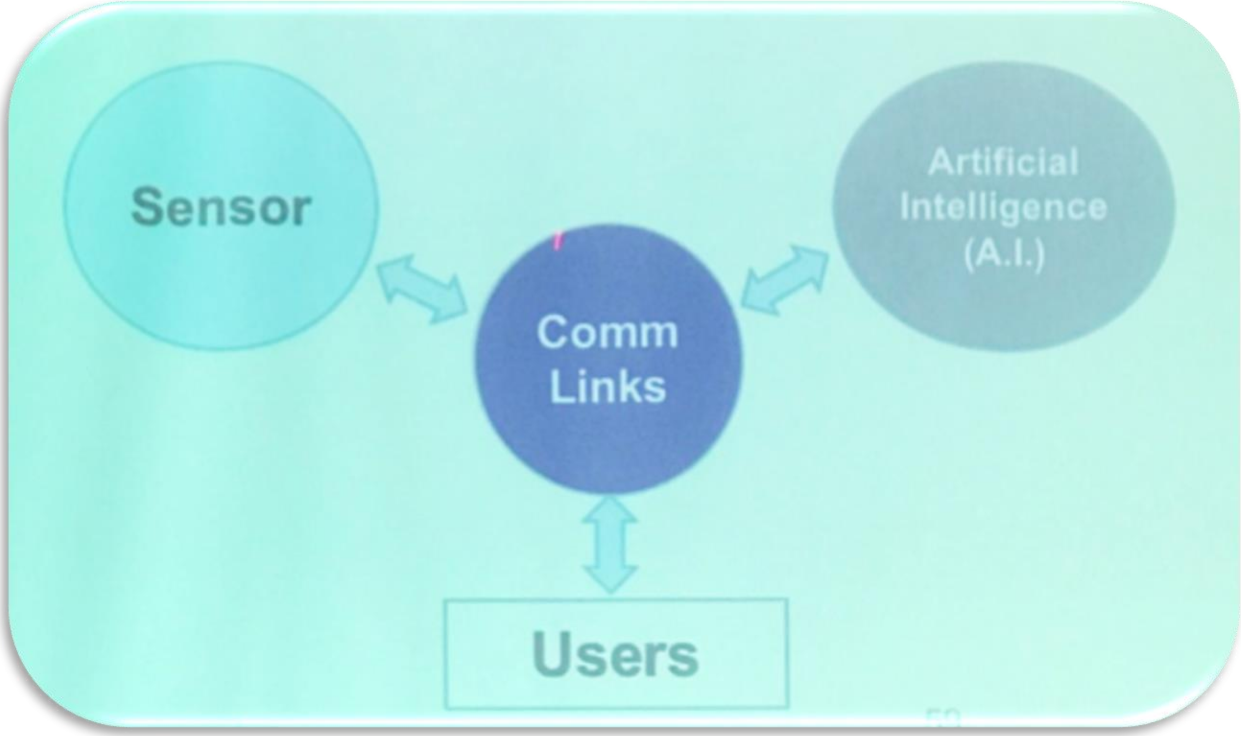
- Multi-material Integration
  - Silicon-Photonics
  - Thin-film LN photonics
  - Multi-functional optical fibers







Future Smart Systems



From Prof. Bahram Jalali in UCLA

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Thanks！