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Winter College on Optics: Fundamentals of Photonics - Theory, Devices and Applications

10 - 21 February 2014

optical communPhotonics for ications

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Faculty of Electrical Engineering
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Slovakia

PHOTONICS FOR OPTICAL COMMUNICATIONS

Winter College On Optics, ICTP Trieste, February 2014

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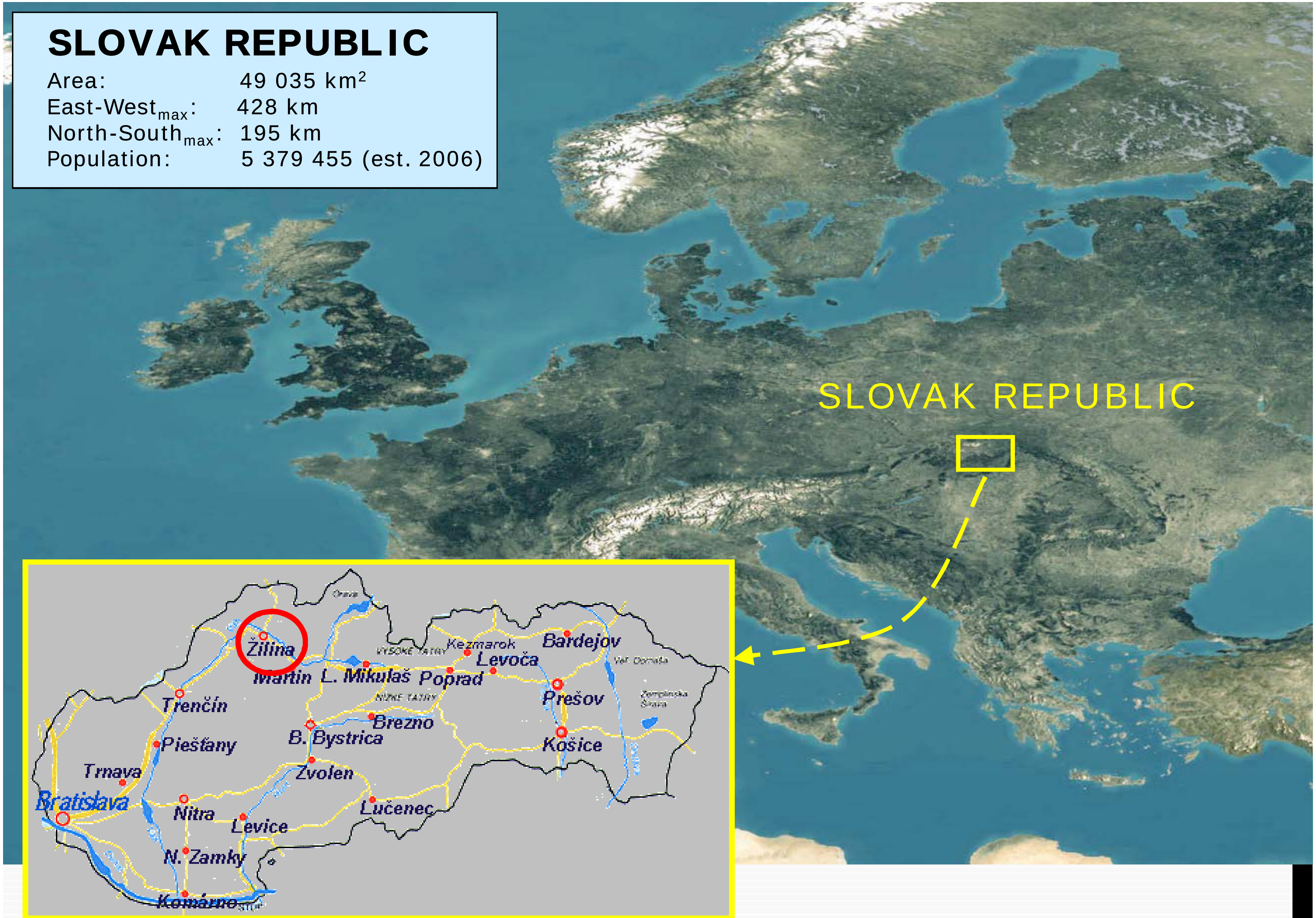
49°12'8.26"N
18°45'23.6"E

SLOVAK REPUBLIC

Area:	49 035 km^2
East-West$_{max}$:	428 km
North-South$_{max}$:	195 km
Population:	5 379 455 (est. 2006)



HISTORY

1st October 1953 …..

College of Railways

Faculty of Electrical Engineering
Faculty of Mechanical Engineering
Faculty of Civil Engineering
Transport Faculty
+ Military Faculty

Prague, The Czech Republic

1959 ……. **University of Transport in Prague**

1960-62 … **University of Transport in Žilina**

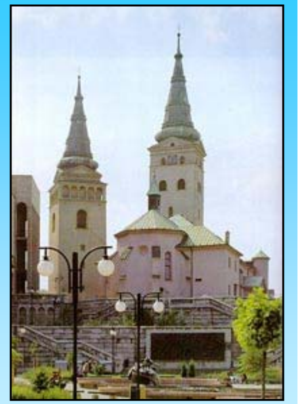
1978 ……. **University of Transport and Communications in Žilina**

1989

Nov 1996 **University of Žilina (UNIZA)**

2006

More than 33 000 graduates during the first 50 years of existence



Žilina, The Slovak Republic


STROJNÍCKA FAKULTA
ELEKTROTECHNICKÁ FAKULTA
ŽILINSKÁ UNIVERZITA
University Campus

JÁNOŠÍK'S HOLES TRAIL

OUTLINE OF PRESENTATION

General trends and milestones

Brief chronology

Optical communication system

Transmission medium

Lasers and transmitters/modulators for OCS

Optical filters in OCS

Optical switches and wavelength convertors

Optical amplifiers in OCS

Receivers

Optical communication systems

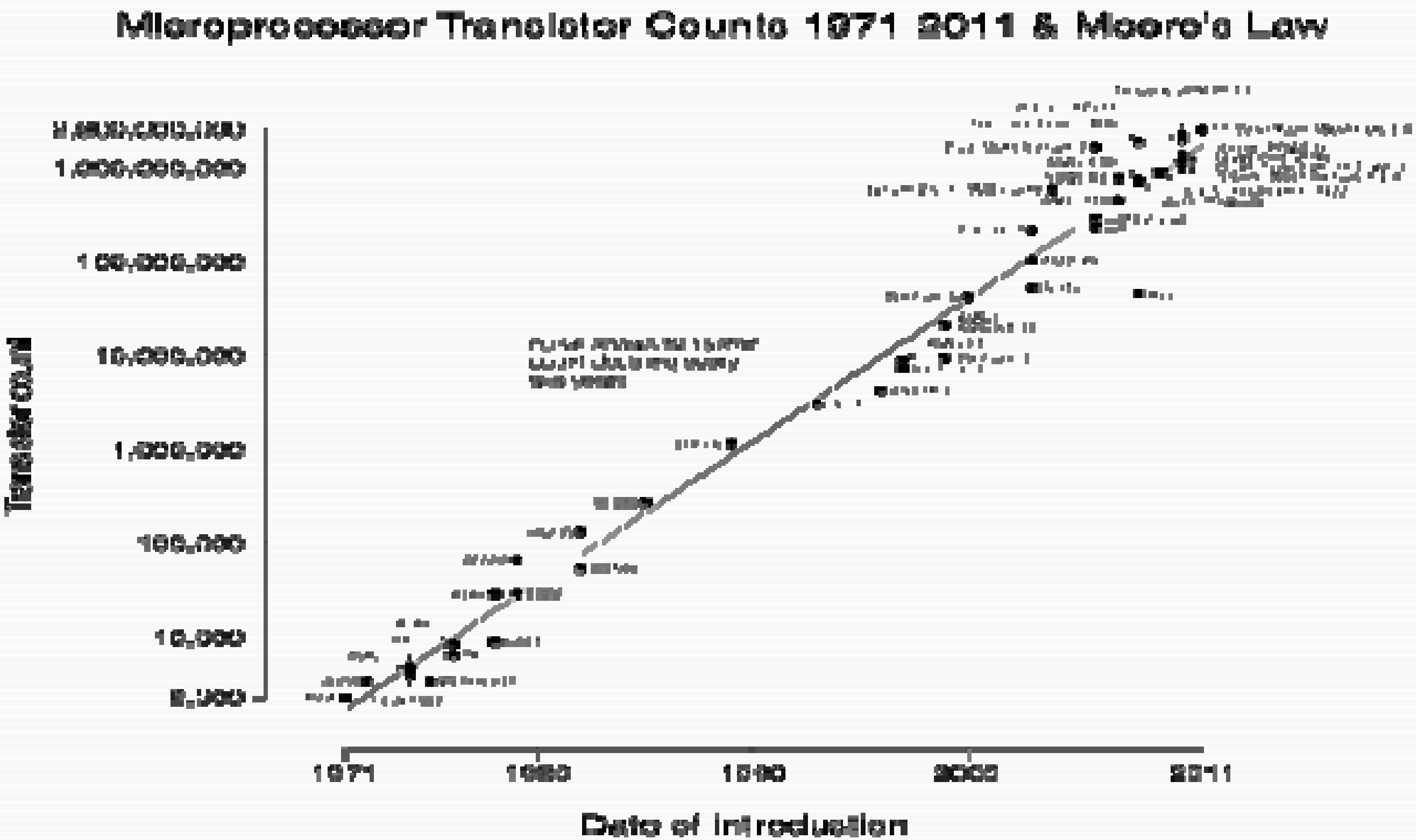
Multiplexing in OCS

What will influence the development in real applications

Research in OCS and photonic at U of Zilina

GENERAL TRENDS AND MILESTONES

MICROPROCESSOR TRANSISTOR COUNTS 1971-2011 & MOORE'S LAW



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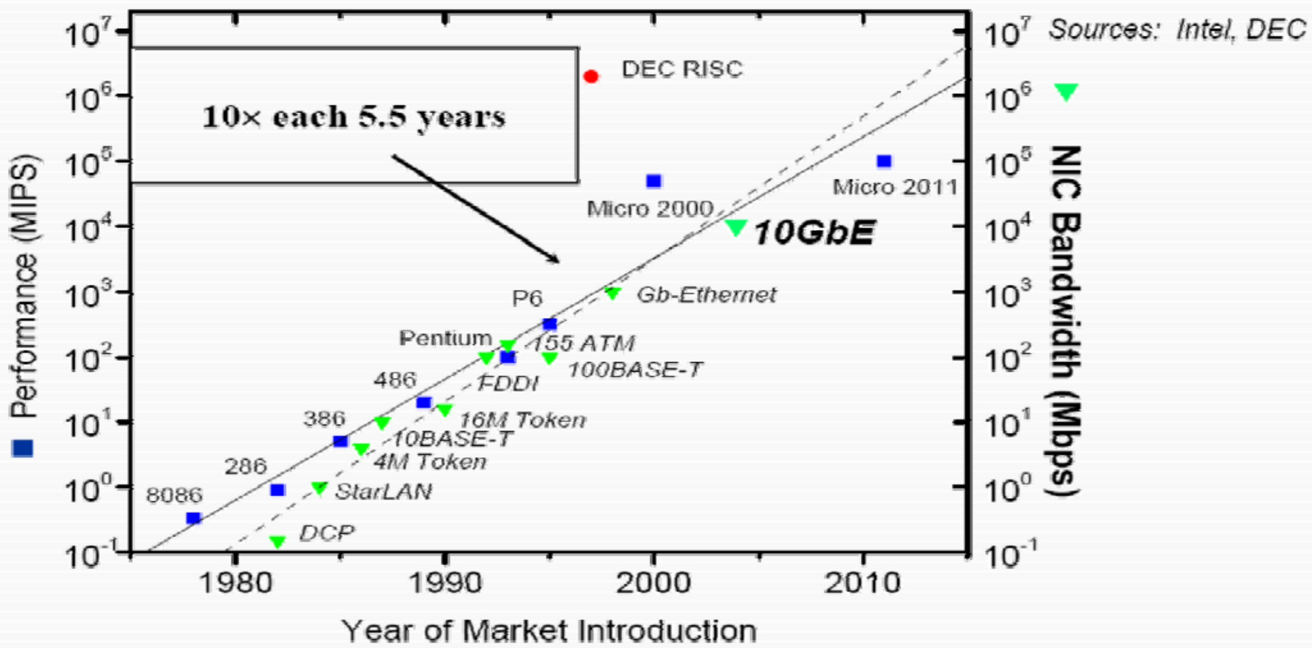
COMPUTING AND NETWORKING BANDWIDTH

OFC 2008 Kogelnik

Computing & Networking Bandwidth



Amdahl's Law: 1 MIPS networked computing power requires 1 Mbps I/O bandwidth

BRIEF CHRONOLOGY

ADAPTED FROM: JEFF HECHT: CITY OF LIGHT, OXFORD UNIVERSITY PRESS, 1999

1841 – Daniel Colladon demonstrates light guiding in a jet of water
1880 – Alexander Graham Bell‘s Photophone
1960 – first working laser was reported
1962 – General Electric's Dr Robert N. Hall filed his patent for the idea ("Stimulated emission semiconductor devices") - it was granted as US Patent #3,245,002 on April 5, 1966
1966 – Charles Kao and George Hockham publish their „Paper“ in Proc. of the Institution of Electrical Engineers
1970 – Corning invented the first commercially viable low-loss optical fiber
1970 – STL demonstrates optical transmission at Physisc Exhibition in London
1970 – first continuous-wave room-temperature semiconductor laser at the Ioffe Physical Institute in Leningrad
http://en.wikipedia.org/wiki/Ioffe_Instituteand a little later at Bell Labs
1971 – STL demonstrates digital video transmission to Queen Elisabeth
1976 – NTT and Fujikura Cable make fibre having 0.47 dB loss per km at 1.2 μm wavelengths
1980 – Bellcore developed the Synchronous Optical Network (SONET) standard
1987 – D Payne (Univ of Southampton) develops EDFA for 1.55 μm
1988 – TAT8: first transatlantic FOC begins service at 1.3 μm

CHARLES KAO AND GEORGE HOCKHAM

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.

OPTICAL FIBRE COMMUNICATIONS

The 1966 Paper by
Charles Kao and George Hockham

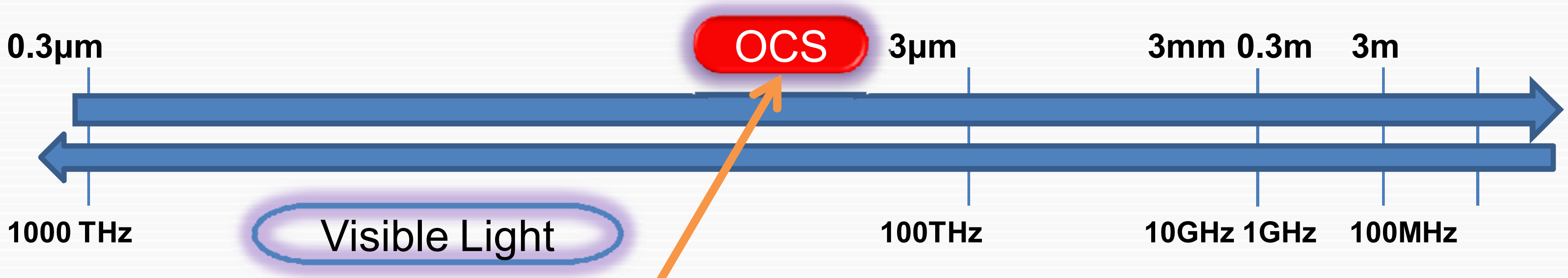
Dielectric-fibre surface waveguides for optical frequencies
K.C. Kao, B.Sc.(Eng.), Ph.D., A M I E E and G. A. Hockham, B.Sc.(Eng.), Graduate I.E.E. *PROC. IEE, Vol. 113, No. 7, JULY 1966*

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.“

Physical-realisation aspects were also discussed. Experimental investigations at both optical and microwave wavelengths were included.

EM SPECTRUM FOR OPTICAL COMMUNICATION



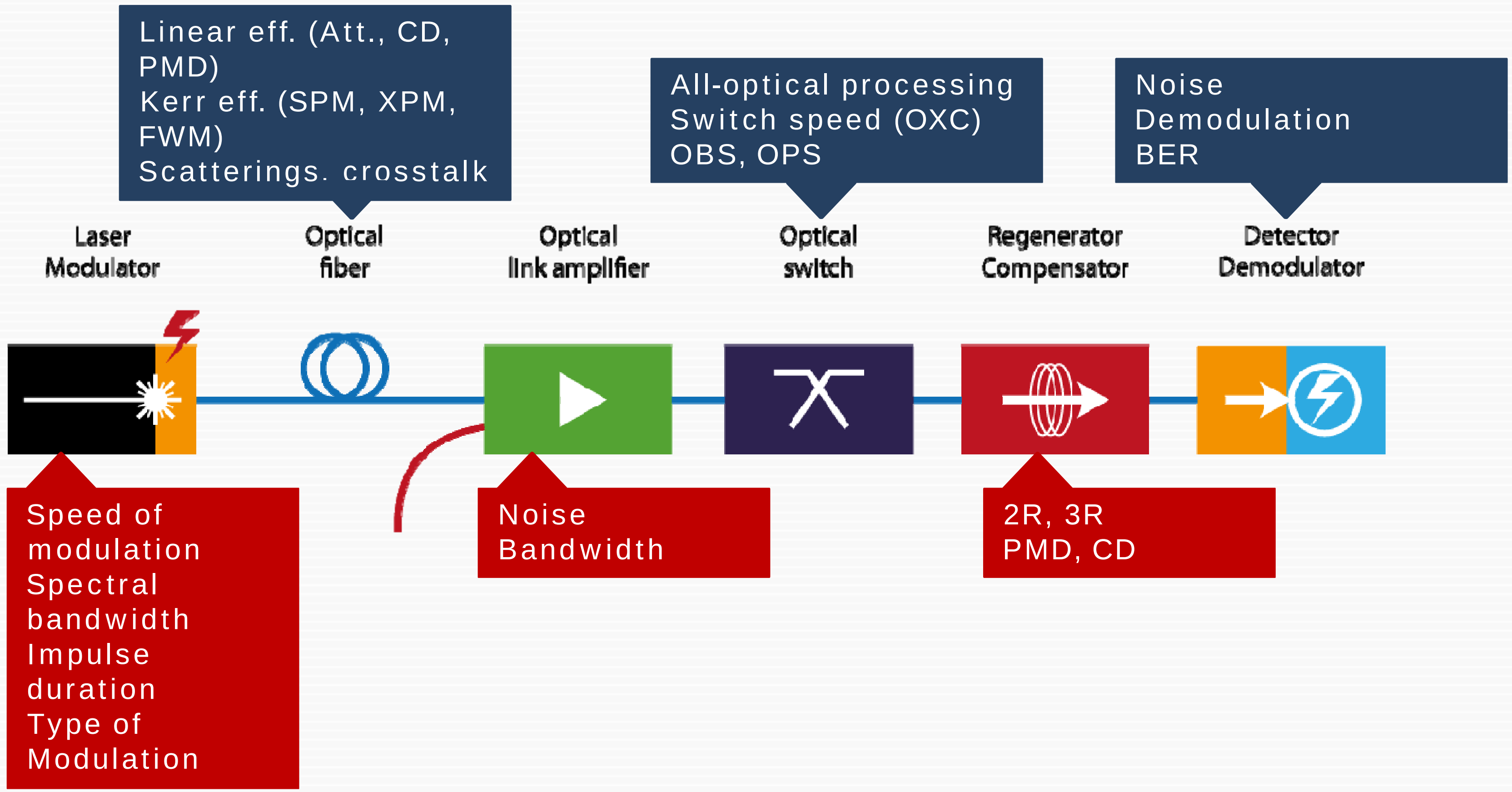
Drivers in development of OC:

- LED,SL, (800-1600 nm)
- Attenuation of SiO_2 (800 – 1600 nm)
- Digitalisation e.g. SONET (SDH)

Optical CommunicationSystems

OPTICAL COMMUNICATION SYSTEMS

Simplified Optical Communication System



OPTICAL FIBRES FOR OPTICAL COMMUNICATION

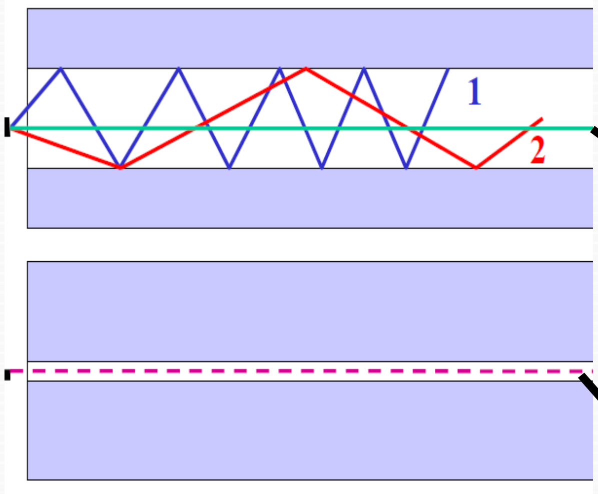
TRANSMISSION MEDIUM

Main factors influencing transmission in OF

- Attenuation
- Dispersion
- Nonlinearities

Raj Jain: All-Optical Networks
(Washington University in Saint Louis)

MM AND SM OPTICAL FIBRES



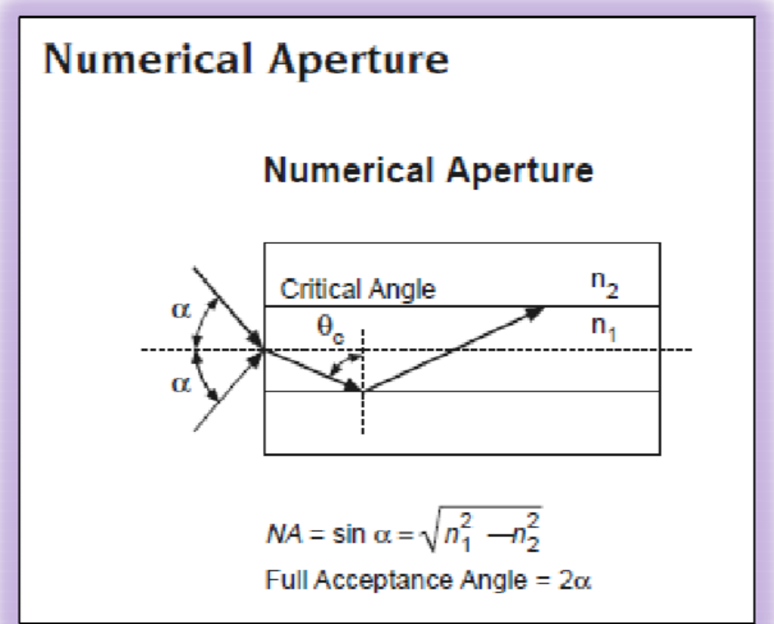
Multimode

Step Index
Gradient index

$$V = \frac{2\pi a}{\lambda}\sqrt{(n_1^2 - n_2^2)} \gg 2.4.....$$

Singlemode

$$V = \frac{2\pi a}{\lambda}\sqrt{(n_1^2 - n_2^2)} < 2.4....$$



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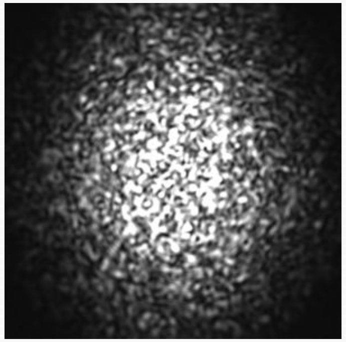
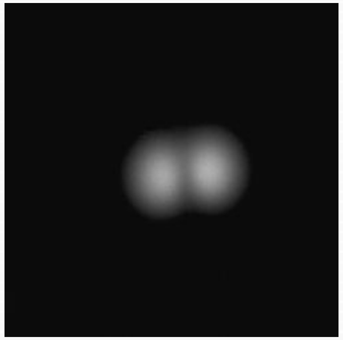
MODES IN OF

Alcatel – Lucent

Light Distribution in MM OF

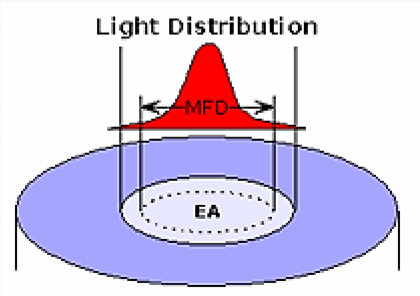


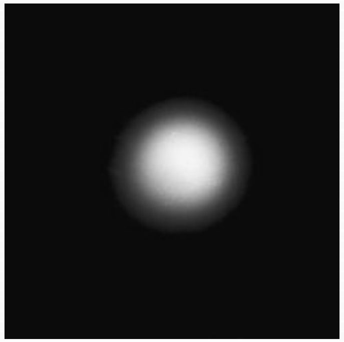
Normalized Frequency
$V = 2\pi a/\lambda . NA > 2.4$



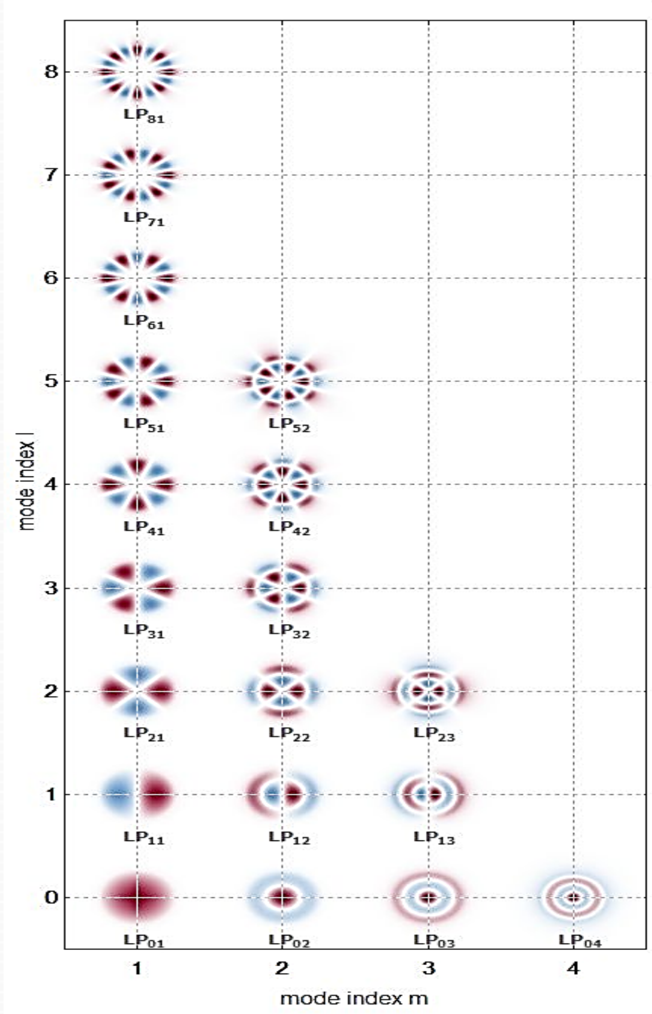
LP$_{11}$

Light Distribution in SM OF

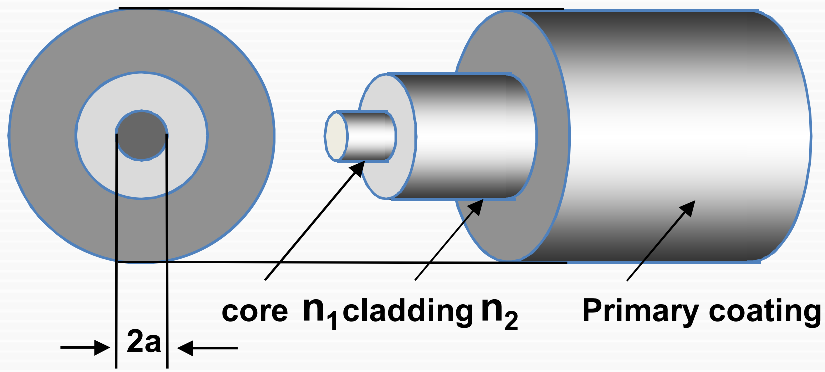


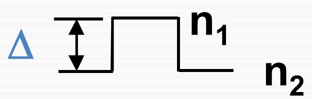


LP$_{01}$

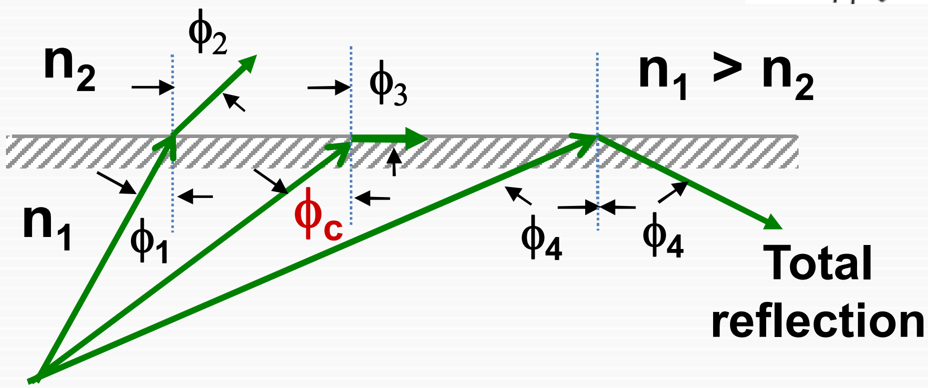


OPTICAL FIBRES

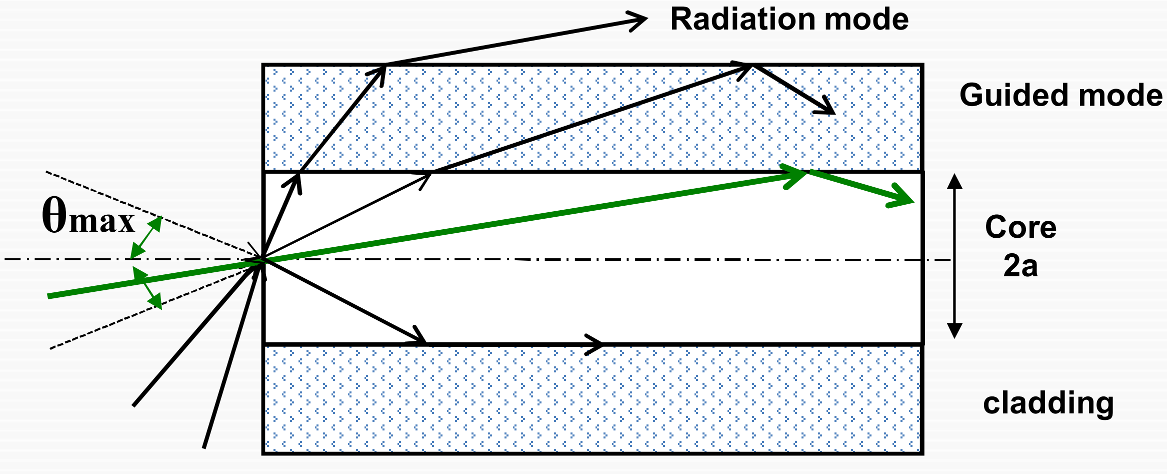




$$\Delta \approx \frac{n_1 - n_2}{n_1} \qquad n_1 > n_2$$



$$n = \text{Refrac index} = \frac{\text{Velocity in vacuum}}{\text{Velocity in material}}$$



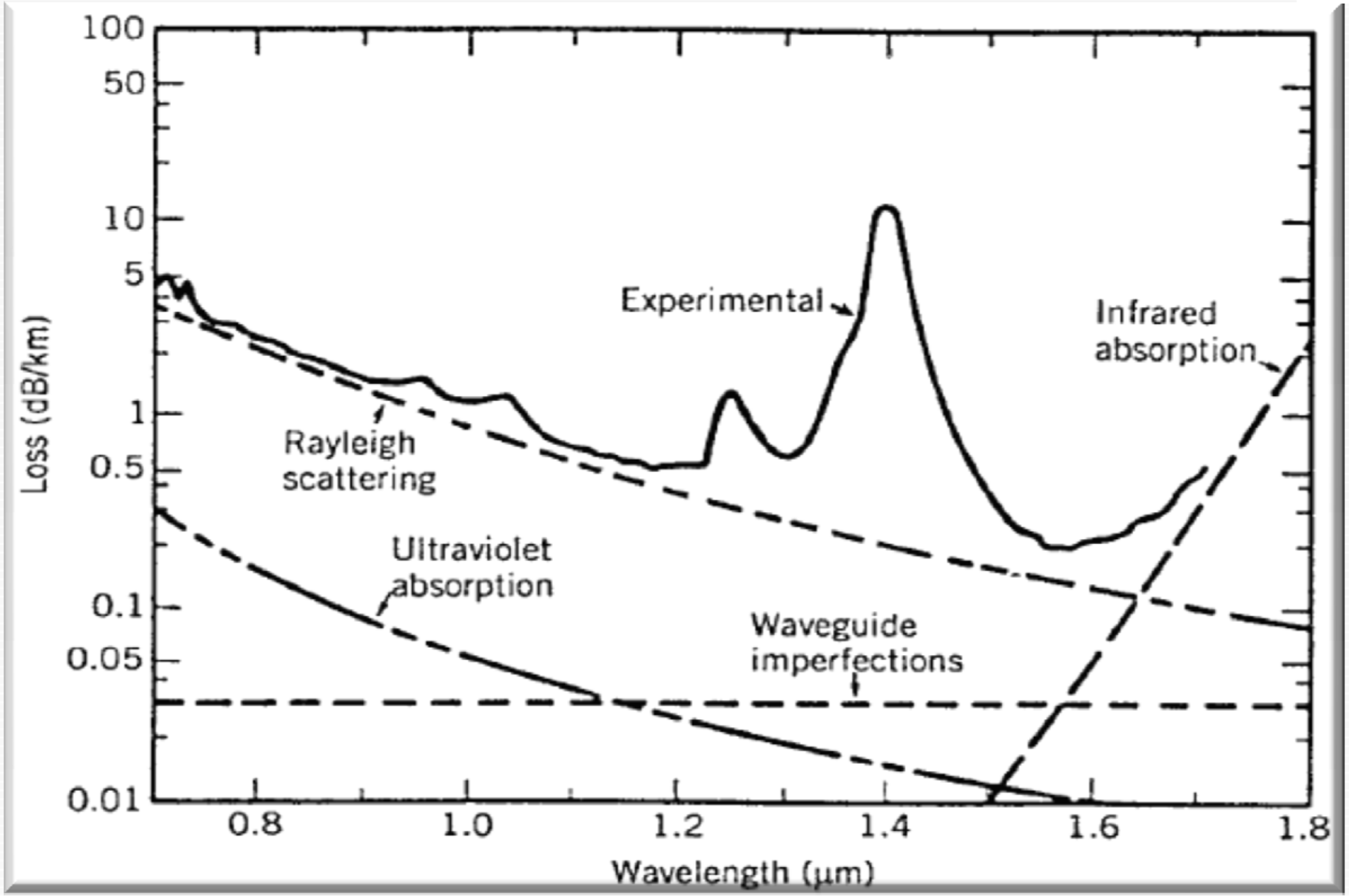
Snell law:

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1}$$

$$\sin \phi_c = \frac{n_2}{n_1}$$

ϕ_c – critical angle of incidence

ATTENUATION



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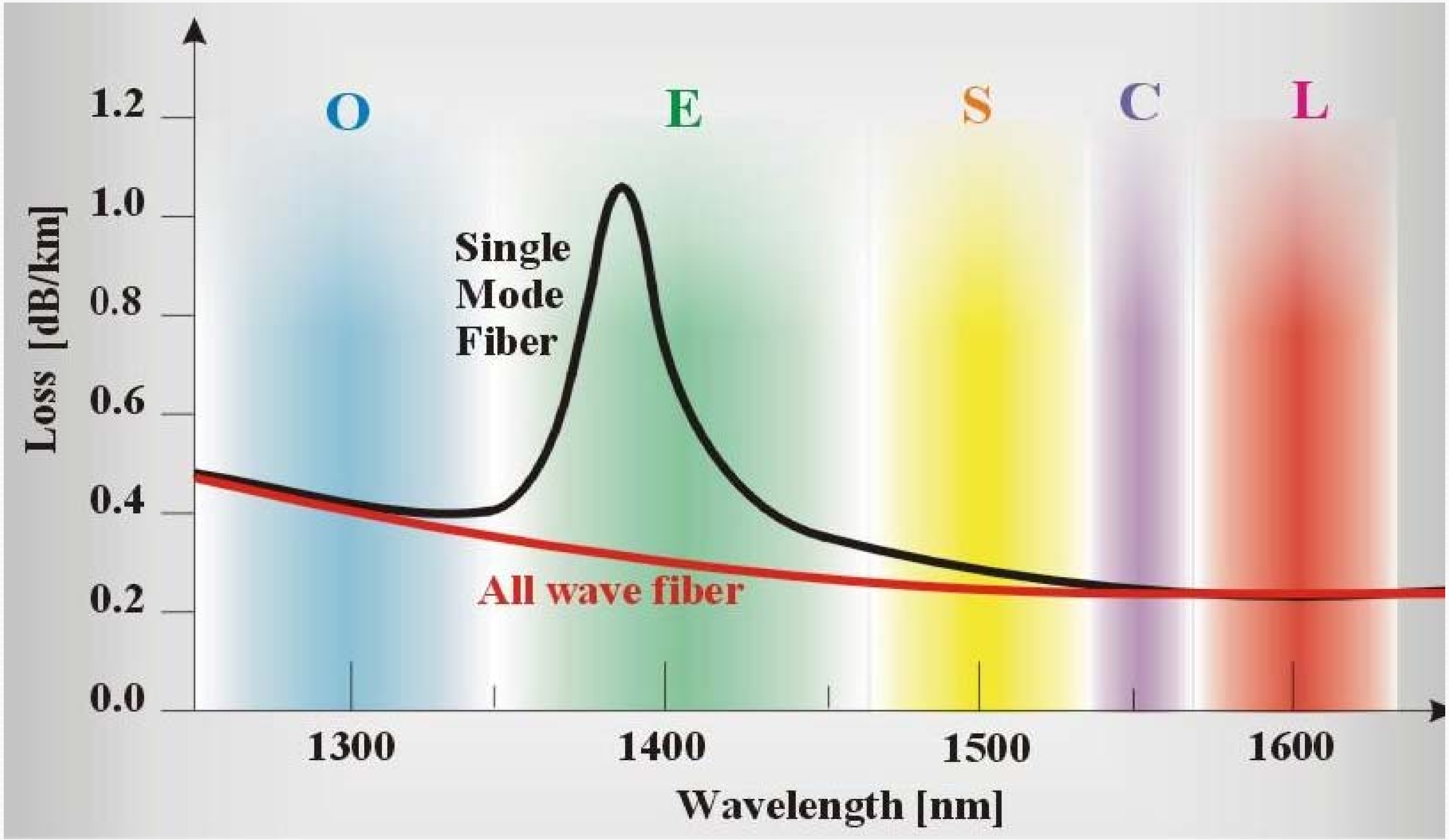
SINGLE MODE FIBRE SPECTRAL BANDS

ITU-T-REC-G.SUP39-20812



SINGLE MODE FIBRE SPECTRAL BANDS

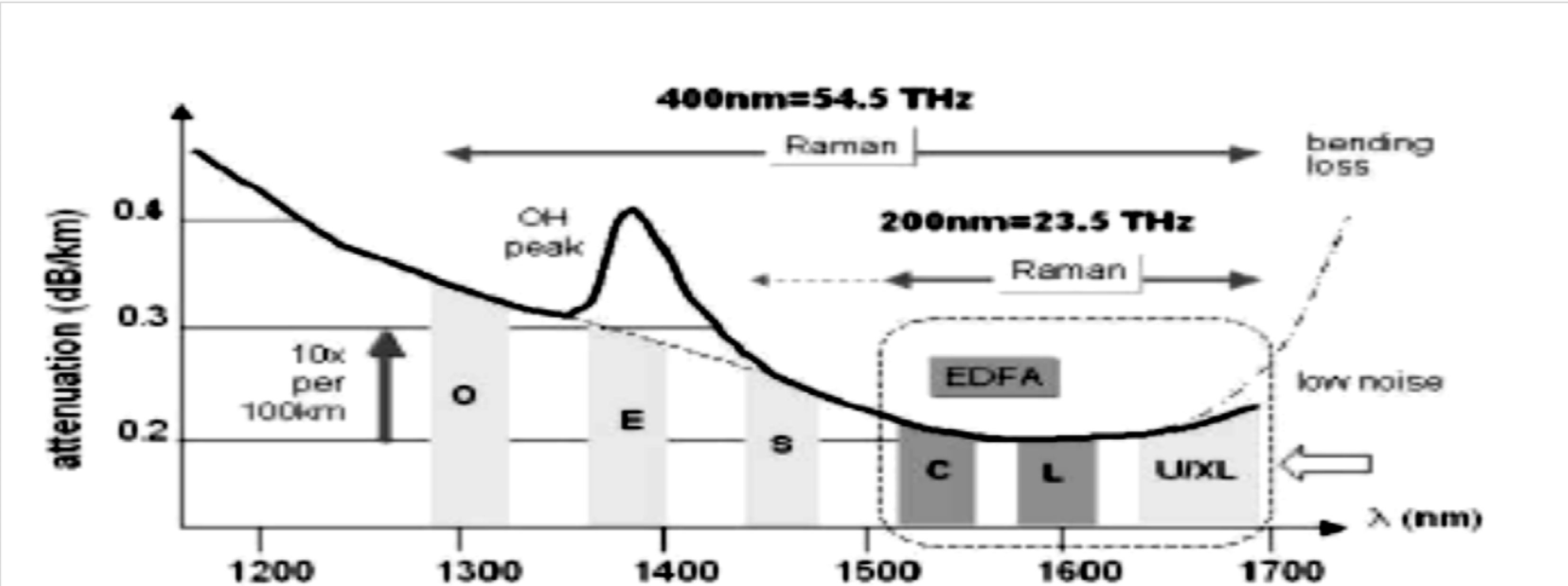
ITU-T-REC-G.SUP39-20812

Band	Descriptor	Range nm
O-band	Original	1260 to1360
E-band	Extended	1360 to 1460
S-band	Short wavelength	1460 to 1530
C-band	Conventional	1530 to 1565
L-band	Long wavelength	1565 to 1625
U-band	Ultra-long wavelength	1625 to 1675

OPTICAL COMMUNICATIONS IN 2025

EMMANUEL DESURVIRE
ALCATEL CTO OFFICE, BUSINESS DEVELOPMENT, 91460 MARCOUSSIS-CEDEX FRANCE
EMMANUEL.DESURVIRE@ALCATEL.FR

„In 20 years, optical networks will have to carry vastly increased amounts of IP traffic. Today's knowledge points to ultimate technology limits, which are discordant with market prospects. Basic research must urgently be revived today in order to meet tomorrow's needs.“



MATERIAL DISPERSION

$$\frac{t_{gL}}{L} = \frac{1}{v_g} = \frac{n_g}{c} = \frac{d\beta}{d\omega};$$

where $n_g = n - \lambda \frac{dn}{d\lambda} = n + \frac{dn}{d\omega}\omega;$

and $\frac{\Delta t_{sk}}{L} = -\frac{\lambda}{c}\frac{d^2n}{d\lambda^2}\Delta\lambda - \frac{1}{2c}\left(\frac{d^2n}{d\lambda^2} + \lambda\frac{d^3n}{d\lambda^3}\right)(\Delta\lambda)^2 + \cdots$

for pure fused silica SiO_2 $\frac{d^2n}{d\lambda^2}$ **is equal zero for** λ**= 1270 nm**

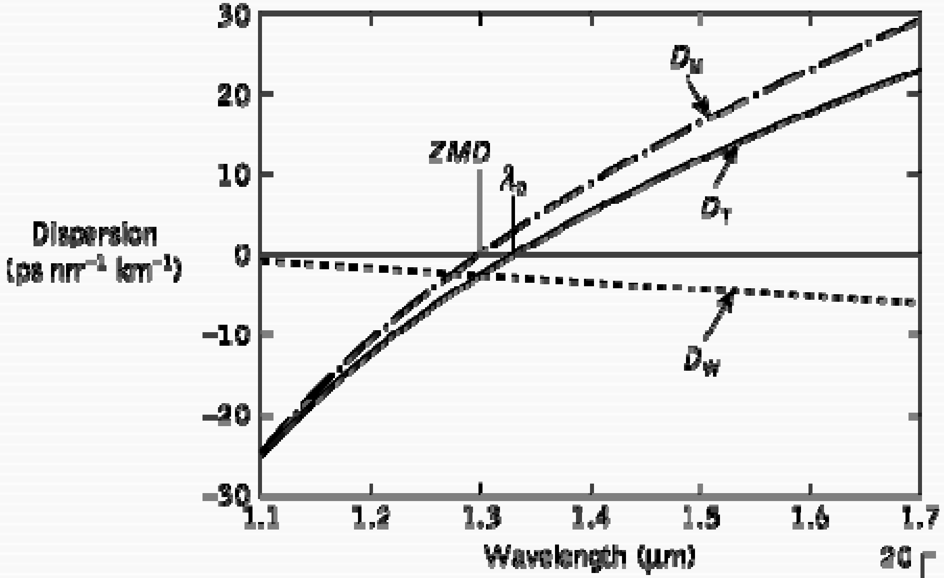
Sellmeier equation for index profile

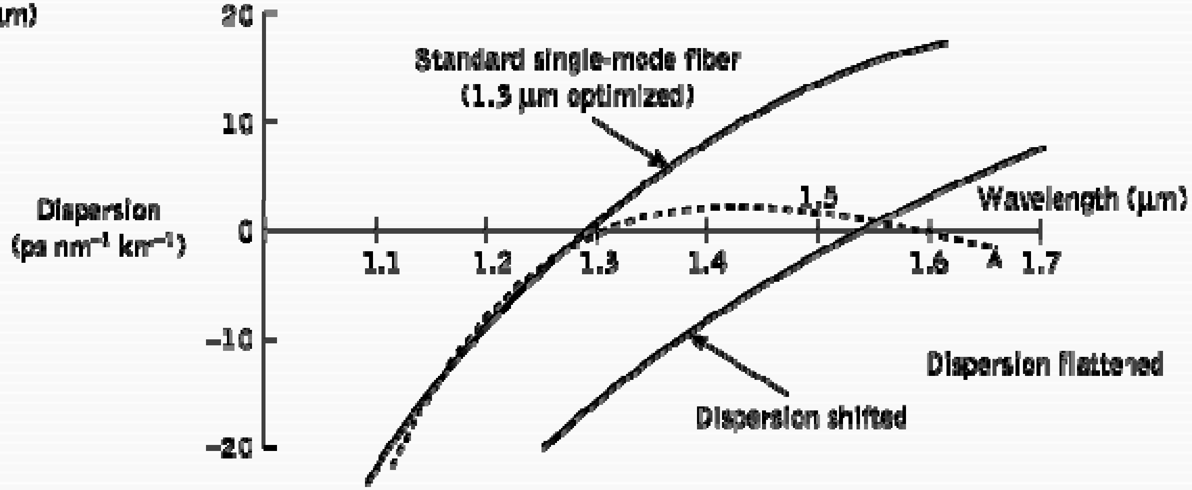
WAVEGUIDE DISPERSION

Waveguide dispersion-different „n“ in core and cladding of OFs in which mode spreads;

„MDF is f(λ)“

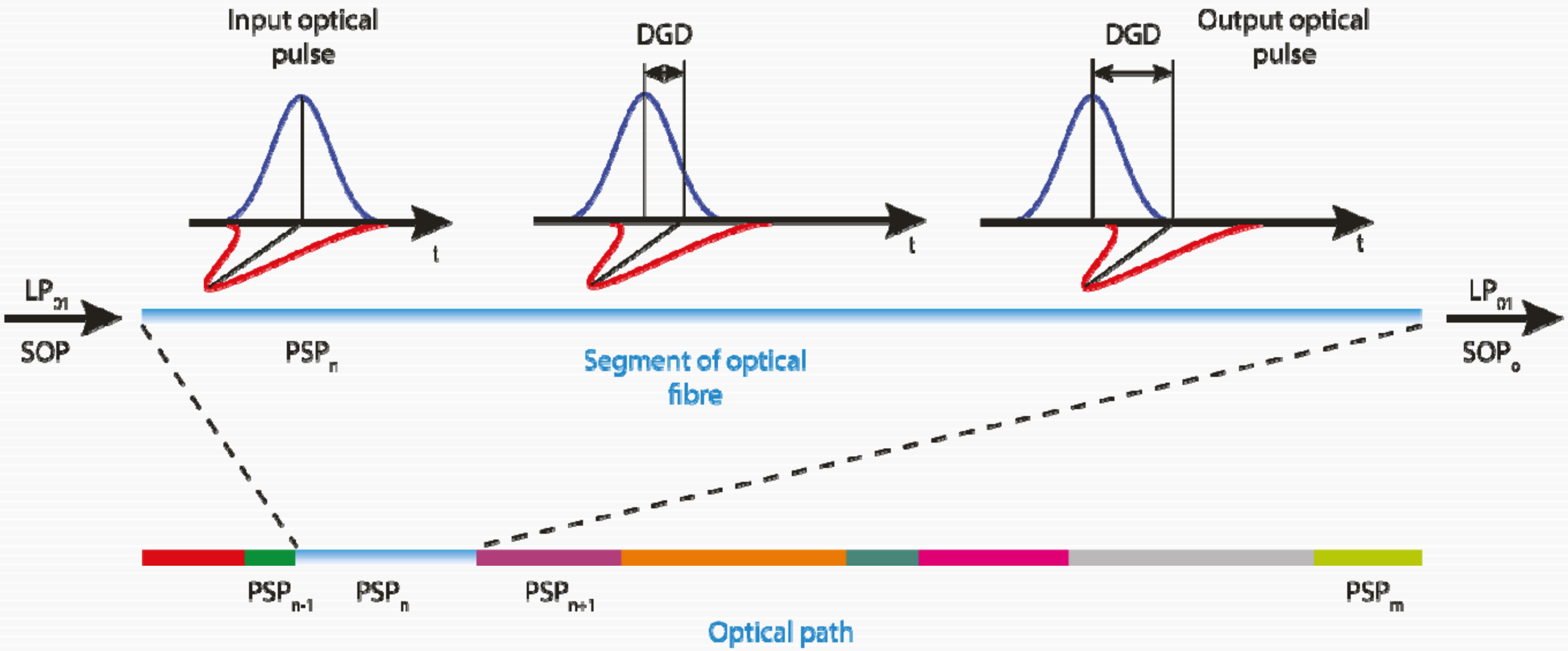
CHROMATIC DISPERSION





John M. Senior: *Optical Fiber Communications Principles and Practice,* Pearson Education, 2009

POLARIZATION MODE DISPERSION (PMD)



OF NONLINEARITIES

Kerr effects

$$n = n_0 + \delta n_{nl} = n_0 + \tilde{n}_2 \frac{P_{in}}{A_{eff}}$$

- **Self Phase Modulation - SPM,**
- **Cross Phase Modulation – XPM,**
- **Four Wave Mixing – FWM**

Schrödinger equation

$$\frac{\partial A(z,t)}{\partial z} = -\beta_1 \frac{\partial A(z,t)}{\partial t} - j\frac{\beta_2}{2}\frac{\partial^2 A_m(z,t)}{\partial t^2} + j\beta_{NL} A(z,t) - \frac{\alpha}{2} A(z,t)$$

OF NONLINEARITIES (2)

where

$$\beta_i = \beta_L(\omega);\ \beta_{NL} = \gamma |A^2|;$$

$$\beta_L(\omega) = \frac{\omega}{c} n(\omega);$$

$$\beta_i(\omega) = \frac{d^i \beta(\omega)}{d\omega^i};$$

$$\beta_1 = \frac{1}{v_g};\ v_g - \text{group velocity};$$

$$\beta_2 = \frac{\partial \beta_1}{\partial \omega} = \frac{\partial^2 \beta}{\partial \omega^2} = -\frac{\lambda^2}{2\Pi c} D$$; D[ps.nm^{-1}.km $^{-1}$] Chromatic Dispersion

β_2 - GVD Parameter of Group Velocity Dispersion)

OPTICAL FIBRES

Applications

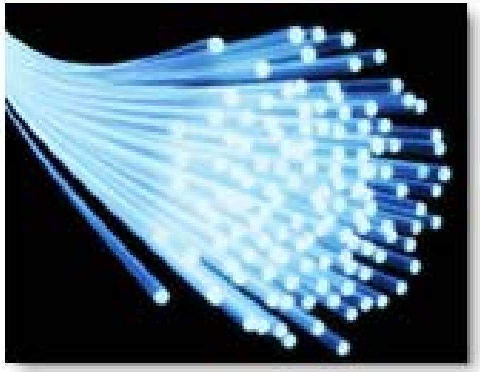
- Communication systems – submarine, long haul, access, local networks
- Sensors
- Signal processing – amplification, signal equalizers, filters

International standards

- ITU-T G.651 – G657
- IEC 60793-2-10, IEC 60793-2-20, IEC 60793-2-30, IEC 60793-2-40, IEC 60793-2-50
- IEC 60793-1, ITU-T G.650
- TIA 492, TIA 455, TIA 568B
- ISO/IEC 11801 – OS1, OS2, OM1, OM2, OM3, OM4 – Structured cable standard

Materials

- Glass
- Plastic



Transmitted modes

- Single mode
- Multi mode

Diameters

MM fibres

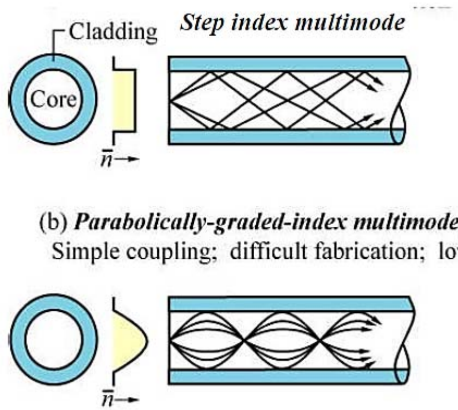
according IEC International Standard 60793-2

Categories of multimode fibres

Category	Material	Type	Limits
A1	Glass core/glass cladding	Graded index fibre	$1 \le g < 3$
A2	Glass core/glass cladding	Step and quasi step index fibre	$3 \le g < \infty$
A3	Glass core/plastic cladding	Step index fibre	$10 \le g < \infty$
A4	Plastic core/plastic cladding	Step, multi-step, or graded index fibre	$1 \le g < \infty$

NOTE Attention is drawn to the index profile as stated in the detail specification. The fibre category is determined on the basis of the material type and the g value which best fits the normalized refractive index profile, falling within the category defined above.

SI

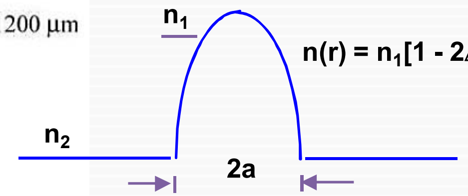


GI

Typical diameters and refractive indices

Core/cladding diameter	62.5/125, 100/140, ... , 1000/1200 µm
Core index	1.45
Index difference	1 % – 2 %

Core/cladding diameter	50/125, 62.5/125, 85/125
Core index at center	1.45
Index difference	1 % – 2 % in graded index profile



$$n(r) = n_1[1 - 2\Delta(r/a)^g]^{0.5}$$

$1.7 < g < 2$

$$\Delta \approx \frac{n_1 - n_2}{n_1}$$

MM fibres in accordance with IEC

Category	Type	Description
A1a.1	50/125µm	Type A1a.1 fibre is a 50/125 µm all-glass graded index fibre and meets the cabled optical fibre performance categories OM1 and OM2 specified by ISO/IEC with a specific bandwidth cell. The requirements for OM1 and OM2 are a subset of the more general IEC requirements for IEC fibre type A1a.1.
A1a.2	50/125µm	Type A1a.2 fibre is a 50/125 µm all-glass graded index fibre. The requirements for IEC Type A1a.2 are identical to the cabled optical fibre performance category OM3 specified by ISO/IEC.
A1a.3	50/125µm	Type A1a.3 fibre is a 50/125 µm all-glass graded index fibre. The requirements for IEC Type A1a.3 are identical to the cabled optical fibre performance category OM4 specified by ISO/IEC.
A1b	62.5/125µm	Type A1b fibre is a 62.5/125 µm all-glass graded index fibre and meets the cabled optical fibre performance category specified by ISO/IEC with a specific bandwidth cell. The requirements for OM1 are a subset of the more general IEC requirements for IEC fibre type A1b.
A1d	100/140µm	Type A1d fibre is a 100/140 µm all-glass graded index fibre.
A2a	100/140µm	Type A2a fibre is a 100/140 µm all-glass graded index fibre with a theoretical NA of 0,23 or 0,26
A2b	200/240µm	Type A2b fibre is a 200/240 µm all-glass graded index fibre with a theoretical NA of 0,23 or 0,26
A2c	200/280µm	Type A2c fibre is a 200/280 µm all-glass graded index fibre with a theoretical NA of 0,23 or 0,26
A3a	200/300µm	Type A3a fibre is a 200/300 µm graded index fibre with a glass core and a plastic cladding and an NA of 0,40
A3b	200/380µm	Type A3b fibre is a 200/380 µm graded index fibre with a glass core and a plastic cladding and an NA of 0,40
A3c	200/230µm	Type A3c fibre is a 200/230 µm graded index fibre with a glass core and a plastic cladding and an NA of 0,40
A3d	200/230µm	Type A3a fibre is a 200/230 µm graded index fibre with a glass core and a plastic cladding and an NA of 0,35
A4a	975/1000	Type A4a fibre is a 975/1000 µm step index fibre with a plastic core and a plastic cladding with a theoretical NA of 0,5
A4b	725/750	Type A4b fibre is a 725/750 µm step index fibre with a plastic core and a plastic cladding with a theoretical NA of 0,5
A4c	475/500	Type A4c fibre is a 475/500 µm step index fibre with a plastic core and a plastic cladding with a theoretical NA of 0,5
A4d	975/1000	Type A4d fibre is a 975/1000 µm step index fibre with a plastic core and a plastic cladding with a theoretical NA of 0,3
A4e	500/750	Type A4e fibre is a 500/750 µm multi-step index fibre with a plastic core and a plastic cladding and an NA of 0,25
A4f	200/490	Type A4f fibre is a 200/490 µm graded index fibre with a plastic core and a plastic cladding and an NA of 0,190
A4g	120/490	Type A4g fibre is 120/490 µm graded index fibre with a plastic core and a plastic cladding and an NA of 0,190
A4h	62.5/245	Type A4h fibre is a 62.5/245 µm graded index fibre with a plastic core and a plastic cladding and an NA of 0,190

50/125
ITU-T G.651

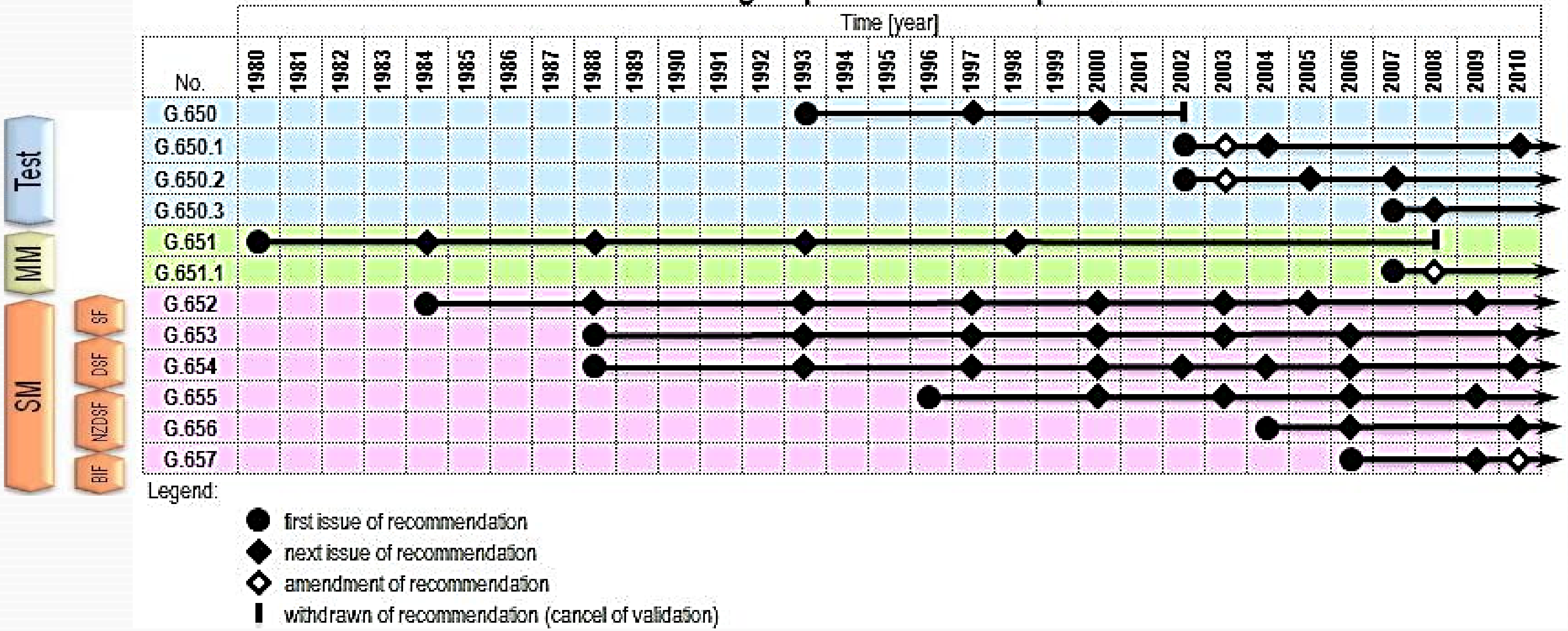
62.5/125

Glass core/cladding

Glass core

Plastic core/cladding

ITU-T Recommendation group G.650-G-659: Optical fibre cables



POWER DENSITY IN OPTICAL FIBRES

Very High

?

MAIN PHENOMENAS INFLUENCING FUTURE DEVELOPMENT OF OPTICAL SYSTEMS AND NETWORKS

- **New types of optical fibres and cable technologies**
- **Optical amplifiers (EDFA, SOA, RFA,...)**
- **Nonlinear phenomenas (beneficial and detrimental) as FWM, SPM, XPM, Solitons...)**
- **Lasers tuning and coherence it means more optical channels and new modulation formats e.g. M-PSK**
- **Systems for wavelength conversion**
- **Optical bistability...**

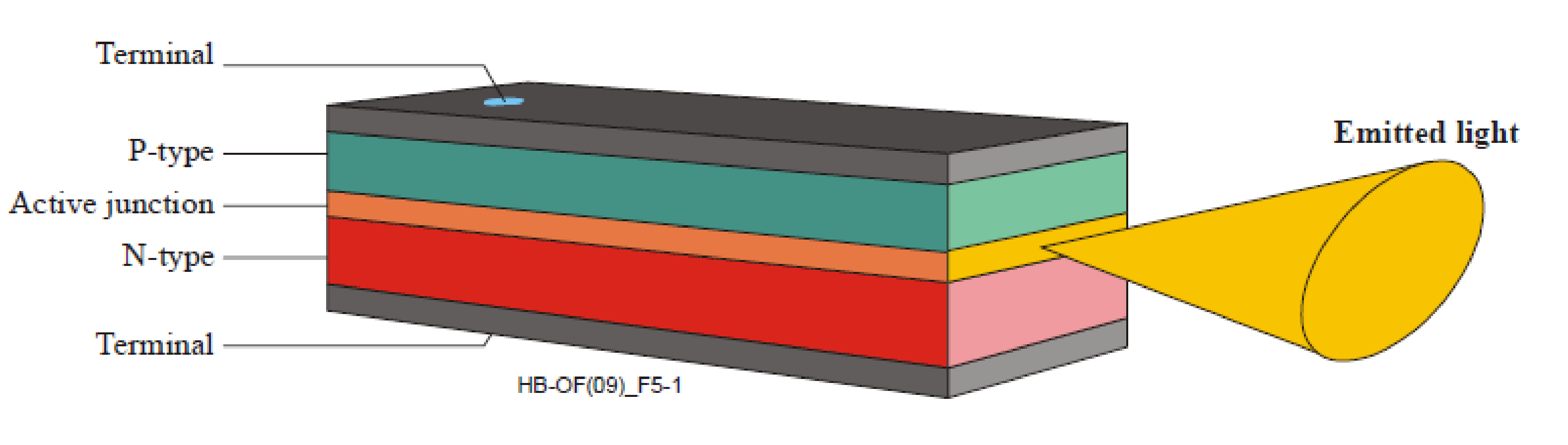
Towards DWDM and OTDM next OPS and OBS and IP transparent optical networks

LASERS FOR OCS

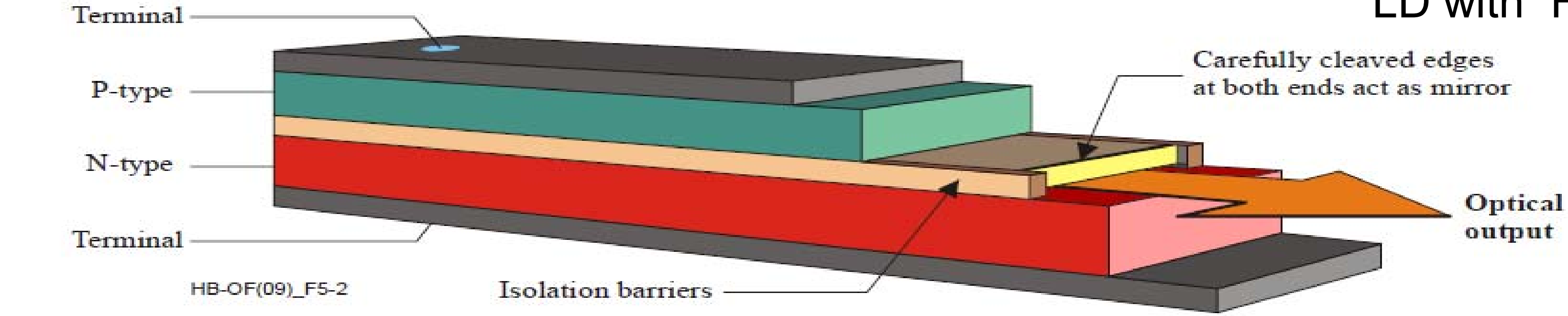
EXAMLE OF LED AND LD WITH FP STRUCTURE

OPTICAL FIBRES, CABLES AND SYSTEMS, ITU-T MANUAL 2009

LED



LD with FP



TYPES OF SEMICONDUCTOR LASERS USED IN OPTICAL COMMUNICATION

Fabry–Perot (FP) Lasers.

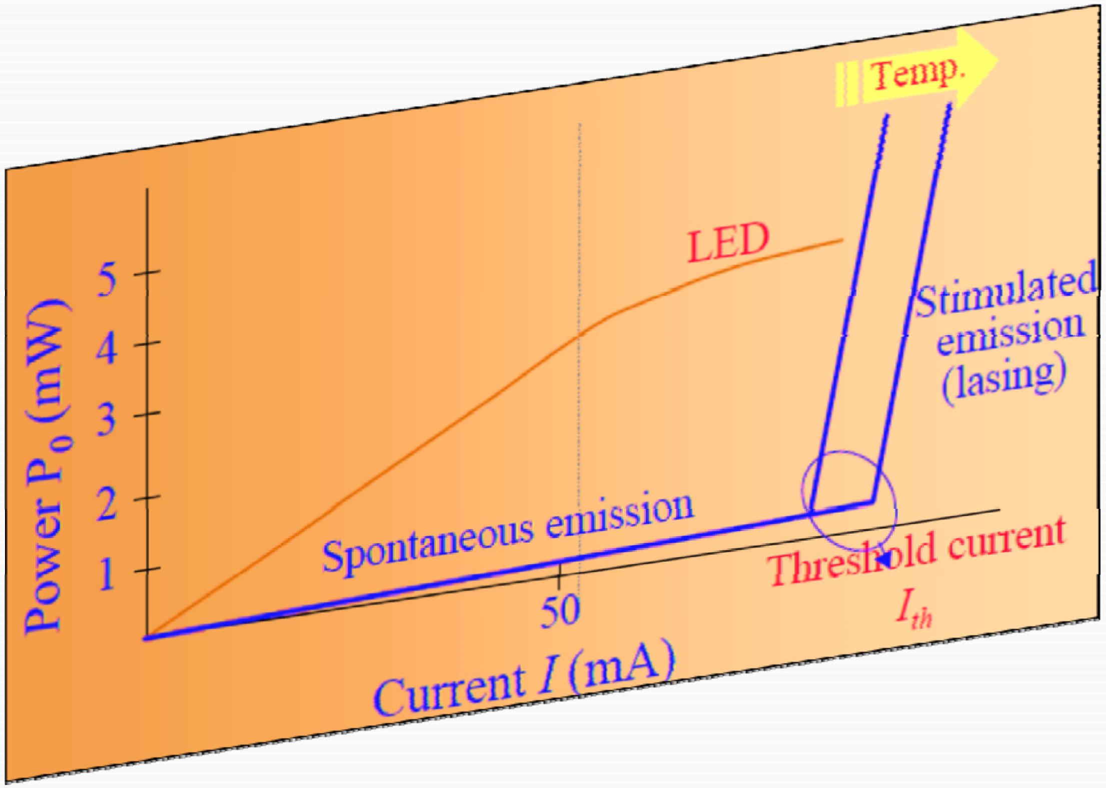
Distributed Feedback (DFB) lasers.

Multiple Quantum Well (MQW) lasers.

External Cavity Diode Lasers (ECDL).

Vertical Cavity Surface Emitting Lasers (VCSEL).

LIGHT – CURRENT CHARACTERISTICS



UTILISATION OF SL FOR DIFFERENT TYPES OF OCN

Semiconductor Lasers	Types of networks
FP	LAN and MAN
DFB	WAN mainly
MQW Multiple Quantum Well	LAN and MAN
ECDL	WAN
VCSEL	LAN and MAN

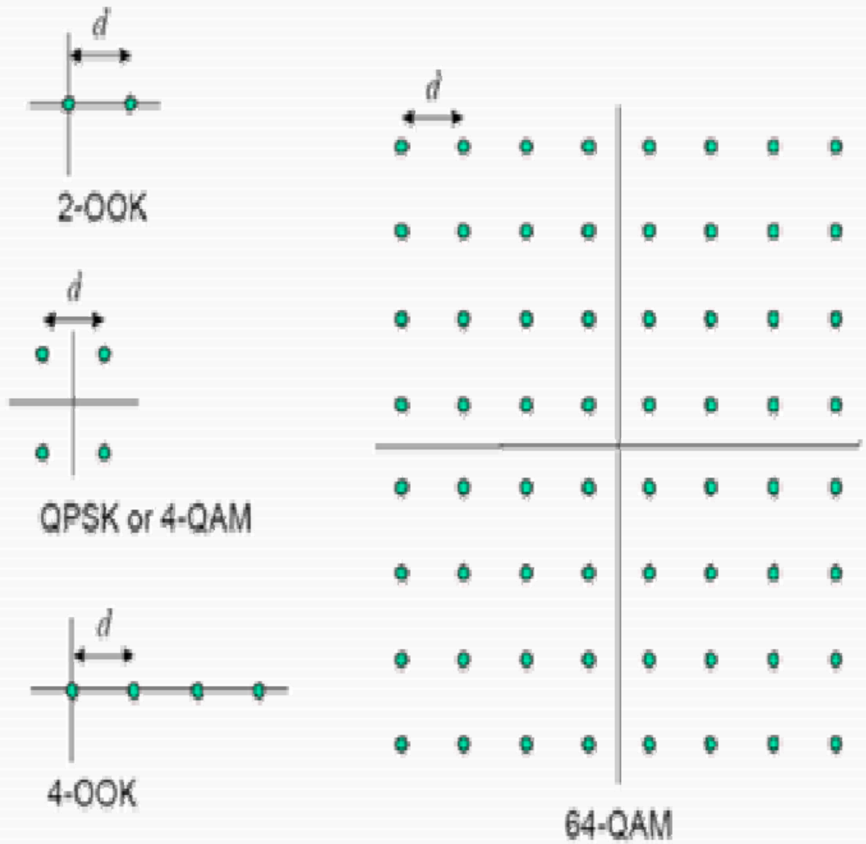
NEW APPROACHES IN LASERS FOR OCS

Great efforts have been made not only for improving the performance of existing devices but also for realizing new functional devices such as:

- **wavelength tunable laser,**
- **wavelength converter,**
- **monolithic integrated ONU (Optical Network Unit),**
- **optical network node device etc.**

TRANSMITTERS/MODULATORS

Transmitters/modulators



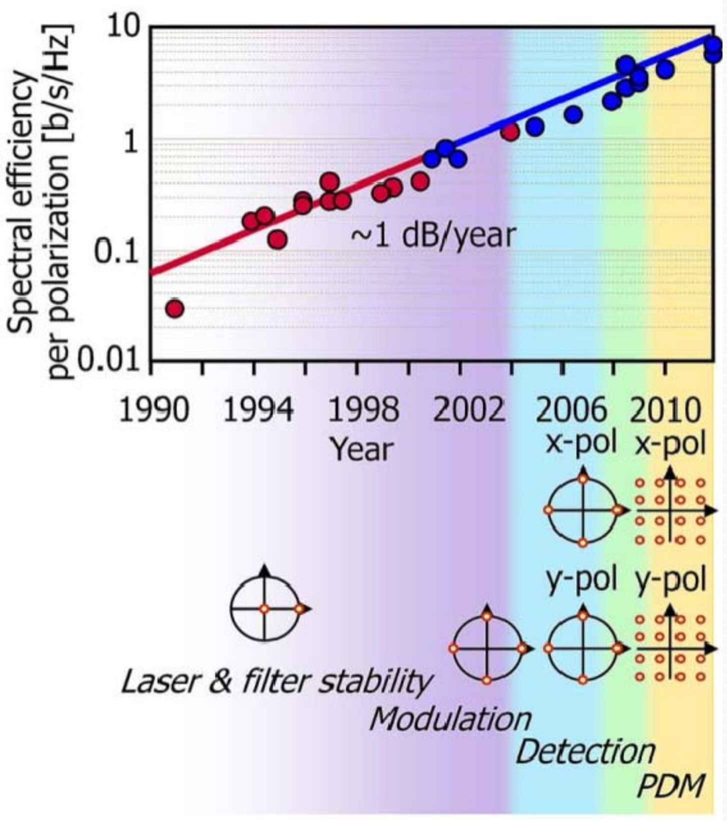
- Direct modulated lasers
- Lasers with external modulation

SPECTRAL EFFICIENCY

Spectral efficiency - ratio of the data rate per channel to the WDM channel spacing

High order modulation formats - higher spectral efficiency enable decrease symbol (modulation) rate

Coherent detection, high order modulation formats, polarization multiplexing enables approach to the spectral efficiency limit



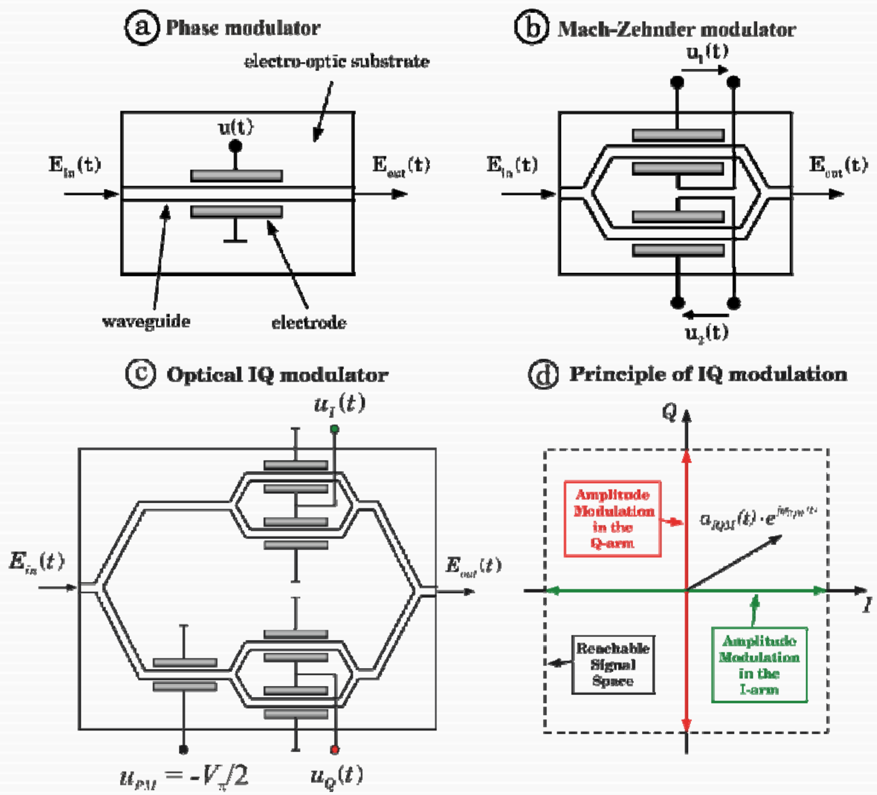
Winzer; High-spectral-efficiency optical, Journal of lightwave technology, vol. 30, no. 24, 2012

OPTICAL MODULATORS

Optical phase modulator - integrated optical device embedded to the optical waveguide in electro-optic substrate (commonly used *$LiNbO_3$*)

Mach – Zehnder modulator - integrated device employing interferometric structure and phase modulators

Optical IQ modulator - consist from phase and two Mach-Zehnder modulators

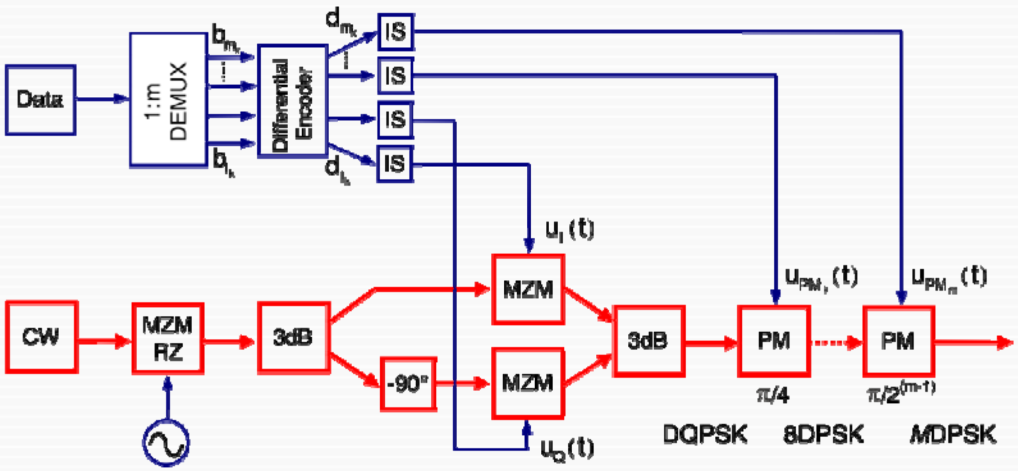


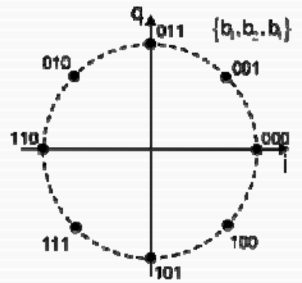
Seimetz; High-order modulation for optical fiber transmission, Springer, 2009

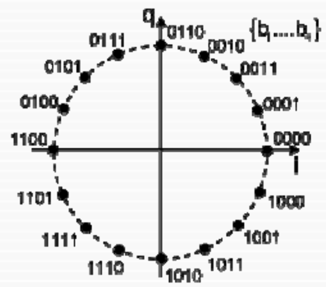
OPTICAL TRANSMITTERS

Parallel *DPSK* transmitter:

- uses binary electrical
- combination of optical IQ modulator and phase modulators





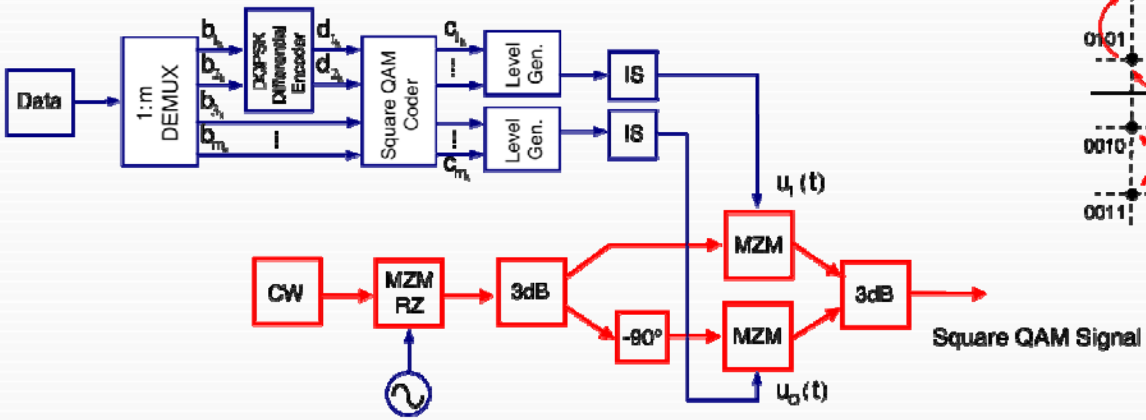


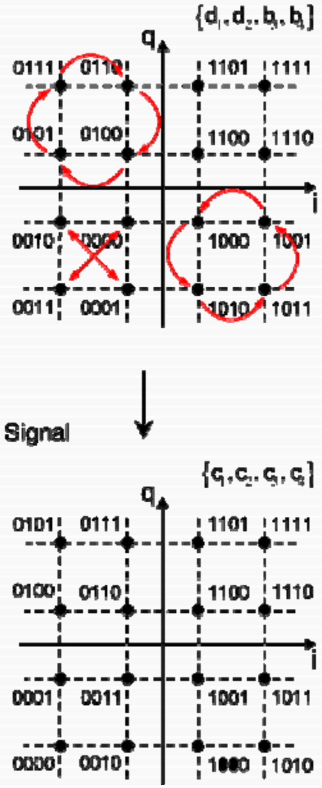
Seimetz; High-order modulation for optical fiber transmission, Springer, 2009

OPTICAL TRANSMITTERS

Serial Square QAM transmitter:

- simple optical part
- complex electrically part
- IQ modulator



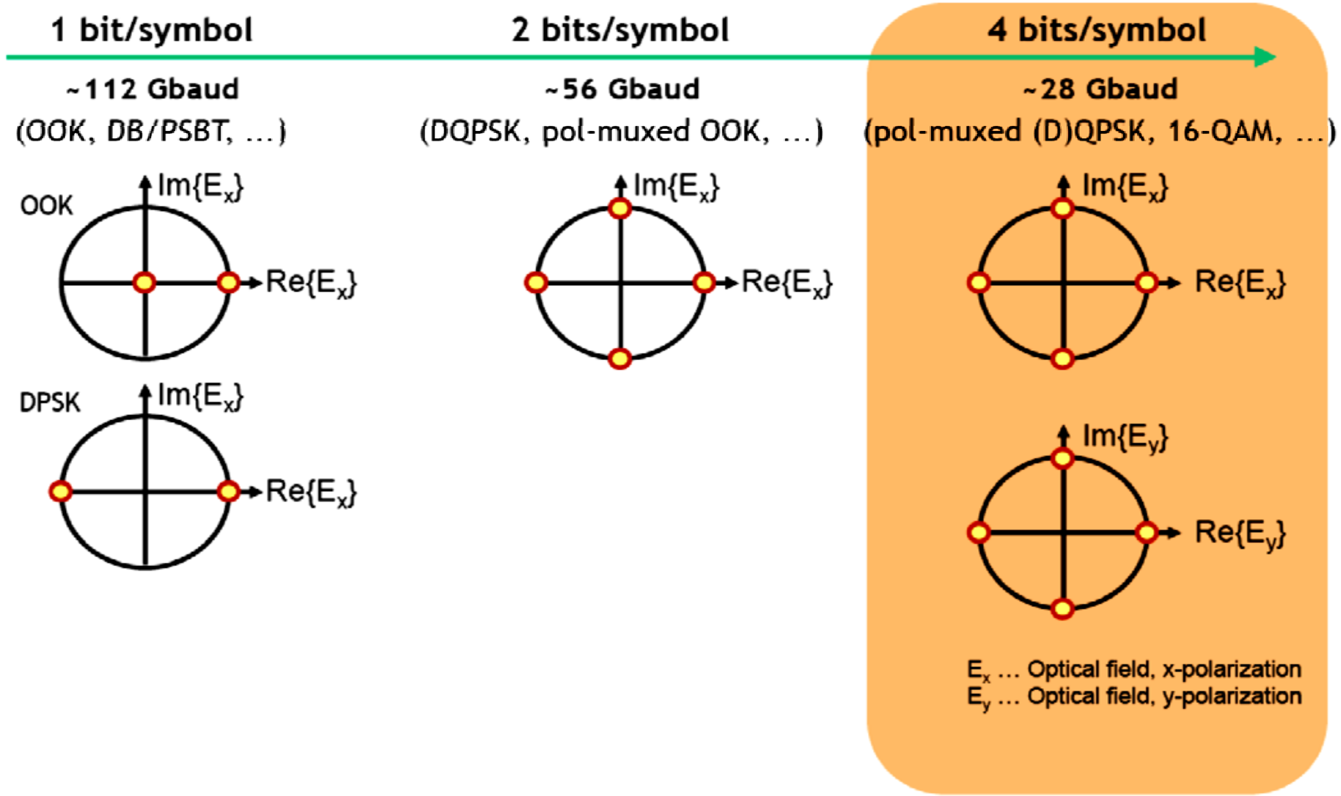


Seimetz; High-order modulation for optical fiber transmission, Springer, 2009

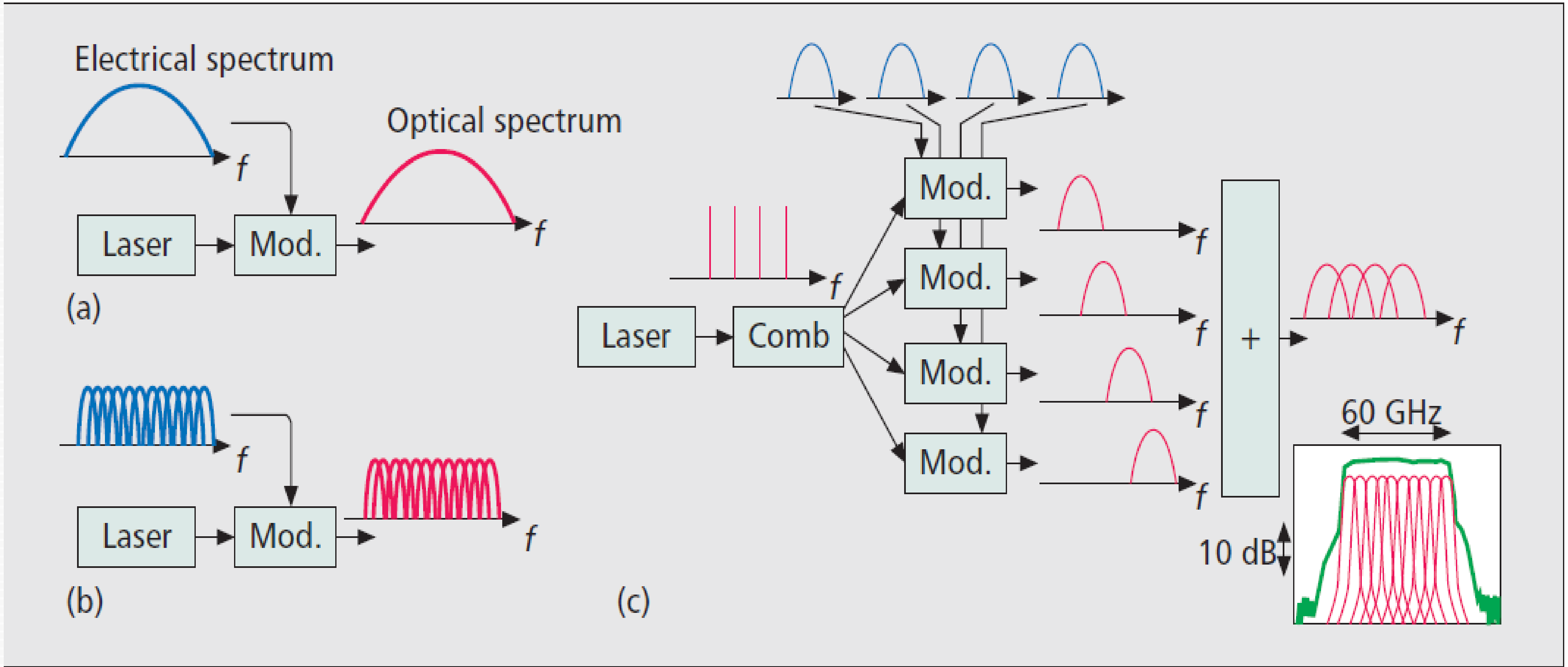
ADVANCED MODULATION FORMATS

OFC 2008 KOGELNIK

Advanced modulation formats



Optical transmitter options.



PETER J. WINZER, BEYOND 100G ETHERNET, BELL LABS, ALCATEL-LUCENT
IEEE Communications Magazine • July 2010

PETER J. WINZER, BEYOND 100G ETHERNET, BELL LABS, ALCATEL-LUCENT IEEE Communications Magazine • July 2010

[23] P. J. Winzer *et al.*, "Spectrally Efficient Long-Haul Optical Networking Using 112-Gb/s PDM 16-QAM," *J. Lightwave Tech.*, vol. 28, 2009, p 547.

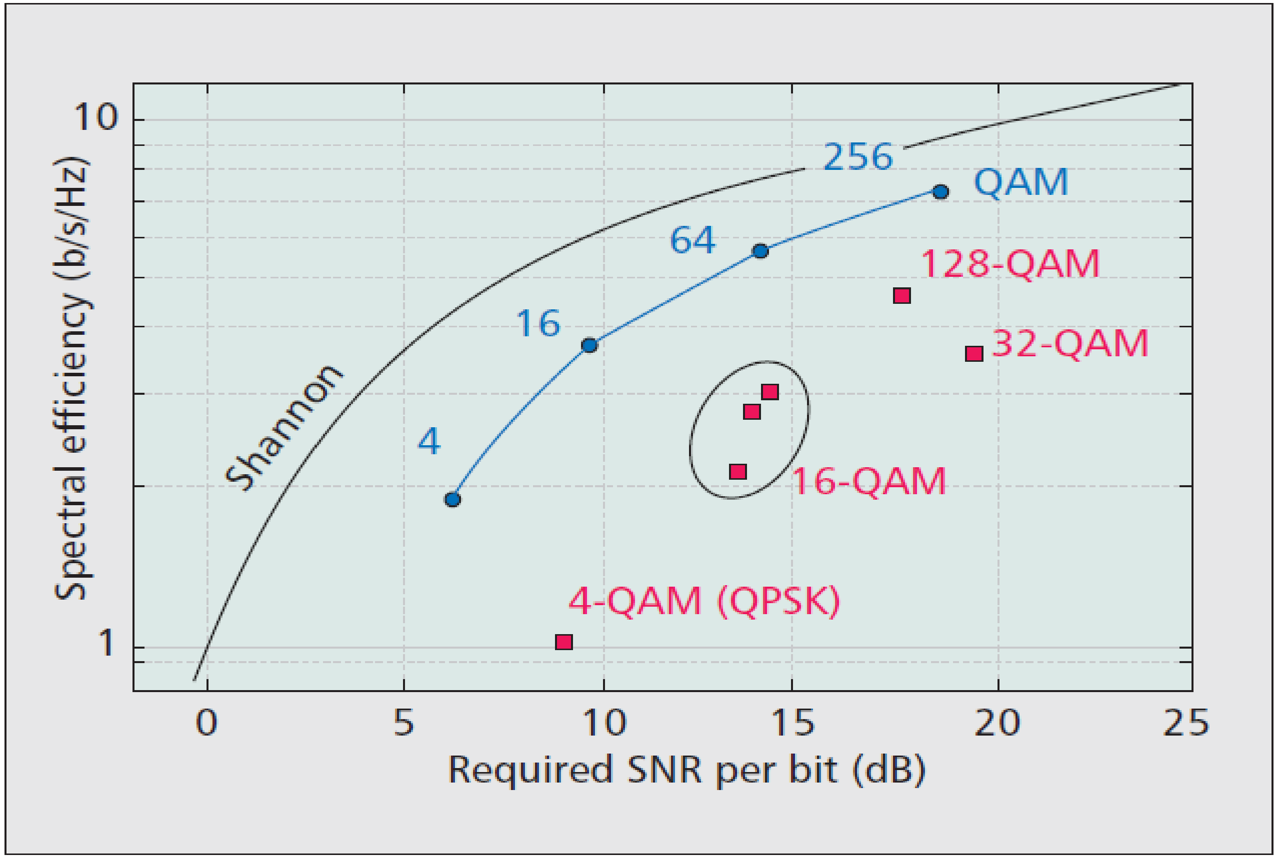


Figure 4. *Trade-off between spectral efficiency and SNR as dictated by Shannon; spectral efficiency values refer to a single polarization. (Circles: Theoretical performance; squares: experimental results.) From [23], reproduced with permission.*

PETER J. WINZER, BEYOND 100G ETHERNET, BELL LABS, ALCATEL-LUCENT IEEE Communications Magazine • July 2010

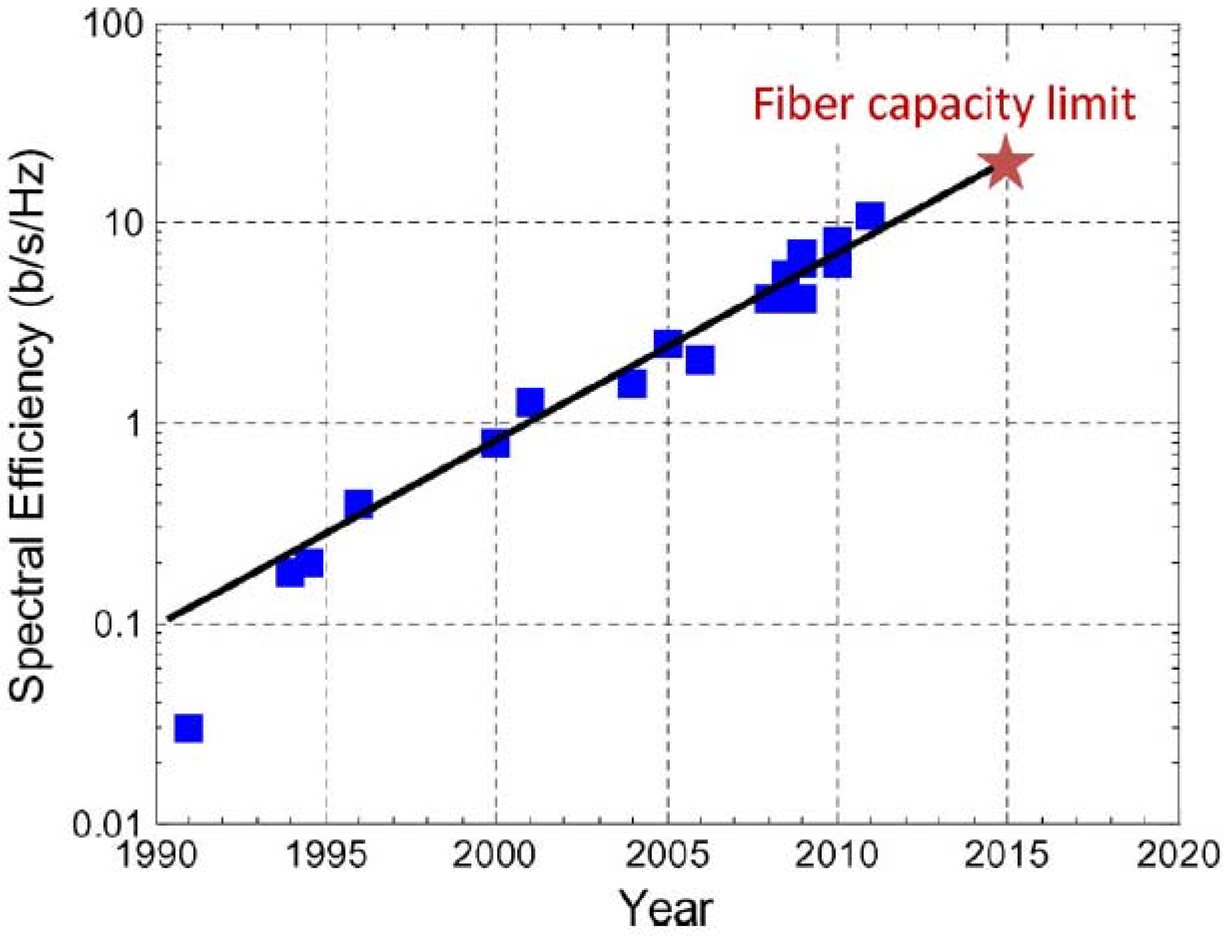


Fig. 3. ***Spectral efficiency achieved in research demonstrations versus year.***

OPTICAL FILTERS IN OCS

OPTICAL FILTERS IN OCS

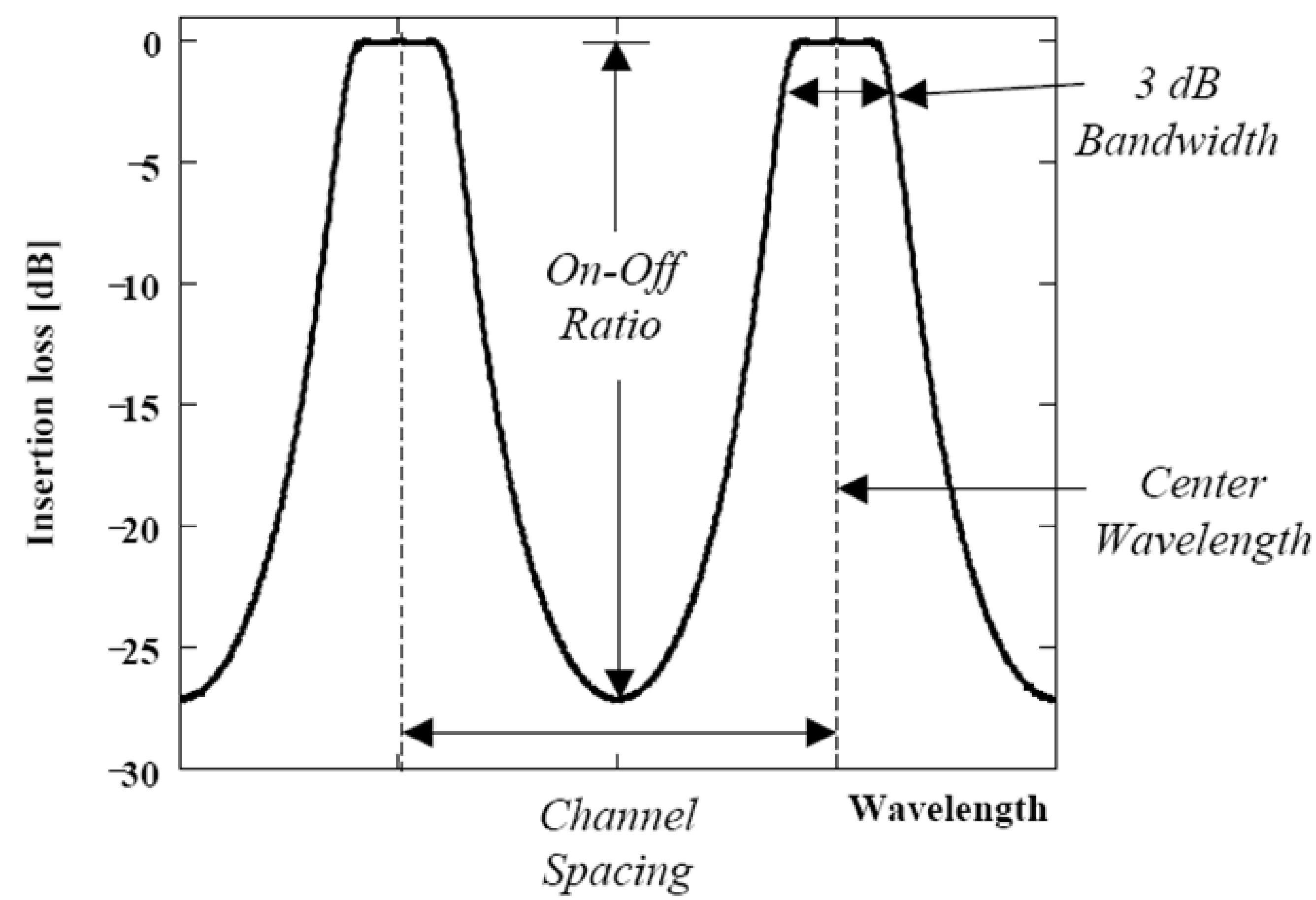
Optical filters in OCS mainly

- (Mux/Demux)
- OXC a ADM
- For dispersion compensation FBG (FibreBraggGrating)
- Gain Equalization ......

MAIN OPTICAL FILTER CHARACTERISTICS

- **Insertion loses**
  - Loses influence useful signal
- **Polarisation dependence**
  - Signal Polarisation in Fibre is random
- **Temperature dependence**
  - In working area
- **Bandwidth**
  - Shape is dependent on requirements
- **Small crosstalk in to neighbouring channels**
  - Transmission shape

SOME PARAMETERS OF OPTICAL FILTERS



FABRY-PEROT OPTICAL FILTER

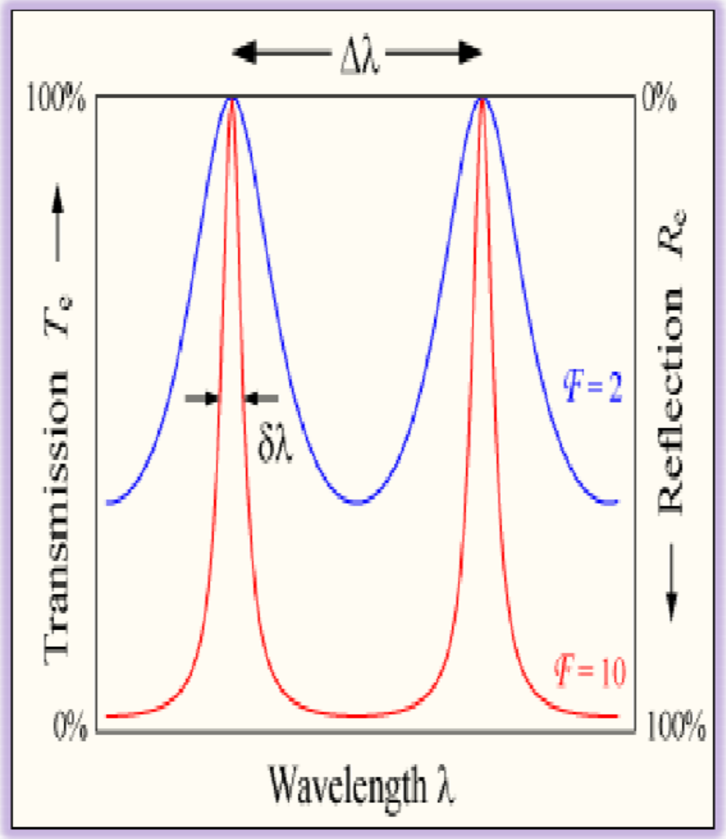
FSR (Full Spectral Range) – spectra distance between two maxima

$$FSR = \frac{c}{2nl}$$

FWHM (Full Width in Half Maximum)

$$F = \frac{\pi\sqrt{R}}{1-R} = \frac{FWHM}{FSR}$$

F (Finesse)



DIFFRACTION GRATINGS

- Diffracts incident light in specific directions according to the angle of incidence on the grating.
- Changing transfer characteristics: a (line spacing), Θ_B(blaze angle), α (angle of incidence),…

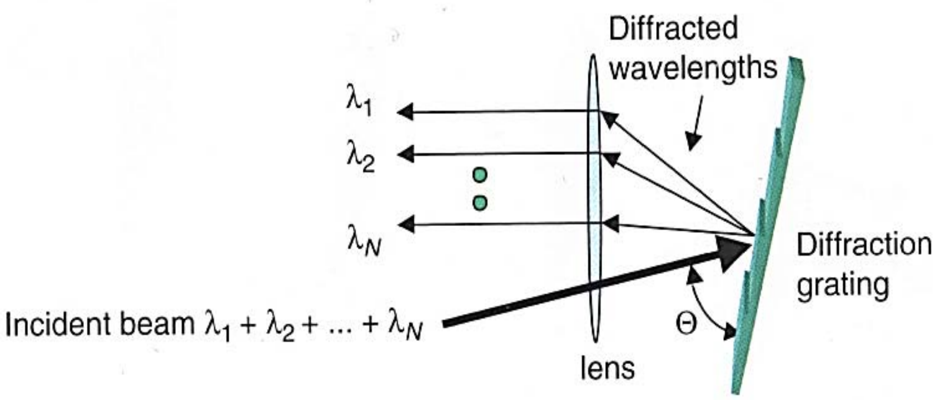


Figure 2.16 Operation of a diffraction gratings.

DWDM- Networks Devices and Technology, 2003

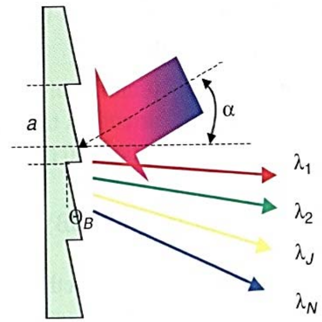


Figure 2.12 A diffraction grating.

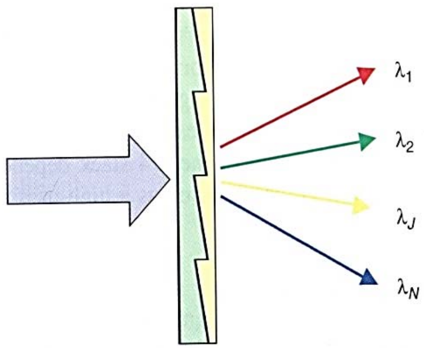
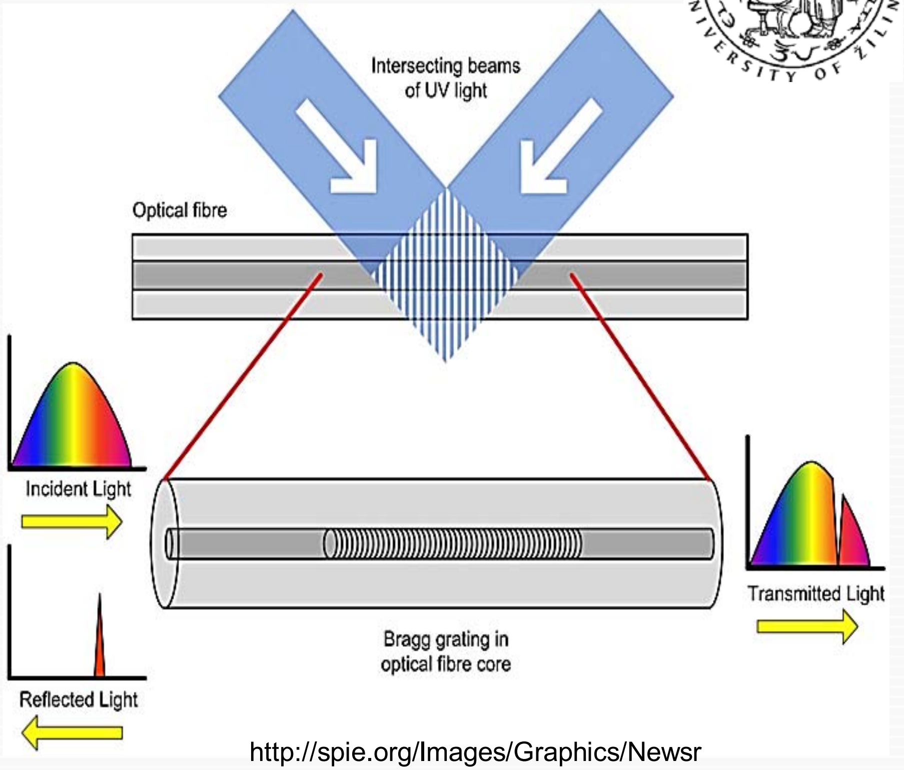


Figure 2.13 A pass-through grating diffracts each wavelength in different angle.

DWDM- Networks Devices and Technology, 2003

FIBER BRAGG GRATINGS

- Is a type of a distributed Bragg reflector constructed in a short segment of the optical fiber that reflects particular wavelengths of light and transmits all others
- Is achieved by creating a periodic variation in the refraction index of the fiber core



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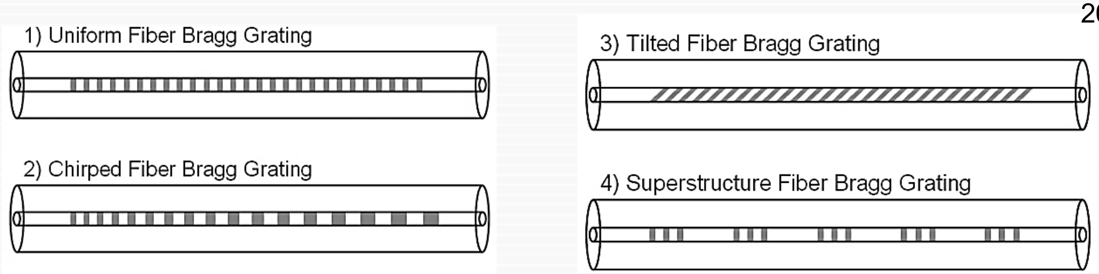
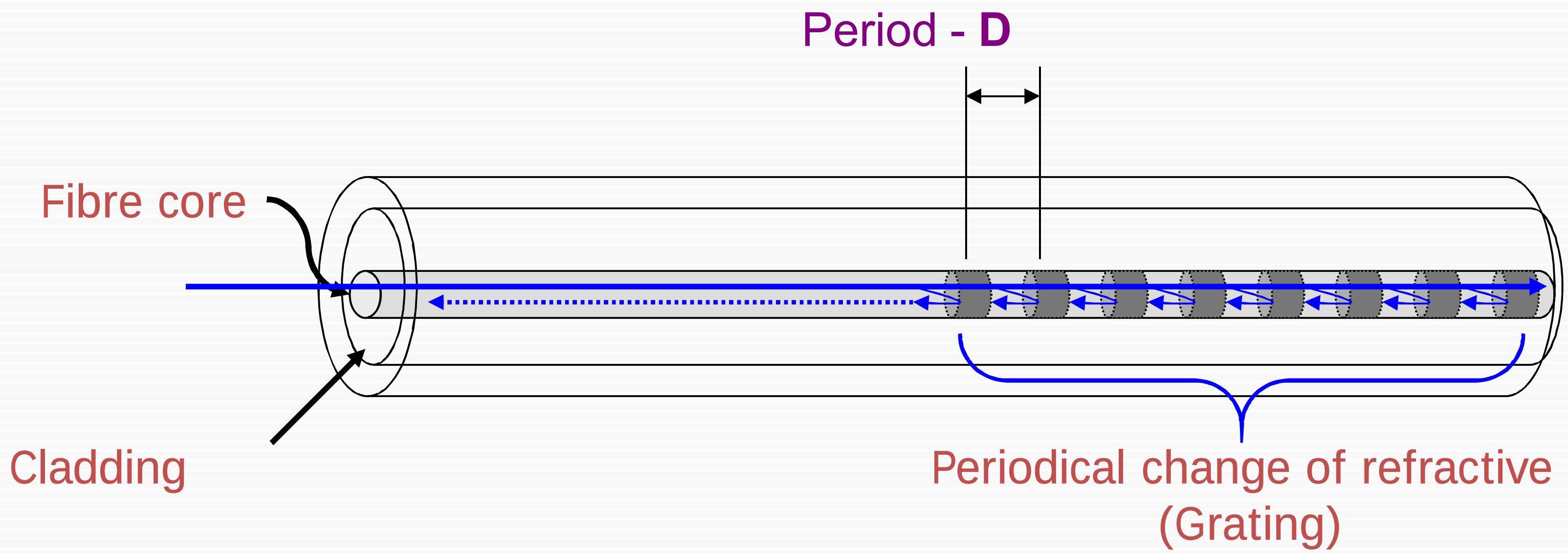


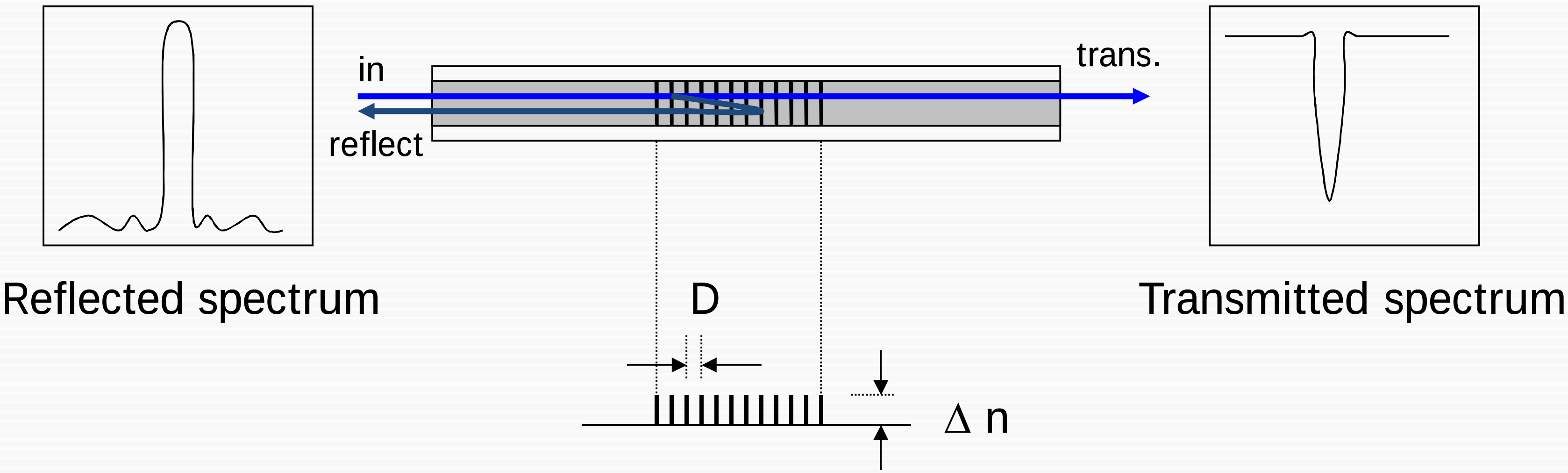
http://upload.wikimedia.org/wikipedia/en/thumb/e/ea/Fbg3.GIF/300px-Fbg3.GIF

FBG – FIBER BRAGG GRATING

$$D = \frac{l\lambda_B}{2n_{eff}}$$

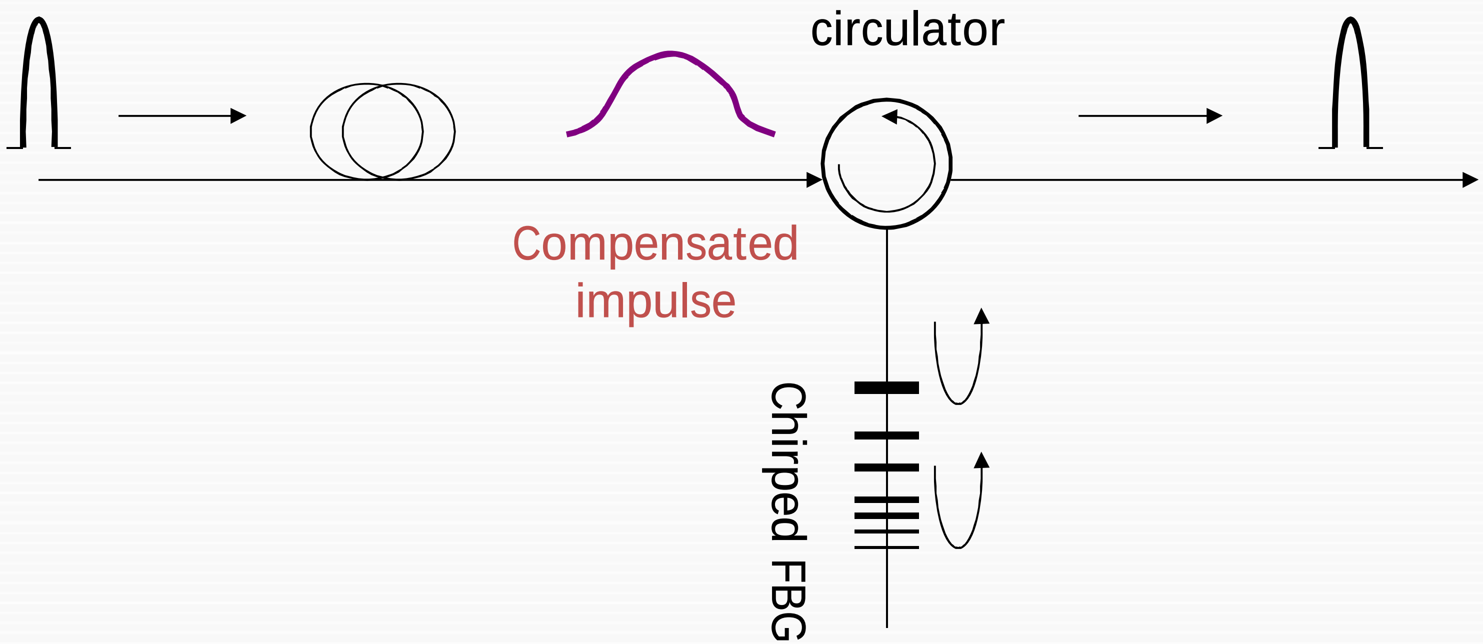


BRAGG CONDITION

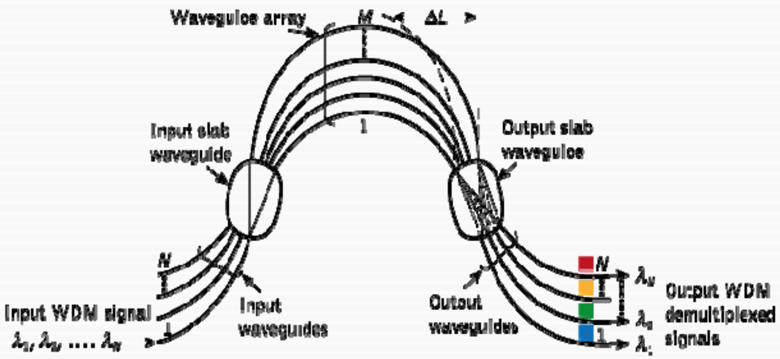


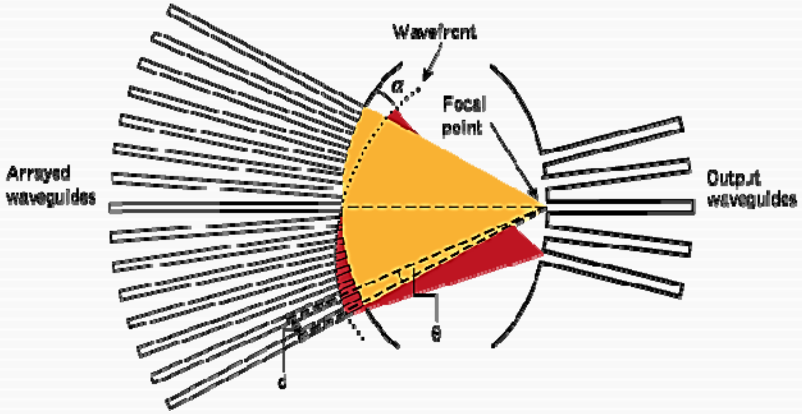
$$\lambda_r = 2n_{eff}\,D$$

EXAMPLE OF DISPERSION COMPENSATION



ARRAYED WAVEGUIDE GRATING (AWG)



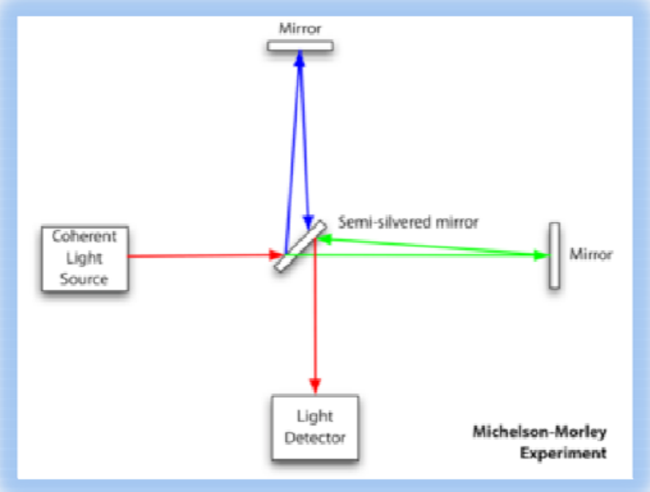


- **Arrayed Waveguide Grating (AWG) multiplexer and demultiplexer provides key WDM function in single device.**
- **A single waveguide input is spread over an array of waveguides at the input coupler.**
- **Light launched in to the different waveguide travels over different distances before reaching the output coupler.**
- **The light is refocused into different output waveguides depending on the phase trajectory it has experienced in the waveguides and that depending on its wavelength.**
- **The AWG may be operated in reverse in order to combine many frequency channels on to a single fibre.**

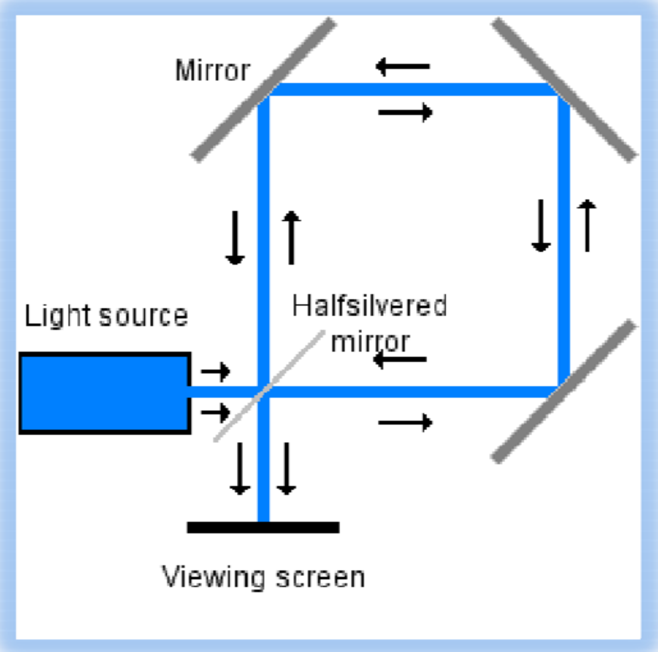
John M. Senior: *Optical Fiber Communications Principles and Practice,* Pearson Education, 2009

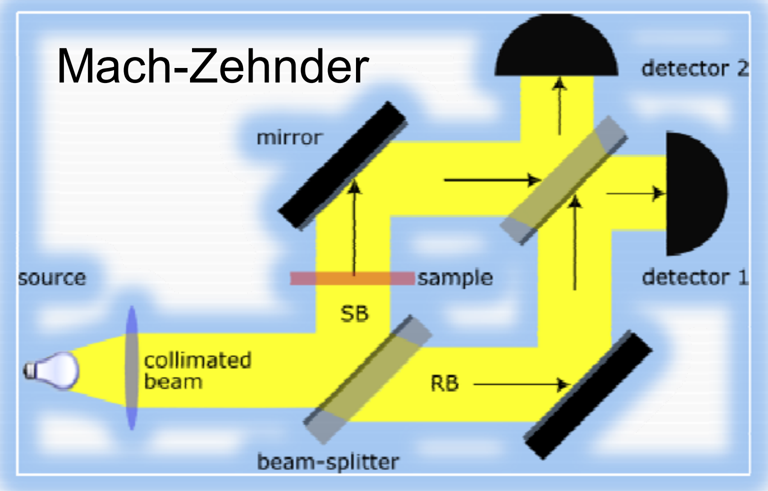
INTERFEROMETERS

Michelsen



Sagnac



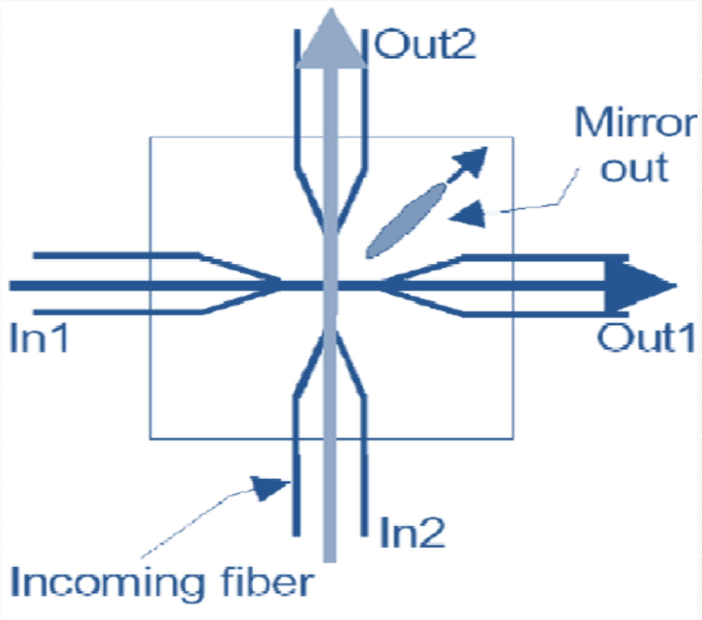


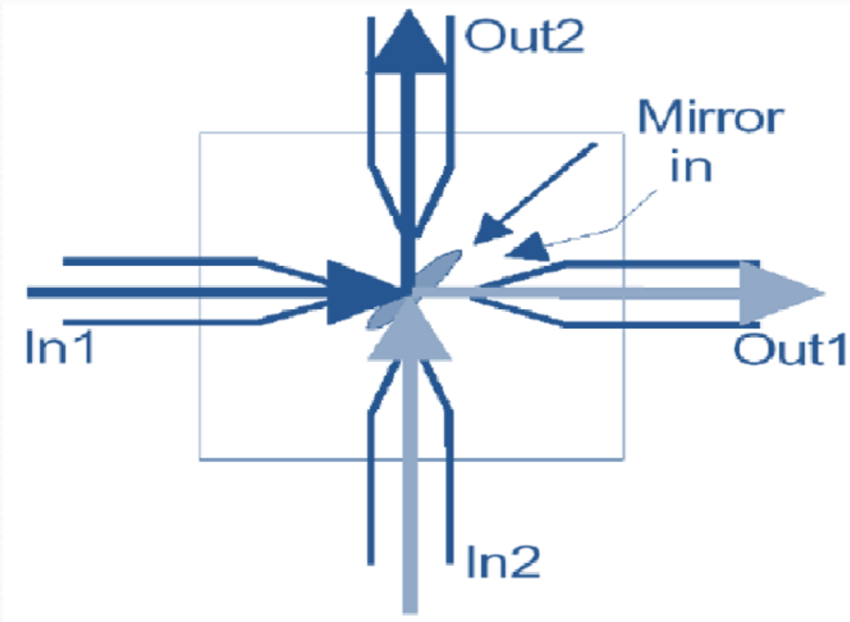
OPTICAL SWITCHES

OPTICAL SWITCHES

- **Hybrid switches**

- **All-optical switches**





OPTICAL CROSS CONNECTS

- **May be classified according to several criteria**
  - **O/E, E/O conversion**
    - **Hybrid approach**
      - **O/E -> electronic cross-connect -> E/O**
    - **All-optical switching**
      - **Cross-connect in photonic domain**

- **All- optical switching**
  - **Fiber cross-connect (FXC)**
    - **All channels from one fiber are switched to another fiber**
  - **Wavelength cross-connect (WXC)**
    - **Wavelength selective cross-connect (WSXC)**
      - **Connect a wavelength from one fiber to another fiber without wavelength conversion**
    - **Wavelength interchanging cross-connect (WIXC)**
      - **Connect a wavelength from one fiber to another fiber within wavelength conversion**

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HYBRID OPTICAL SWITCHES

Optic-mechanic switches,

Micro-electro-mechanic systems,

Electro-optical switches,

Acoustic-optical switches,

Thermo-optical switches,

Magneto-optical switches,

Switches based on liquid crystals,

Semiconductor optical amplifiers.

MAIN REQUIREMENTS ON OPTICAL SWITCHES

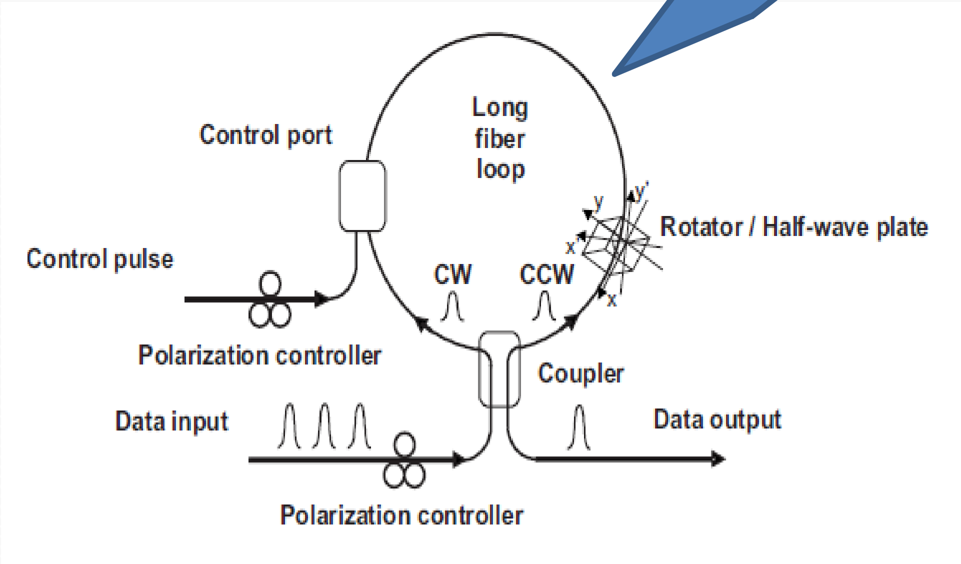
- Fast optical switching (μs-ns),
- Robustness of switching structure e.g. for 4 fibres (N) with 64 wavelength (M) is needed switch 256x256 (*NM*x*NM*),
- Ability to work with many wavelengths,
- Compatibility to fibre and/or integrated structure,
- Low insertion losses and/or in/out amplifiers,
- Small crosstalk among optical channels,
- Wavelength independence in working bandwidth e.g. EDFA ,
- Small PDL,
- Easy integrated,
- High switch ratio „on/off“.

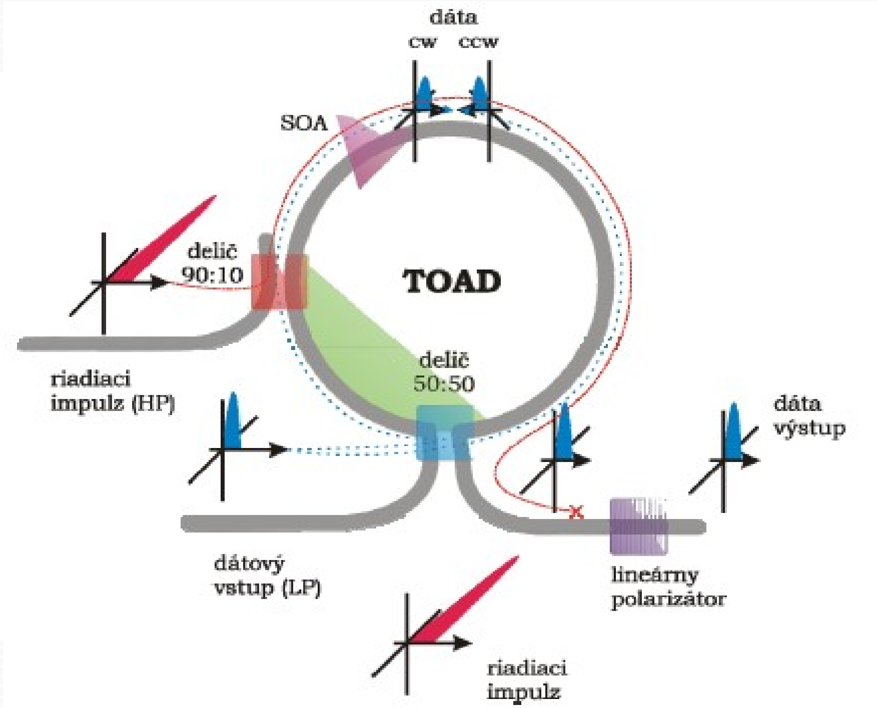
COMPARISON OF PROPERTIES OF DIFFERENT TYPES OF SWITCHES

Technology \ Properties	Size	Time of switching	Insertion losses [dB]	Crosstalk [dB]	PDL [dB]
Opto-mechanical	16 x 16	< 10 ms	3	< -55	0.2
2D MEMS	32 x 32	< 10 ms	1.7-6.9	< -60	0.11-0.16
3D MEMS	350 x 350 160 x 160	< 10 ms < 10 ms	6 ± 1 < 2	< -60 < -55	0.4 0.5
Thermo-optical **Silica** **Polymer**	 8 x 8 16 x 16	 < 10 ms < 10 ms	 8 6	 < -35 < -30	 0.5 0.4
Liquid crystal	2 x 2	< 10 ms	1.5	< -35	0.1
Acoustic-optical	1 x N	< 3 µs	6	< -35	
Electro-optical **$LiNbO_3$** **InP**	 8 x 8 1 x 2	 < 10 ns < 10 ns	 9	 < -35 < -25	 0.5
SOA		1 ns	~ 0	< -50	< 1

OPTICAL ENGINEERING 485, 055002 MAY 2009:

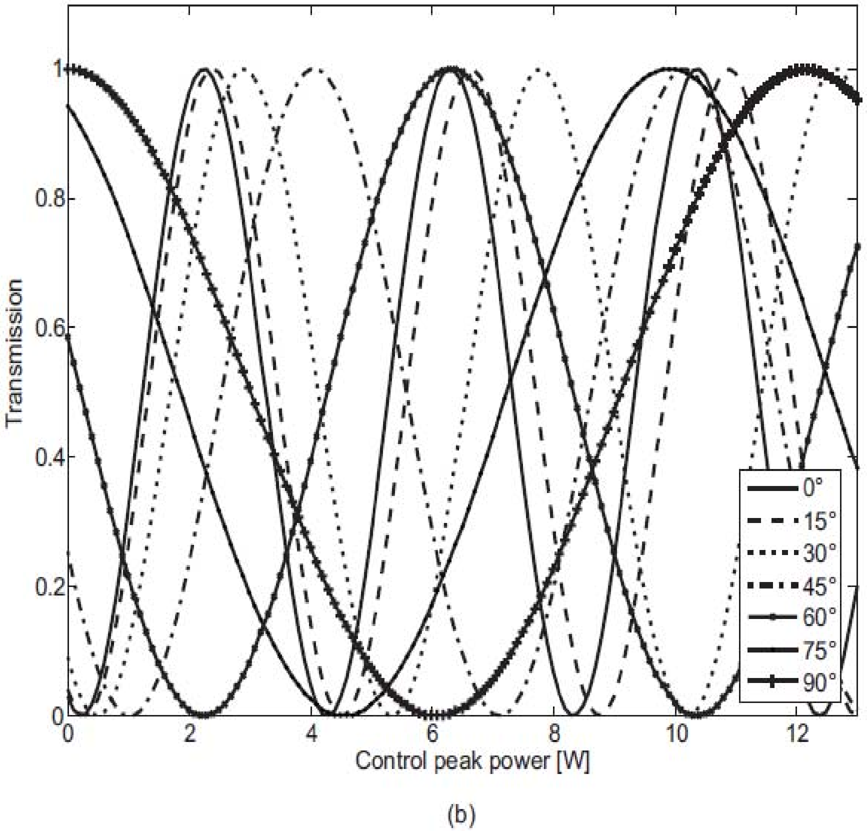
Abstract. A new scheme of a control-beam-driven nonlinear optical loop mirror (NOLM) with a birefringent twisted fiber and a symmetrical coupler designed for optical time division demultiplexing (OTDM) is analyzed.





Grendár et al.: Effect of control-beam polarization and power on optical time-domain demul

Optical Engineering 485, 055002 May 2009:



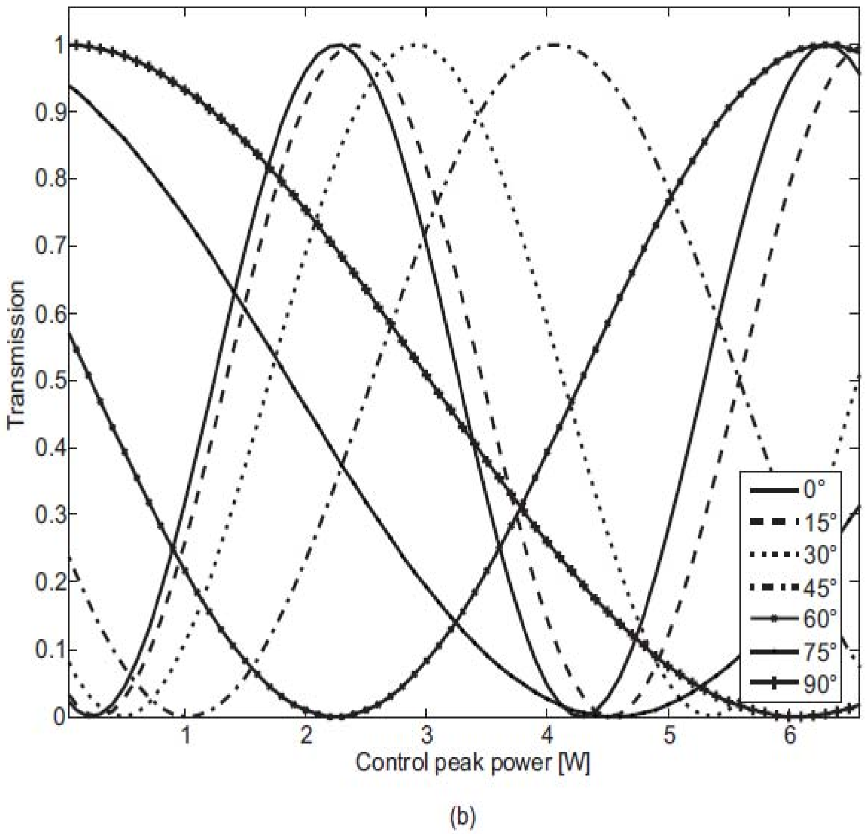


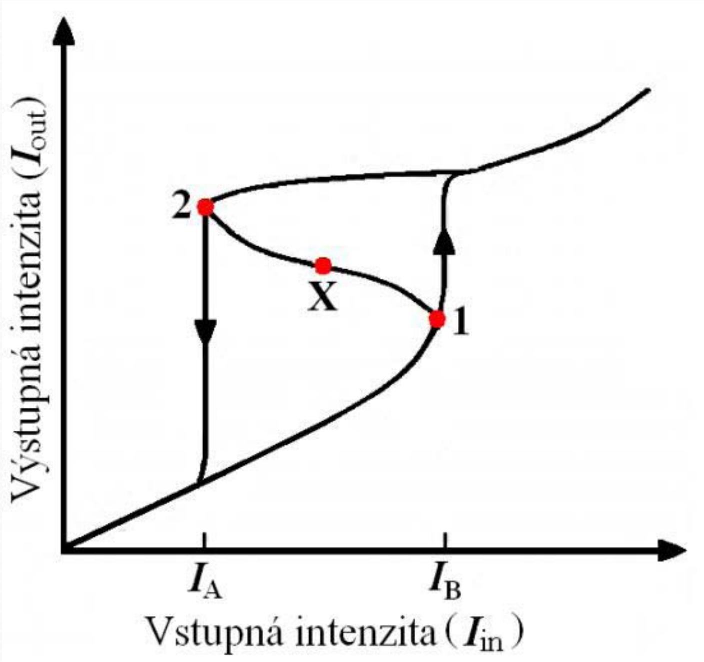
Fig. 4 (a) Transmission of the NOLM, including the rotator versus the peak control-beam power and the mutual angles of polarization between the linearly polarized input data and control beam. (b) Zooms in on a part of Fig. 4(a).

OPTICAL BISTABILITY AND WAVELENGTH CONVERSION

PRINCIPLES OF OPTICAL BISTABILITY

System transmission T is nonlinear function of input intensity I_{inpu}

$$T = T(I_{input}).$$



Hysteresion curve

WAVELENGTH CONVERTORS

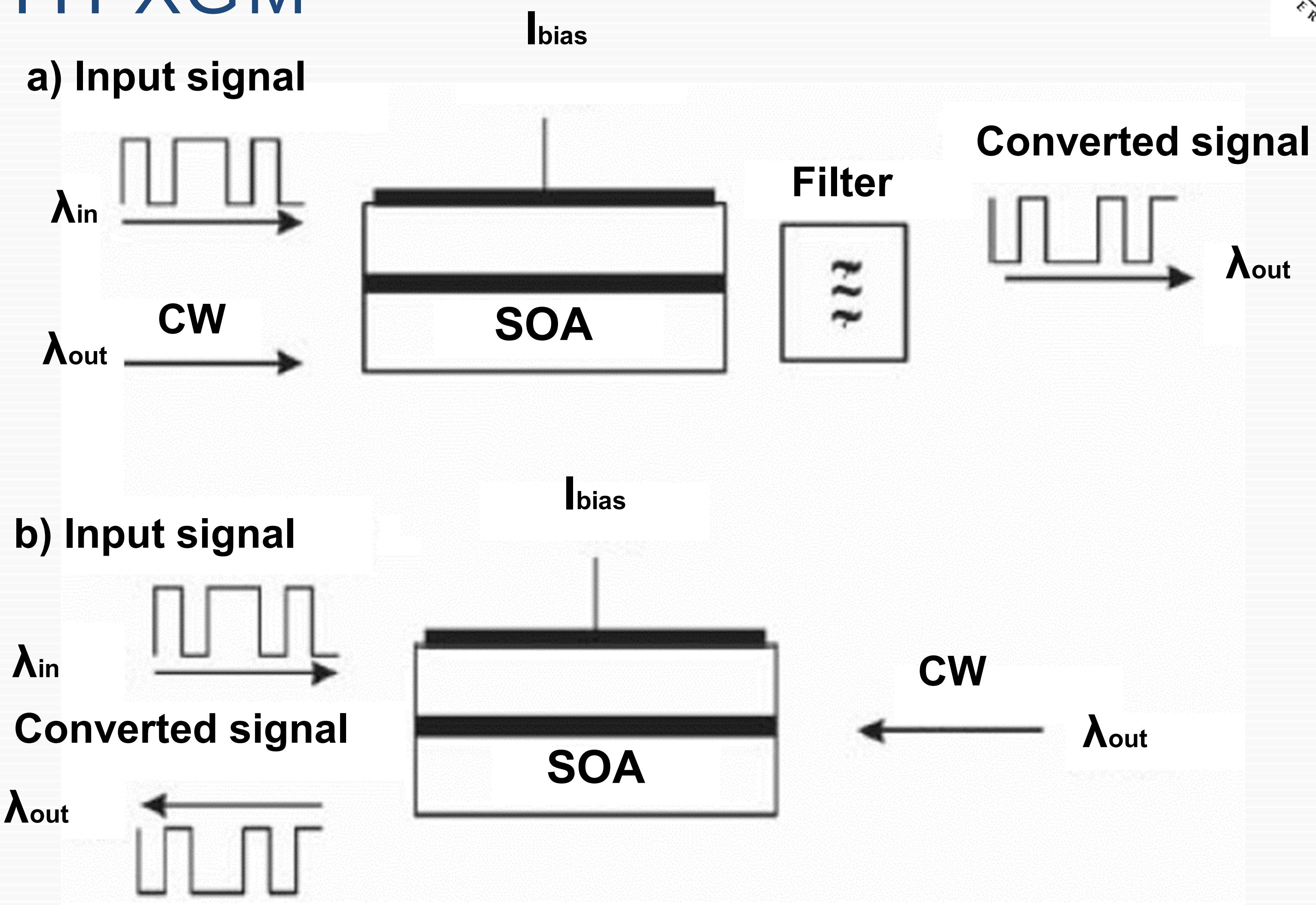
Types of Wavelength convertors:

- **O/E/O conversion,**
- **All optical wavelength conversion.**

All optical wavelength conversion :

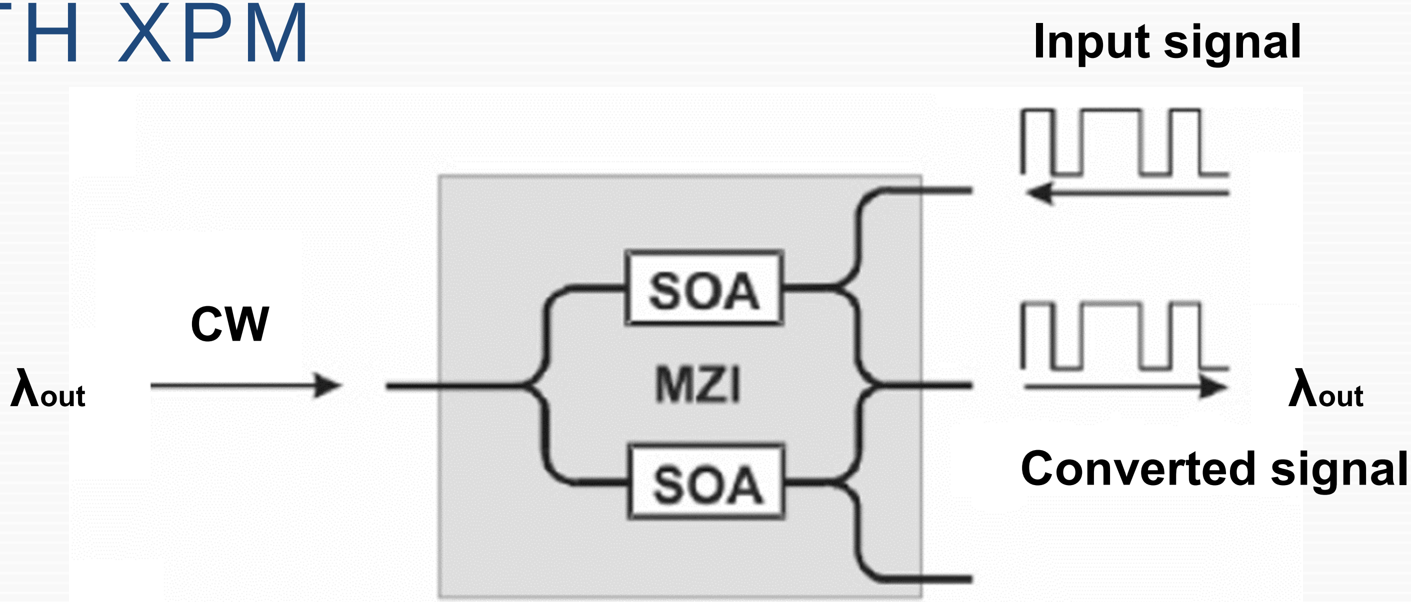
- **Cross gain modulation (XGM),**
- **Cross phase modulation (XPM),**
- **Four wave mixing (FWM).**

WAVELENGTH CONVERSION WITH XGM

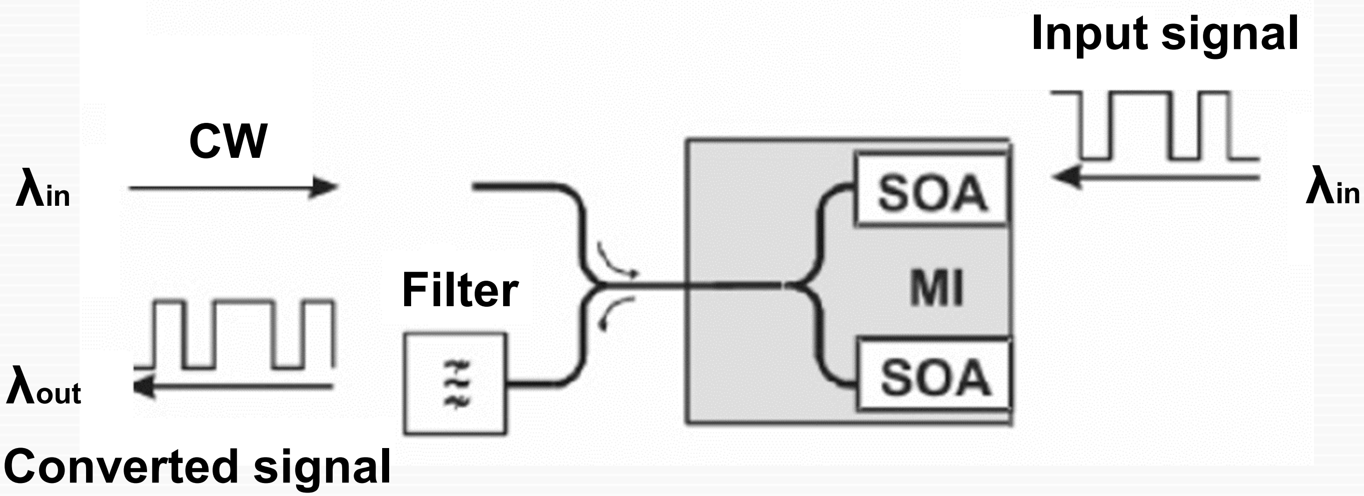


WAVELENGTH CONVERSION WITH XPM

a)

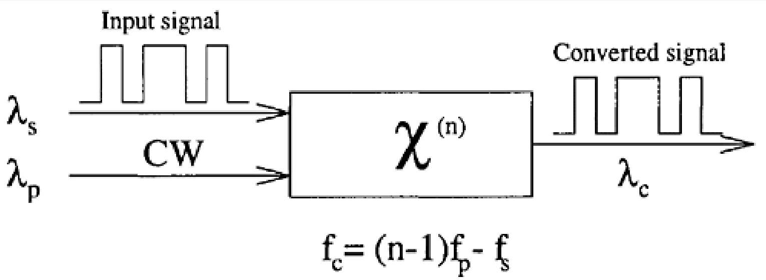


b)



FOUR-WAVE MIXING WAVELENGTH CONVERTERS

- For the purposes of wavelength conversion, the four-wave mixing power can be enhanced by using an SOA because of the higher intensities within the device.
- If we have a signal at frequency f_s and a probe at frequency f_p, then four-wave mixing will produce signals at frequencies $2f_p-f_s$ and $2f_s-f_p$, as long as all these frequencies lie within the amplifier bandwidth



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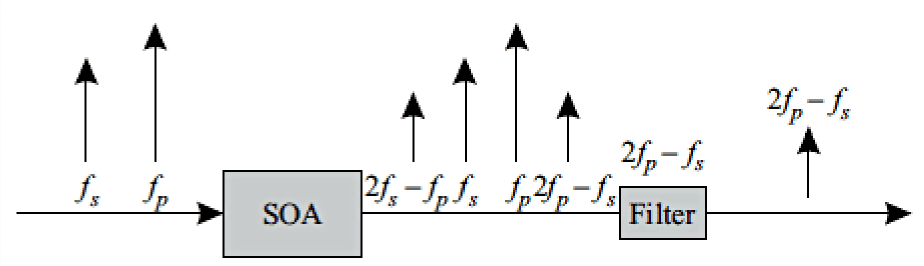


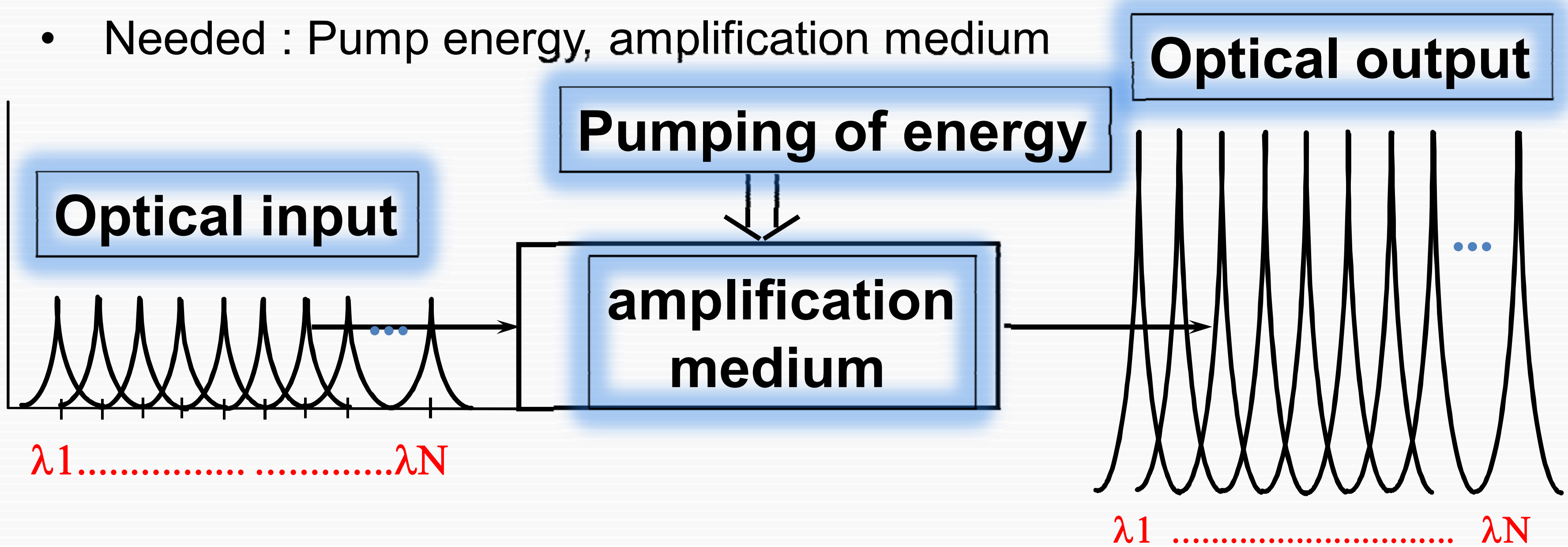
http://www.fiberoptics4sale.com/Merchant2/graphics/00000001/What-Is-A-Wavelength-Converter_9221/cross-gain-modulation-wavelength-converter.png

OPTICAL AMPLIFIERS

WHY OPTICAL AMPLIFIERS?

- **Increase transmission distance**
  - by increasing optical power coupled to transmission fiber(power booster)
  - by compensating optical fiber losses(in-line amplifier, remote pump amplifier)
  - by improving receiver sensitivity (optical preamplifier)

- Function : Amplification of optical signal without conversion to electrical signal
- Needed : Pump energy, amplification medium



THE NEED OF OPTICAL AMPLIFICATION

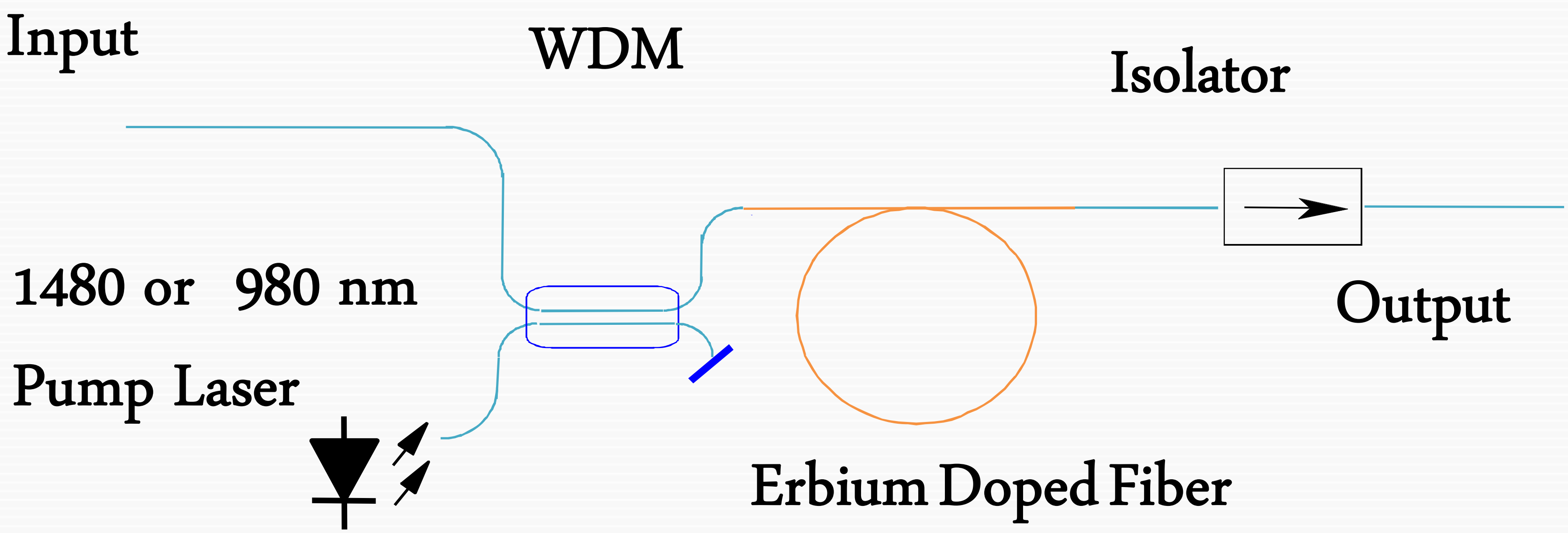
Why? – Extend distance light signal can travel without regeneration

- **Erbium-Doped Fiber Amplifiers (EDFAs)** – application in long haul. Today's amplifier of choice.
- **Erbium-Doped Waveguide Amplifiers (EDWAs)** – application in metro and access networks
- **Raman Amplifiers** – application in DWDM
- **Semiconductor Optical Amplifiers (SOA)** – not fiber based type, application in metro and access networks

BASIC EDF AMPLIFIER DESIGN

Erbium-doped fiber amplifier (EDFA) most common

- Commercially available since the early 1990's
- Works best in the range 1530 to 1565 nm
- Gain up to 30 dB



ISSUES OF AMPLIFIER DESIGN

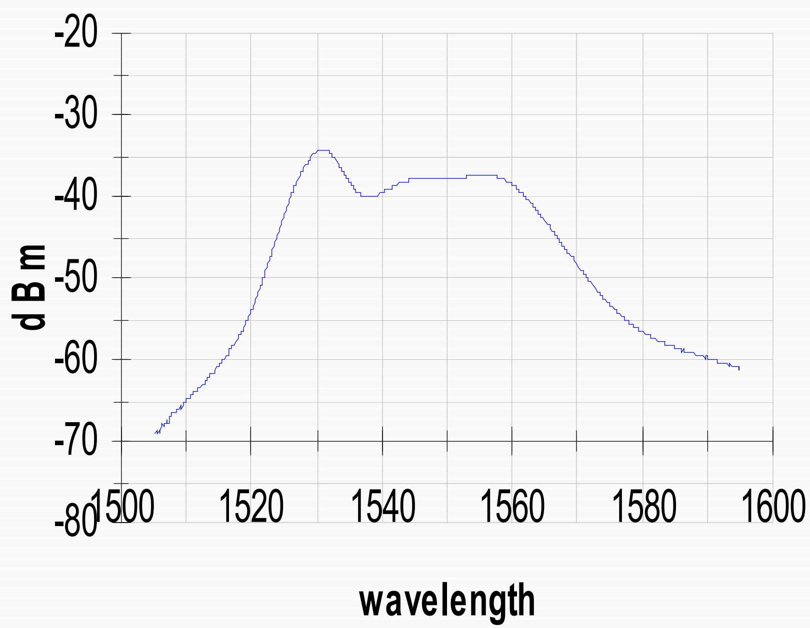
- Optimization
  - maximum efficiency
  - minimum noise figure
  - maximum gain
  - maximum gain flatness/gain peak wavelength
- Dynamic range, operation wavelength
- Gain equalization
- Control circuit
- Monitoring of amplifier performance

ERBIUM-DOPED FIBRE AMPLIFIER

Gain, G (dB)

$10\log[(P_{Signal\_Out} - P_{ase}) / P_{Signal\_In}]$

Spectrum of a typical EDFA



Noise Figure, $F = SNR_{out} / SNR_{in}$

S-band : 1440 - 1530nm

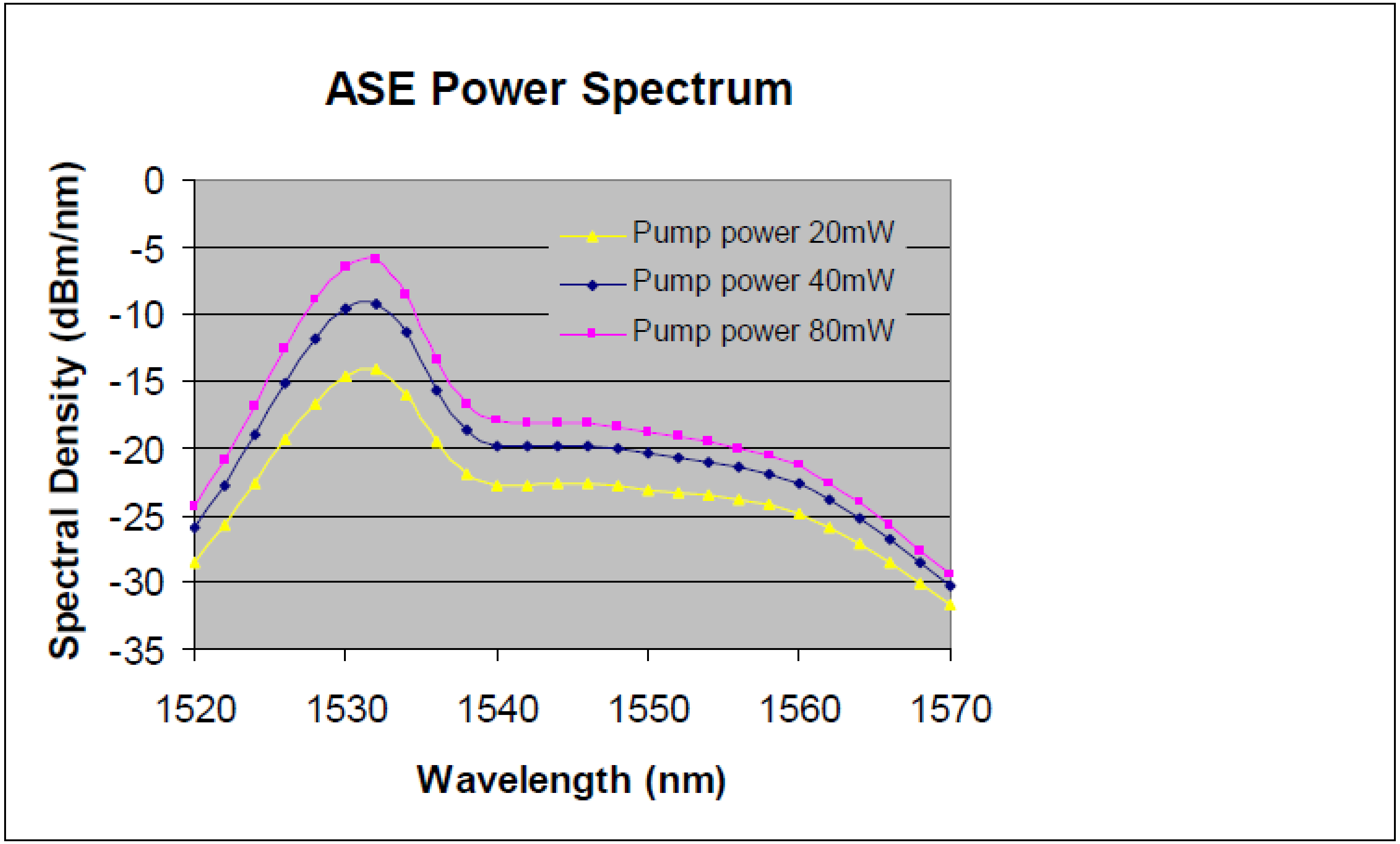
C-band : 1530 - 1565nm

L-band : 1565 - 1625nm

Implementation of three functional devices using Erbium-doped Fibers: An Advanced Photonics Lab

Wen Zhu, Li Qian, Amr S. Helmy

Department of Electrical and Computer Engineering, University of Toronto, 10 King's College Road, Toronto, ON M5S 3G4, Canada
Tel: (416) 946-873, wen.zhu@utoronto.ca



Amplified spontaneous emission (ASE) spectrum of erbium-doped fiber pumped by a 974 nm laser diode

NOISE FIGURE (NF)

$NF = P_{ASE} / (h \cdot \nu \cdot G \cdot B_{OSA})$

P_{ASE}: Amplified Spontaneous Emission (ASE) power measured by OSA

- h: Plank's constant
- ν: Optical frequency
- G: Gain of EDFA
- B_{OSA}: Optical bandwidth [Hz] of OSA

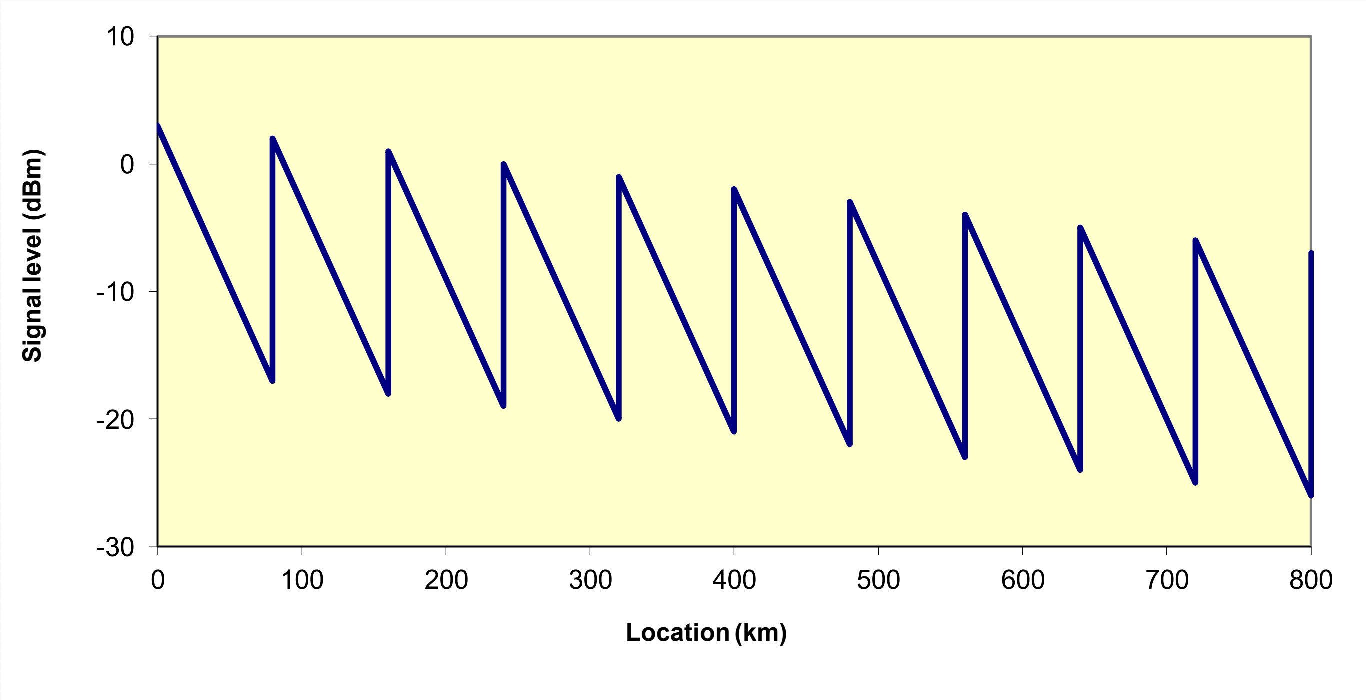
Input signal dependent

- In a saturated EDFA, the NF (3 – 10)dB
- depends mostly on the wavelength of the signal
- Physical limit: 3.0 dB

AMPLIFIERS CHAINS AND SIGNAL LEVEL

SOURCE: APPLIED ELECTRONIC CENTRE

- Sample system uses 0.25 atten fibre, 80 km fibre sections, 19 dB amplifiers with a noise figure of 5 dB

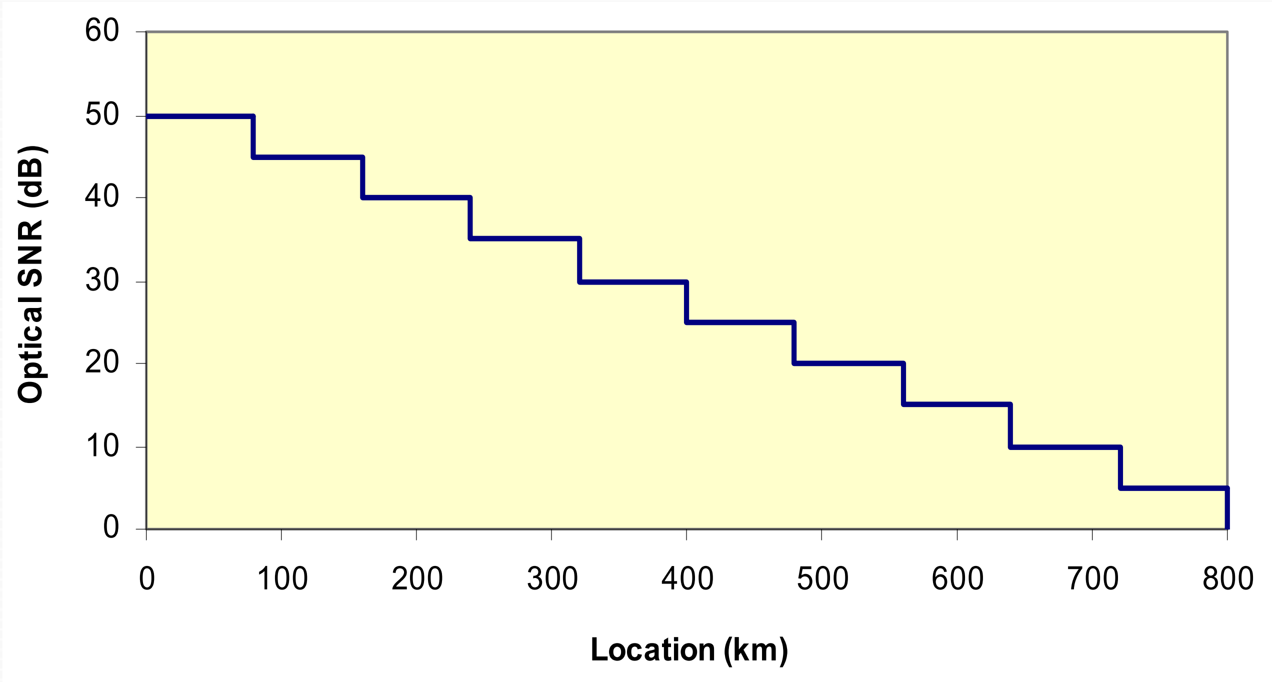


- Each amplifier restores the signal level to a value almost equivalent to the level at the start of the section - in principle reach is extended to 700 km +

AMPLIFIERS CHAINS AND OPTICAL SNR

SOURCE: APPLIED ELECTRONIC CENTRE

- Same sample system: Transmitter SNR is 50 dB, amplifier noise figure of 5 dB,



- Optical SNR drops with distance, so that if we take 30 dB as a reasonable limit, the max distance between T/X and R/X is only 300 km

EDFA CATEGORIES

SOURCE: APPLIED ELECTRONIC CENTRE

In-line amplifiers

- Installed every 30 to 70 km along a link
- Good noise figure, medium output power

Power boosters

- Up to +17 dBm power, amplifies transmitter output
- Also used in cable TV systems before a star coupler

Pre-amplifiers

- Low noise amplifier in front of receiver

Bi-directional amplifiers

- An amplifier which work in both ways

Remotely pumped

- Electronic free extending links up to 200 km and more (often found in submarine applications)

IMPROVEMENT OF SYSTEM GAIN

	Improvement in gain(dB)	Improvement in length(km)	Key technology
Booster amplifier	10 - 15	40 - 60	High efficiency
Preamplifier	5 - 10 (APD) 10 - 15 (PIN)	20 - 40 40- 60	Low noise
In-line amplifier	15 - 30	60 - 120	Low noise
Remote pump amplifier	5 - 15	30 - 60	High pumping power

EDFAS IN DWDM SYSTEMS

Optical amplifiers in DWDM systems require special considerations because of:

Gain flatness requirements

Gain competition

Nonlinear effects in fibers

OUTPUT POWER LIMITATIONS

High power densities in SM fiber can cause

- Stimulated Brillouin scattering (SBS)
- Stimulated Raman scattering (SRS)
- Four wave mixing (FWM)
- Self-phase and cross-phase modulation (SPM, CPM)

Most designs limit total output power to +17 dBm

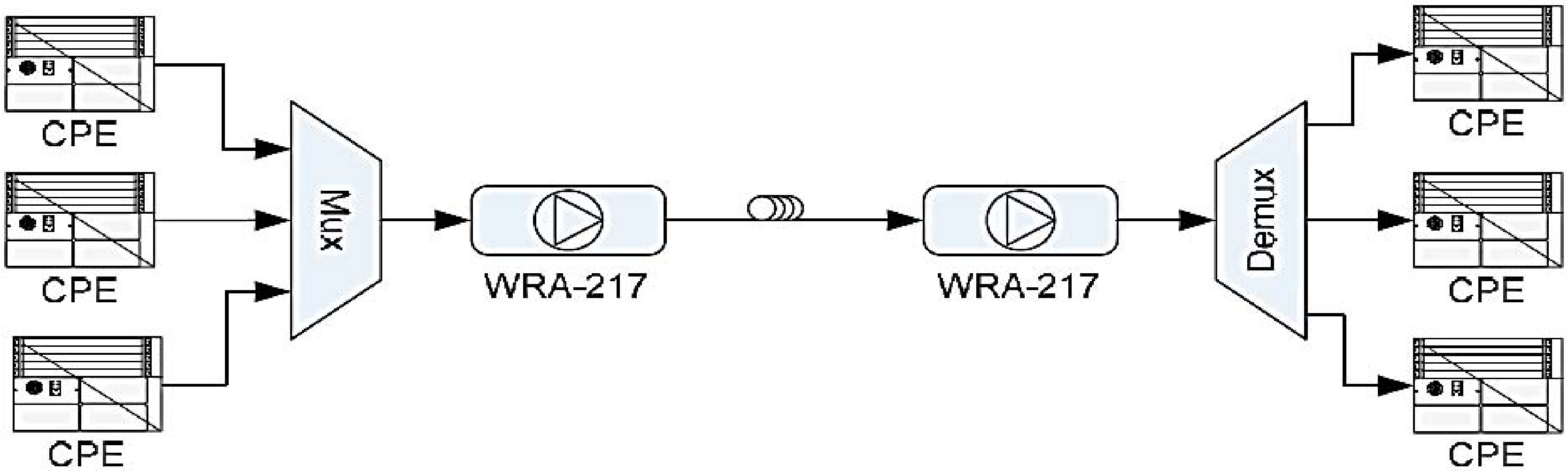
- Available channel power: 50/N (mW)
  (N = number of channels)

ERBIUM DOPED WAVEGUIDE AMPLIFIER (EDWA)

EDWA advantages

- EDWAs are inherently compact
- One of the smallest gain block amplifiers to date, featuring 15-dB gain at 1,535 nm, fits in a 130x11x6-mm package
- EDWAs also offer a better price/performance ratio than comparable EDFAs for access and metro network applications

EXAMPLE: WAVEREADY™WRA-217 MULTICHANNEL ERBIUM-DOPED FIBER AMPLIFIER (EDFA)



Typical Link Budget

Number of wavelengths	Power	Total power budget	Maximum distance
1	+17 dBm	46 dB	184 km
16	+17 dBm	34 dB	136 km

EXAMPLE: WAVEREADY™WRA-217 MULTICHANNEL ERBIUM-DOPED FIBER AMPLIFIER (EDFA)

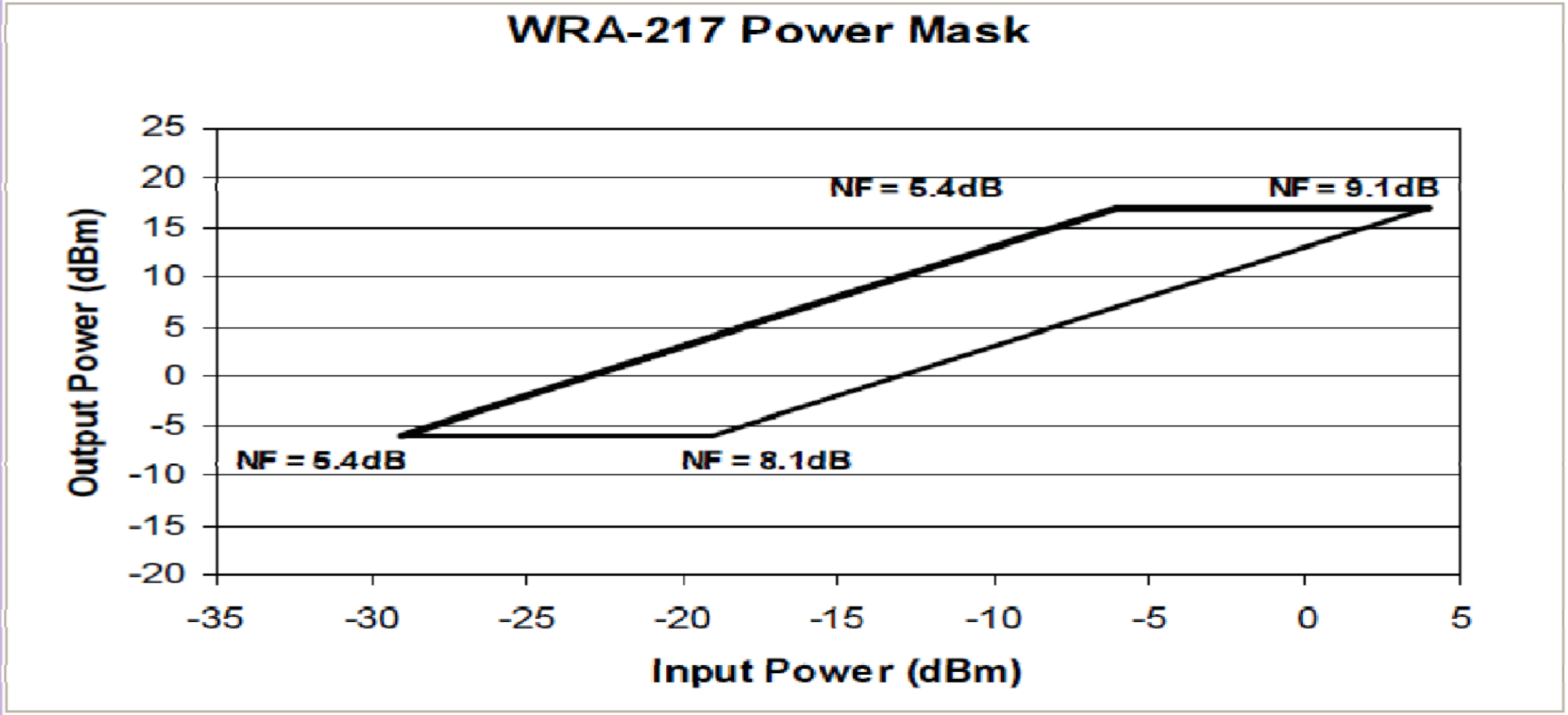


Figure 1: Power mask with noise figures[1] for WRA-217

RAMAN AMPLIFIER

First Raman Amplifiers were demonstrated in the 1980s

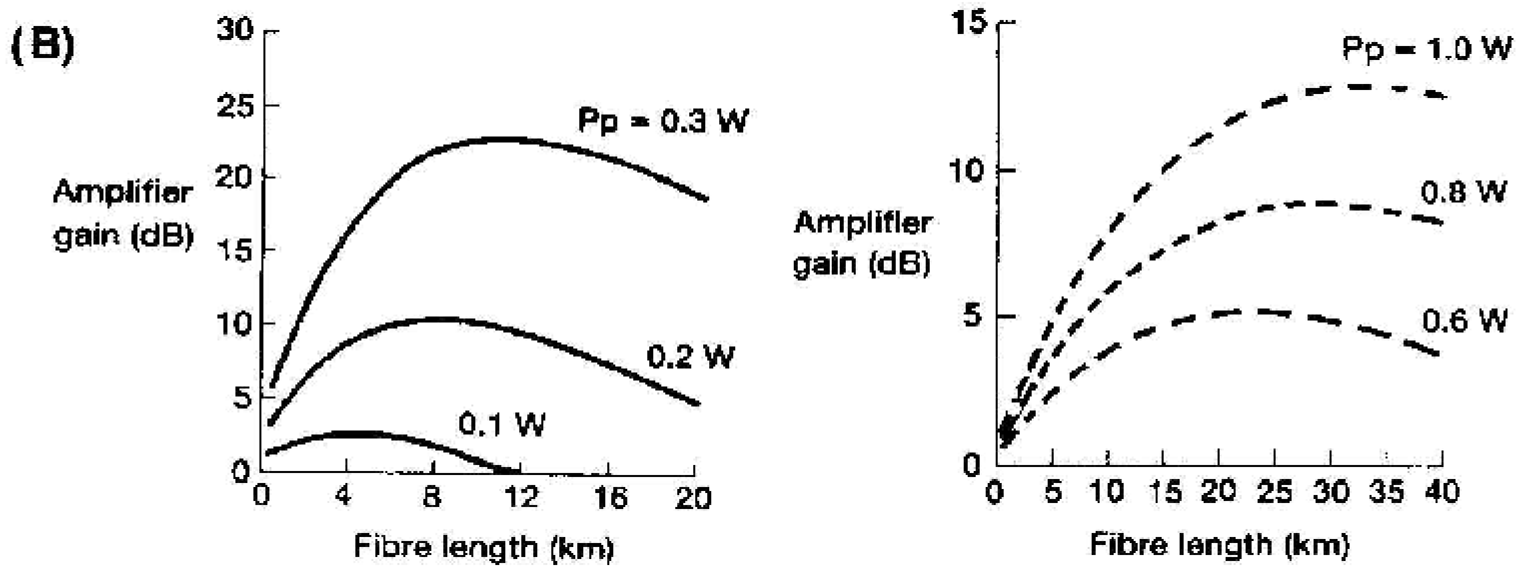
- amplify signals from 1270 to 1670 nm
- any optical fiber can serve as the amplifying medium

Raman process itself provides high-power laser

RAMAN AMPLIFIER

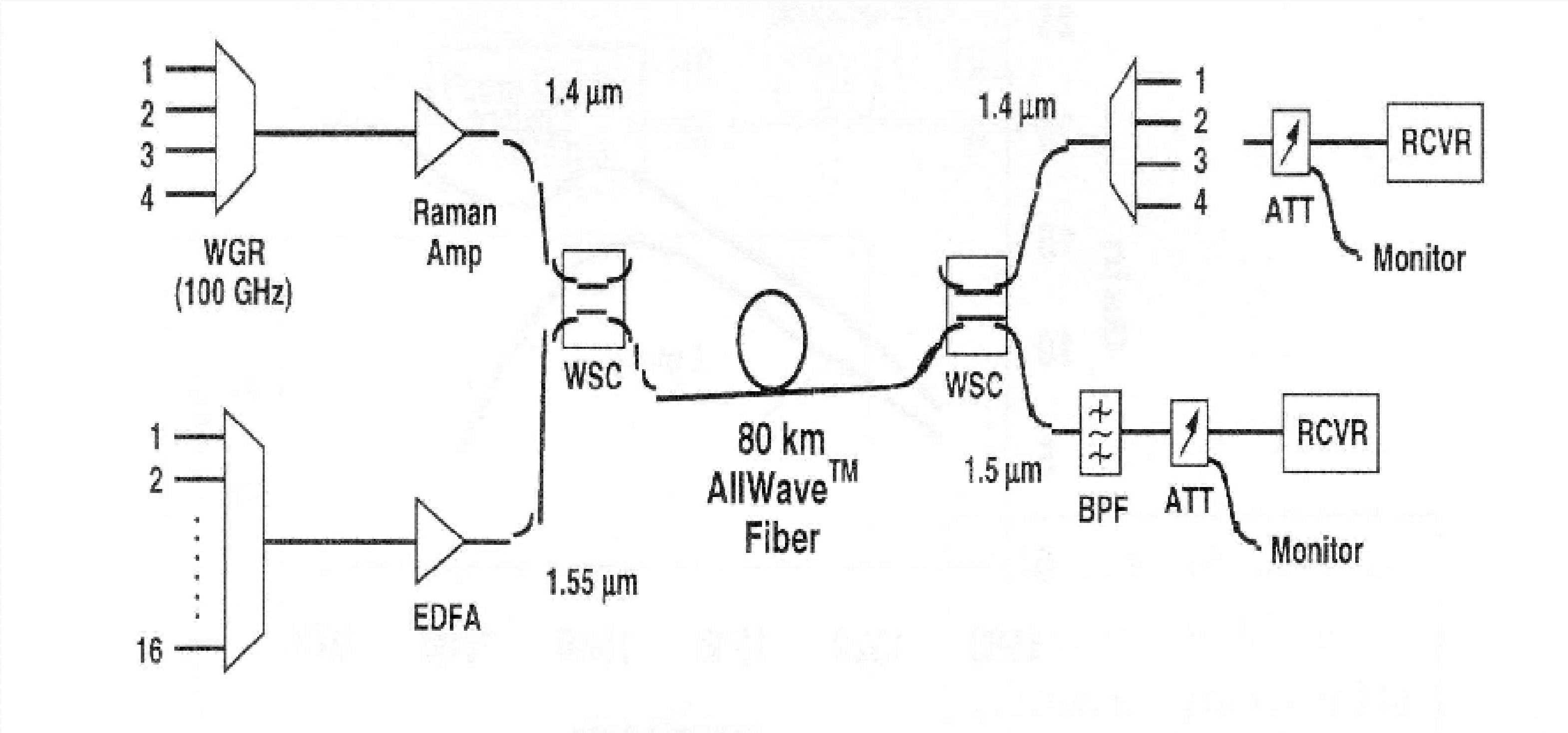
- Advantages
  - Variable wavelength amplification possible
  - Compatible with installed SM fibre
  - Can be used to "extend" EDFAs
  - Can result in a lower average power over a span, good for lower crosstalk
  - Very broadband operation may be possible
- Disadvantages
  - High pump power requirements, high pump power lasers have only recently arrived
  - Sophisticated gain control needed
  - Noise is also an issue

RAMAN AMPLIFIER



Raman Amplifier Gain (Measurements Lucent)

EDFA+RAMAN



Combined Raman and EDFA transmission Experiment: DWDM (Lucent)

SEMICONDUCTOR OPTICAL AMPLIFIER (SOA)

- Basically a laser chip without any mirrors
- Potential for switches and wavelength converters
    - Advantage: bidirectional
    - Drawbacks:
        - High-coupling losses
        - High noise figure
        - They are highly polarisation sensitive
        - Metastable state has nanoseconds lifetime (-> nonlinearity and crosstalk problems), They can produce severe crosstalk when multiple optical channels are amplified (WDM)
        - Insufficient power (only a few mW). This is usually sufficient for single channel operation but in a WDM system you usually want up to a few mW per channel.

A MAJOR ADVANTAGE OF SOA

They can be integrated with other components on a single planar substrate to overcome some of the coupling losses.

RECEIVERS
DIRECT VERSUS COHERENT

DD $$I = \frac{\eta e}{hf} P_s$$

CD $$I = 2\,\frac{\eta e}{hf}\sqrt{P_s . P_l}\,cos\varphi$$

COHERENT RECEIVERS

OFC 2008 KOGELNIK

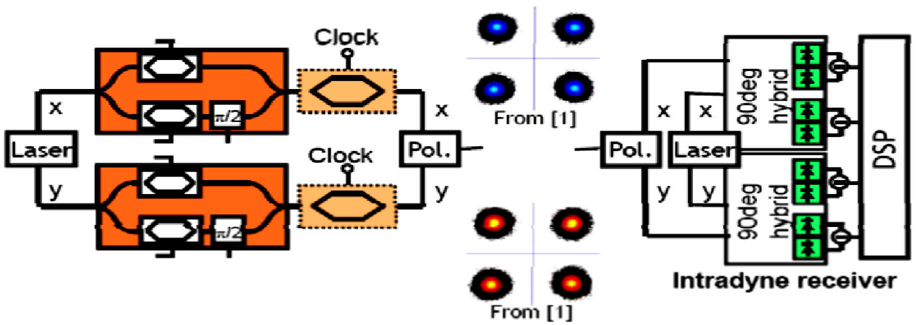
Coherent receivers in optical networking

Spectral efficiency:

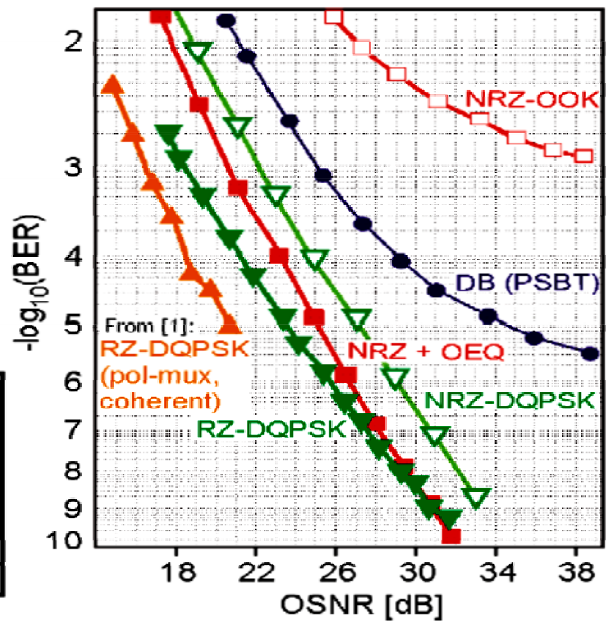
- **Richer symbol constellations, > 4-level**
- **Pol-mux**

Digital signal processing:

- **intradyning**
- ***Simple impairment mitigation***



C.R.S.Fludger et al., OFC, PDP22 (2007)



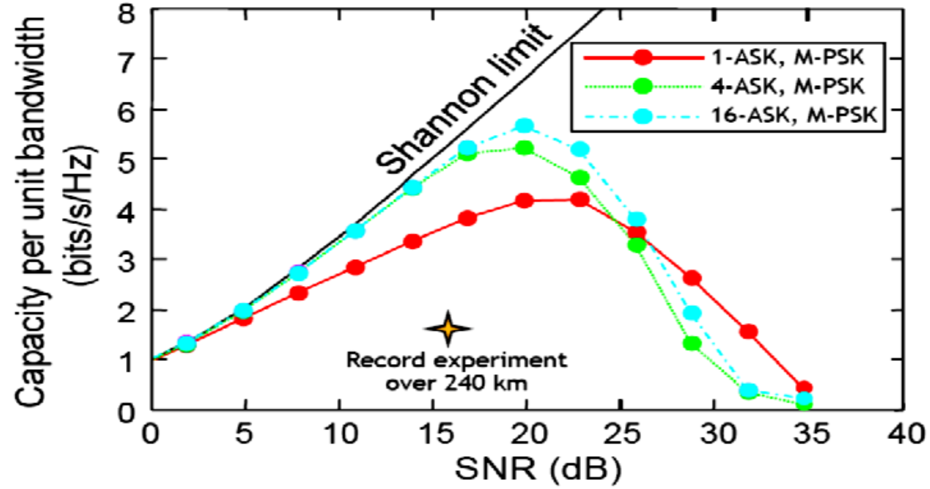
P.J.Winzer et al., LEOS Summer Topicals, 2007

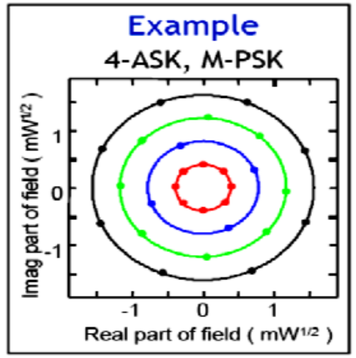
FIBER CAPACITY ESTIMATE

OFC 2008 KOGELNIK

Fiber Capacity Estimate

Capacity per unit bandwidth (spectral efficiency) for 2000-km transmission



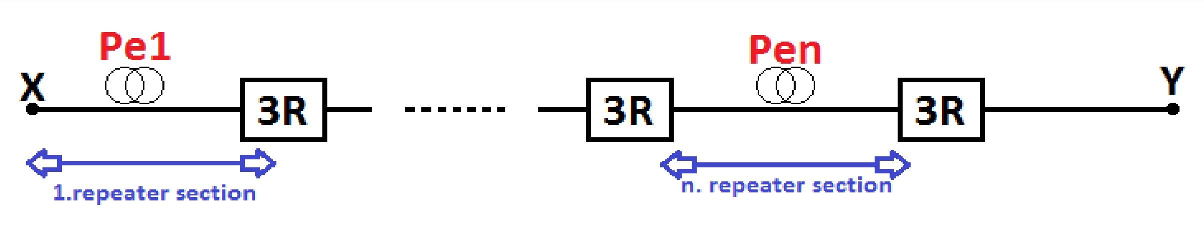


- Signal is distorted by nonlinear transmission → there is a maximum spectral density of information that can be transmitted over optical fibers
- For 2000 km a spectral efficiency of ~5.5 bits/s/Hz can be achieved
- This corresponds to an increase by a factor ~10 in distance and ~3 in spectral efficiency over record experiments

Courtesy: Rene Essiambre

ASK: Amplitude-shift keying, M-PSK: M-ary Phase-shift keying

BER in OCS by ON-OFF keying



$P_{e1} = P_{e2} = P_{e3} = \ldots = P_{en}$ $(P_e \approx 10^{-11}, 10^{-12})$

$1 - P_e$ - complementary to error probability in one repeater section

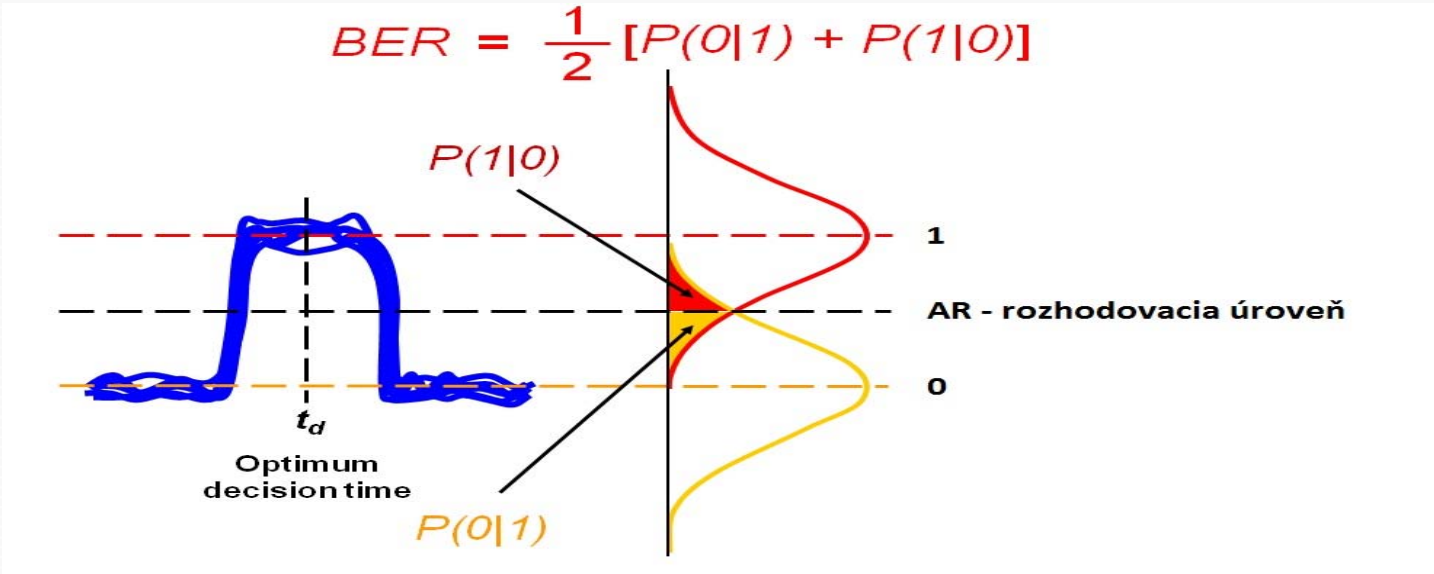
$(1 - P_e)^n$ - complementary to error probability in n-th repeater section

$P_{eT} = 1 - (1 - P_e)^n$ - total error probability in n repeater section in cascade

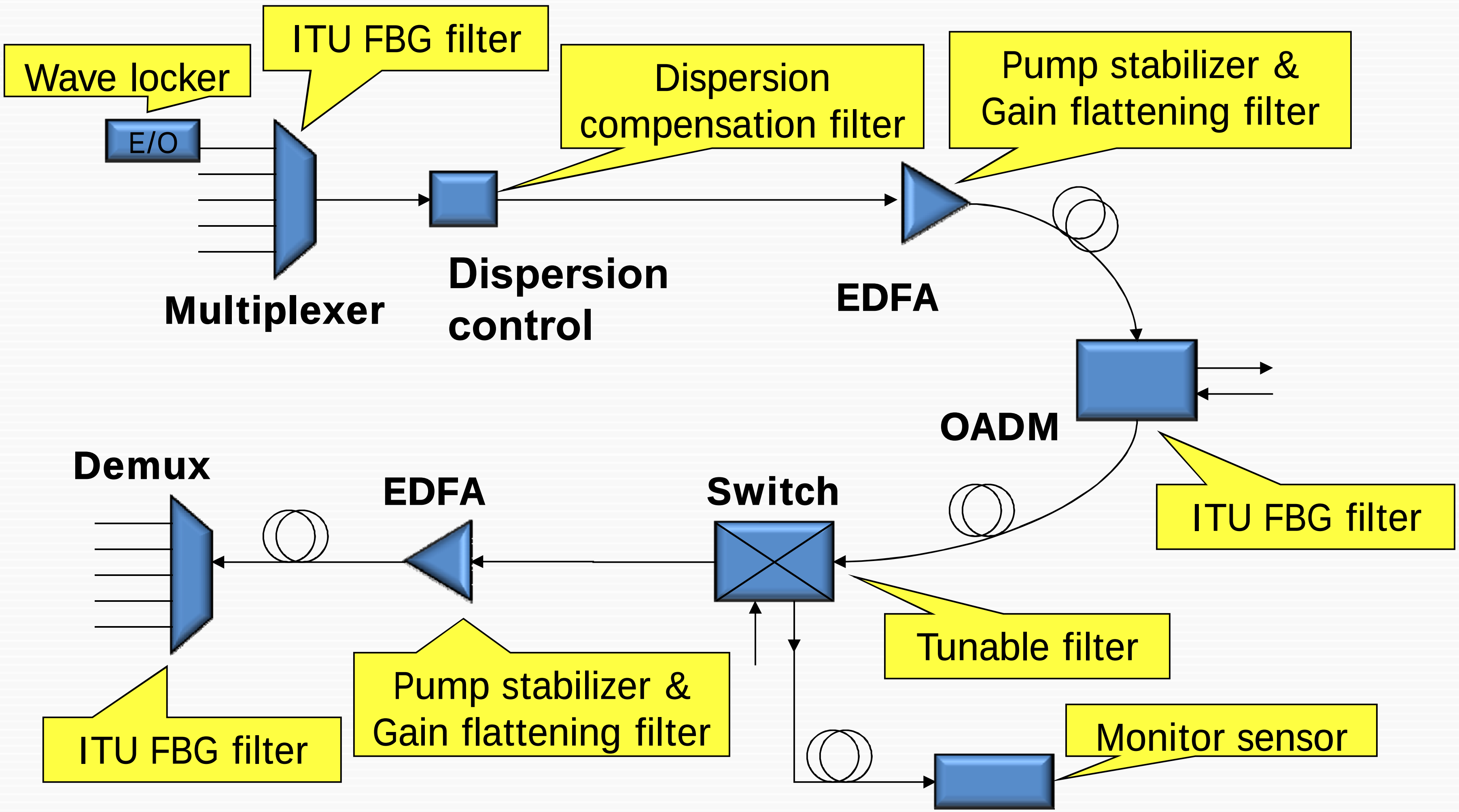
$$P_e = P(1).P(0/1) + P(0).P(1/0)$$

$$P(1) = P(0) = 0{,}5$$

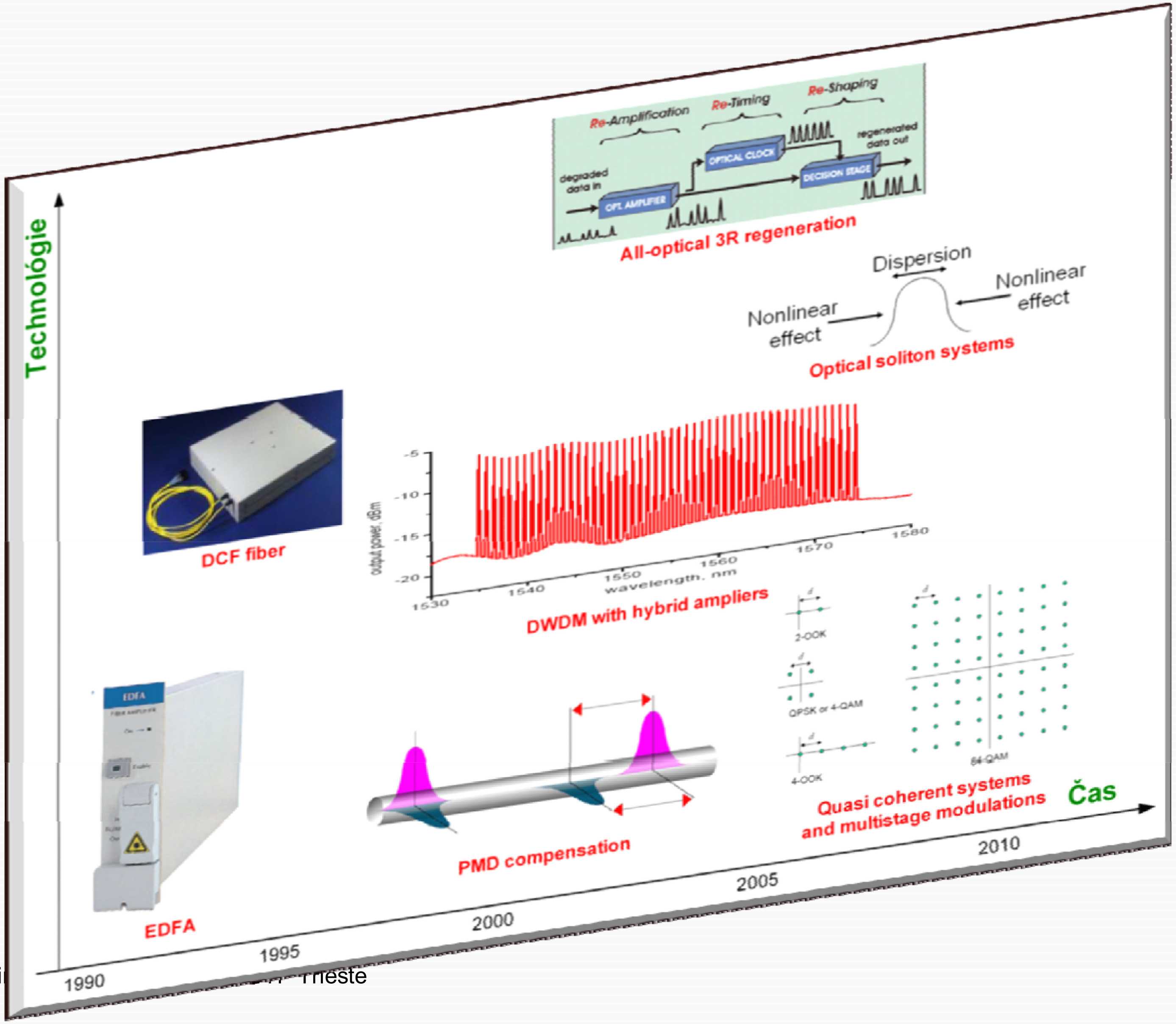
$$P(1/0) = P(0/1) \Rightarrow P_e = P(1/0) = \frac{1}{\sqrt{2\pi}\,.\sigma} \int_{A_R}^{\infty} e^{-\frac{n^2}{2.\sigma_n{}^2}}\, dn$$



SOME APLICATION IN OCS



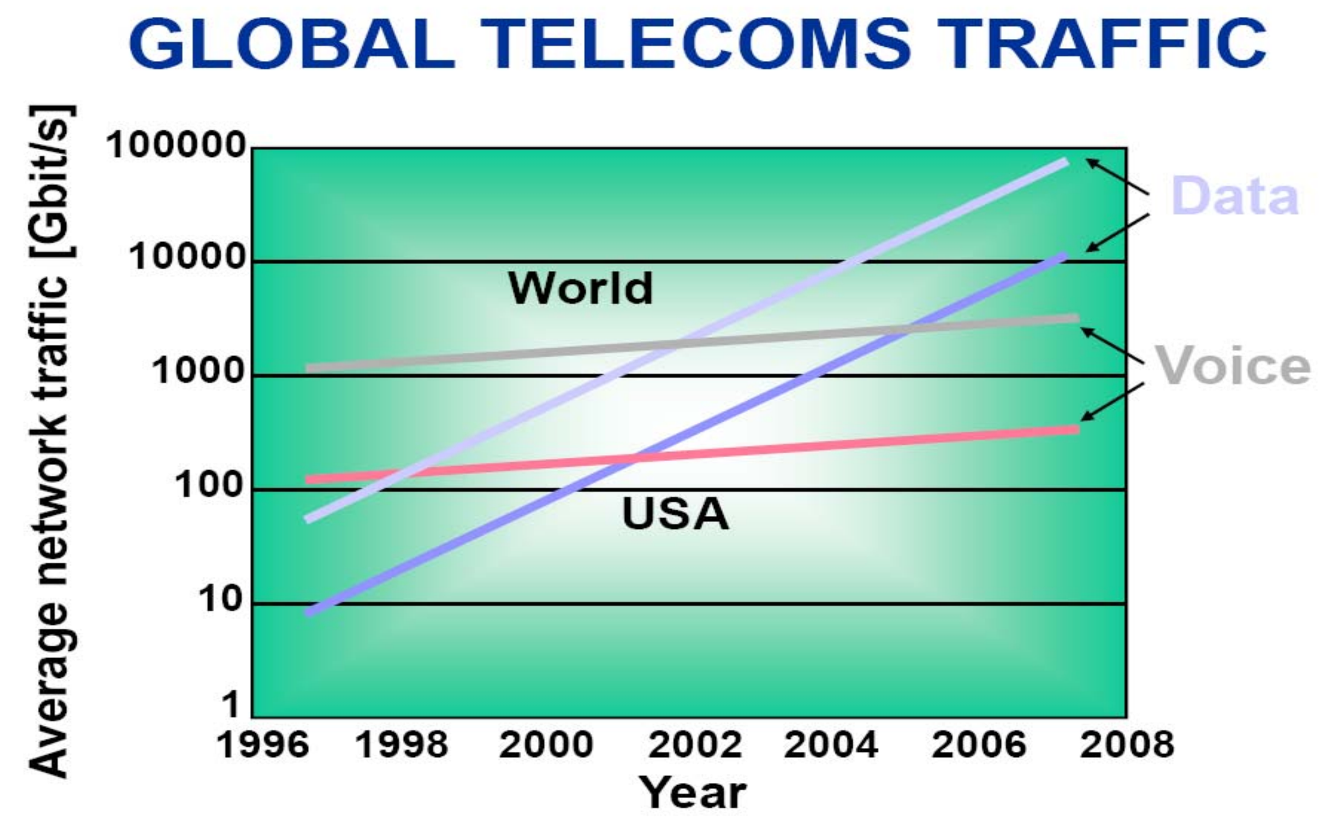
MAIN TECHNOLOGIES



OPTICAL COMMUNICATION SYSTEMS

GLOBAL TELECOMS TRAFFIC

OFC 2008 Kogelnik

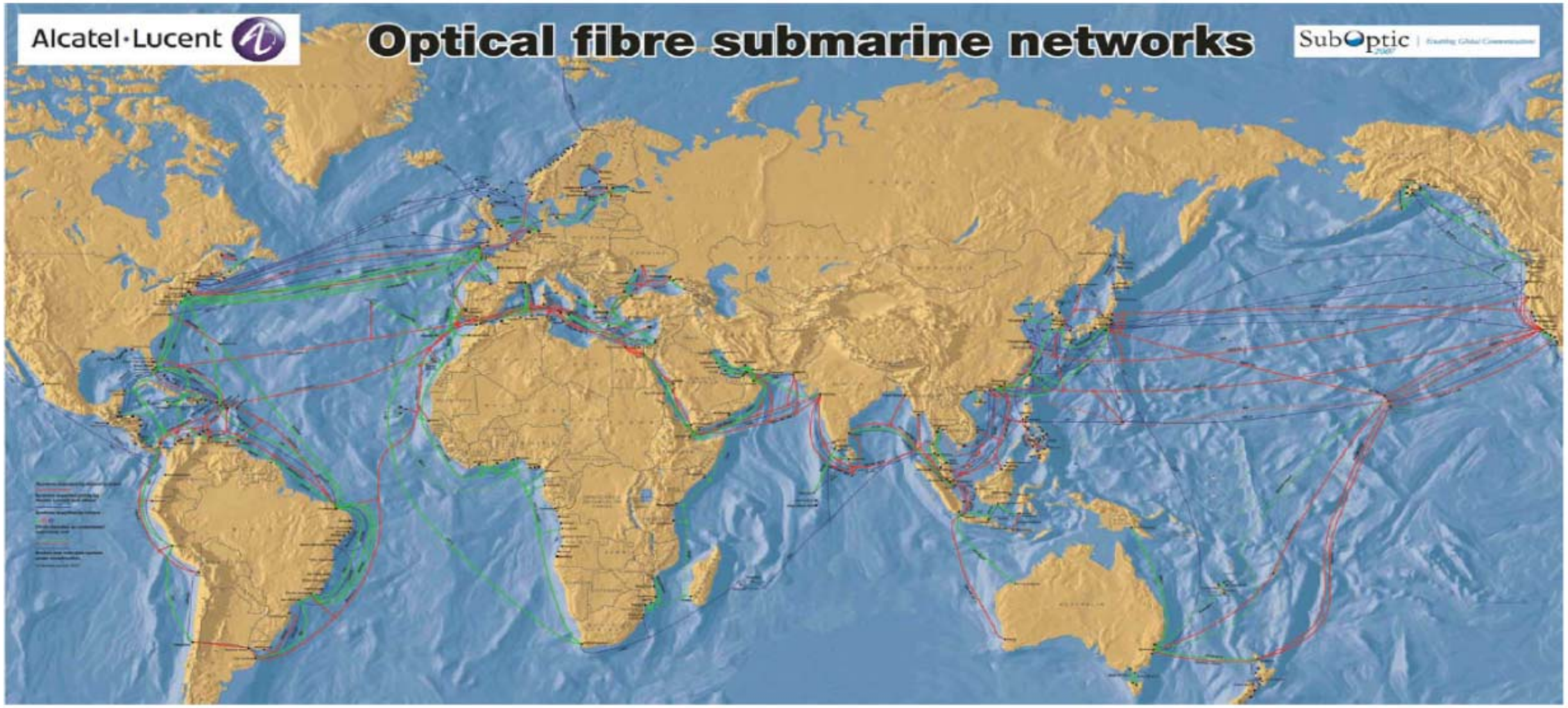


Sources:
A. M. Odlyzko, Internet Traffic Growth: Sources and Implications (2003).
S. Perrin et al., Worldwide Bandwidth End-Use Forecast and Analysis, IDC Market Analysis (2003).

UNDERSEA CABLE

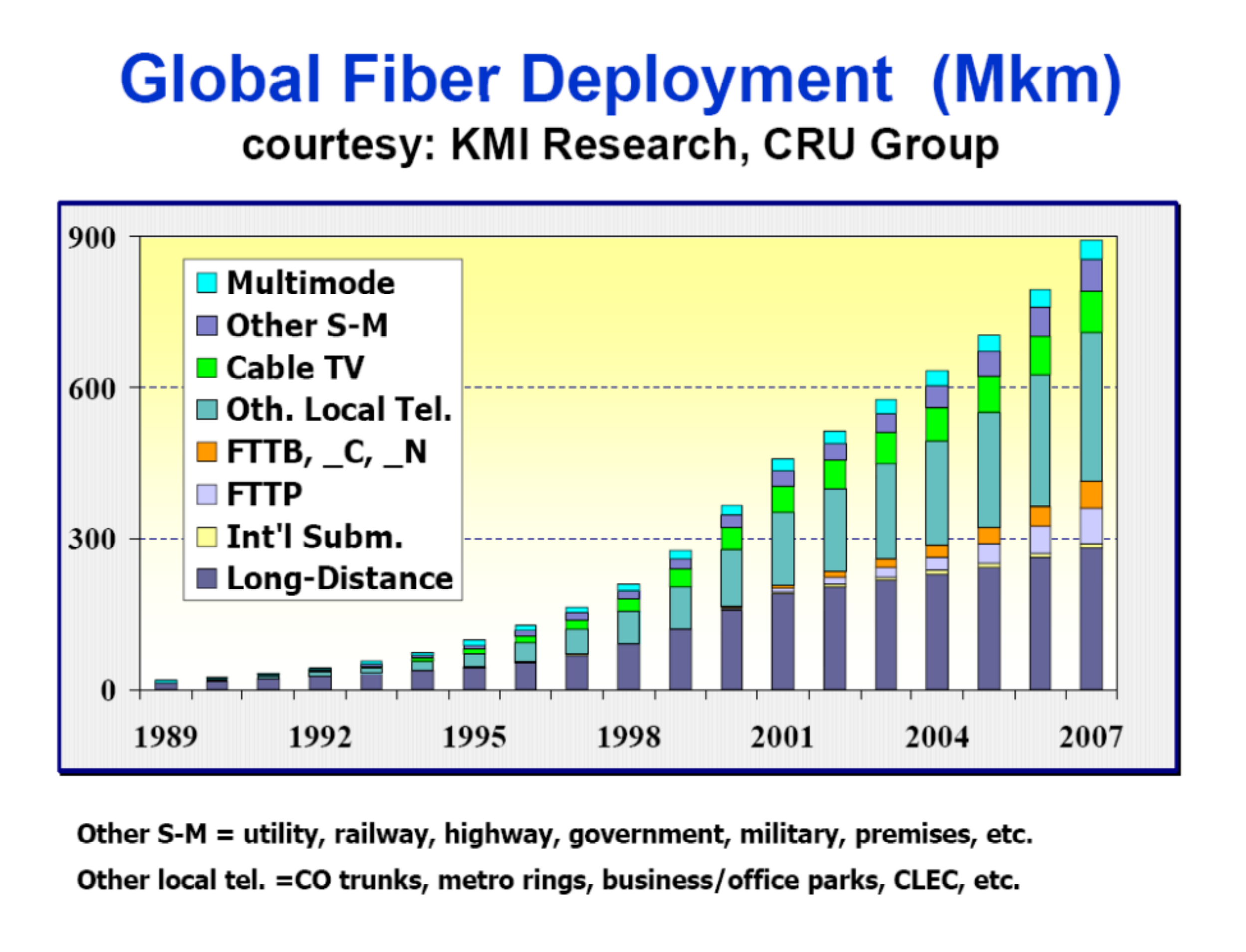
OFC 2008 Kogelnik

Today: > 500 000 km of undersea cable

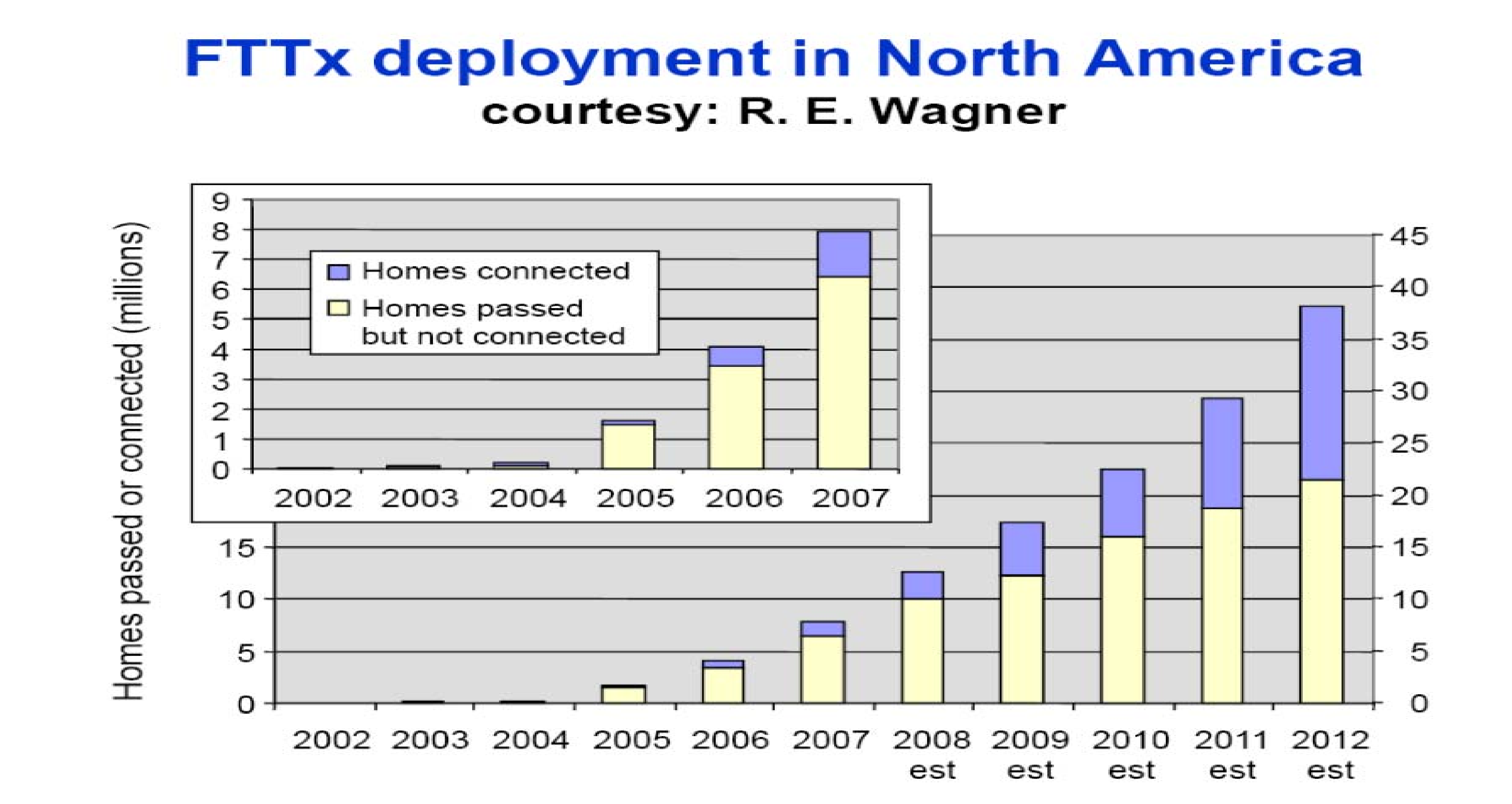


GLOBAL FIBER DEPLOYMENT

OFC 2008 Kogelnik



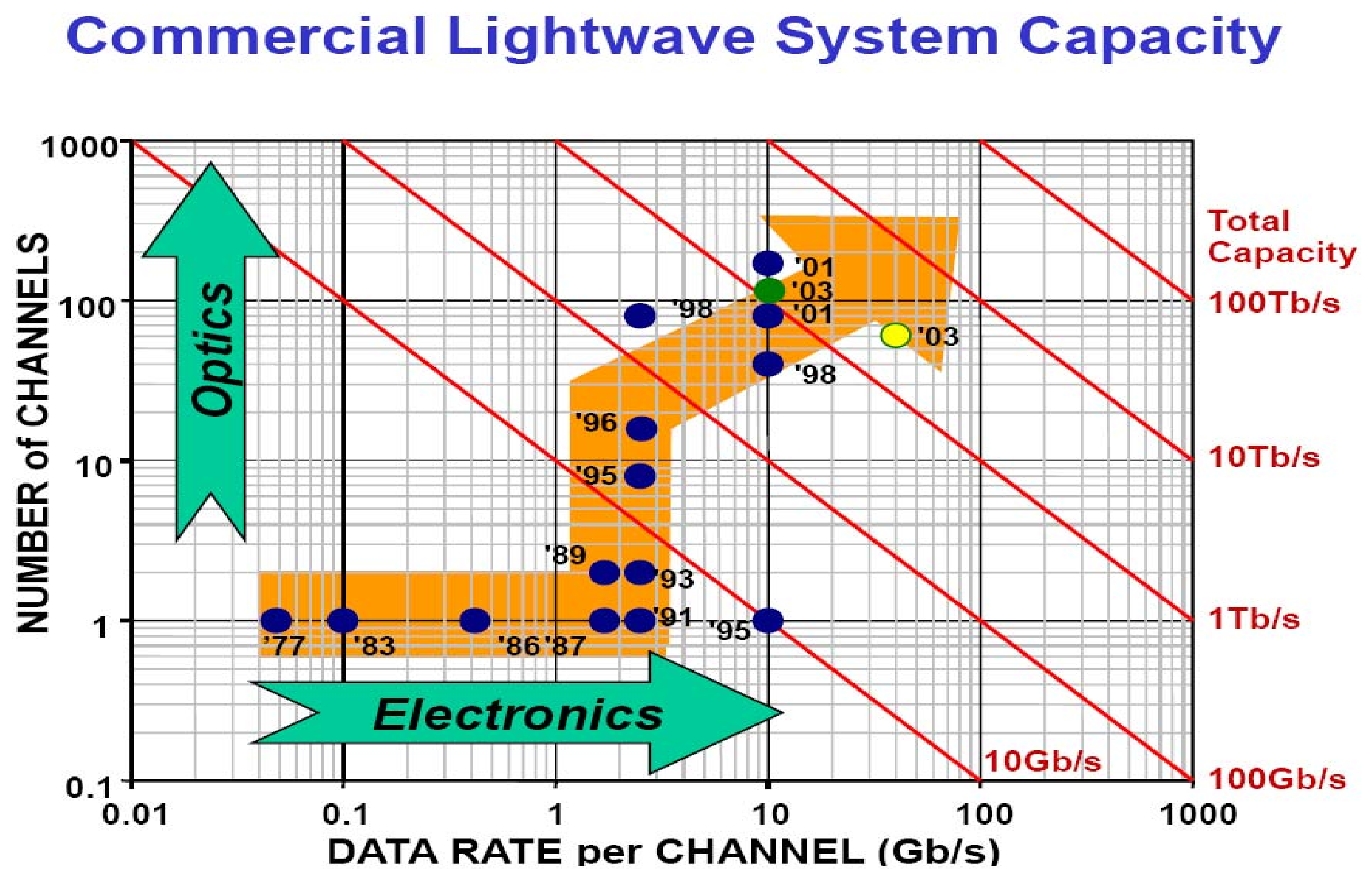
FTTx DEPLOYMENT IN NORTH AMERICA



Winter College On Optics, ICTP Trieste

COMMERCIAL LIGHTWAVE CAPACITY

OFC 2008 Kogelnik



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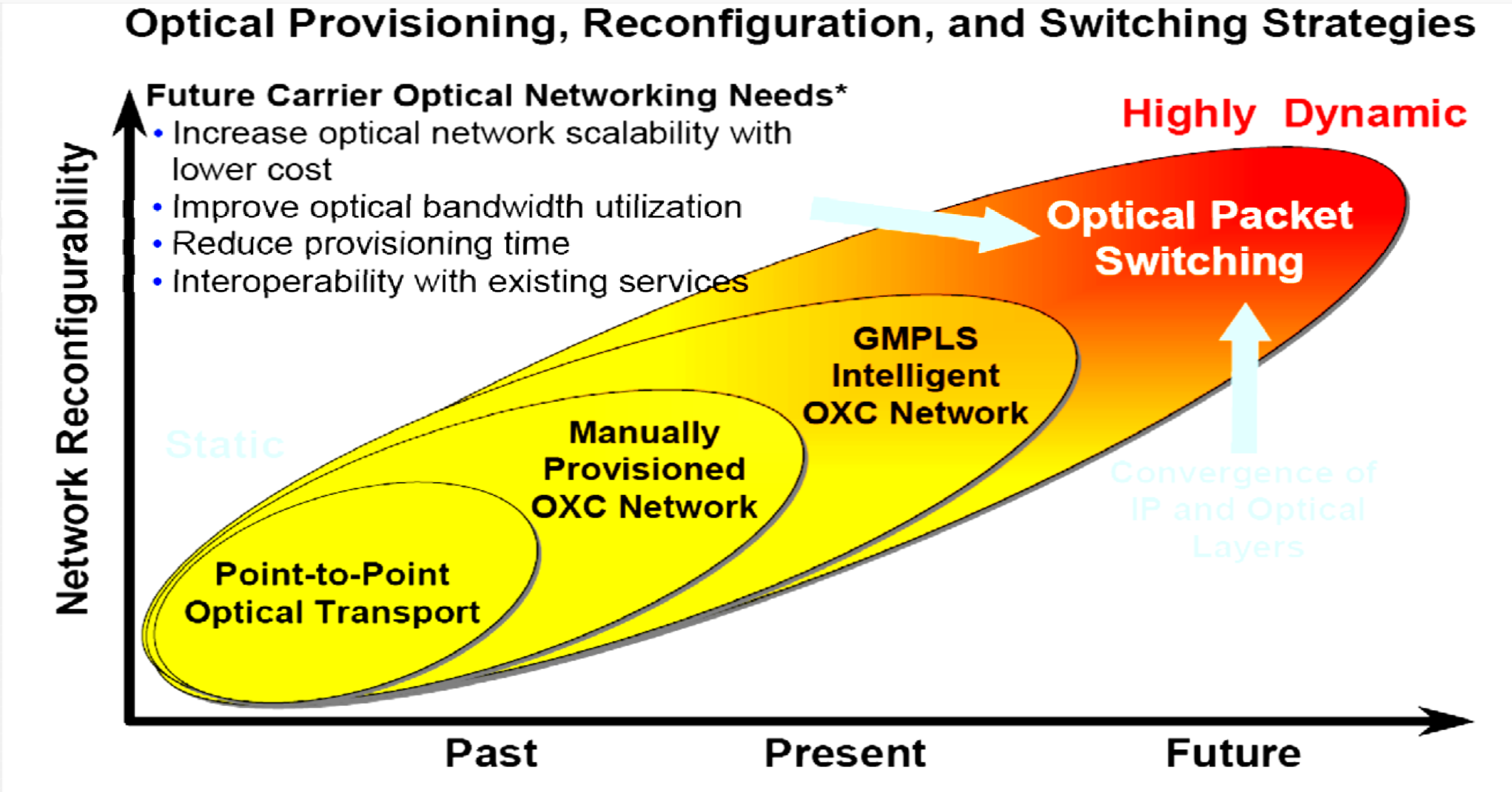
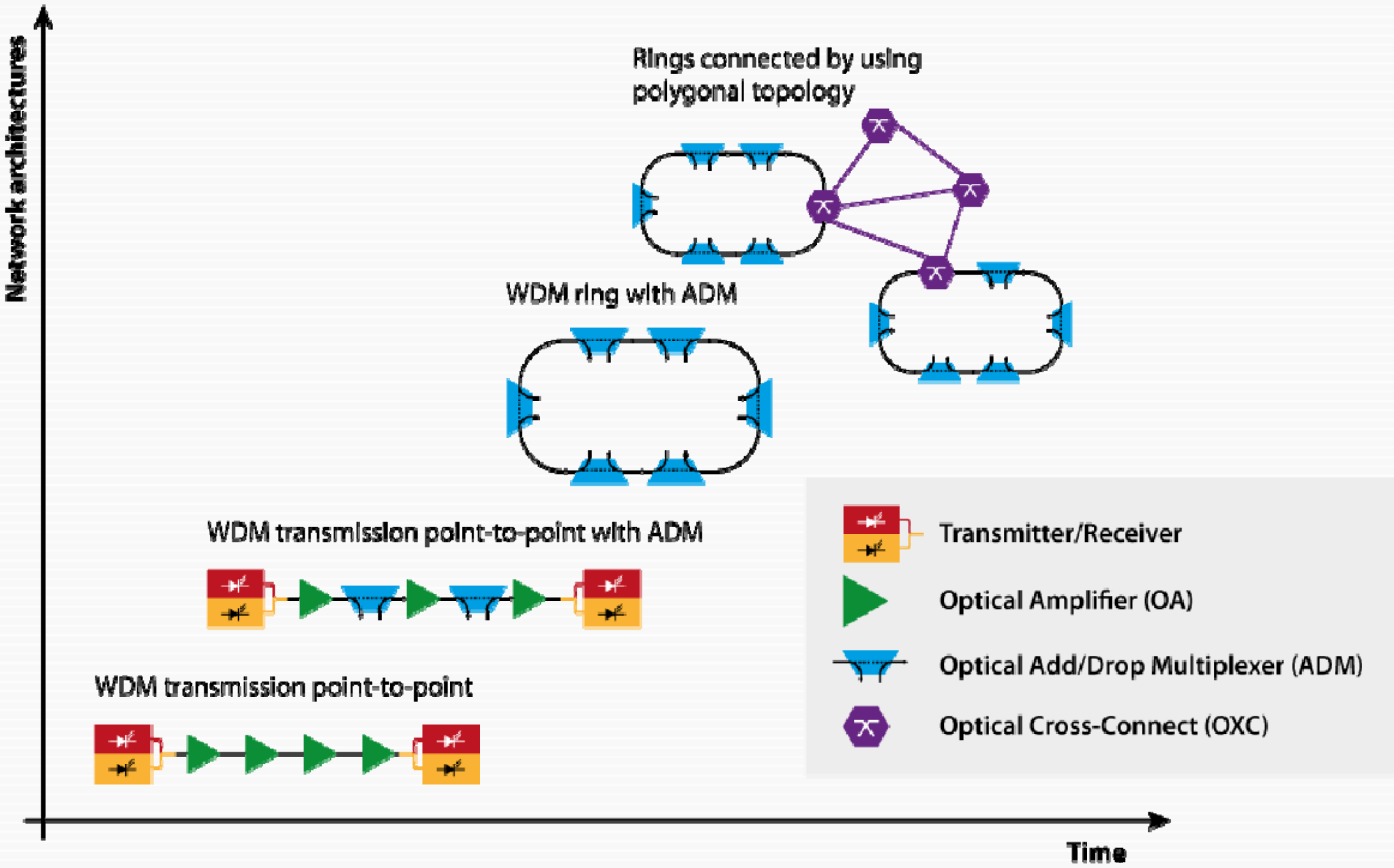
DEPLOYMENT OF OPTICAL NETWORKS

SOURCE: PROF. IBRAHIM HABBIB
WWW.CCNY.CUNY.EDU



OPTICAL NETWORKS STRUCTURE DEVELOPMENT

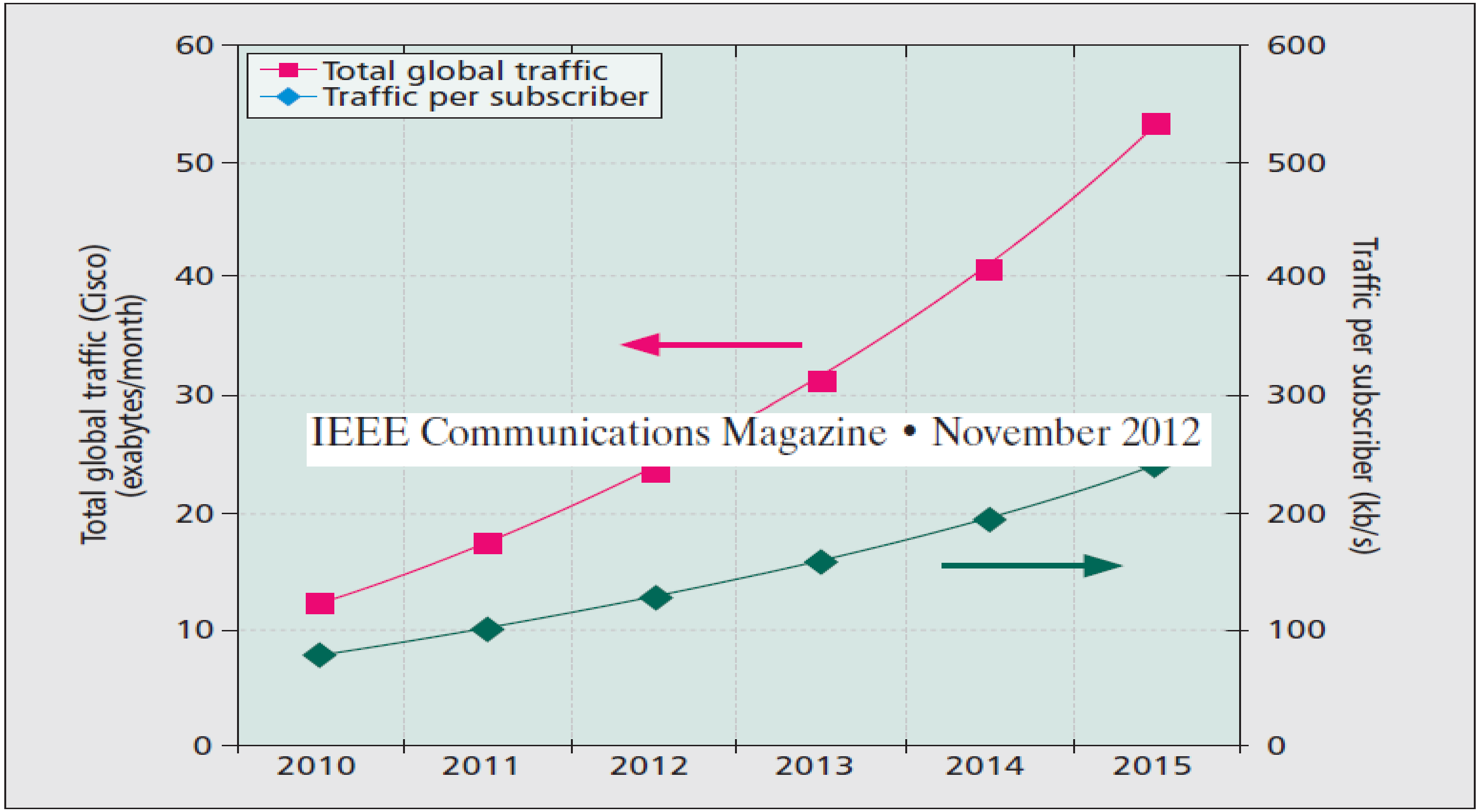


PRESENT AND FUTURE OCS „STATE OF THE ART“

- **present optical communication systems requirements:**
  - Transmission capacity requirements,
  - Bit rate requirements ,
  - Quality of transmission (service) requirements .

- **Future All optical networks with optical components only.**

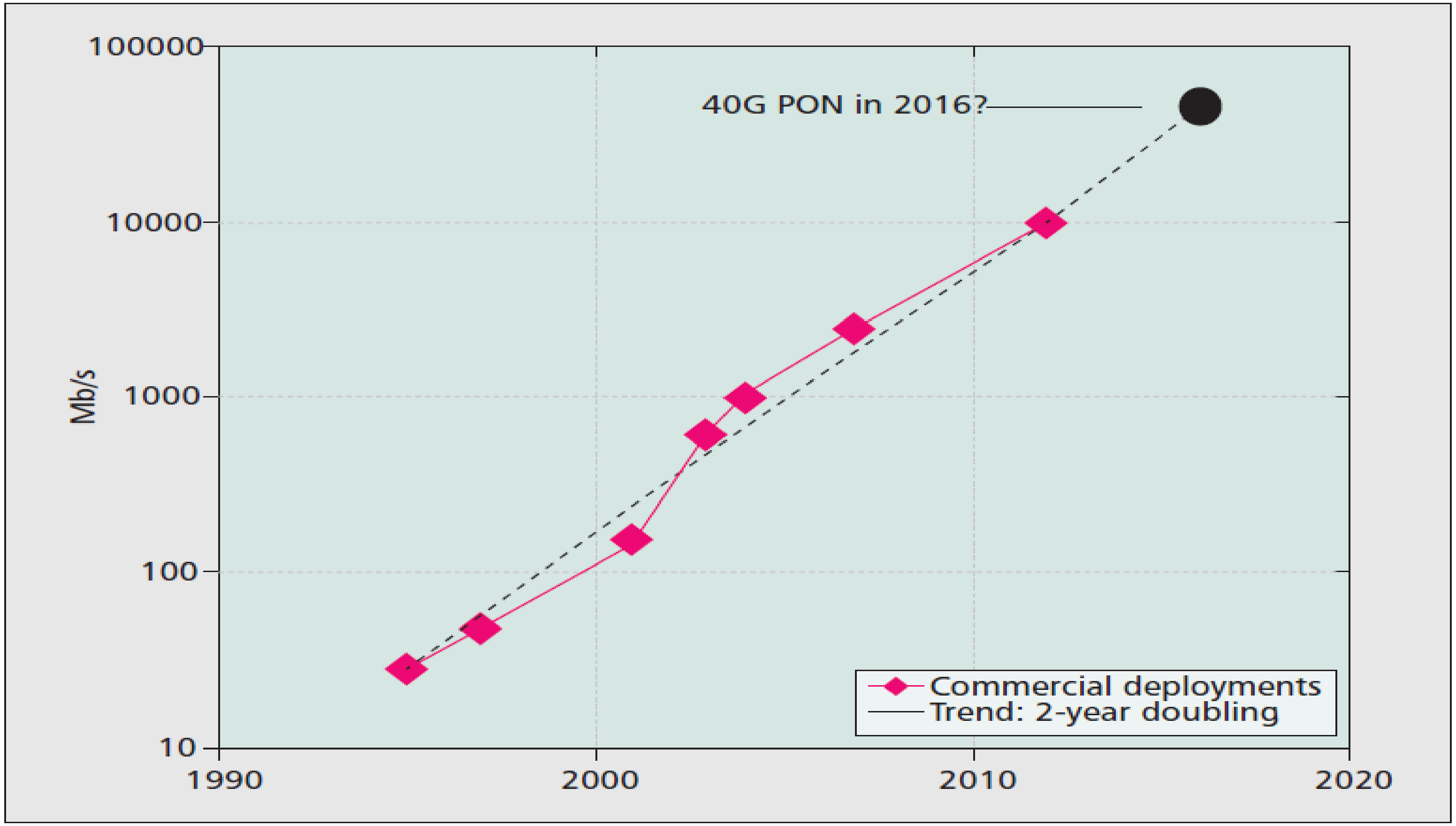
Consumer Internet traffic forecast



Future Fiber-To-The-Home bandwidth demands favor Time Division Multiplexing Passive Optical Networks

Ed Harstead and Randy Sharpe, Alcatel-Lucent

Evolution of TDM PON downstream bit rate.



Future Fiber-To-The-Home bandwidth demands favor Time Division Multiplexing Passive Optical Networks

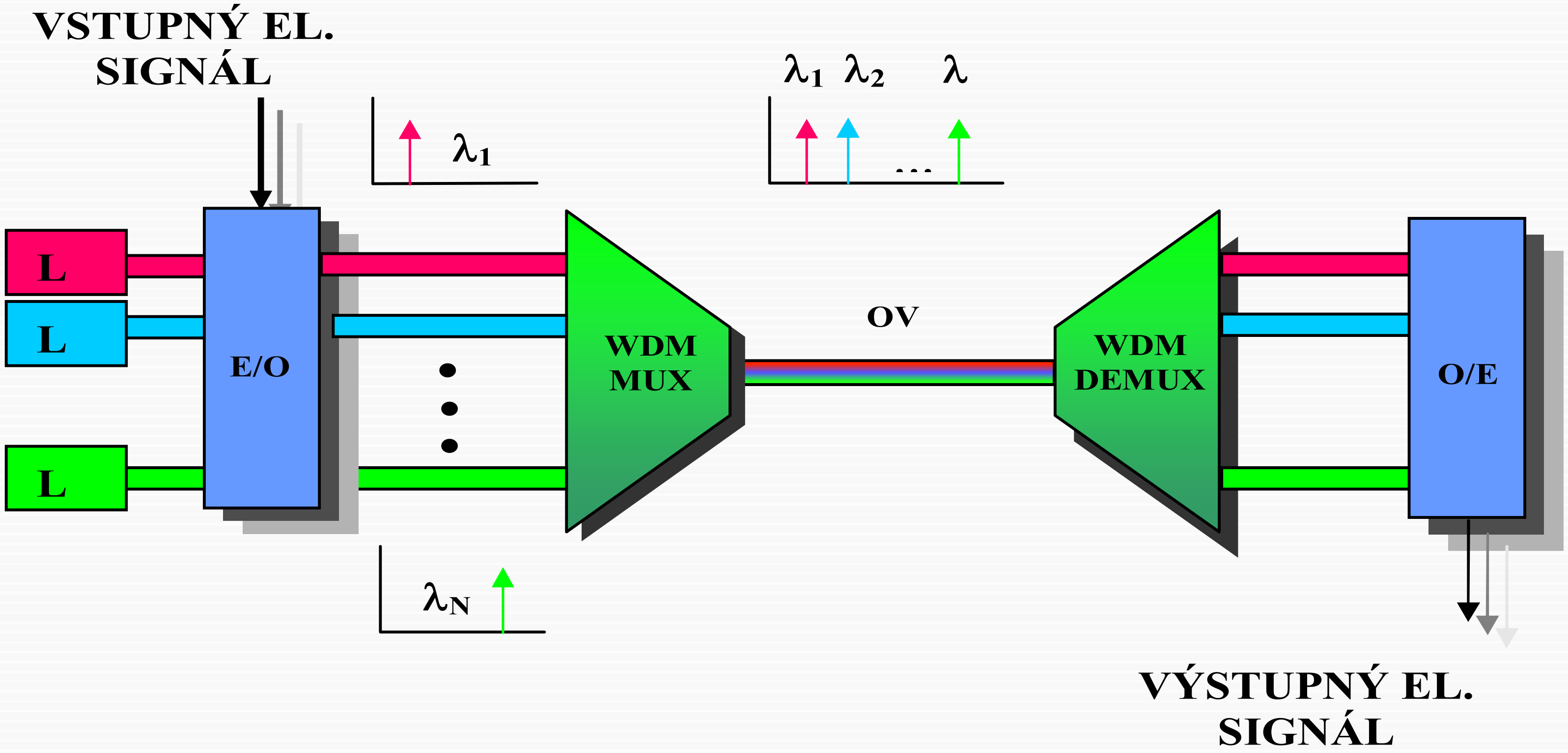
IEEE Communications Magazine • November 2012

Ed Harstead and Randy Sharpe, Alcatel-Lucent

MULTIPLEXING

- **Merging of more signals carrying information for common transmission via one transmission medium- optical fibre**
- **Types of multiplexing:**
  - **SDM** (Space Division Multiplexing),
  - **WDM** (Wavelength Division Multiplexing),
  - **TDM** (Time Division Multiplexing),
  - **OCDM** (Optical Code Division Multiplexing)

WAVELENGTH MULTIPLEXING WDM



Principal scheme of WDM system

MULTIPLEXORS AND DEMULTIPLEXORS

Basic parameters

- Channel attenuation
  (as few as possible)
- Attenuation of neighbouring channels
  (as full fart)
- Bandwidth per channel
  (shaping)
- Temperature independence

WDM WAVELENGTH DIVISION MULTIPLEXING

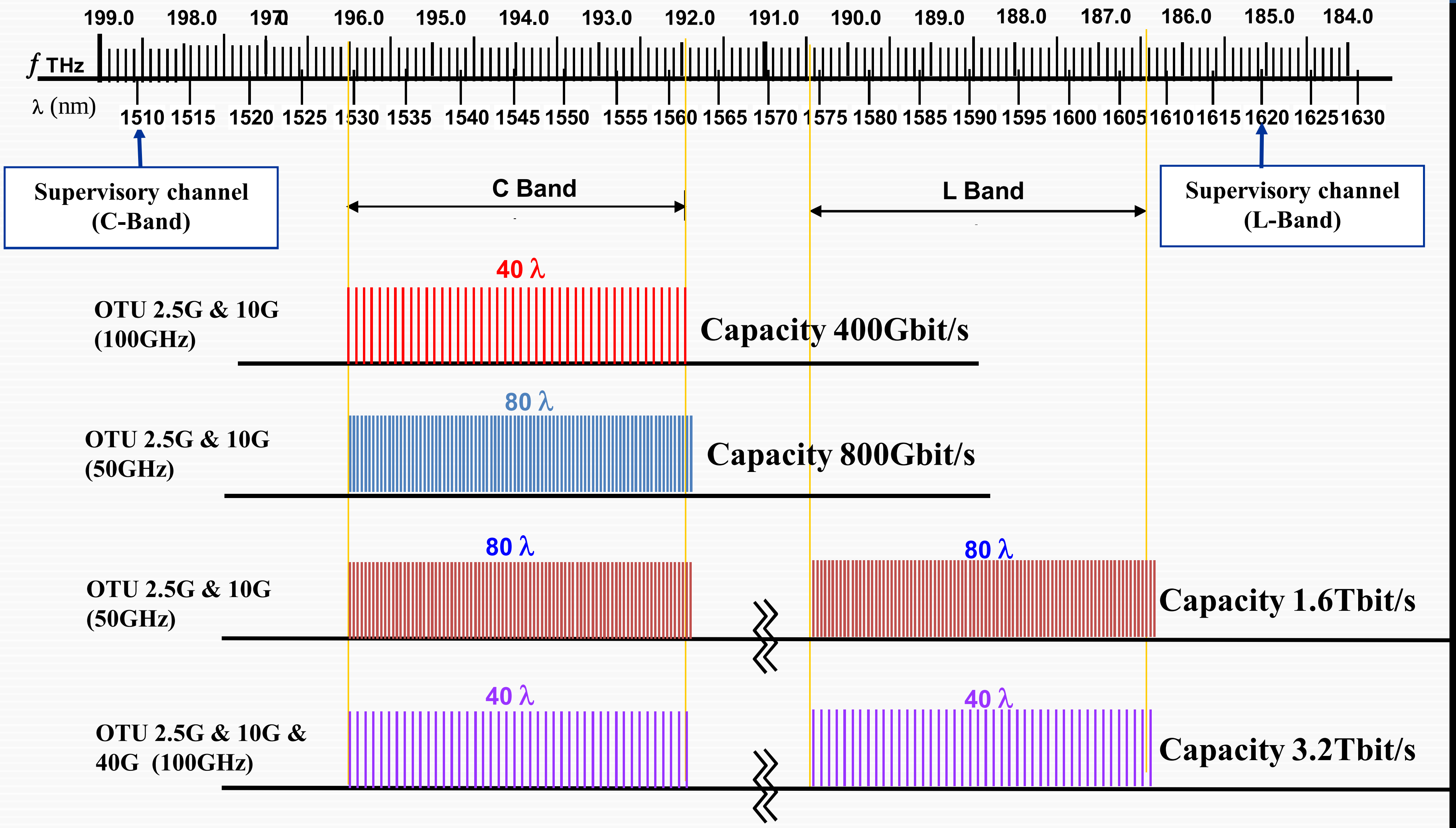
CWDM - Coarse Wavelength Division Multiplexing

DWDM- Dense Wavelength Division Multiplexing

CWDM - COARSE WAVELENGTH DIVISION MULTIPLEXING

- CWDM systems can realize cost-effective applications, through a combination of uncooled lasers, relaxed laser wavelength selection tolerances and wide passband filters
- CWDM systems can be used in transport networks in metropolitan areas for a variety of clients, services and protocols
- The CWDM grid wavelengths are recommended within the range 1271 nm to 1611 nm with channel spacing of 20 nm

WAVELENGTH SPEKTRUM IN PRESENT DWDM



COMPARISON OF VARIANTS FOR WDM TECHNOLOGIES

Application/ parameter	CWDM (metropolitan networks)	DWDM (metropolitan networks)	DWDM (long-haul networks)
Channels per fibre	4 - 16	32 – 80	80 - 160
Spectrum	Wavelength bandwidths S,C,L	Wavelength bandwidths C,L	Wavelength bandwidths C,L,S
Channel Spacing	20 nm (2500 GHz)	0,8 nm (100 GHz)	0,2 nm (25 GHz)
Capacity per Wavelength	2,5 Gbit/s	10-40 Gbit/s	10 - 40 Gbit/s
Fibre capacity	20 – 40 Gbit/s	100 – 1000 Gbit/s	Tbits/s
Reach	Up to 50 – 80 km	Hundreds km	Thousands km
Optical Amplifier	No	Yes	Yes

ADVANTAGES AND LIMITING FACTORS IN WDM

Advantages

- Better utilised capacity of optical fibres,
- Channels are independent,
- Flexibility by capacity widening,
- Multiplexing and demultiplexing is usually not complicate and technologically not difficult. In comparison with electrical MUX and DEMUX it is more compact

Limiting factors

- Fibre nonlinearities can arise and have detrimental influence of SNR,
- FWM limits channel spacing,
- XPM limits and number of channels,
- Crosstalk among optical channels.

INCREASING OF THE CAPACITY OF WDM SYSTEMS

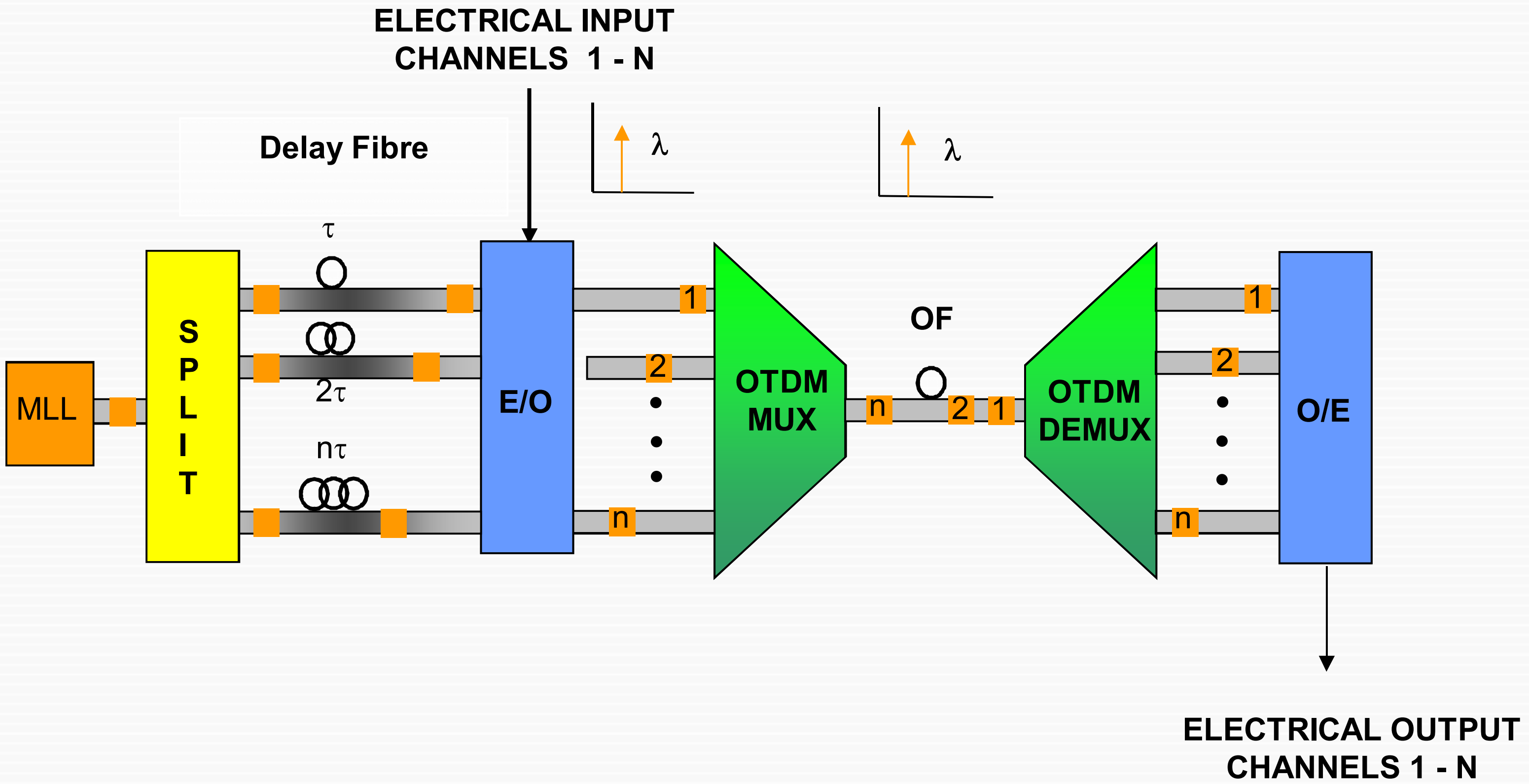
Optical bandwidth – utilisation of whole bandwidth of optical fibres with small attenuation (approximately 400 THz)

Bitrates per channel– increasing of modulation bitrate of lasers (40 Gbps)

Decreasing of the channel spacing - min. 25 GHz

Multistage modulation (M-PSK, QAM)

OPTICAL TIME DIVISION MULTIPLEXING - OTDM



Principle scheme of OTDM system

REQUIREMENTS FOR OTDM PARTS

Lasers for generation of very short pulses

Solutions for all optical switching and routing of packets or bursts

- Wavelength convertors
- Demultiplexors for OTDM stream

Logic (gate) arrays with fast keying

High requirements on time synchronisation

ADVANTAGES AND LIMITING FACTORS IN OTDM

Advantages

- Only one channel approach, therefore single node and end equipment,
- All wavelength possible to use,
- More easy management and control

Limiting factors

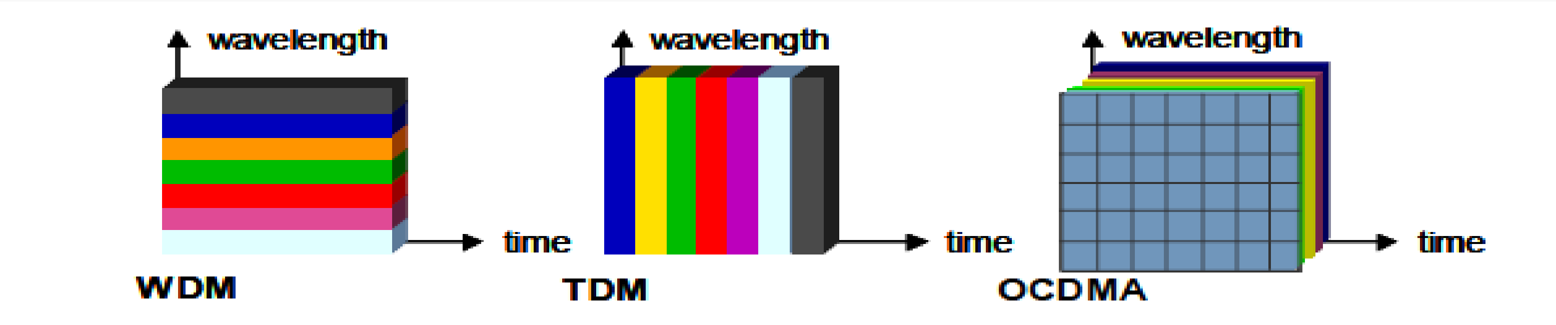
- Fibre dispersion,
- ISI in demultiplexors

MULTIPLEXING SCHEMES

PROF. IVAN GLESK PRESENTATION ZILINA, APRIL 2013

Transmission of multiple channels over fiber extends the system capacity

- Can multiplex channels in wavelength (WDM) and in time domain (TDM)
- Optical Code Division Multiple Access (OCDMA) assigns each user a code that can be in time, wavelength or time/wavelength domain



Advantages

– Random access to bandwidth

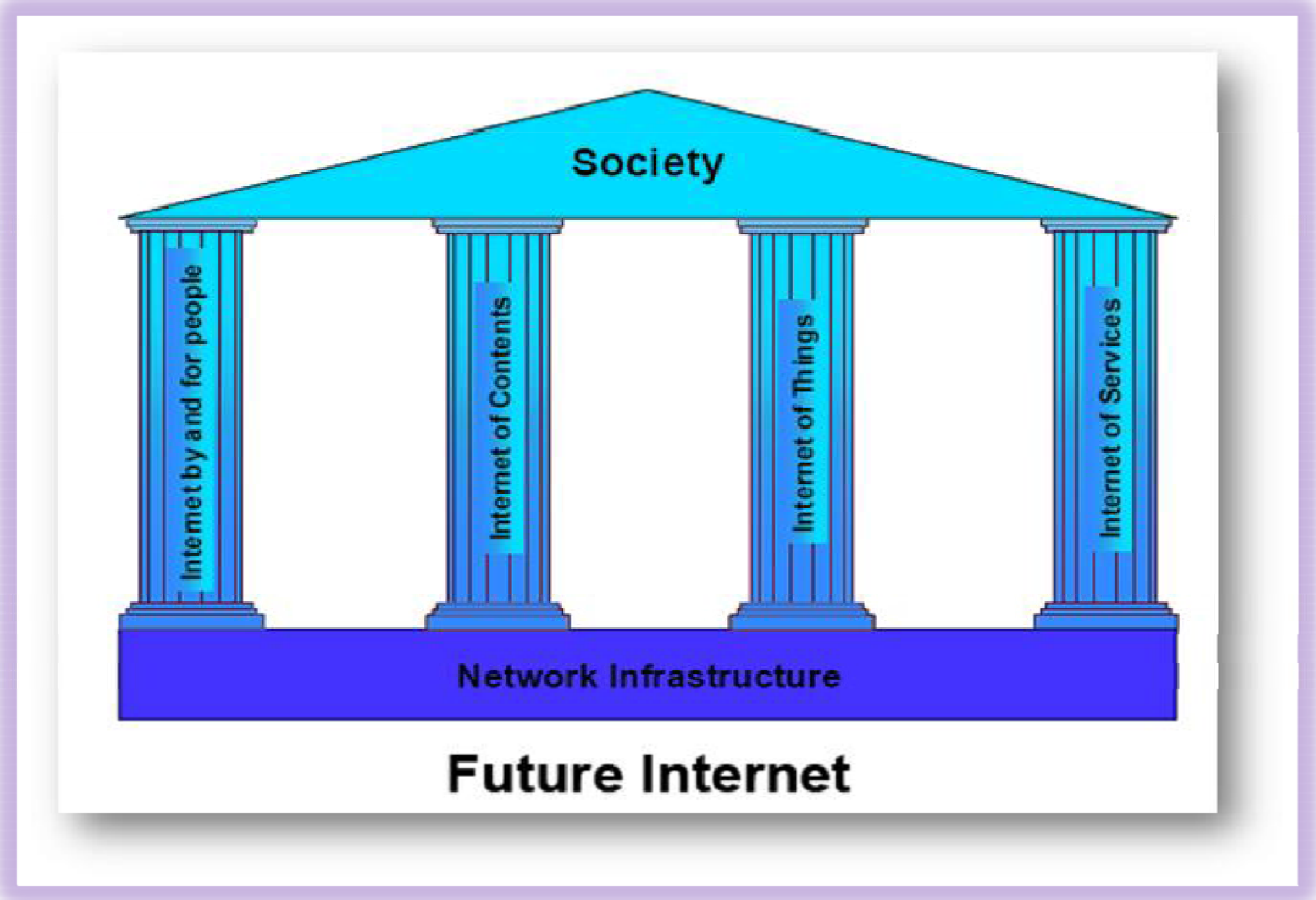
– Multi-rate, differentiated services

– Soft limit on number of users: increased flexibility

– Simplified network control

FUTURE INTERNET

CELTIC-PLUS PURPLE BOOK 2012



PHOTONICS FOR OPTICAL COMMUNICATIONS- MAIN REQUIREMENTS

Make networks faster
Make networks more transparent
Make networks more dynamic
Make networks greener

PHOTONICS FOR OPTICAL COMMUNICATIONS …MAKE NETWORKS FASTER…

CELTIC-PLUS PURPLE BOOK 2012

Since the beginning of the years 2000, the internet traffic is observed to grow at a rate of 60% per year, or equivalently at a factor of 10 over a 5 years period (ref: Minnesota Internet Traffic Studies).

Up to now, the traffic increase is supported by optical networks providing the requested capacity thanks to the wavelength division multiplexing and transport of several high speed optical channels through a single fibre.

The very key point is to still better exploit the available bandwidth of optical fibres; this is obtained by packing channels closer to each other while simultaneously increasing their individual bit rate.

At a research level, WDM capacity transmission records beyond 10 Terabit/s have been reported, and the total capacity growth is still observed, even at a more modest pace since the recent years.

The capacity performance is characterized through the so-called information spectral efficiency, expressed in bit/s/Hz

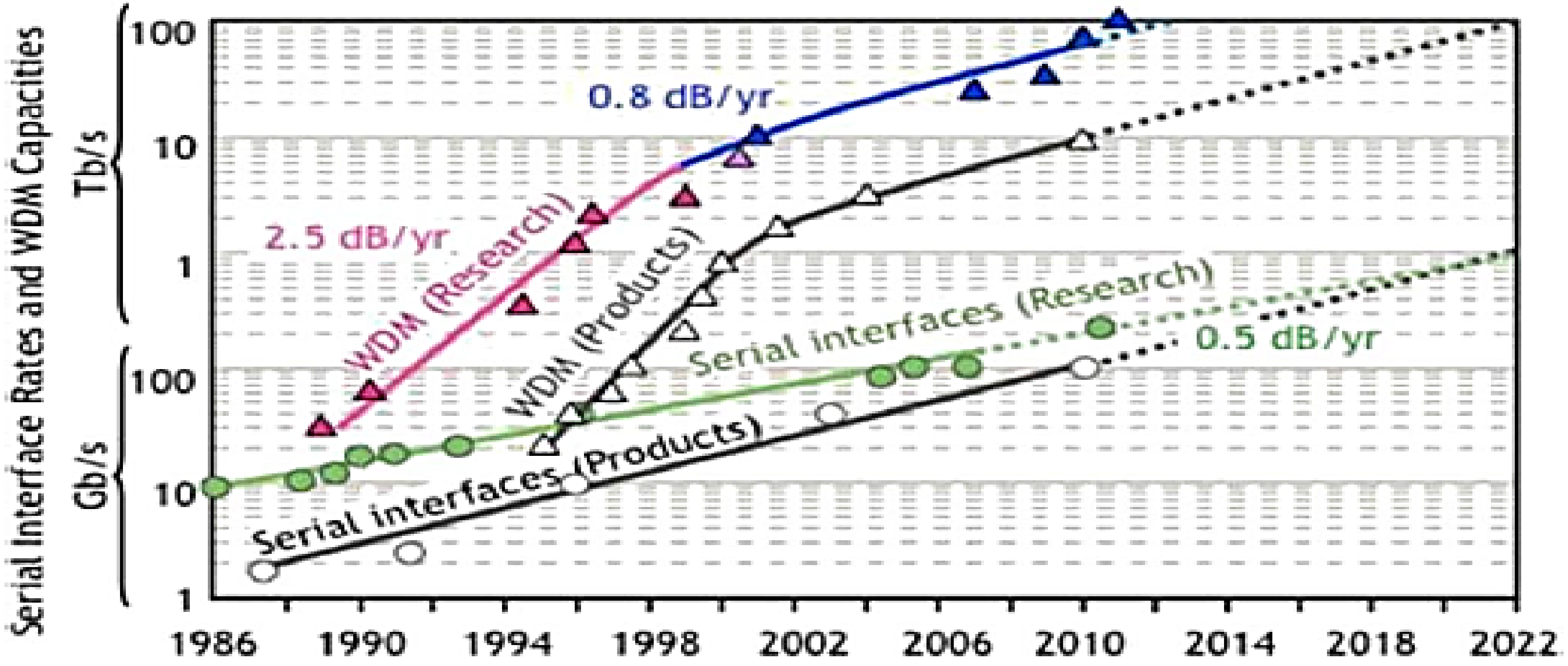


Fig. 10. ***Historic serial bit rate and wavelength-division-multiplexed system capacity scaling in research and products [203].***

Willner *et al.*: Optics and Photonics: Key Enabling Technologies
Proceedings of the IEEE | Vol. 100, May 13th, 2012

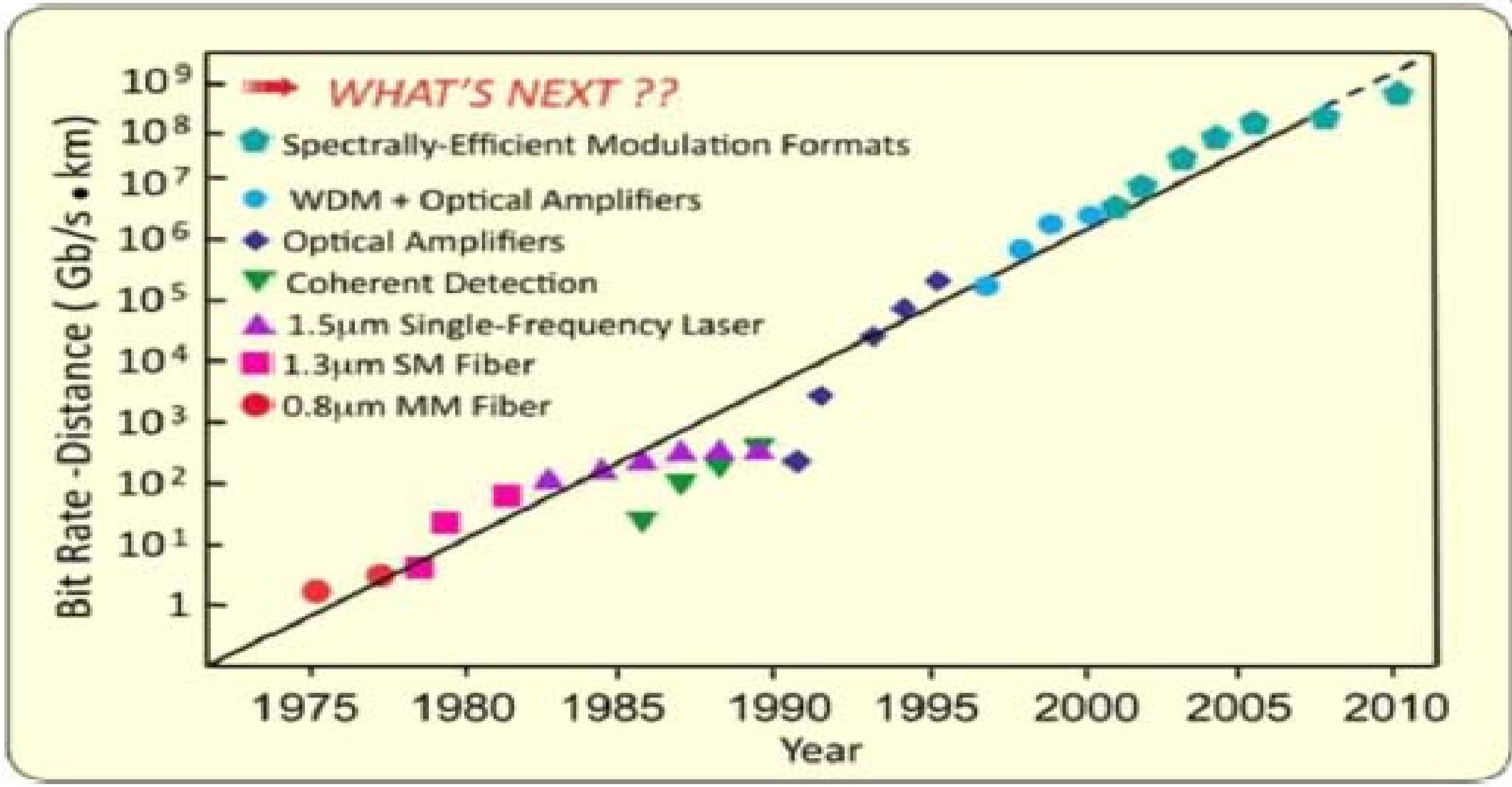
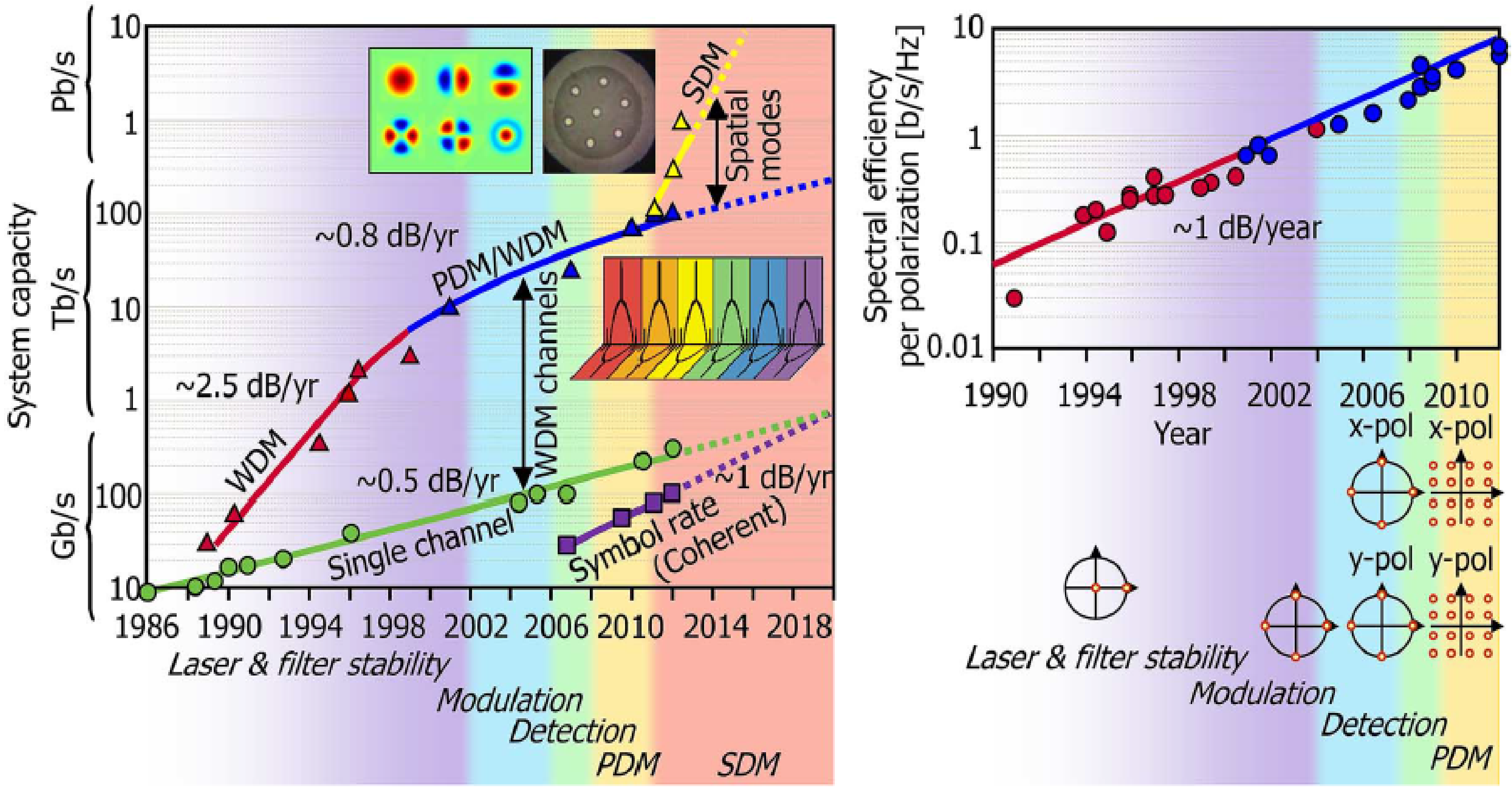


Fig. 14. ***Bit-rate distance product for transmission over a single optical fiber, highlighting the different key technologies that enabled the advances.***

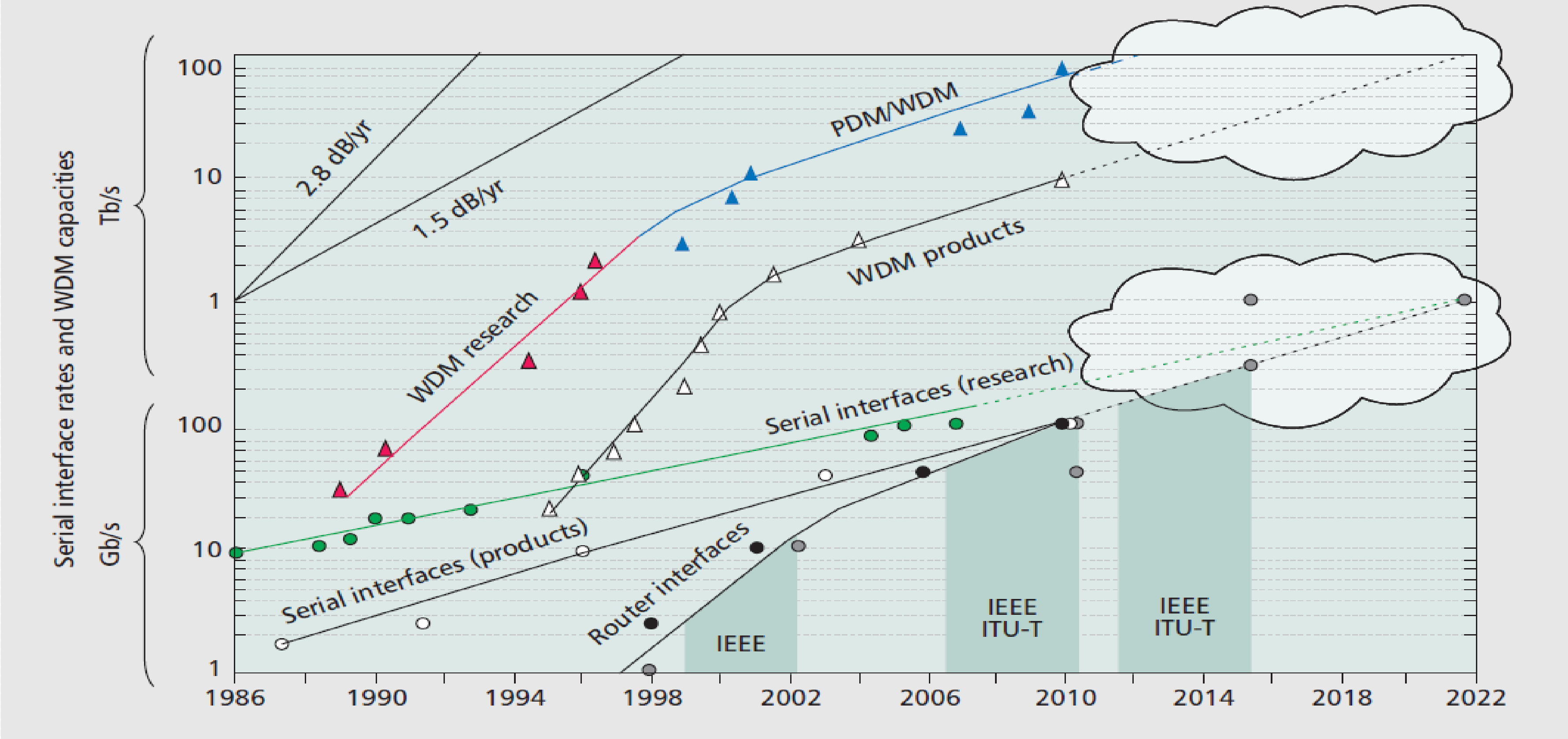
Willner *et al*.: Optics and Photonics: Key Enabling Technologies
Proceedings of the IEEE | Vol. 100, May 13th, 2012

Fig. 1. (a) Evolution of experimentally achieved *single-channel bit rates* (single-carrier, single-polarization, electronically multiplexed; green circles), *symbol rates* in digital coherent detection (purple squares), and *aggregate per-fiber capacities* (triangles) using wavelength-division multiplexing (WDM; red), polarization-division multiplexing (PDM; blue), and space-division multiplexing (SDM; yellow). (b) Evolution of experimentally achieved *per-polarization* spectral efficiencies in single- (red) and dual-polarization (blue) experiments..



JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 30, NO. 24, DECEMBER 15, 2012, High-Spectral-Efficiency Optical Modulation Formats Peter J. Winzer

Historic serial bit rate and WDM system capacity scaling in research and products



PETER J. WINZER, BEYOND 100G ETHERNET, BELL LABS, ALCATEL-LUCENT
IEEE Communications Magazine • July 2010

PHOTONICS FOR OPTICAL COMMUNICATIONS ...MAKE NETWORKS MORE TRANSPARENT...

CELTIC-PLUS PURPLE BOOK 2012

Many optical-electrical conversions are performed in today's optical networks

Increasing optical transparency is obtained by removing these conversions as much as possible

In the ideal scenario, an optical data stream enters the network though the input node, possibly travel across several intermediate nodes, and reaches its destination node without conversion to electronics along the route

Overall, optical transparency is a useful feature for decreasing cost (cost/bit) and energy consumption (J/bit)

PHOTONICS FOR OPTICAL COMMUNICATIONS ...MAKE NETWORKS MORE DYNAMIC...

CELTIC-PLUS PURPLE BOOK 2012

The dynamicity of the optical network is related to the possibility for the network to automatically and dynamically control and manage connections:

- for protection or restoration purposes in case of equipment failure
- for traffic engineering purposes, or
- at the customer's demand.

The introduction of optical cross-connects is one of the first requirements for transport network dynamicity. But dynamicity also requires a control software (or plane) of the network. In each node, it should drive the configuration of the optical cross-connects (which wavelength from an input fibre goes to which output fibre) but also force electronic regeneration of a given wavelength, that cannot be sent transparently all the way to its destination.

PHOTONICS FOR OPTICAL COMMUNICATIONS ...MAKE NETWORKS GREENER...

CELTIC-PLUS PURPLE BOOK 2012

First, the routing function at the (electronic) layer-3 level is known as an energy consuming network function of the infrastructure

It is estimated that 80% of traffic entering a node is a pass-through traffic, with a destination located in another node.

It is then particularly efficient to keep that part of the traffic in the optics domain, without electronic conversion or packet processing.

This novel, not yet developed approach, requests a close relationship between the network layers (0, 1, 2 and 3) and intelligent cooperating management, control and data planes.

Second, optical technologies could be envisaged to perform limited and optimized series of network operations, at a packet level, or more reasonably at a burst level. These operations could be realised at the layer 1 or 2 levels, without the ambition to replace the router technology, but more pragmatically to process large entities that would be more and more abundant in the frame of video services

OPTICAL NETWORK ARCHITECTURES

Switching structures:

- Links
- Packets
- Burst

LINKS SWITCHING

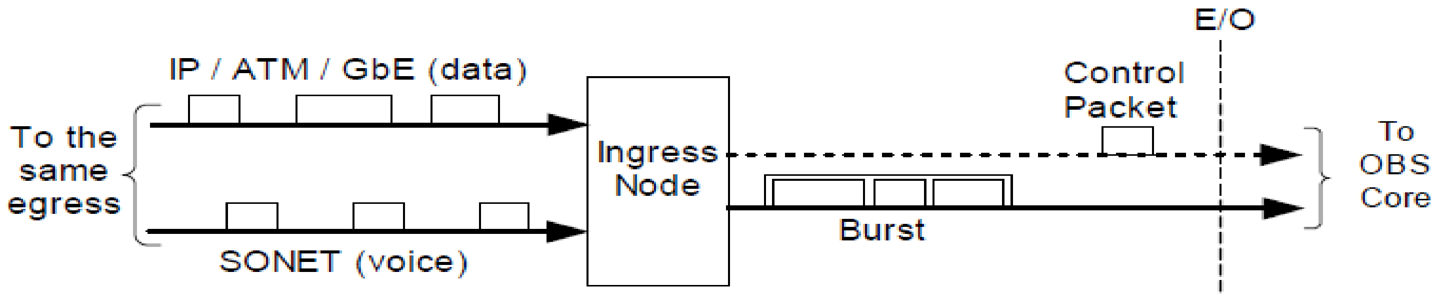
- **Optical wavelength routing**
- **Optical channel is :**
  - Created during establishing of connection,
  - Hold during transmission of information,
  - Terminated after completion of information transmission.
- **Nodes are connected by the optical lines during transmission is not needed opto-electrical conversion**

NEXT THREE SLIDES ARE FROM:

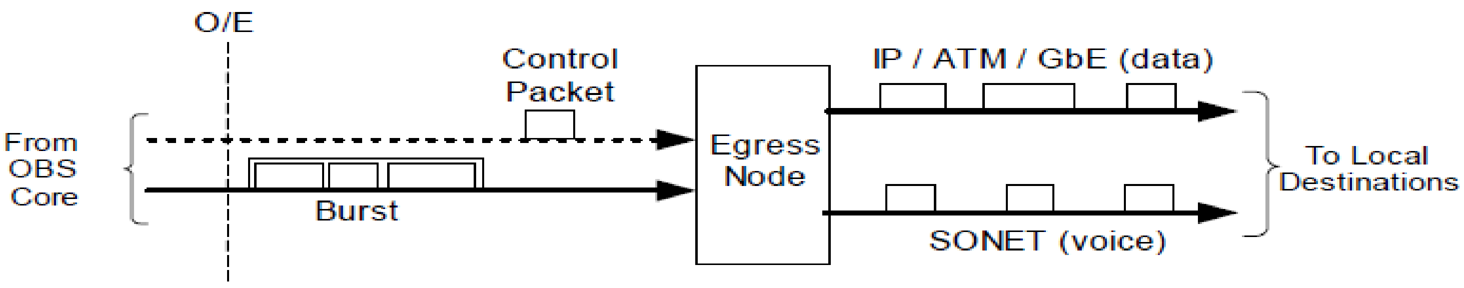
Yang Chen, Chunming Qiao and Xiang Yu
Computer Science and Engineering Department
State University of New York at Buffalo
{yangchen,qiao,xiangyu}@cse.buffalo.edu

Optical Burst Switching (OBS): A New Area in Optical Networking Research

Burst Assembly/Disassembly at the Edge of an OBS Network

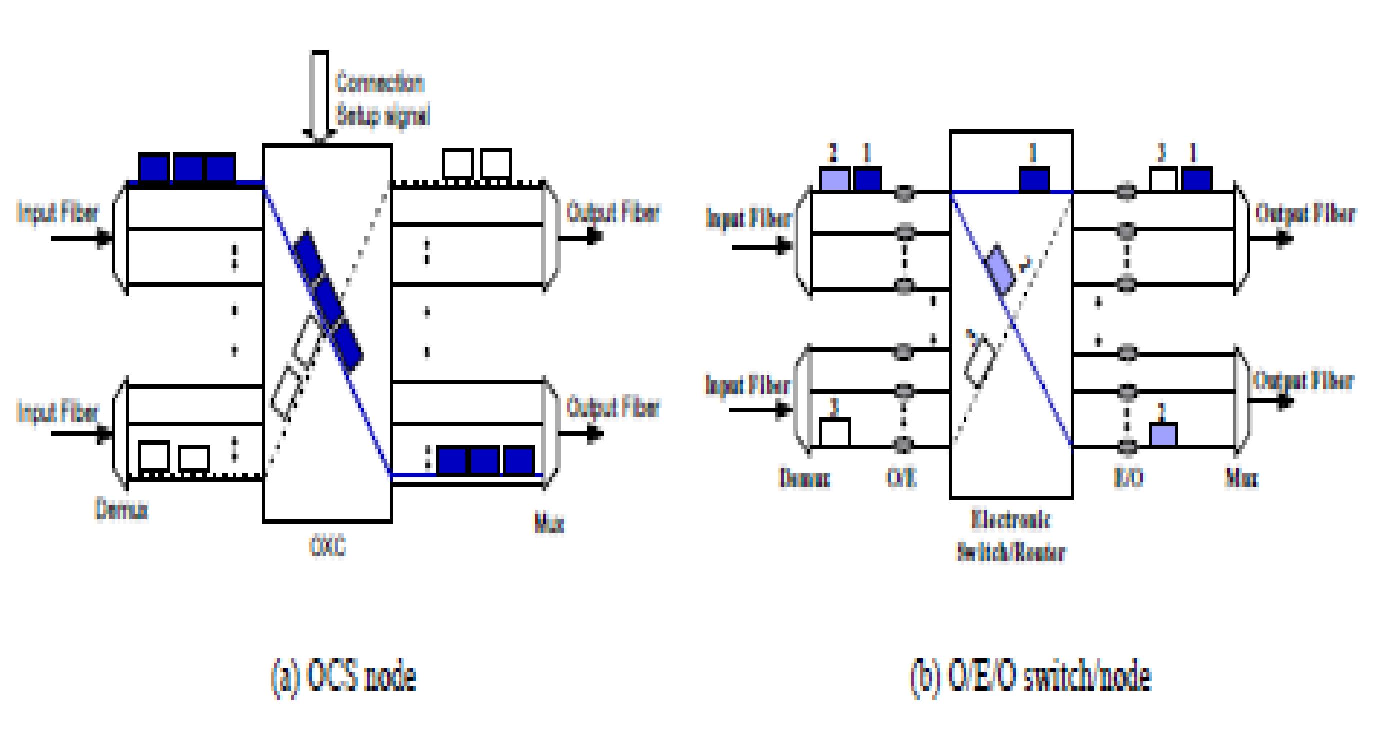


(a) Burst Assembly

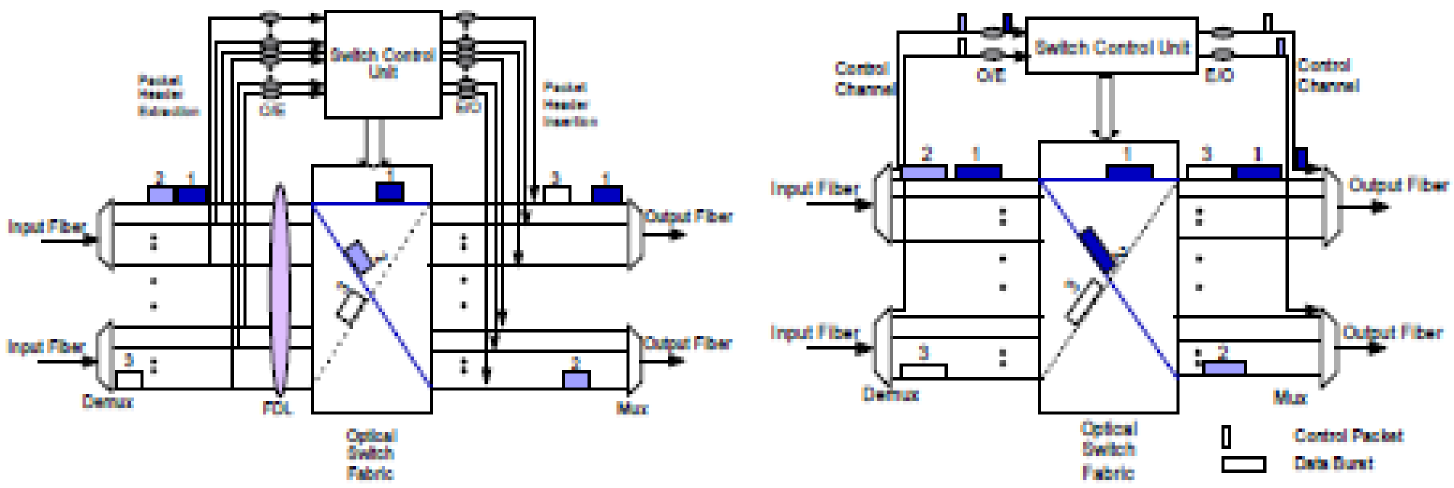


(b) Burst Disassembly

COMPARISON OF DIFFERENT SWITCHING NODE ARCHITECTURE (1)



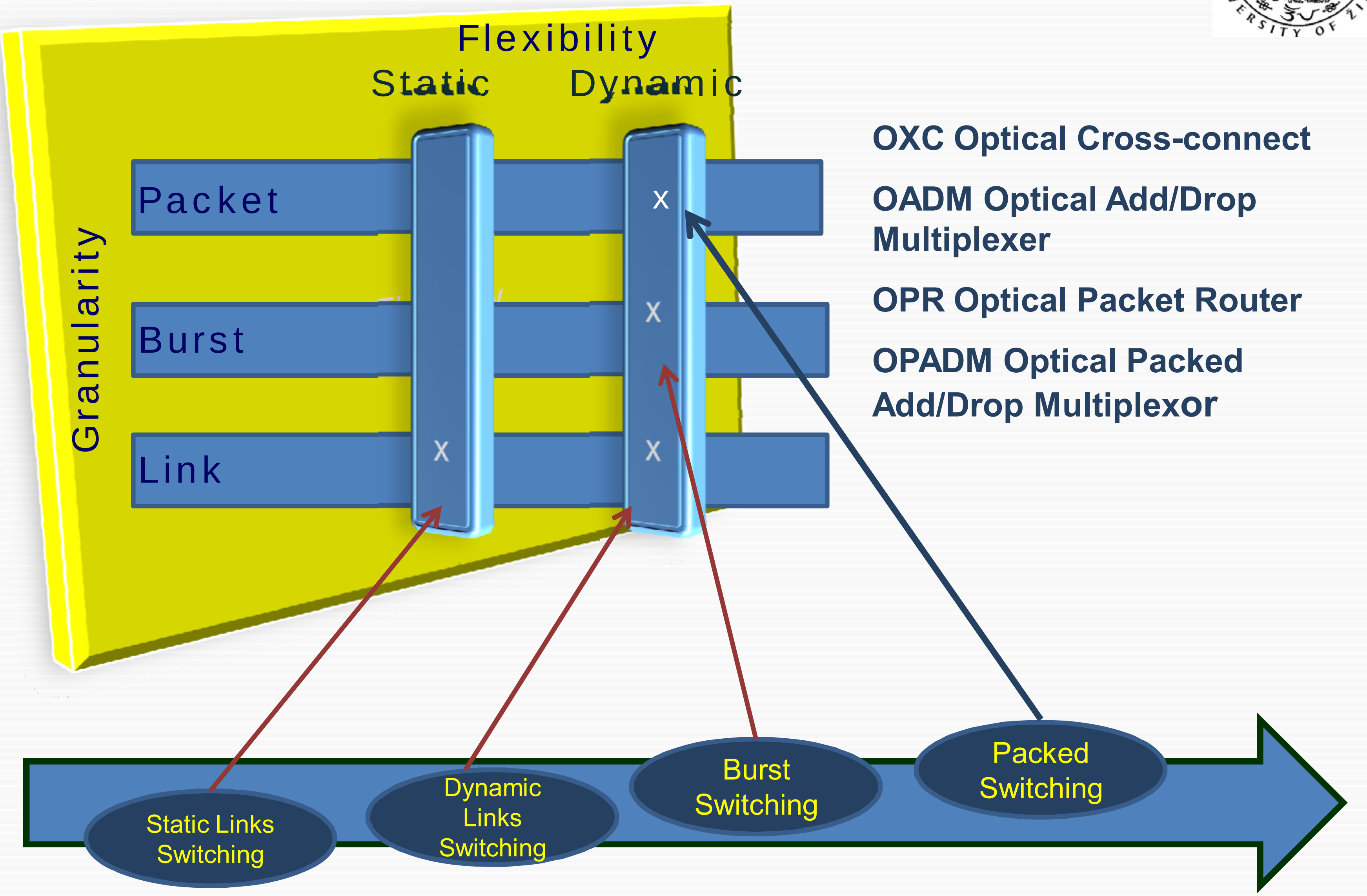
COMPARISON OF DIFFERENT SWITCHING NODE ARCHITECTURE (2)



(c) OPS node

(d) OBS node

FLEXIBILITY AND GRANULARITY IN OPTICAL NETWORKS



OXC Optical Cross-connect

OADM Optical Add/Drop Multiplexer

OPR Optical Packet Router

OPADM Optical Packed Add/Drop Multiplexor

PRESENTATION OF RESEARCH RESULTS IN OPTICAL COMMUNICATION AT THE UNIVERSITY OF ŽILINA

OPTICAL TEAMS AT THE:

- DEPARTMENT OF TELECOMMUNICATIONS AND MULTIMEDIA,
- DEPARTMENT OF PHYSICS AND
- AUREL STODOLA INSTITUTE IN LIPTOVSKÝ MIKULÁŠ

FACULTY OF ELECTRICAL ENGINEERING

... Activities are focused on the research in the area of linear and non-linear effects with specific respect to the stochastic manifestation in the area of optical signals.

The goal is to provide united picture about origin of these effects and their impact on the various types of the high-order modulated optical signals.

Similarly another goal is advert to the opportunities of the mitigation these degradations mechanism and for this purpose will be utilized protocols in all-optical networks...

DESCRIPTION AND MITIGATION OF PMD

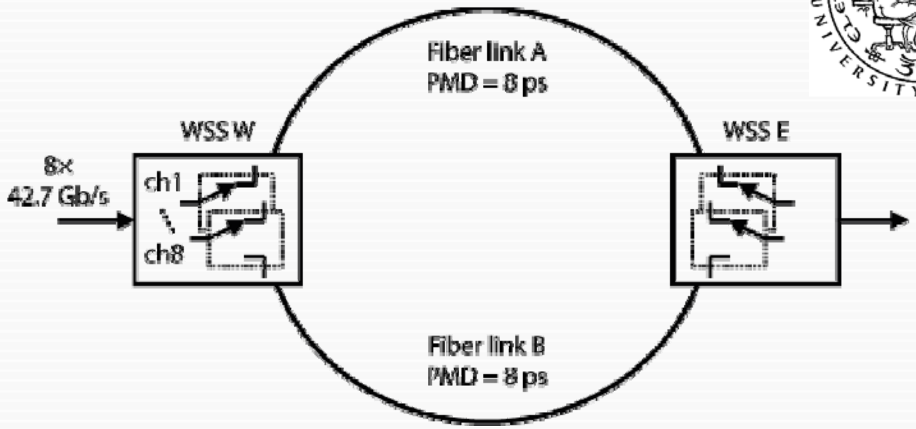
OUTAGE DYNAMICS OF 40GB/S OPTICAL PATHS ROUTED OVER PMD-IMPAIRED FIBER LINKS

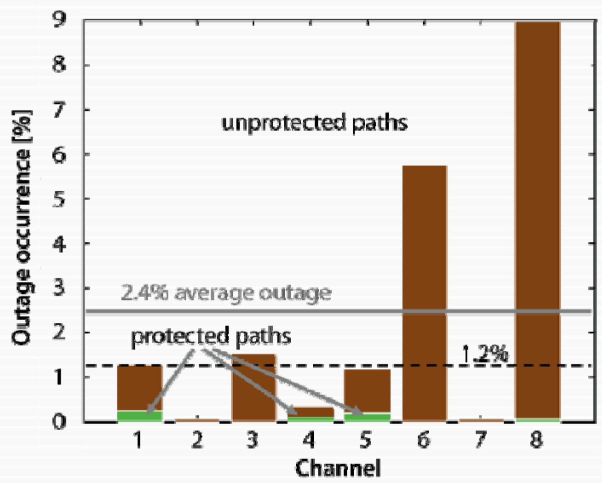
Henning Bülow, Jozef Dubovan, Reinhold Herschel

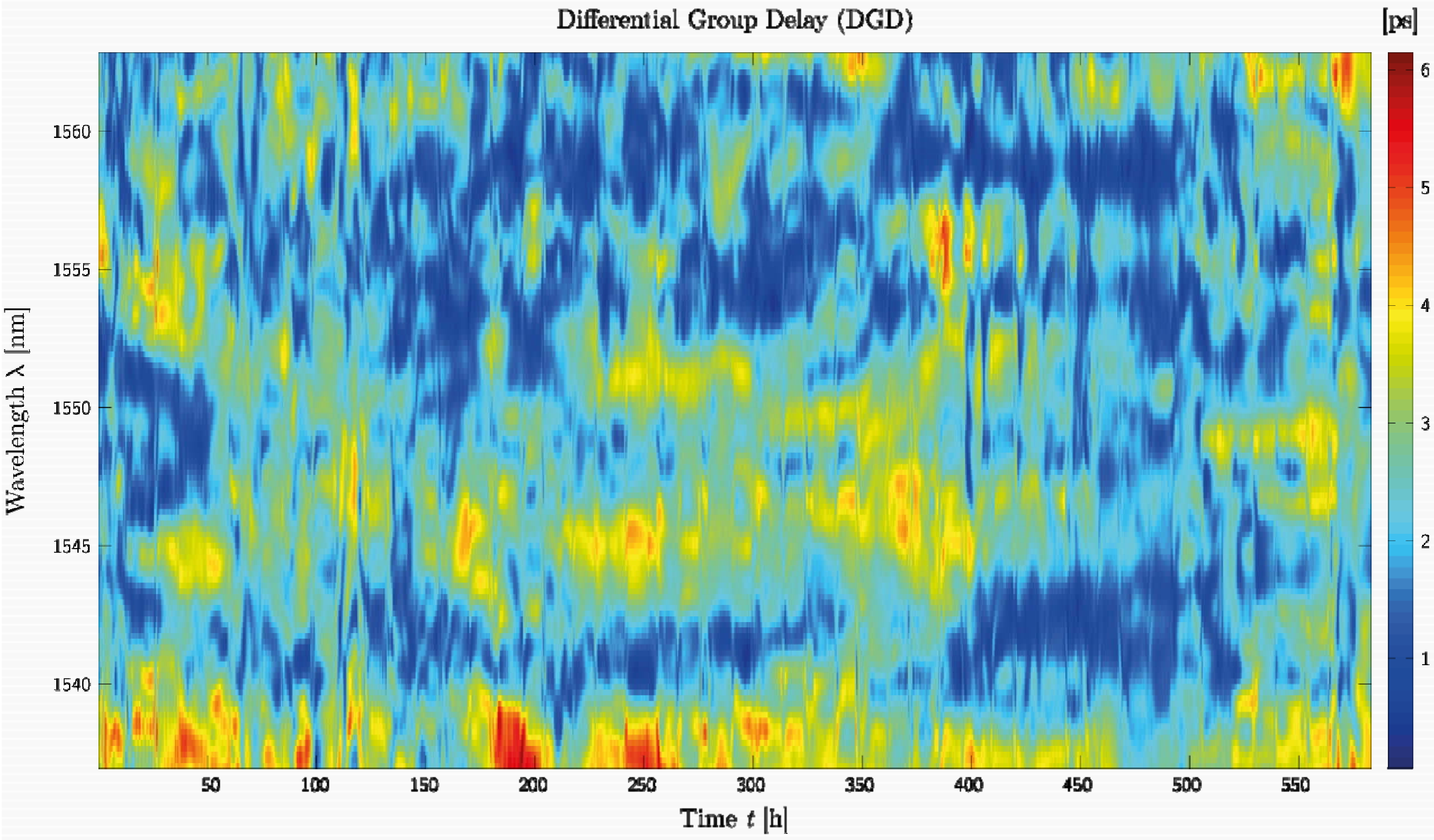
OFC, 2008

PMD related routing criteria are discussed for transparent dynamic routing of 40Gb/s channels using realistic PMD dynamics obtained from measurement of an installed multi-span fiber link exhibiting simulated outage events of 2min up to 7h duration.

Transparent dynamic routing of 40Gb/s channels transported over PMD-impaired fiber links was numerically studied at a simple example of a fiber ring. Realistic dynamics of drifting PMD and the associated signal distortion was taken into account by copying PMD dynamics extracted from long-term PMD measurements of installed fiber links formed by deployed fibers and dispersion compensating modules. So called fiber "clones" were built for numerical simulation with different PMD values but similar dynamics as measured. Heavily distorted channels of a link with 8 ps PMD exhibit outage durations between about 2 minutes and 7 hours during the 24 days observation period. The calculated examples illustrate that a routing decision based on the outage probability needs only to execute few routing decision per wavelength (in the example 1 within the 24 days) but guarantees a successful routing (outage < 1.2%) for only 75% of the channels in average.







DIFFERENTIAL GROUP DELAY (DATA OF ALCATEL-LUCENT)

Contour plot shows measured PMD characteristics (DGD vs. time and wavelength) of an installed mutlispan fiber link with EDFAs and DCFs.

NUMERICAL MODELING OF NONLINEAR POLARIZATION MODE DISPERSION (PMD)

Jan Litvik, Daniel Benedikovic, Marc Wuilpart, Milan Dado, Michal Kuba (SPIE-Optics + Optoelectronics 2013)

The aim is to investigate nonlinear and polarization effects in optical transmission systems. The main attention is focused on fundamental description of refractive index in nonlinear birefringent environment. Model is suitable for estimation of DGD parameter in nonlinear birefringence medium. The DGD is crucial for evaluation of the impact of PMD in high-bit-rates fiber-optic system.

Our model describes real optical fibers with random character of birefringence. Each segment of modeled optical fiber exhibits linear behavior of birefringence. The random nature of birefringence orientation has been modeled via random white Gaussian noise process. The concept of PSP has been used to estimate DGD.

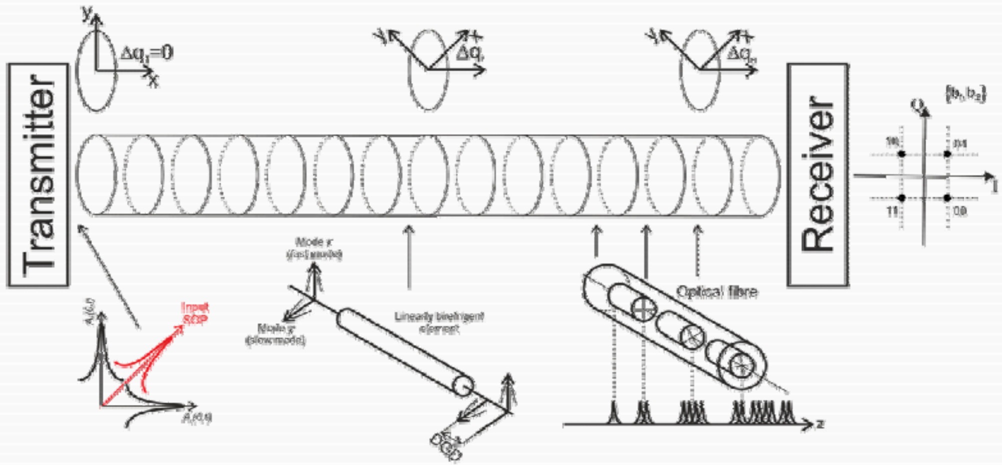
From obtained results can be seen that the major factor which has the dominant impact on the total value of DGD is the intrinsic birefringence. The presented model has provided good agreement with standard measurements of investigated parameters.

Coupled nonlinear Schrödinger equations

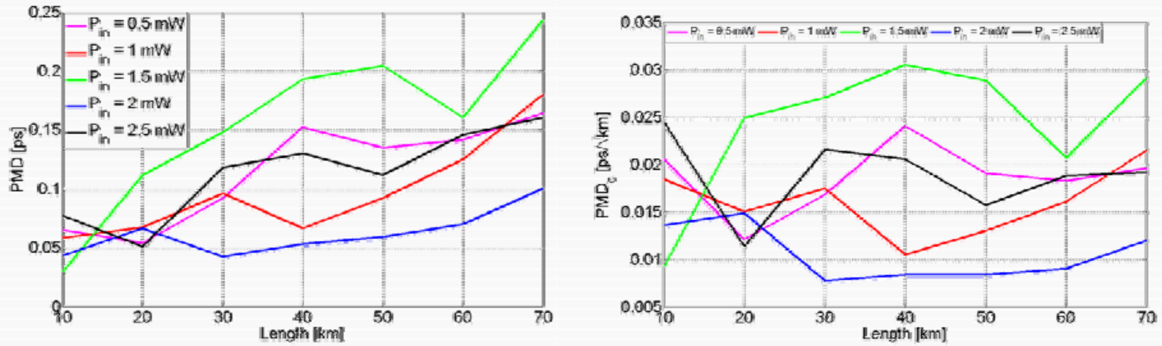
$$\frac{\partial A_x(z,t)}{\partial z}+\beta_1^x\frac{\partial A_x(z,t)}{\partial t}+\frac{j}{2}\beta_2\frac{\partial^2 A_x(z,t)}{\partial t^2}-\frac{1}{6}\beta_3\frac{\partial^3 A_x(z,t)}{\partial t^3}+\frac{\alpha}{2}A_x(z,t)=j\gamma\left(|A_x(z,t)|^2+\frac{2}{3}|A_y(z,t)|^2\right)A_x(z,t)$$

$$\frac{\partial A_y(z,t)}{\partial z}+\beta_1^y\frac{\partial A_y(z,t)}{\partial t}+\frac{j}{2}\beta_2\frac{\partial^2 A_y(z,t)}{\partial t^2}-\frac{1}{6}\beta_3\frac{\partial^3 A_y(z,t)}{\partial t^3}+\frac{\alpha}{2}A_y(z,t)=j\gamma\left(|A_y(z,t)|^2+\frac{2}{3}|A_x(z,t)|^2\right)A_y(z,t)$$

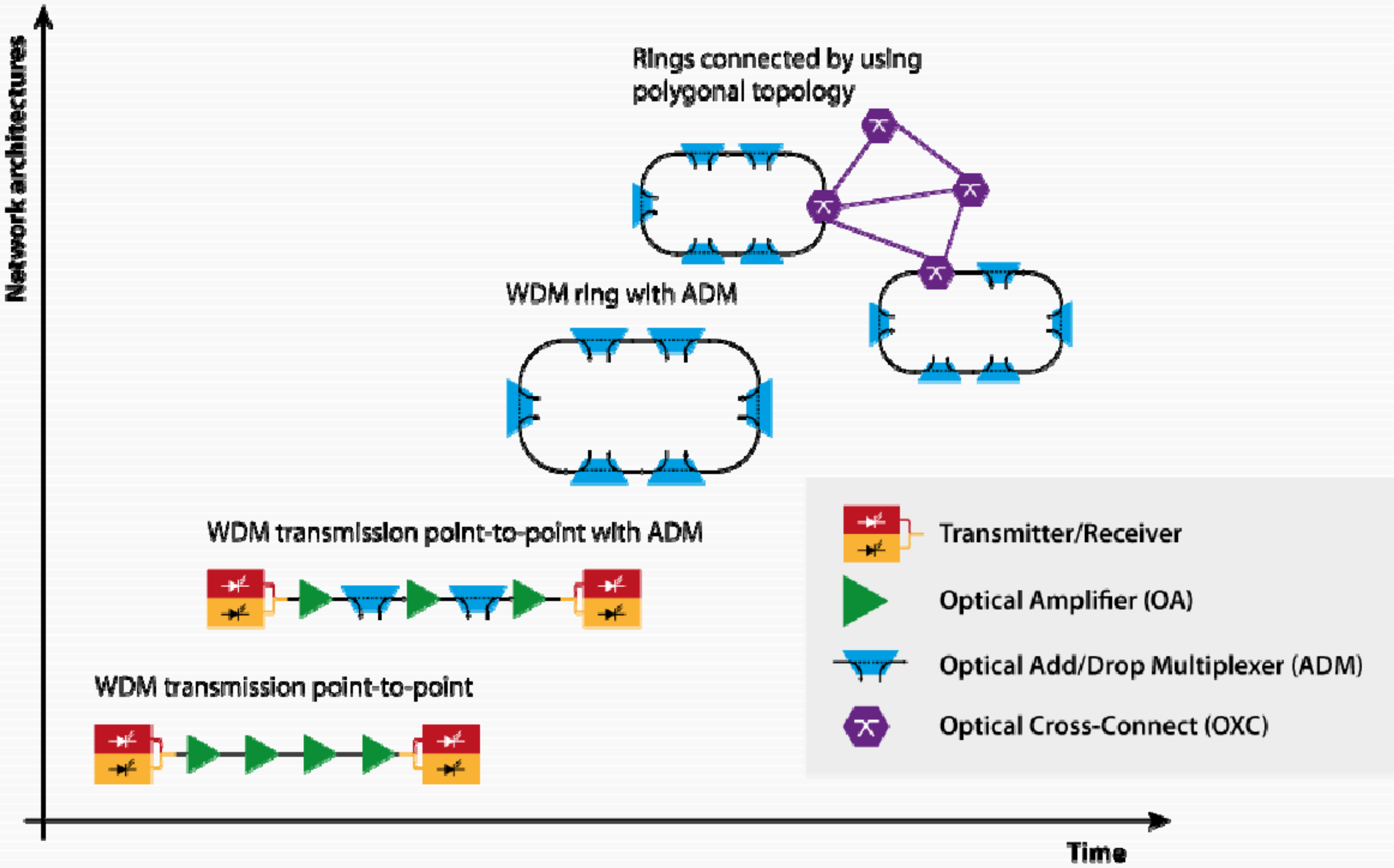
Schematic illustration of numerical model

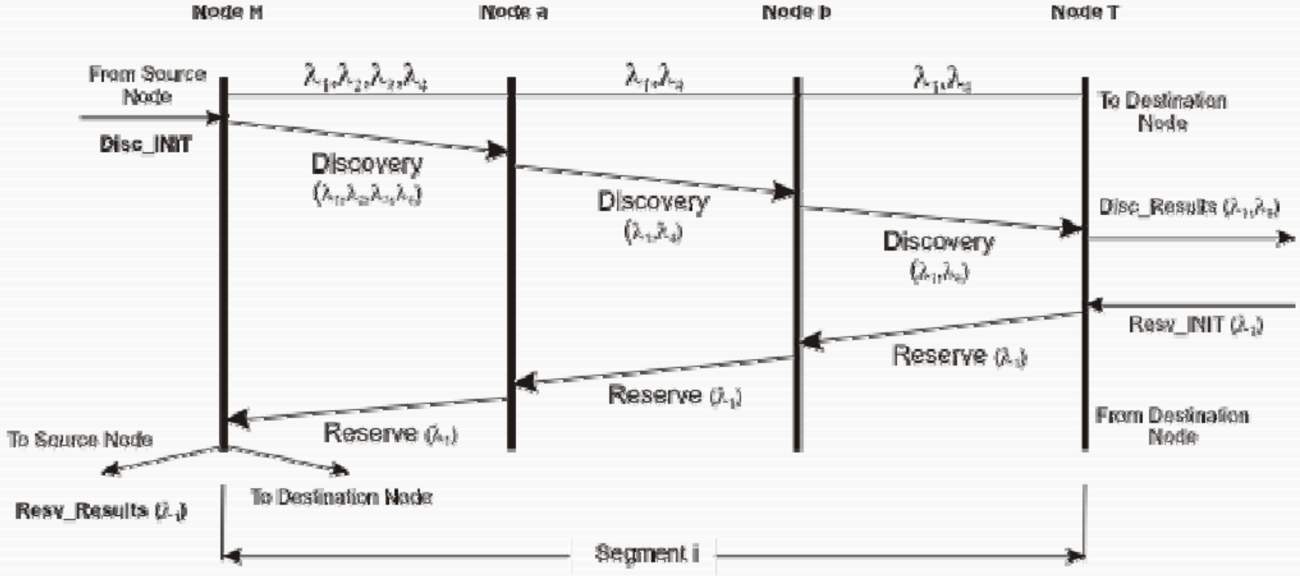


Value of PMD [ps] and PMD_c [ps/√km] for standard SMF



OPTICAL NETWORKS STRUCTURE DEVELOPMENT





S-RFORP – INTRA-SEGMENT

Segment time analysis of segment-based robust fast optical reservation protocol, Miroslav Markovič, Jozef Dubovan, Milan Dado – SPIE SCPOC, 2010

In the present, many reservation protocols exist in a high-speed optical networks with burst switching, such as Resource Reservation Protocol - Traffic Engineering (RSVP-TE), Intermediate-node Initiated Reservation (IIR), Robust Fast Optical Reservation Protocol (RFORP) and S-RFORP. All of these have pros and cons. The best of before motioned protocols is the S-RFORP5, which takes advantage of the parallel segment-based discovery/reservation.

The reservation protocols are very important in a high speed optical networks, therefore good reservation protocols can save big amount of data losses.

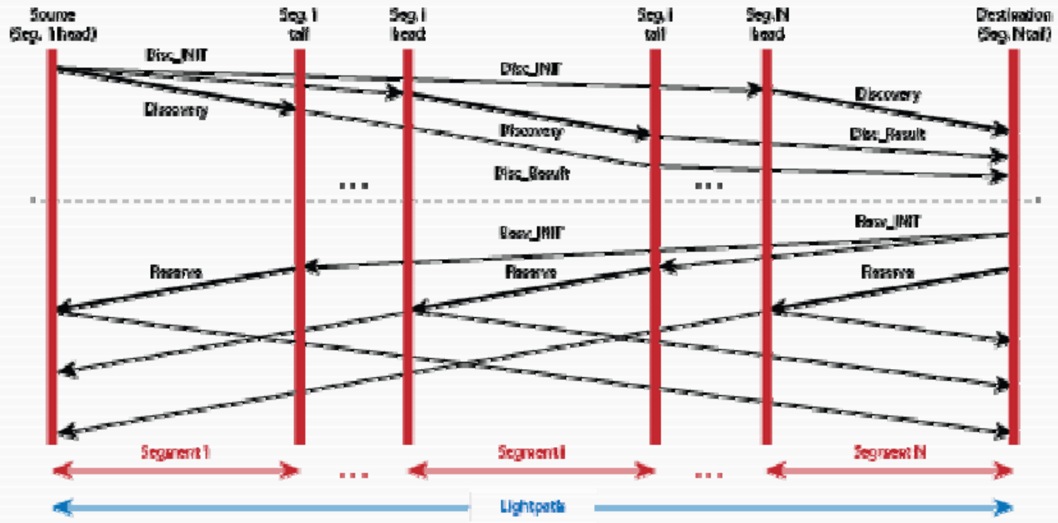
SEARCH & COMPARE (S&C) - RESERVATION PROTOCOL IN HIGH-SPEED OPTICAL NETWORKS

M. Markovic, J. Dubovan, M. Dado, Electronics and Electrical Engineering, 2011

The steps of the S-RFORP discovery phase are:

- Discovery phase starts in the source node (Seg. 1 head) of the first segment;
- Source node sends parallel discovery initialization message to all head nodes in all segments;
- Head node (“Node H”) in the segment inserts its free wavelengths ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) into the discovery message;
- Head node sends the discovery message to another node (“Node a”);
- “Node a” compares its free wavelength (λ_1, λ_4) with wavelength from the discovery message ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) and generates a new discovery message as a conjunction;
- The previous step is repeated until the discovery message arrives into the tail node (“Node T”);
- The tail node generates the discovery results message (information about discovery wavelength) and sends it to the destination node.

Inter-segment S&C



$$DT = D_{ts1} + (D_{ts2} + D_{tC2}) + (D_{ts3} + D_{tC3}) + \ldots + (D_{tsn} + D_{tCn})$$

Discovery time

$$R_{t_1} = R_{t_2} = R_{t_3} = \ldots = R_{t_i} \rightarrow R_{t_{SRFORP}} = nR_{t_n}$$

$$R_{t_{SRFORP}} = \sum_{i=1}^{n} R_{t_i} \qquad R_{t_{SRFORP}} = R_{t_1} + R_{t_2} + \ldots + R_{t_n}$$

Reservation

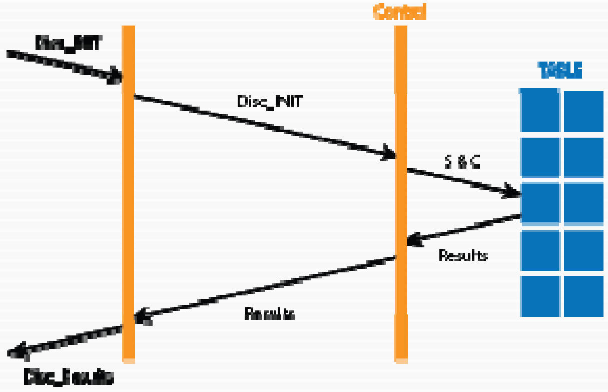
SEARCH & COMPARE (S&C) - RESERVATION PROTOCOL IN HIGH-SPEED OPTICAL NETWORKS

The main element of the intra-segment discovery is "MASTER NODE". This node stores all available free wavelengths used in all nodes in the segment (data are stored in the discovery table). In this case it is not necessary to wait for node by node discovery because all information is available in the discovery table and primary alternative wavelengths are selected.

The main principle for selecting the primary and alternative wavelength from the discovery table is the same as with S-RFORP protocol, i.e. the first row corresponds to the first node in the segment and it is compared with the second row, the second row is compared with the third one, etc. This procedure is repeated until the algorithm compares all rows in the table (number of rows is equal to number of active nodes in the segments).

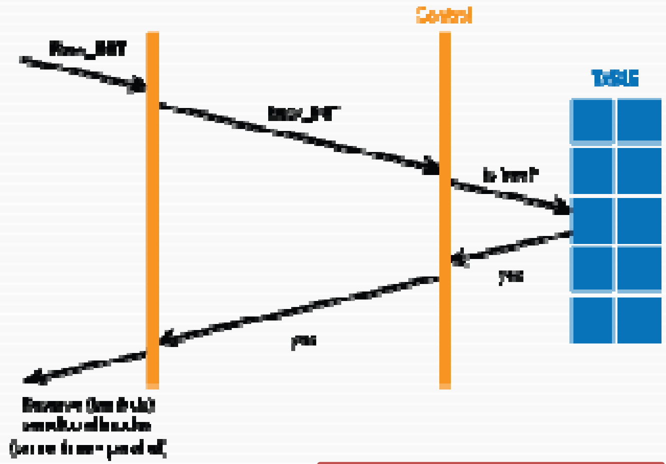
When the discovery process finishes, master node generates a new message called "Disc_Results", which is sent into the destination node (Seg. N tail - see Fig.). This process is much faster than the serial discovery in S-RFORP protocols.

Intra-segment S&C



$$D_{tsc} = t_s + t_c$$

$$R_{tsc} = t_v + R_{ts}$$



Compare this two discovery time, we get

Discovery time new reservation protocol S&C

Discovery time old reservation protocol S&C

$$D_{tsc} = \frac{D_{tSRFORP}}{\frac{2n-1}{2}}$$

DATA STRUCTURE OF SEARCH & COMPARE (S&C) RESERVATION PROTOCOL

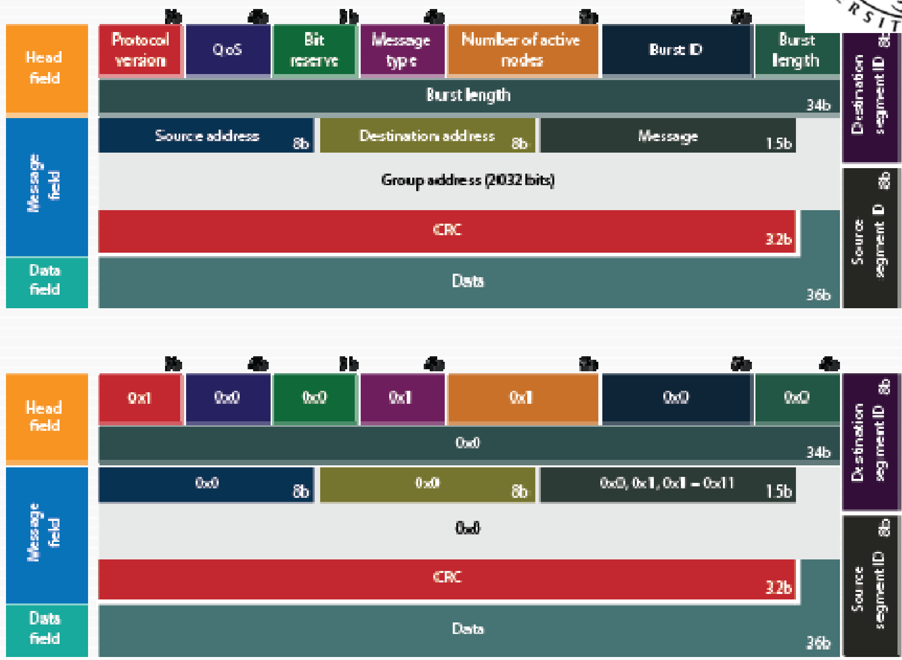
Markovič M., Dubovan, J., Dado, M., Benedikovič, D., Litvík, J., SPIE CPSOC 2012

When we want to designate a data structure of the reservation protocol, we must know these parameters:

- transmit wavelength (λ) of burst,
- length of burst (in bits),
- source, destination and group address in the segment (the main reservation node will be automatic assigned
- address to each node after node connection),
- number of nodes in the segment includes MASTER NODE and SLAVE NODE,
- time needed for adjustment switching structure.

We designed data structure from these parameters (see fig.). New data structure is divided into three parts, head field, message field and data field.

Data structure S&C



Type of messages	Value of message
Control	0x1
Information	[illegible]
Backup	[illegible]

OPTICAL SOURCES, OPTICAL MODULATION FORMATS, COHERENT RECEIVERS AND NONLINEAR EFFECTS

NUMERICAL MODELS OF SEMICONDUCTOR CW-DFB LASERS

Jan Litvik, Michal Kuba, Daniel Benedikovic, Milan Dado (Telecommunications and Signal Processing-TSP 2013, Advances in Electronic and Photonic Technologies - ADEPT 2013)

The numerical model of CW-DFB optical source is suitable for fiber-optic transmission systems employing coherent detection technique. The model is based on numerical solution of quantum-mechanical coupled rate equations. The main attention of proposed optical source model is focused on signal, time-dependent characteristics to determine spectral properties of presented laser. The numerical model is compatible with numerical models based on FDM and SSFM methods.

The noise properties of laser are mainly dominant in steady state, because the fluctuating nature of corresponding parameters caused by noise is so much smaller than their average values. From a transmission point of view, the steady state operation of laser is important to ensure that laser radiates the continuous wave.

The re-sampling approach was employed, which improves the accuracy of presented numerical model of laser source in sense to better estimate the laser bandwidth, which in our case has been estimated at 35 MHz. This value is in good agreement with sub-MHz laser requirements.

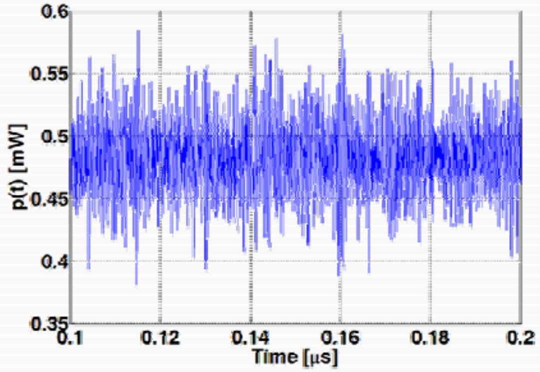
Laser rate equation with Langevin noise sources

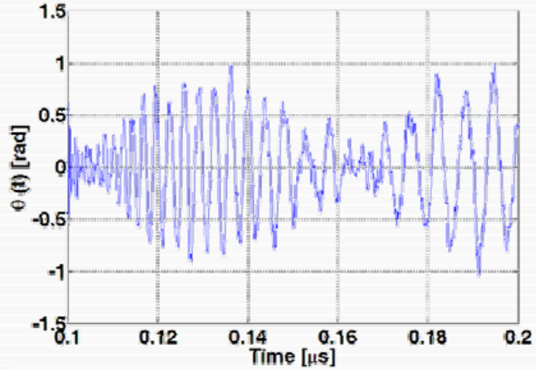
$$\frac{dN(t)}{dt} = \frac{I(t)}{q} - \frac{N(t)}{\tau_n} - g\frac{N(t)-N_0}{1+\varepsilon S(t)}S(t) + F_N(t)$$

$$\frac{dS(t)}{dt} = g\frac{N(t)-N_0}{1+\varepsilon S(t)}S(t) - \frac{S(t)}{\tau_p} + \frac{\beta N(t)}{\tau_n} + F_S(t)$$

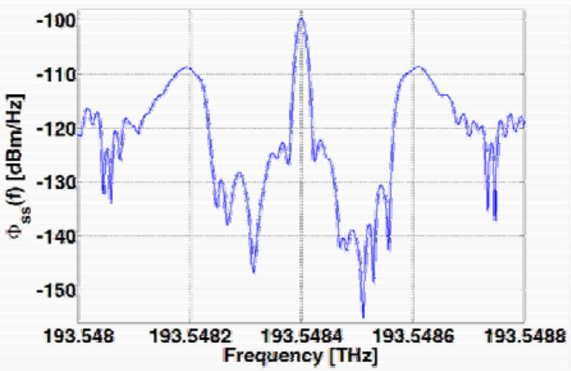
$$\frac{d\theta_S(t)}{dt} = \frac{\alpha}{2}g\left(N(t)-\bar{N}\right)$$

Time variation of output optical power and phase

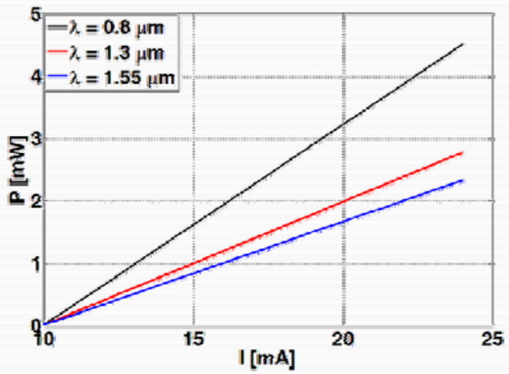




One-side PSD



Output average optical power



NUMERICAL MODELING OF TRANSMISSION SYSTEMS WITH HIGH-ORDER MODULATION FORMATS

Daniel Benedikovic, Jan Litvik, Michal Kuba, Milan Dado (Elektro 2012, Communications 2013)

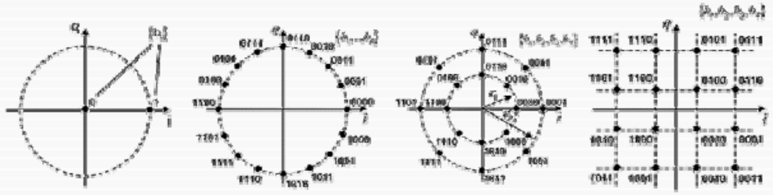
High-order modulation formats in fiber optic transmission systems are very significant for the next generation of communication systems. The most commonly used modulation format in fiber optic systems was on-off keying (OOK) over the years. High-order modulations represent next step in the improvement of transmission system. There exist several types of high-order modulation formats, M-PSK, M-ASK and M-QAM, respectively. High-order modulation formats increase the system capacity and improves the spectral efficiency of currently used fiber optic transmission systems.

The numerical model is based on solving nonlinear Schrödinger equation through the pseudospectral split-step Fourier method. Propagation of optical pulses with high-order modulation formats is very different in comparison with the (OOK), where only the amplitude is changing according to the data sequence. Multilevel amplitude modulation formats, are sensitive to the nonlinear effect of SPM in sense of increasing the value of spectral broadening. The most promising and suitable amplitude format seems to be 4-ASK for SSMF and DSF fibers at moderate powers and bit rates. From point of view of fiber length is more suitable used for the short distances 4-ASK and long haul systems multilevel PSK and QAM modulation formats.

Nonlinear Schrödinger equation

$$\frac{\partial A_m}{\partial z} = j\gamma |A_m|^2 A_m - \frac{\alpha}{2} A_m - \beta_1 \frac{\partial A_m}{\partial t} - j\frac{\beta_2}{2}\frac{\partial^2 A_m}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A_m}{\partial t^3}$$

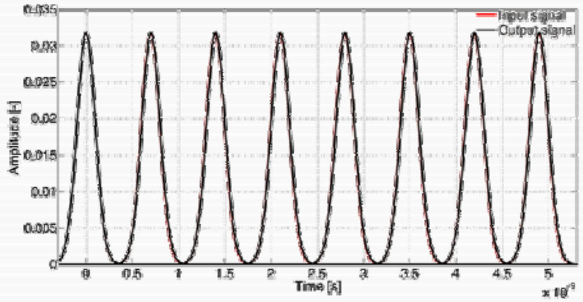
Types of various modulation formats



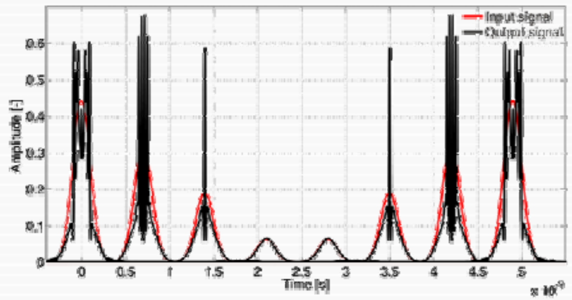
2ASK 16DPSK 16 Star QAM 16 Square QAM

Envelopes of transmitted and received symbols

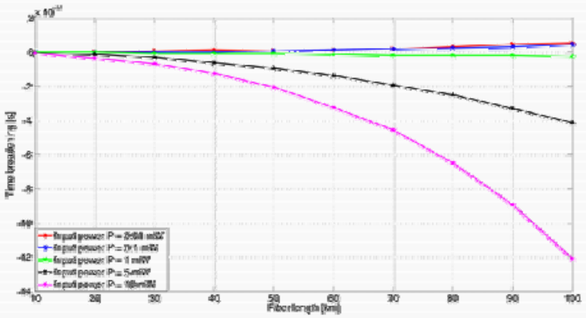
PSK

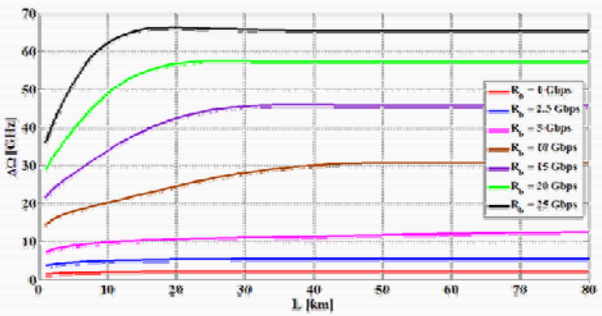


ASK



Time and spectral broadening of transmitted modulated signal





NUMERICAL INVESTIGATION OF FOUR-WAVE MIXING IN DWDM SYSTEMS

Daniel Benedikovic, Jan Conference 2012, SPIE-Optics + Optoelectronics 20Litvik, Michal Kuba, Milan Dado, Miroslav Markovič, Jozef Dubovan (SPIE-18th Czech-Polish-Slovak Optical 12)

The investigation is focused on nonlinear effects in Wavelength-Division Multiplex systems, when are used different types of high-order M-PSK and M-QAM modulation formats for various structures of channel spacing. The future of optical communication systems is characterized by increasing data capacity and data rates. Current situation in the world, where single-channel communication systems are almost replaced by multichannel systems supports this trend.

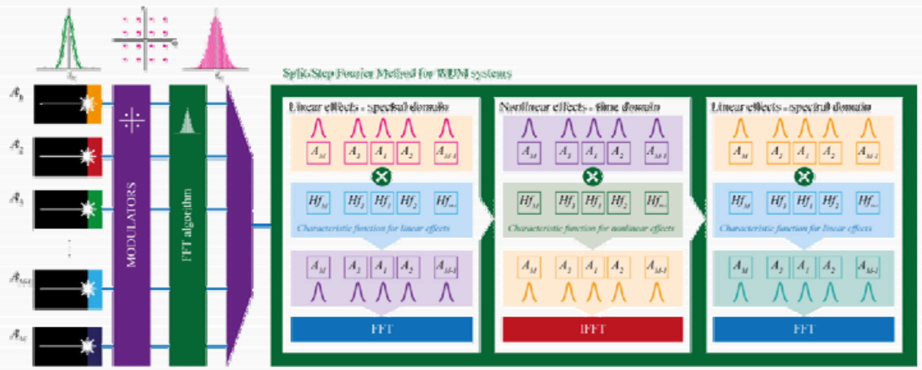
FWM nonlinear effect is highly detrimental effect, because its impact causes serious damage in transmission system. FWM process creates new frequencies components, which influence strongly depends on the level of signal power and dispersion properties of optical fiber. QAM modulation format seem to be more resistant to the impact of nonlinear effect especially for lower number of modulation states and higher value of channel spacing. For new concept of WDM system are taken into the account only channels with linear distortion. Linear distortion of transmitted signal is caused by chromatic dispersion, which can be easily compensated, so on the receiver side we can received all signal correctly.

Coupled nonlinear Schrödinger equations

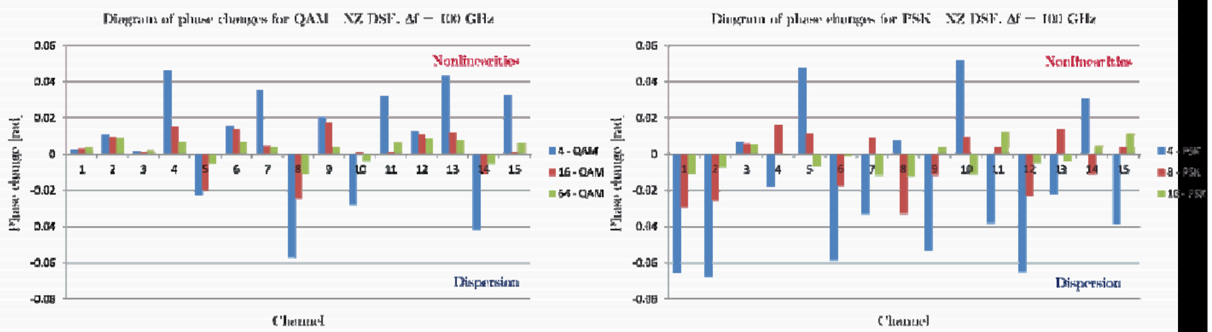
$$\frac{\partial A_n(z,t)}{\partial z} + (\beta_{1,n} - \beta_{1,ref})\frac{\partial A_n(z,t)}{\partial z} + \frac{j}{2}\beta_{2,n}\frac{\partial^2 A_n(z,t)}{\partial t^2} - \frac{1}{6}\beta_{3,n}\frac{\partial^3 A_n(z,t)}{\partial t^3} + \frac{\alpha}{2}A_n(z,t) =$$

$$= j\gamma_n\left\{|A_n(z,t)|^2 + 2\sum_{m=1,m\neq n}^{M_{ch}} |A_m(z,t)|^2\right\} + j\gamma_{ijk} \sum_{\substack{ijk=i+j-k\\ i=j\neq k}}^{M_{ch}} A_i(z,t)\,A_j(z,t)\,A_k^*(z,t)\,e^{(-j\Delta\beta z)}$$

Schematic illustration of numerical model



Decision diagram of phase changes for *M*-QAM and *M*-PSK modulation formats for NZ-DSF optical fiber



NUMERICAL MODELLING OF COHERENT COMMUNICATION SYSTEMS

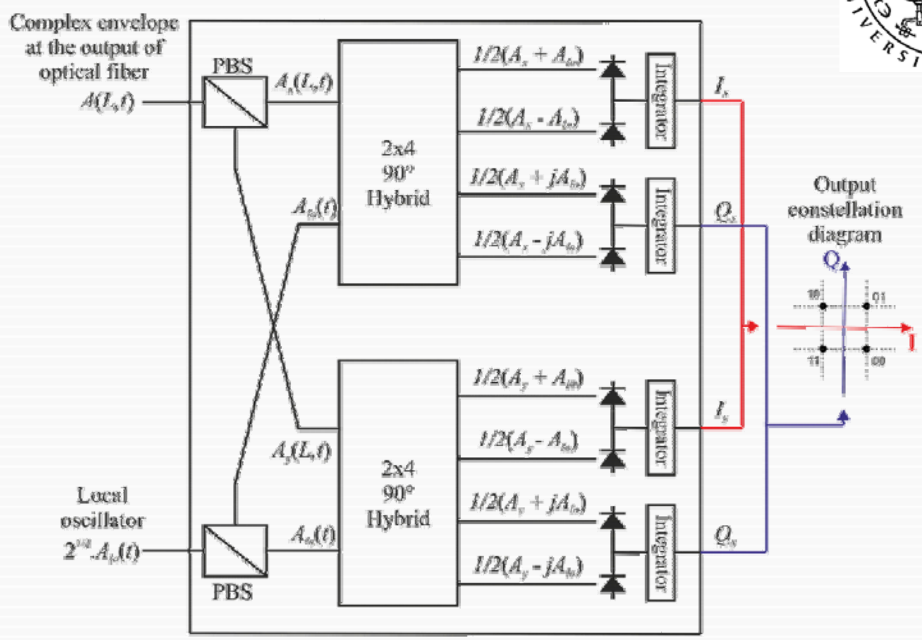
Daniel Benedikovic, Jan Litvik, Michal Kuba, Milan Dado, Jozef Dubovan (unpublished)

The coherent detection enables fully employed advantages of optical system which use high-order modulation formats. By using coherent detection is possible transform all information of transmitted optical signal (optical wave) to the electrical domain. Coherent receiver exhibit enhanced possibilities for electronic compensation of transmission impairments and it can be used as flexible and tuneable WDM receiver with highly selective channel separation.

The detection of received signals is not limited only by the linear and nonlinear effects but also with the polarization effects of the optical fibre and optical source. Also the noise play very significant role in the performance of optical coherent systems. The major sources of noise are laser, amplifiers and photodiode.

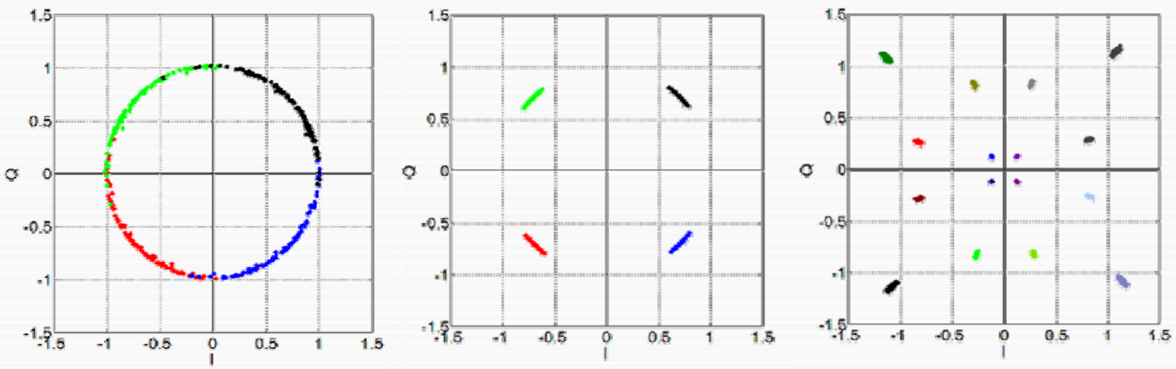
The investigation is focused on the numerical modelling and analysis of active semiconductor devices and passive optical components. Our attention is also focused to numerical estimation of signal to noise ratio and symbol (bit) error rate.

Numerical model of coherent diversity receiver



Impact of laser noise on the 4-QAM

16-QAM

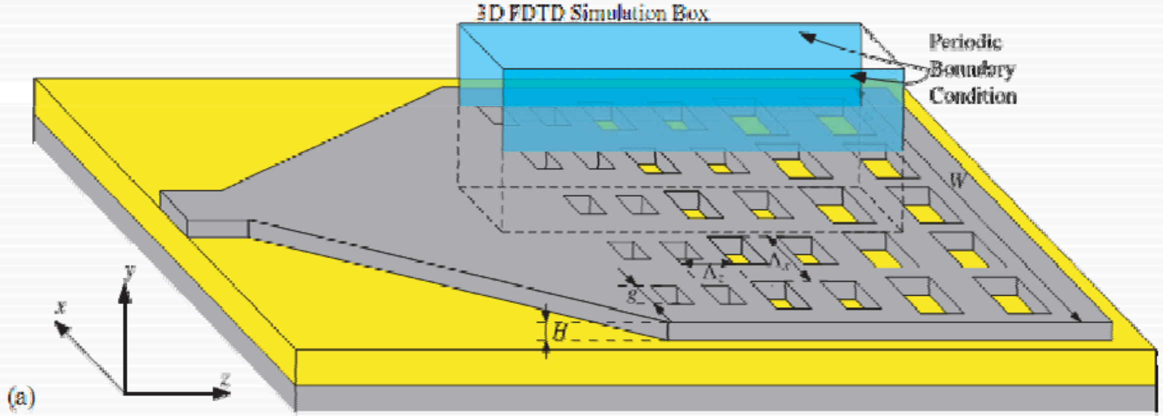


BENEDIKOVIC, D., UNIVERSITY OF ZILINA, SLOVAKIA
CHEBEN, P., NRC CANADA

DESIGN AND ANALYSIS OF SURFACE GRATING COUPLERS IN SILICON-ON-INSULATOR PLATFORM WITH SUBWAVELENGTH STRUCTURES

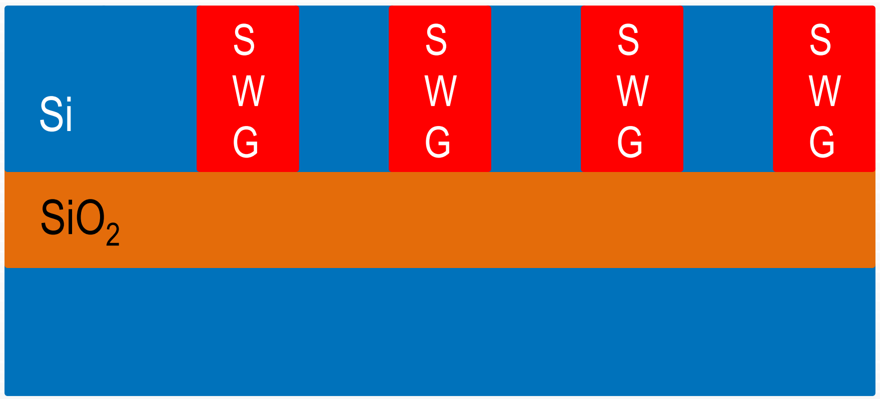
SIMULATION OF GRATING COUPLERS

Grating couplers are 3D devices

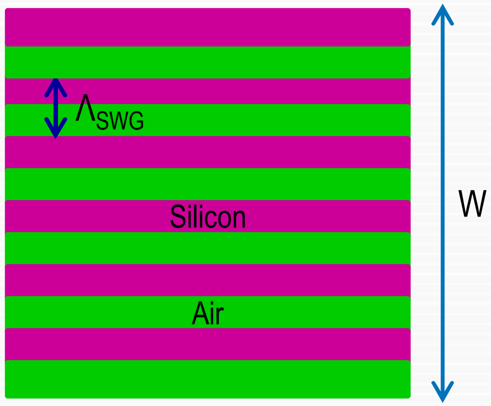


2×2D models

Vertical model (Y-Z plane)



Lateral model (X-Z plane)



$$\Lambda_{SWG} \leqslant \frac{\lambda_0}{n_{eff}}$$

Multilayer slab waveguide

CURRENT AND NG-PON'S, WAVELENGTH PROTECTION, BLOCKING FILTERS FOR TWDM DOWNSTREAM, THIN-FILM SILICON AND ORGANIC SEMICONDUCTORS

COEXISTENCE OF CURRENT AND NG-PON'S

Korček, D., Müllerová, J.: 15th International Conference on Transparent Optical Networks ICTON 2013 (Invited Paper). Cartagena, Spain, 27 – 30 June, 2013, We.C3.3, p. 1-5, IEEE ISBN 978-1-4799-0683

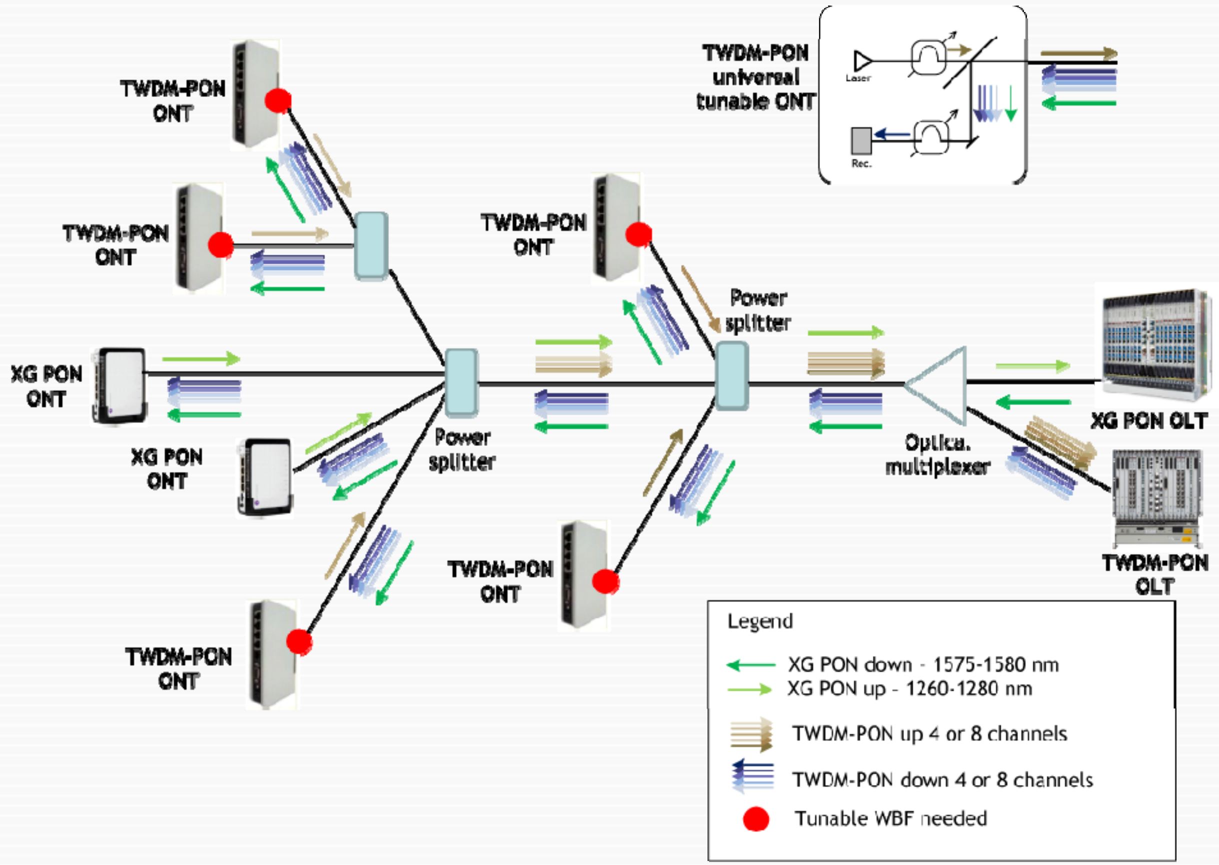
WDM - one of the leading candidates of NG PONs, still not mature, higher costs, competing with TDM-PONs

Hybrid WDM + TDM PONs = TWDM-PONs offering an economical migration from current future optical access

TWDM-PON: a new wavelength scheme in the wavelength regions allocated previously by ITU-T for GPON possible!

Our recommendation:

- to split former GPON up- & downstream regions into 8 CWDM channels, each successively processed by TDM => increased bandwidth
- to secure the desirable signal protection by narrow band-pass thin film filters used in ONUs at different angles of incidence

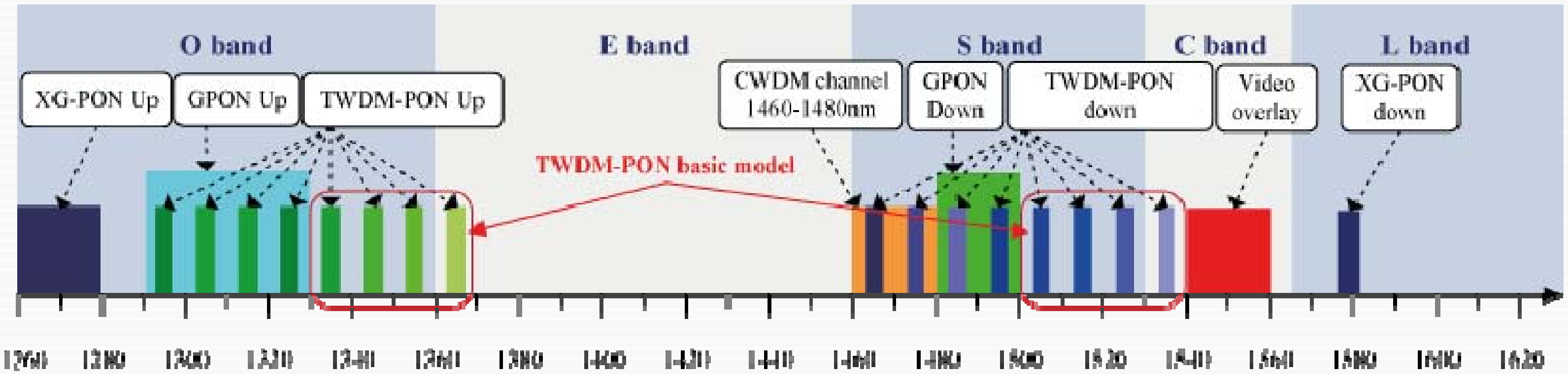


WAVELENGTH PROTECTION WITHIN COEXISTENCE

Müllerová, J., Korček, D.: 13th International Conference on Transparent Optical Networks ICTON 2011 (Invited Paper), Stockholm, Sweden, 27 – 30 June, 2011, Tu.C6.4, 2011, IEEE, ISBN 978-1-4577-0882-4
Müllerová, J., Korček, D., Dado, M.: 14th International Conference on Transparent Optical Networks ICTON 2012 (Invited Paper), Coventry, UK, 2 – 5 July, 2012, Tu.C3.5, 2012, IEEE, ISBN 978-1-4673-2227-0

Necessary due to common broadband ONU receivers:

1. Exact wavelength allocation with guard bands … obligatory
2. Narrow OLT/ONU transmitter signals … obligatory/optional
3. **Wavelength blocking filters (WBF) in coexisting PONs… optional (ITU-T G.984.5)***



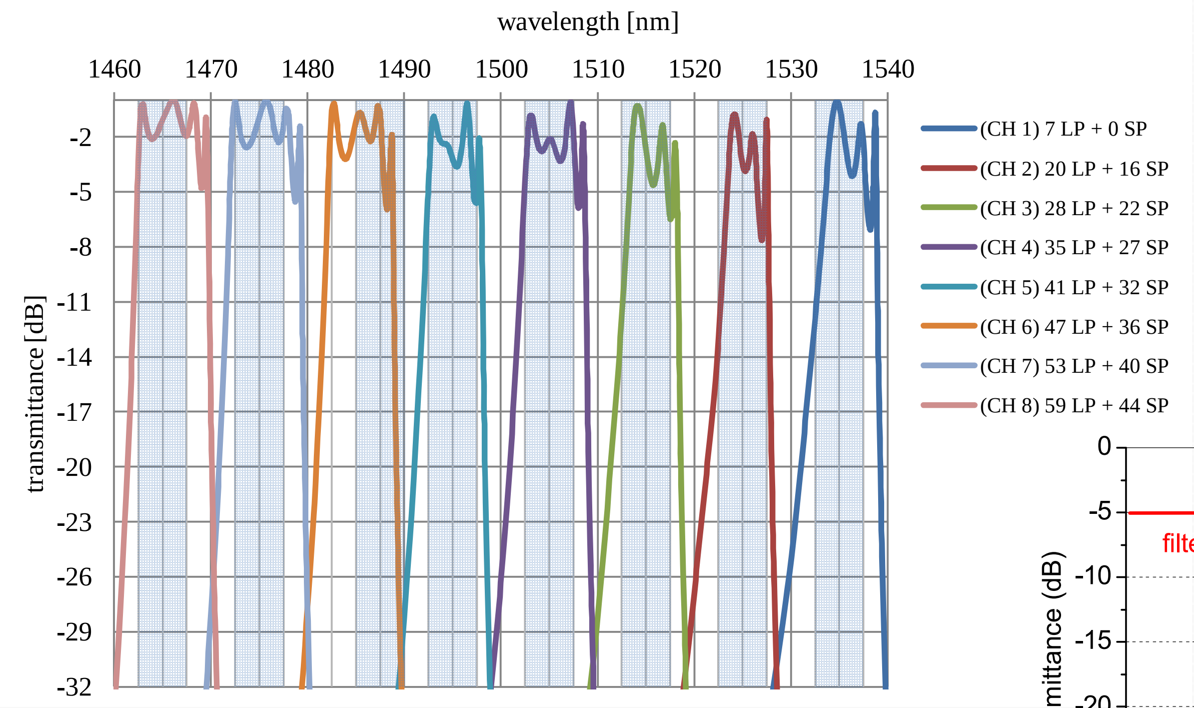
TWDM design with 5 nm-guard bands for the channel reservation:
Basic model: 4 channels, coexistence with GPON, X-GPON and video overlay
Optional model: without mandatory coexistence with GPON

BLOCKING FILTERS FOR TWDM DOWNSTREAM

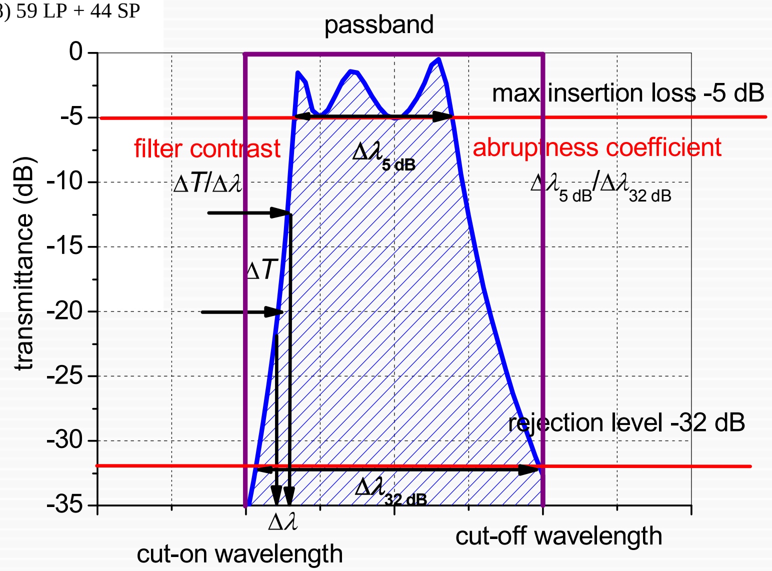
Korček, D., Müllerová, J.: 15th International Conference on Transparent Optical Networks ICTON 2013 (Invited Paper). Cartagena, Spain, 27 – 30 June, 2013, We.C3.3, p. 1-5, ISBN 978-1-4799-0683

Low-cost bandpass optical filters: minimizing severity of production: thin-film filters => amorphous Si & SiO_2

Design of short-pass (SP)/long-pass (LP) filter combinations:



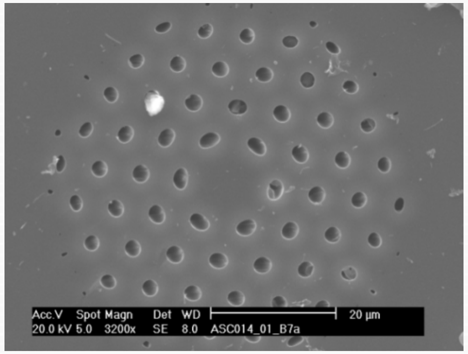
- Band-pass filters for 8 channels model (CH1-8)
- Tuning by varied angles of incidence for LP and SP
- Channel isolation and insertion loss within 5 nm-guards bands



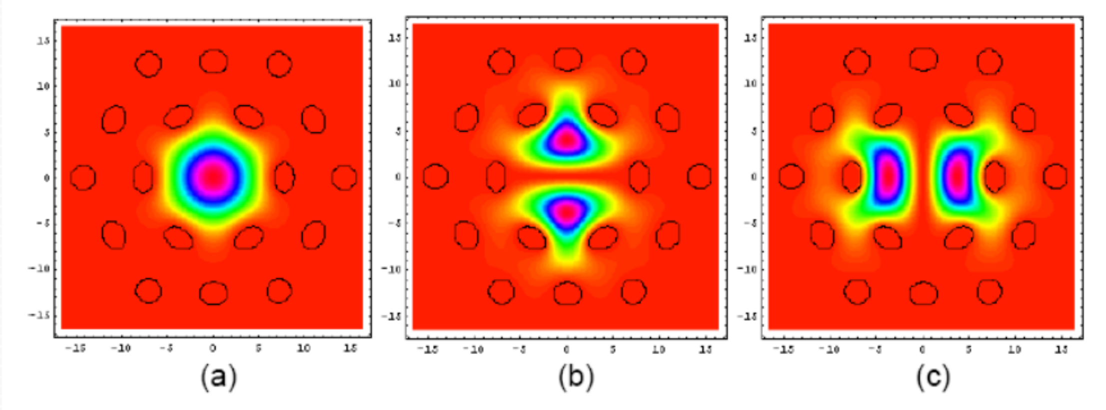
DEPARTMENT OF PHYSICS

INTERMODAL INTERFERENCE IN PHOTONIC CRYSTAL FIBRES

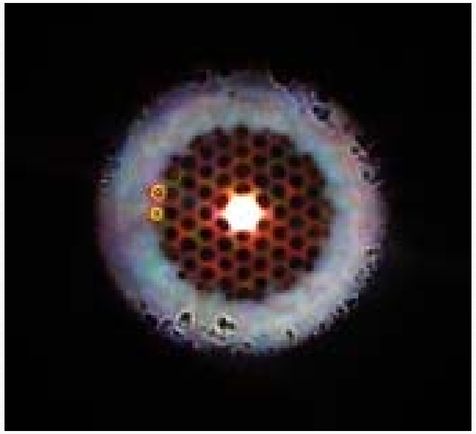
INTERMODAL INTERFERENCE IN PHOTONIC CRYSTAL FIBRES



Triangular structure of the PCF fibre fabricated by OFTC University of Sydney.

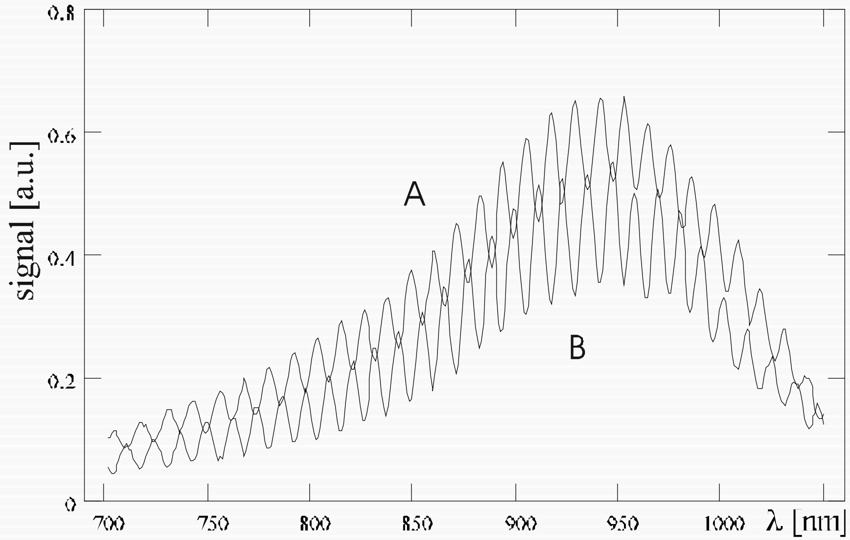


(a) Simulated intensity profile of the fundamental mode. (b, c) Example intensity profiles resembling those observed in the experiment for light guided in higher order modes. They have been simulated by taking simple linear superposition of the TE01, HE21 and TM01 modes.

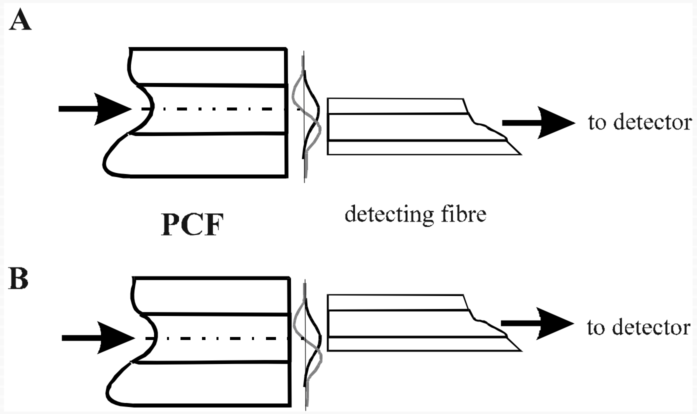


INTERMODAL INTERFERENCE IN PHOTONIC CRYSTAL FIBRES

D.Kacik, I. Turek, I. Martinček, J. Canning, N.A. Issa, K. Lyytikainen, "Intermodal interference in a photonic crystal fibre," Optics Express, vol. 12, 3465-3470, 2004



Spectral dependencies of intermodal interference in wavelength area 700 –1050nm for two positions of the detecting fibre. The length of the fibre was 7.3 cm.



Photonic crystal fibre and standard fibre arrangement for observing modal interference.

DEPARTMENT OF PHYSICS

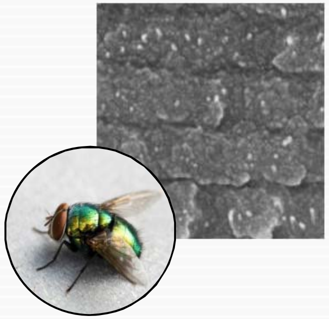
PHOTONICS RESEARCH

Motivation: Photonics in optoelectronics and nature

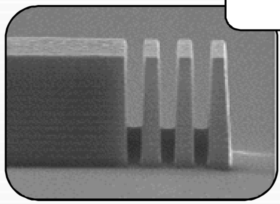
Nature | *Technology*

E.C. Nelson, Nature Materials 10, 676–681 (2011)

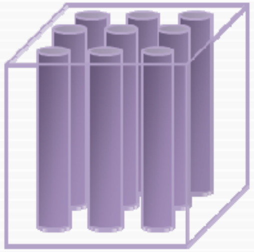
1D

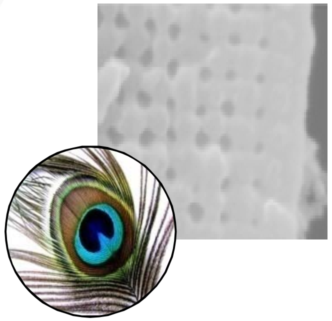


Bragg reflector

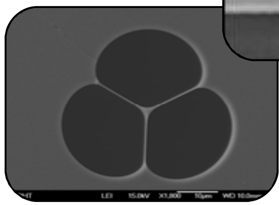


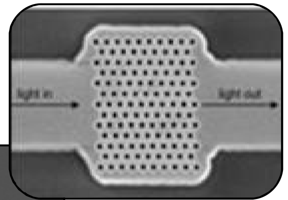
2D





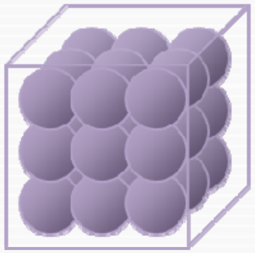
PCF

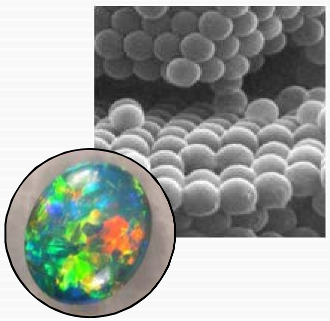


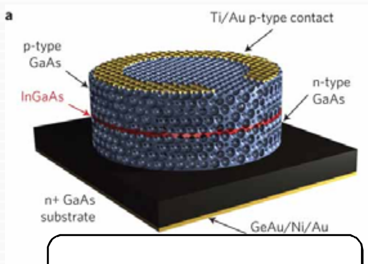


PCS

3D

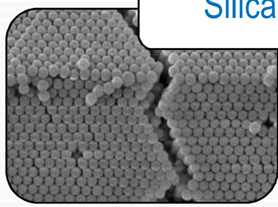






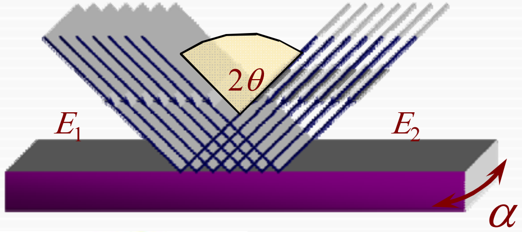
3D PhC laser

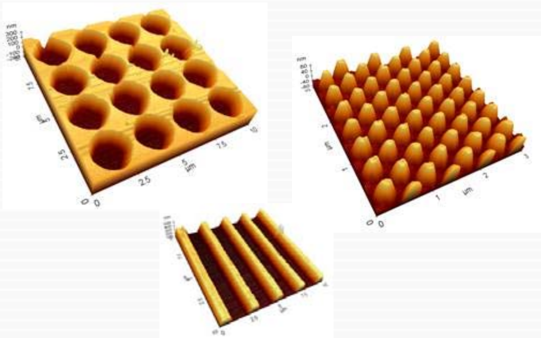
Silica crystals



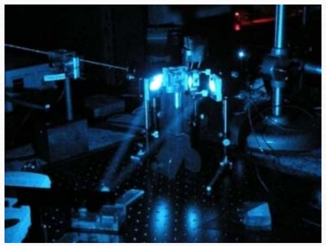
Technologies: Optical lithographies for 2D PhC fabrication

Interference lithography
(only regular structures)

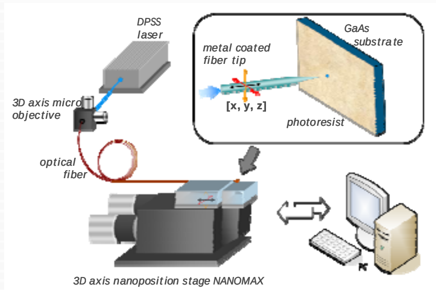


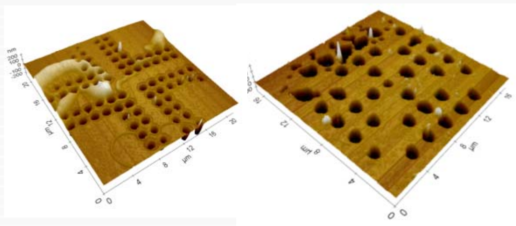


Resolution ~ 250 nm
Area 5 x 5 mm^2

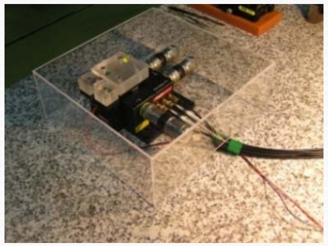


NSOM lithography
(predefined structures)

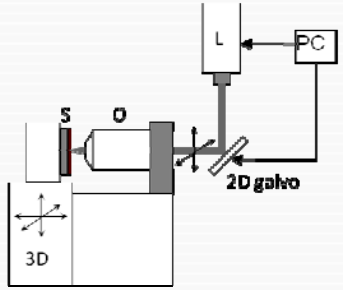


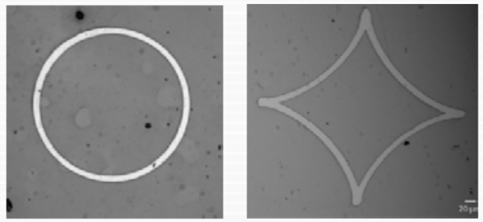


Resolution < 400 nm
Area 20 x 20 µm^2



DLW lithography
(predefined structures)





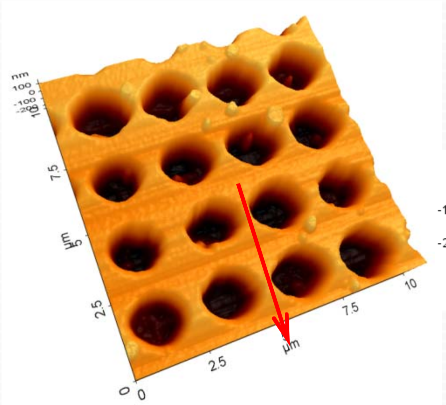
Resolution ~ 3 µm
Area 400 x 400 µm^2

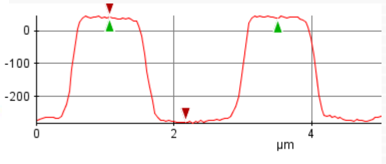
PhC LED: LED with 2D PhC in the surface

D. Pudis et al. Optics and Laser Technol. 43, 917-921 (2011)

D. Pudis et al. Appl. Surf. Sci. 269 161-165 (2013)

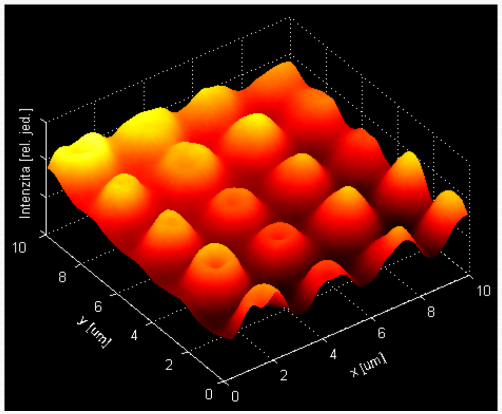
AFM analysis of PhC LED diode



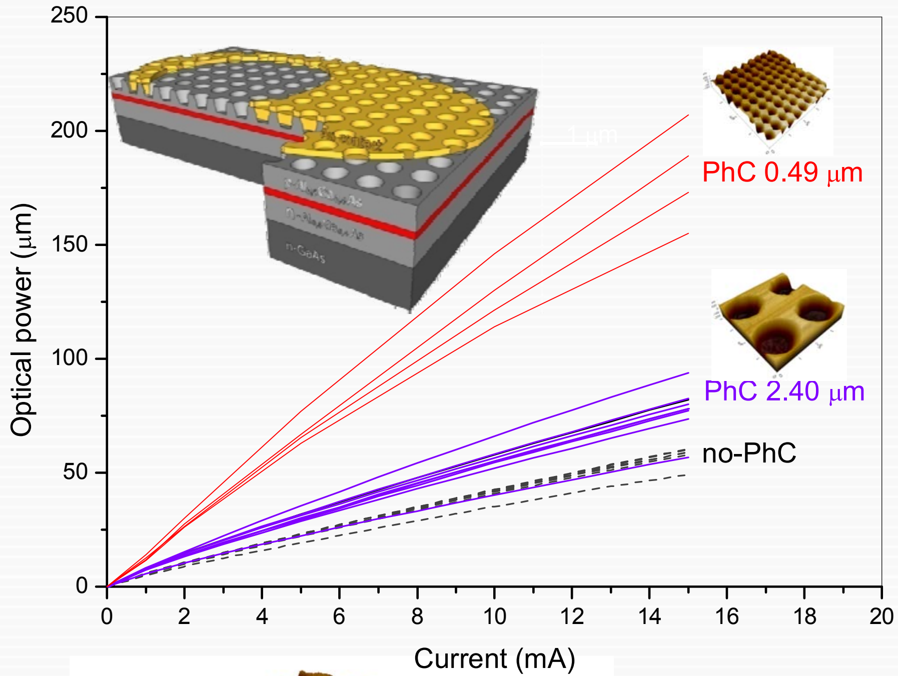


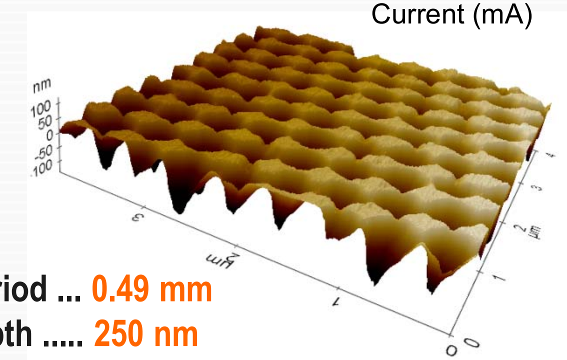
- 2,4 µm
- 320 nm

Near-field analysis of PhC LED diode



PhC LED diode - different PhC periods comparison



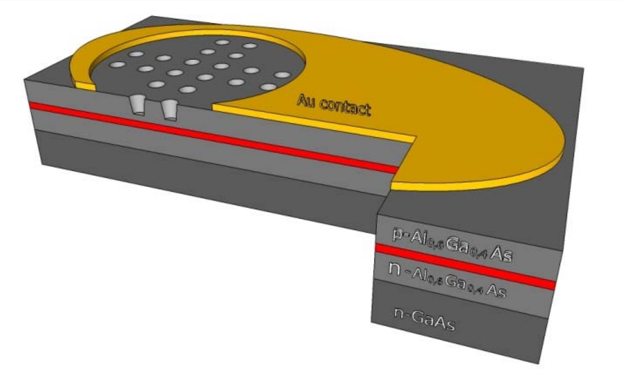


Period ... 0.49 mm
Depth ..... 250 nm

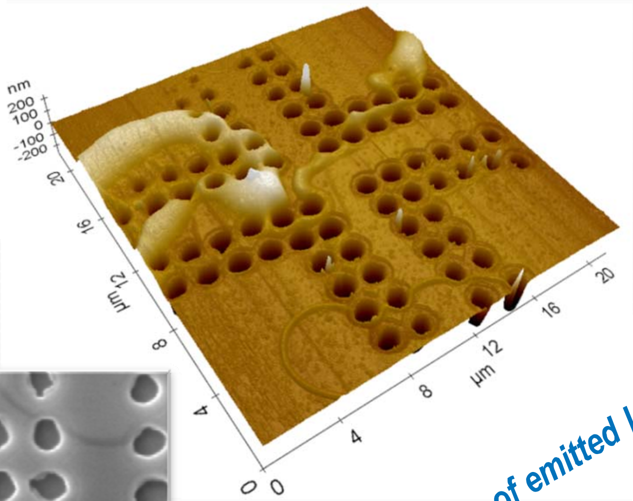
Patterned LED: LED with predefined structure

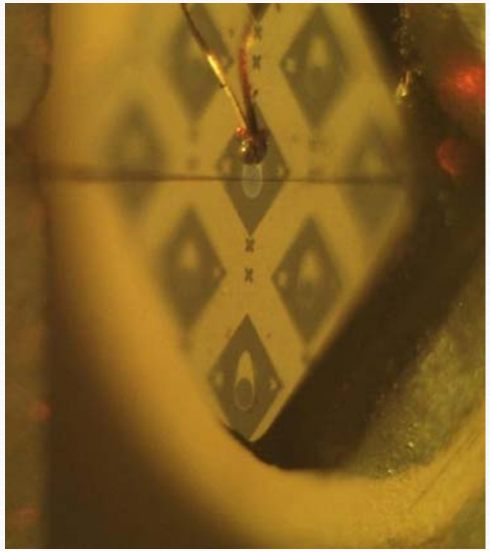
I. Kubicova, D. Pudis, et al. Appl. Surf. Sci., 269, pp. 116-119 (2013)

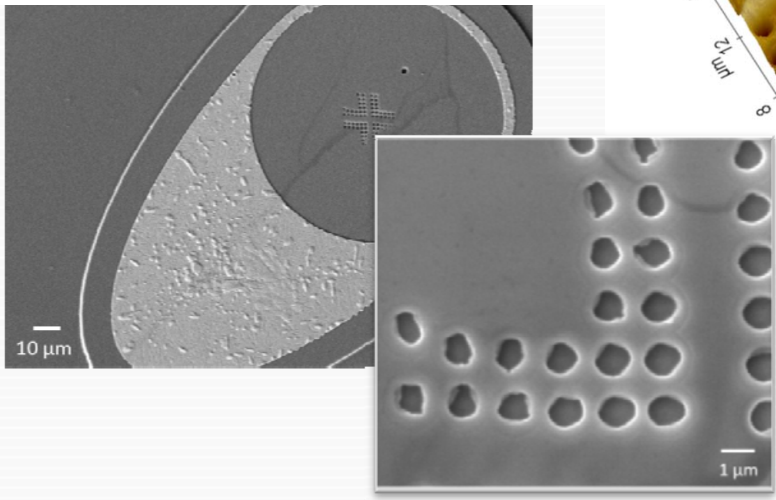
LED surface design for NSOM patterning



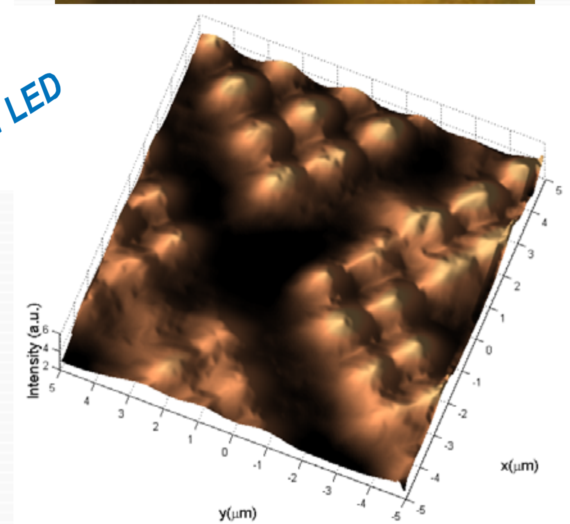
NSOM lithography process







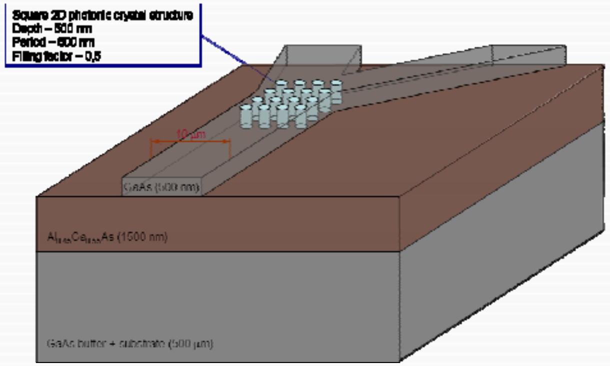
NSOM image of emitted LED

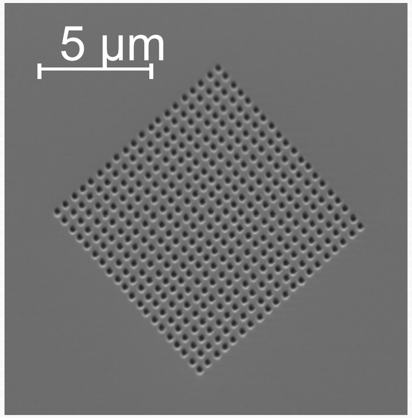


SEM and AFM images of prepared structure

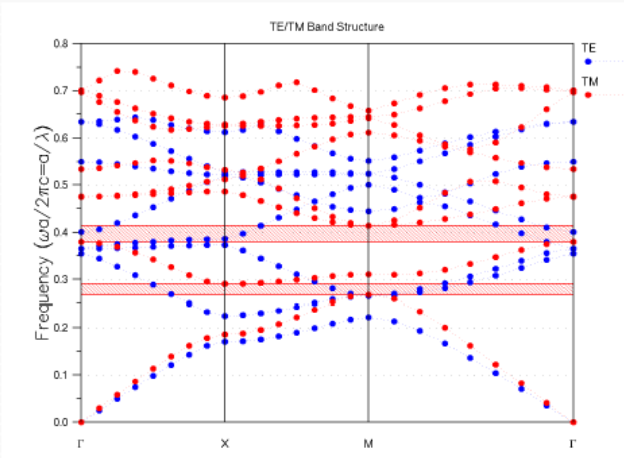
PhC waveguide: PhC Y-splitter

Y-splitter with 2D PhC

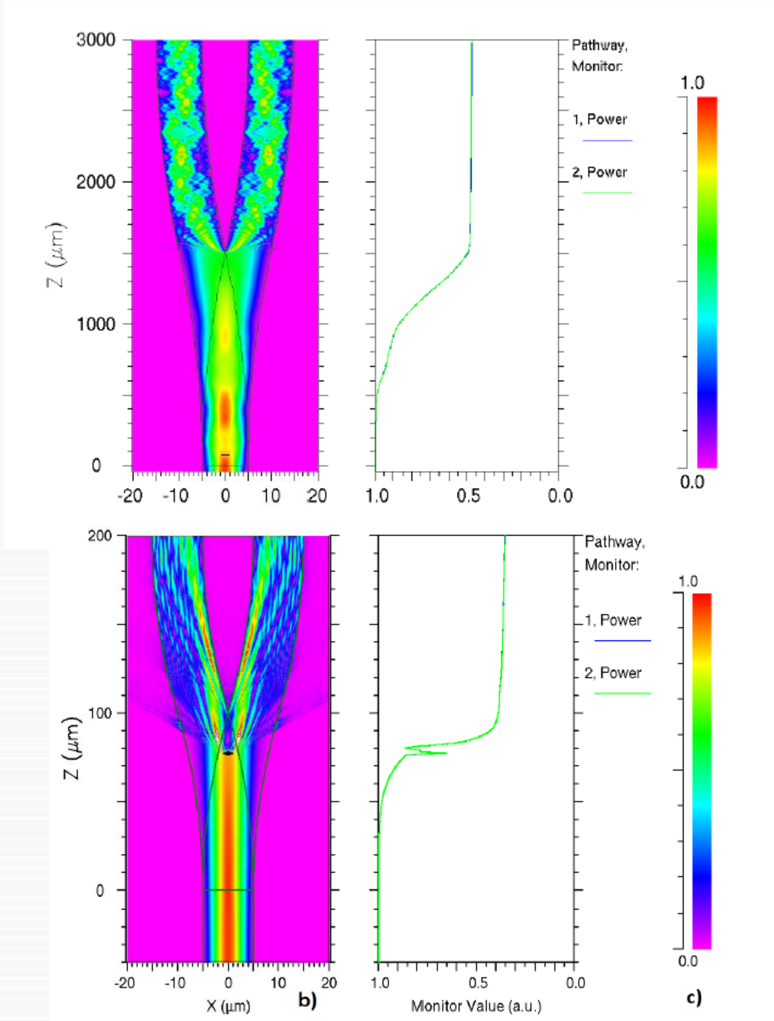




SEM image of PhC



Photonic band gap calculation

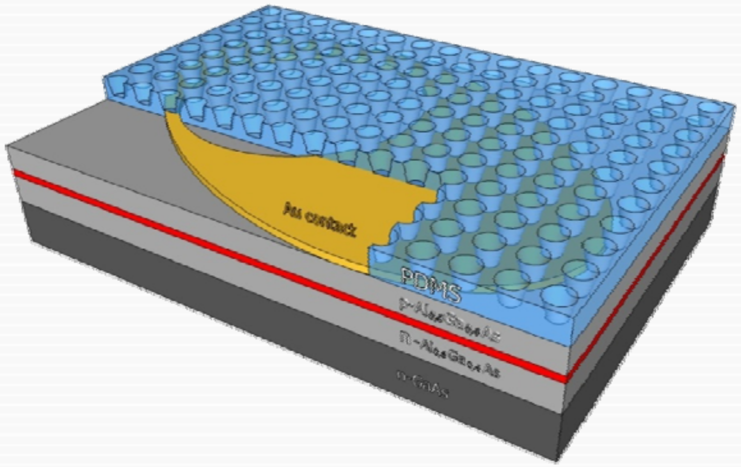


Light propagation (1.31 μm) in Y-splitter with 2D PhC structure (simulation)

PDMS photonics: PDMS for PhC LED and optical fibers

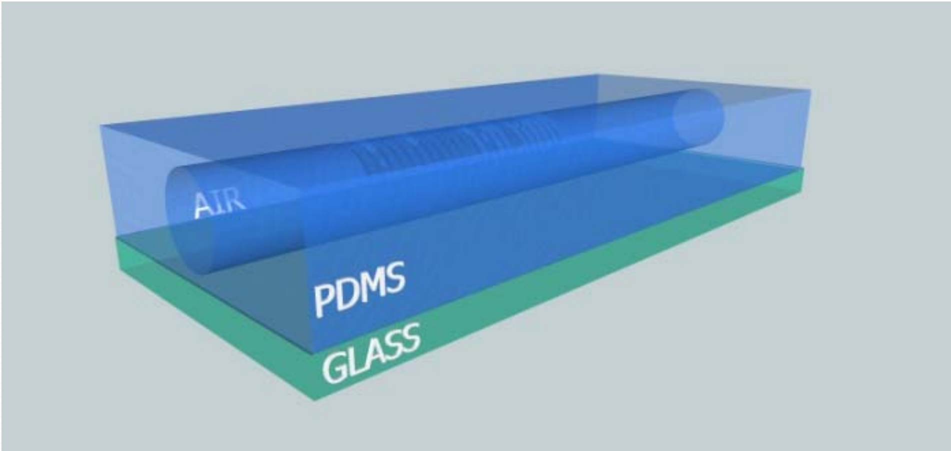
LED with PDMS PhC membrane

Improvement of light extraction efficiency
Selective spectral properties



PDMS based FBG

We expect:
Easy fabrication process
Tunability in wide range

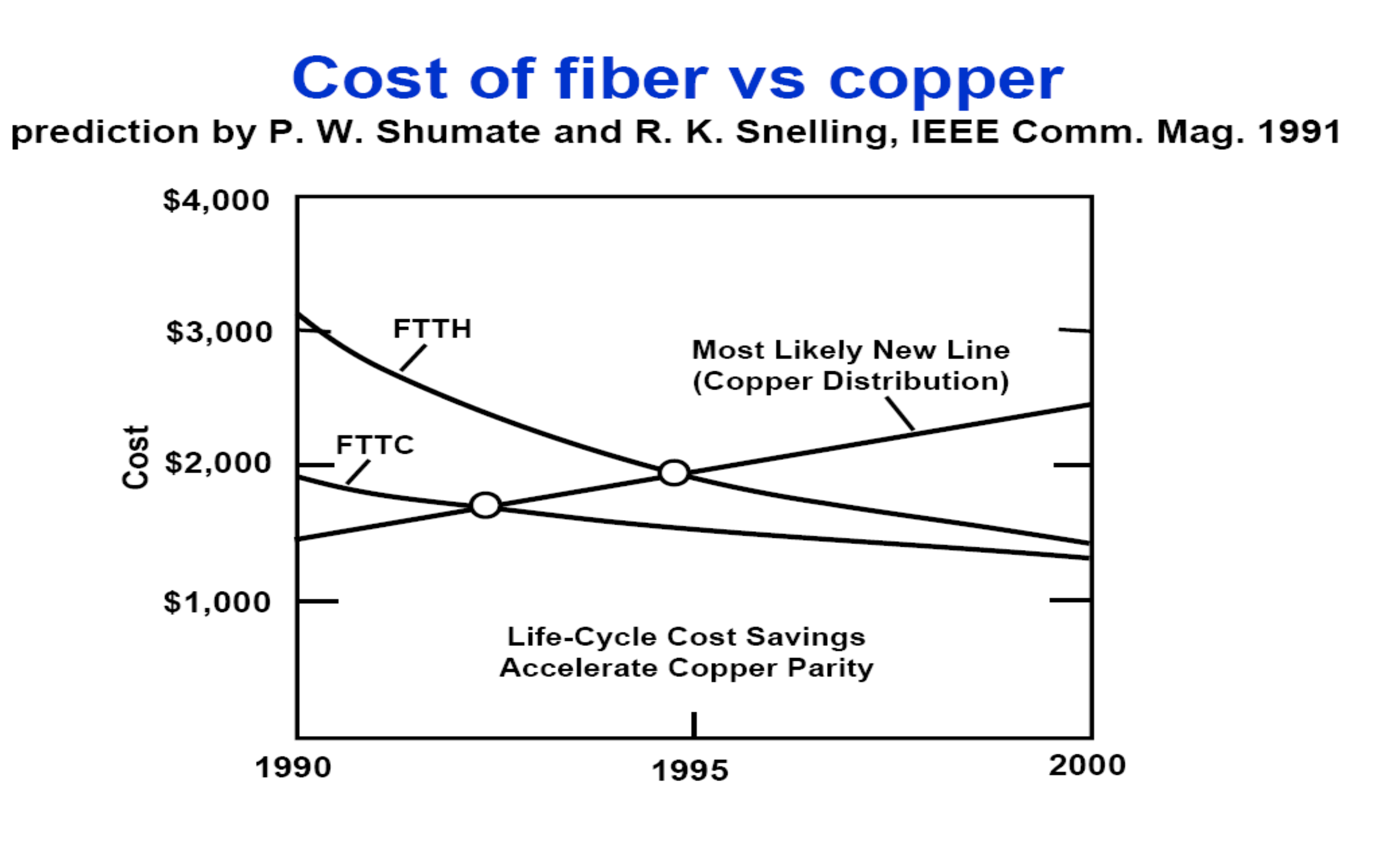


WHAT WILL INFLUENCE THE DEVELOPMENT IN REAL APPLICATIONS?

Present and future development in optical networks will be dependent on:

- Network infrastructure legacy
- New broadband services development
- Development of new technologies for access networks
- Development of technologies for different access technologies integration.
- Density of inhabitants ....

COST OF FIBER VS. COPPER

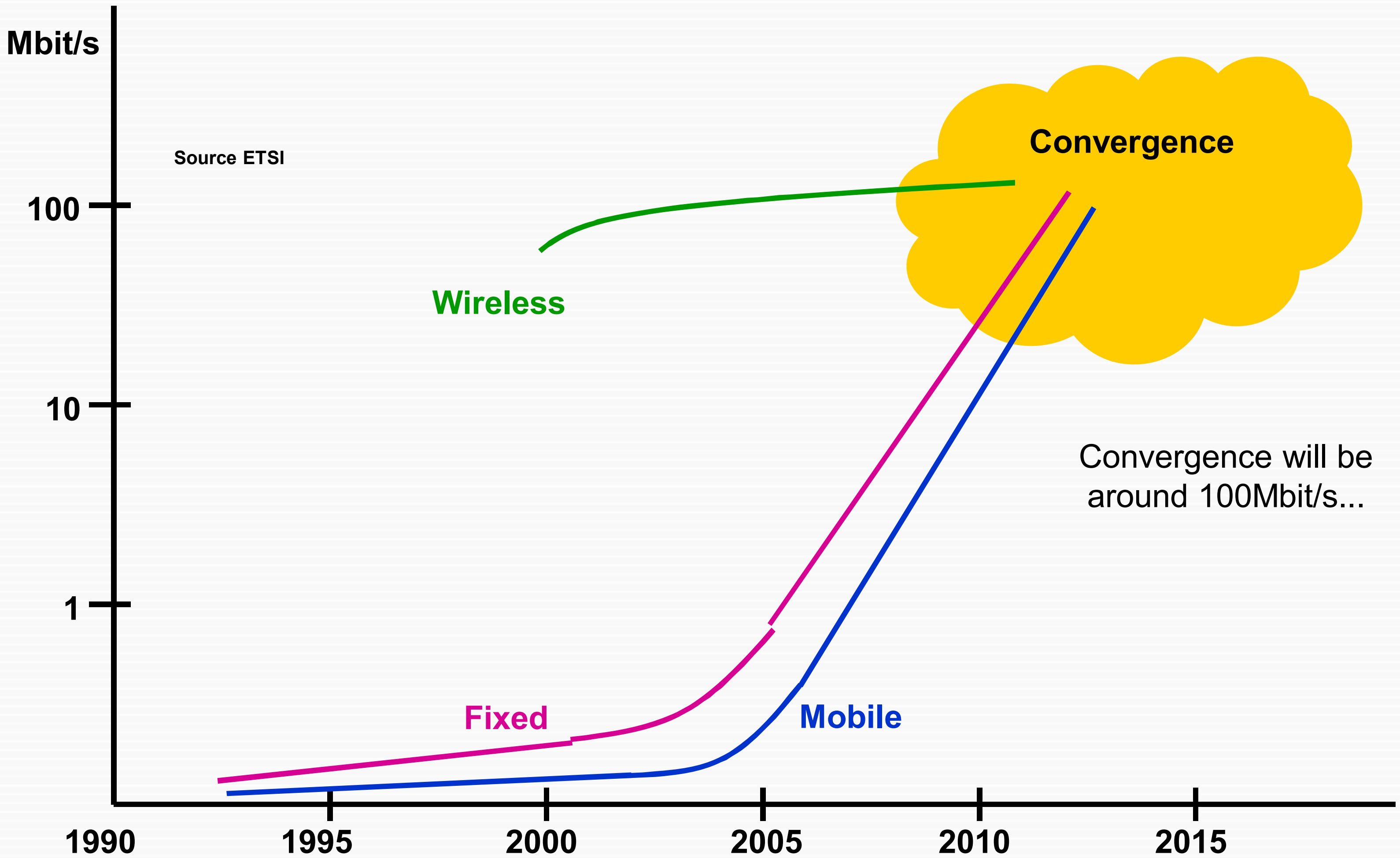


OPTICAL FIBRE

DSL technology uses telephone wires laid in the last century.

Switching to new networks of fibre optic cables is widely viewed as the most appropriate broadband infrastructure for the future.

BIT RATES CONVERGENCE IN ACCESS NETWORKS



Convergence will be around 100Mbit/s...

WHAT ARE THE BUSINESS DRIVERS IN PRESENT DEVELOPMENT?

Drivers are the requirements of networks operators:

- Revenues increasing:
  - New services offering
  - Increasing of productivity of all network technologies
- Decreasing of expenditure
  - CAPEX
  - OPEX

networks technology suppliers and ...

customers .....

One of the direction is „towards optical access networks“

WHAT CAN INCREASE REVENUE?

New services:

- Find the way for creation and distribution of services with high added value.
- Increase of productivity of networks (Wire, Wireless, Opto...).

QUESTIONS CONCERNING EXPENDITURE DECREASING

CAPEX:

- Substitution of SDH systems with OXC a WDM or DWDM needs excellent analyse of new added value (e.g. new service choice, networks and service architecture granularity operation, TDM versus IP,... etc.)

OPEX

- It is needed to put under control intelligence in networks. How it can decrease OPEX for more effective network operation

FUTURE

Optical IP transparence

Dynamic deployment of OXC a WDM

Focus on more fast data transmission

Investing in IP pre signalling and control – GMPLS, IMS

Legacy utilisation where it is possible

Reduction of CAPEX and OPEX

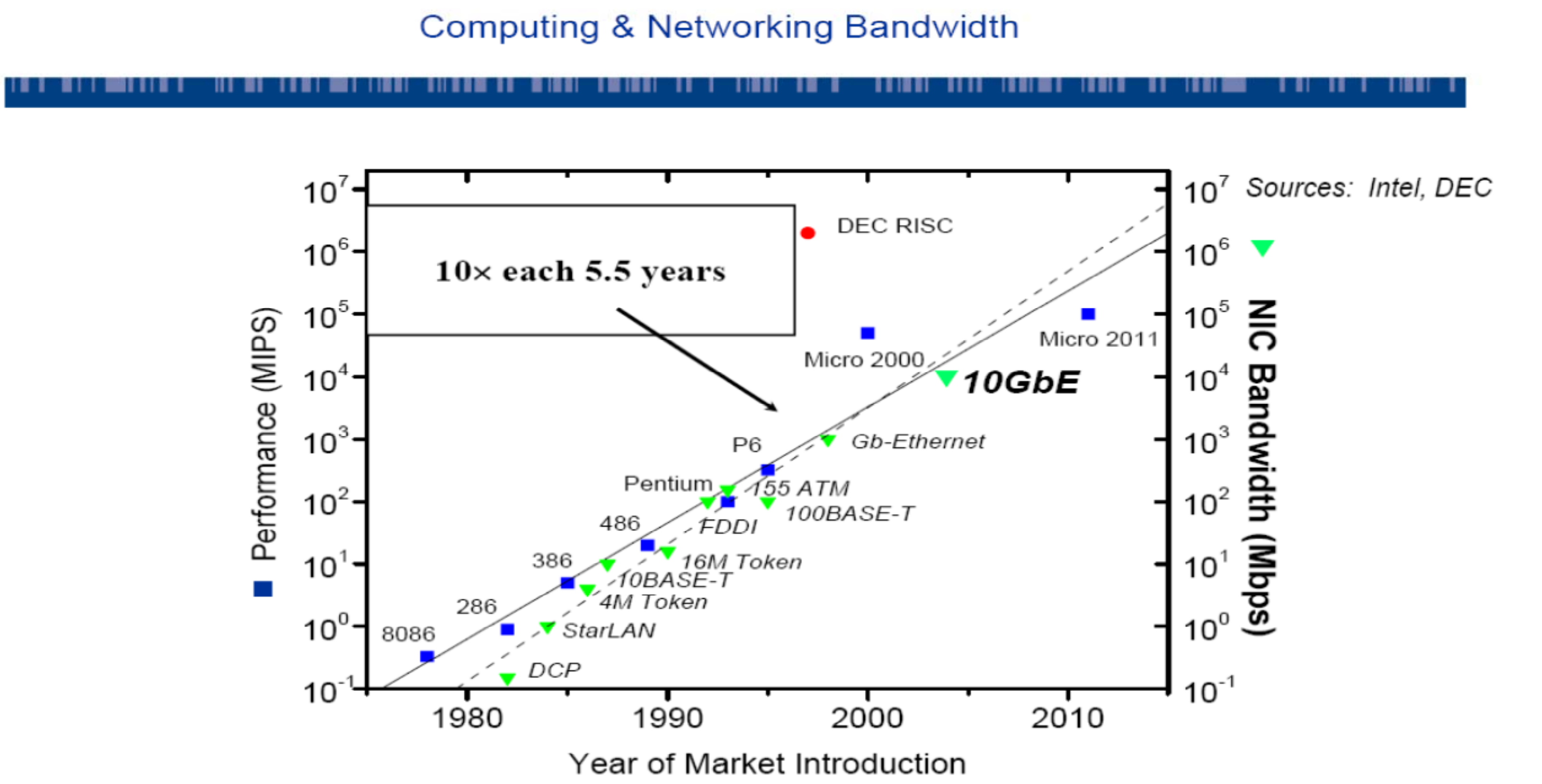
New services with differentiation of QoS

Real near future of optical networks will be in coexistence with other solutions of physical layer whether in GAN, WAN abut mainly in AN.

Looking for economically best and perspective solution is one of the most important tasks of Telco operators at the present and in the future.

COMPUTING AND NETWORKING BANDWIDTH

OFC 2008 KOGELNIK



***Amdahl's Law*: 1 MIPS networked computing power requires 1 Mbps I/O bandwidth**

THANK YOU VERY MUCH FOR YOUR ATTENTION