The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
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SMR 1826 - 9

Preparatory School
to the
Winter College on Fibre Optics, Fibre Lasers and Sensors

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Fiber-Optic Communications

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Fiber-Optic Systems

Basics on Optical Communication Systems
Systems with Optical amplifiers
DWDWM systems
System’s components
System performance

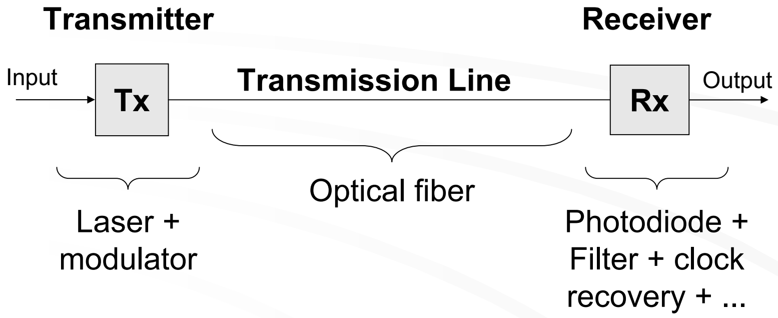
Topics

- Basic system concepts
- Some system components
- System performance
- WDM Systems

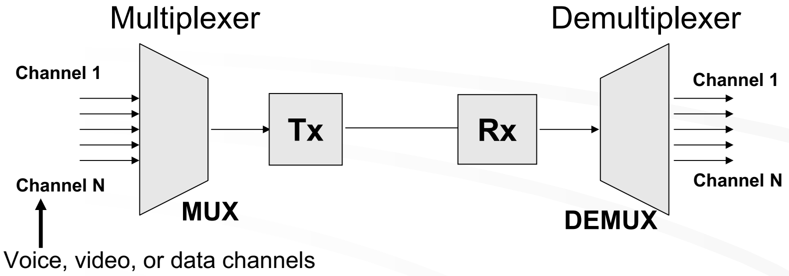
System concepts

Elements of transmission systems
Multiplexing
Modulation Formats
Digital Modulation Keying
TDM standards
Optically amplified systems
WDM systems

Elements of a Communication System



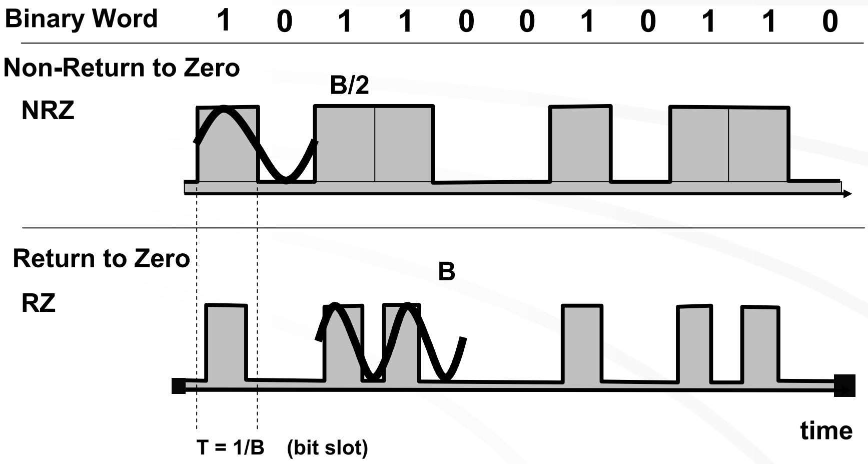
Multiplexing



Multiplexing can be in time domain (TDM), frequency domain (FDM), Polarization (PDM), Wavelength (WDM), ...

TDM = Time Division Multiplexing,
FDM = Frequency Division Multiplexing, …

Digital Modulation Formats



Binary Word 1 0 1 1 0 0 1 0 1 1 0

Non-Return to Zero

NRZ

B/2

Return to Zero

RZ

B

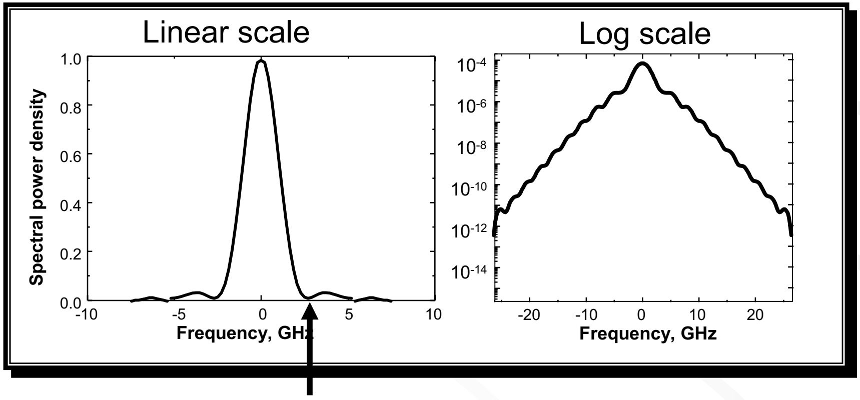
time

T = 1/B (bit slot)

Better for clock recovery

Spectrum of NRZ pulses

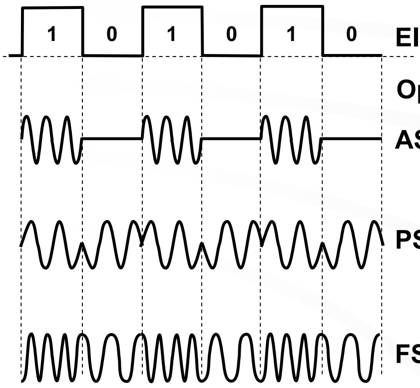
NRZ pulses, 400 ps (2.5 Gb/s)



No Fourier component at f = B (2.5 GHz)

Digital Modulation Keying

Optical field: $E(t) = A(t)\cos[\omega(t)t + \phi(t)]$



Electrical binary data

Optical modulated signal

ASK - Amplitude Shifting Keying:
$A(t) = 0 \text{ or } 1$

PSK - Phase Shifting Keying:
$\phi(t) = -\pi/2 \text{ or } +\pi/2$

FSK - Frequency Shifting Keying:
$\omega(t) = \omega_0 + \delta\omega/2 \text{ or } \omega_0 - \delta\omega/2$

TDM Standards

SONET - Synchronous Optical Network
SDH - Synchronous Digital Hierarchy

SONET	SDH	B(Mb/s)	Channels
OC-1		51.48	672
OC-3	STM-1	155.52	2,016
OC-12	STM-4	622.08	8,064
OC-48	STM-16	2,488.32	32,256
OC-192	STM-64	9,953.28	129,024

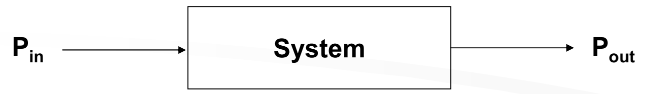
OC = Optical Carrier
STM = Synchronous Transport Mode

Attenuation

Absorption
Scattering
Bending

Decibel units

Input power **Output power**



System Transmission: $T = P_{out}/P_{in}$

$$\boxed{T_{dB} = 10 \log(P_{out}/P_{in})}$$

-10 dB means $P_{out} = P_{in}/10$
-3 dB means $P_{out} = P_{in}/2$
-40 dB means $P_{out} = 10^{-4} P_{in}$

dBm: Power in dB relative to 1 mW

$$\boxed{P_{dBm} = 10 \log (P/mW)}$$

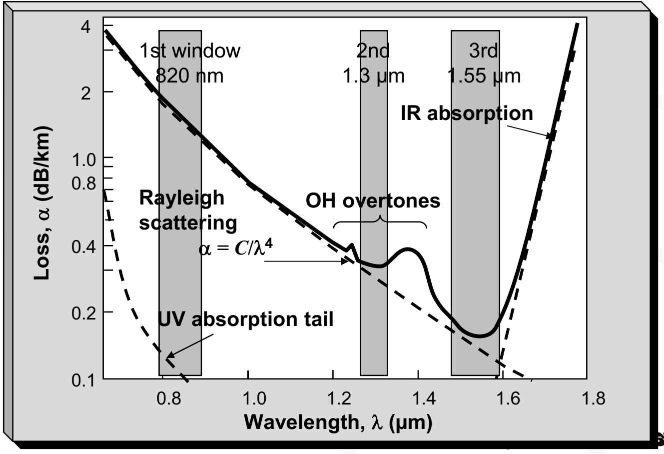
-10 dBm means P = 0.1 mW
3 dBm means P = 2 mW
40 dBm means P = 10 W

$$\boxed{T_{dB} = P_{out} - P_{in}}$$ (P_{in} and P_{out} in dBm)

Attenuation

Optical Power at a distance L: $P(L) = P(0) \times 10^{-\alpha L/10}$

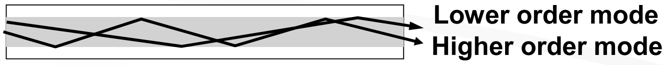
Loss coefficient: α (dB/km) $P_{dBm}(L) = P_{dBm}(0) - \alpha L$

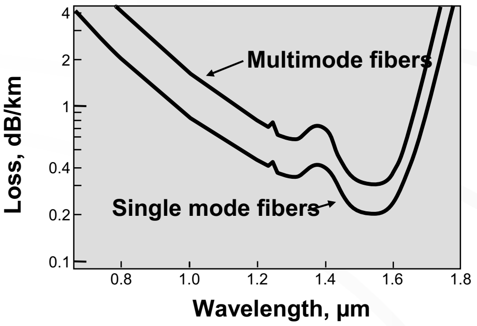


Attenuation of Multi-Mode (MM) and Single Mode (SM) fibers

Multimode (MM) fibers attenuate more than single mode (SM) fibers

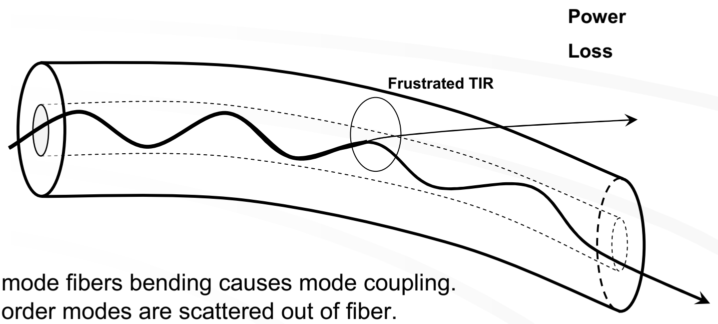
Light in higher order modes travels longer optical paths





Macrobending loss

Shedding of power by the effect of bending

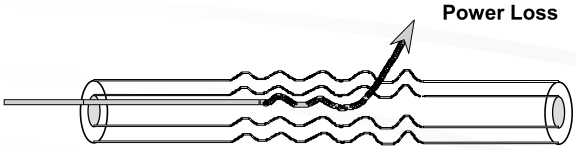


In multimode fibers bending causes mode coupling.
Higher order modes are scattered out of fiber.

In single mode fibers, bending losses are appreciable for curvature radii < 1 cm.

Microbending loss

Scattering loss caused by rugosity of fiber



- **Small axial distortions along the fiber axis**
- **Causes mode mixing and/or loss of optical power**
- **Can be induced by fiber jacketing, cabling, or environment**

Dispersion

Intermodal dispersion

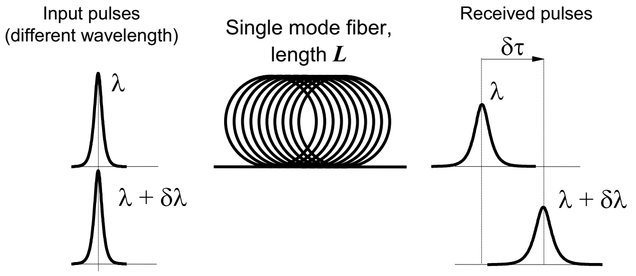
Multimode fibers

Intramodal dispersion

Multimode and singlemode

Dispersion parameter

Measurement of Group Velocity Dispersion (GVD):



$$\boxed{D = \frac{1}{L}\frac{\delta\tau}{\delta\lambda}}$$

Dispersion parameter [ps/nm/km]

Standard SM fibers at 1550 nm: D = 17 (ps/nm)/km

Group Velocity Dispersion (GVD)

Modes propagate as exp($-i\beta z$). **β is the *propagation constant***

Dispersion relation - Taylor series expansion

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

β_1: gives group delay

$$v_{\text{group}} = v_g = 1/\beta_1$$

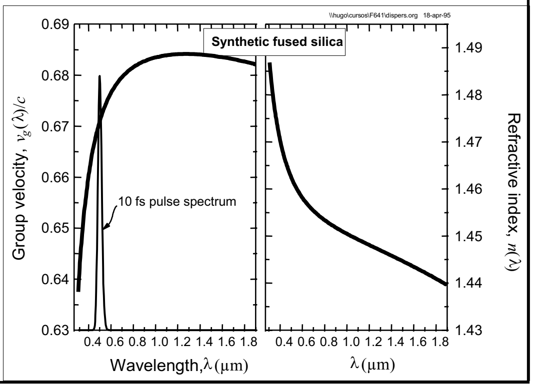
β_2: GVD (Group Velocity dispersion)

$$\beta_2 = \frac{\lambda_0^3}{2\pi c^2}\left(\frac{d^2 n}{d\lambda^2}\right) = -\frac{\lambda_0^2}{2\pi c} D$$

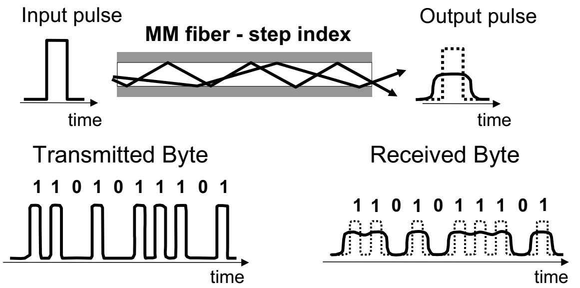
β_3: Third order dispersion coefficient

β_4: Fourth order dispersion coefficient

.....



Modal Dispersion



Dispersion limits the transmission capacity of fiber

Capacity of MM-step-index fibers ≅ 20 Mb/s × km

Dispersion in step index MM fibers

Relation between the propagation constant and frequency is called the Dispersion Relation: $\beta = \beta(\omega)$

Normalized Propagation Constant

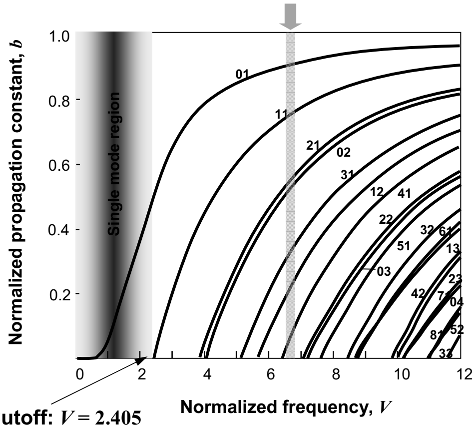
$$b = \frac{(\beta / k_0)^2 - n_2^2}{n_1^2 - n_2^2}$$

Normalized frequency

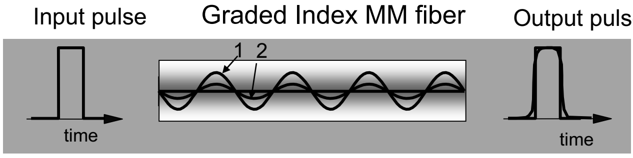
$$V = k_0 a \sqrt{n_1^2 - n_2^2}$$

$$[k_0 = \omega / c = 2\pi / \lambda]$$

At a given frequency, optical field is a superposition of modes, each one with a different propagation constant



Dispersion in graded index MM fibers



- Mode 1 travels a longer *physical* path than mode 2, but through regions of lower index;

$$\text{physical path} = \int d\ell$$

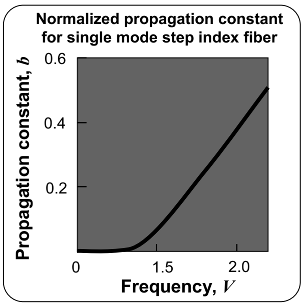
- The *optical* path is approximately the same for both modes.

$$\text{optical path} = \int n d\ell$$

Capacity of MM- graded index fibers $\approx$ 2 Gb/s×km

Dispersion in single mode fibers

- **Chromatic dispersion: group velocity depends on frequency**
  - **Material dispersion: refractive indices depend on frequency**
  - **Waveguide dispersion: boundary conditions depend on frequency**



Normalized propagation constant for single mode step index fiber

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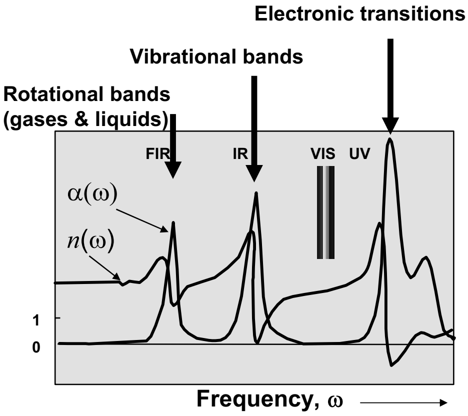
Material dispersion

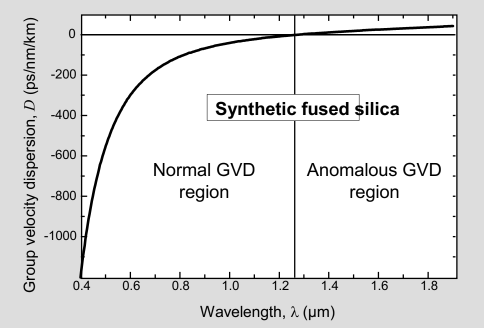
$$\beta(\omega) = \omega n(\omega) / c$$

Refractive index



GVD in silica

Optical fibers for communications are made of silica



Transparent materials exhibit a particular λ_0 where $D(\lambda_0) = 0$.
In pure silica, λ_0 = 1.27 μm (Zero Dispersion Wavelength).

Chromatic dispersion

(another name for GVD)

Group velocity (v_g) depends on λ

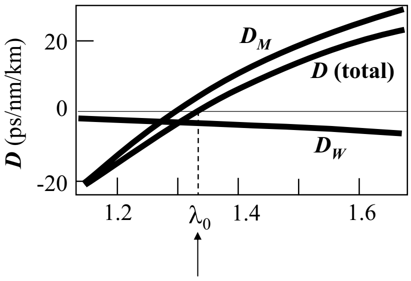
Dispersion parameter:

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi c}{\lambda^2}\frac{d^2\beta}{d\omega^2}$$

$$\boldsymbol{D = D_M + D_W}$$

D_M (Material Dispersion):
n_1 and n_2 depend on λ

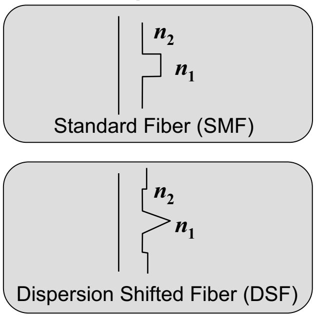
D_W (Waveguide Dispersion):
v_g depends on waveguide geometry



Zero dispersion wavelength

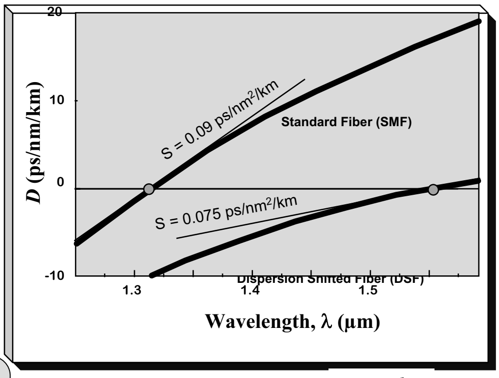
Dispersion Shifted Fibers

Index profile



Standard Fiber (SMF)

Dispersion Shifted Fiber (DSF)



Zero dispersion wavelength (λ_0):

Standard fiber: $\lambda_0 = 1310$ nm
Dispersion Shifted Fiber: $\lambda_0 = 1550$ nm

Dispersion slope: $S = \frac{dD}{d\lambda}$

Fibers for Telecom – Review

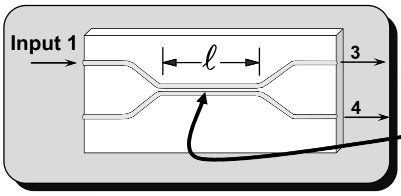
- **Multimode fibers**
  - **Used in local area networks (LANs)**
  - **Capacity limited by intermodal dispersion:**
    - **20 Mb/sxkm (step index)**
    - **2 Gb/sxkm (graded index)**
- **Single Mode Fibers**
  - **Used for long distance**
  - **25 THz bandwidth in 1.55 μm window**
  - **Capacity limited by chromatic dispersion**
  - **Dispersion (D) can be positive, negative or zero**
  - **D = 0 @ 1.3 μm in standard silica fibers**
  - **Waveguide dispersion can be adjusted by index profile**
    - **Dispersion shifted fiber (DSF): D = 0 @ 1.55 μm**
    - **DSF: combines D = 0 and minimum loss**
    - **… so, is DSF the ideal fiber??**
    - **Optical nonlinearities are very large in DSF - See next lectures**

Some system components

Fiber Couplers
Fiber Connectors
Fiber Cables
Fiber pigtailed devices
Lasers
Detectors
Modulators
Integrated optics: Mux
Amplifiers

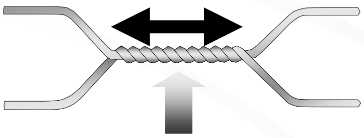
Optical Couplers

Planar waveguide device



Mode coupling through evanescent field

Fiber device

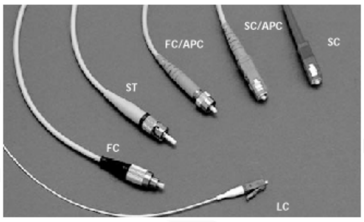


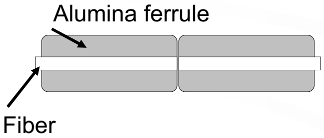
fibers

Fuse and stretch

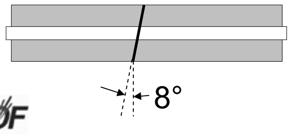
Fiber connectors

- **Various Types**
  - ***FC/PC, SC, LC, SMA, ST***
- **Polishing quality**
  - ***SPC (Super), UPC (Ultra)***





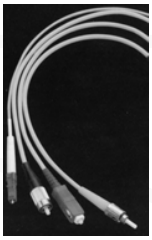
PC = Physical Contact
Insertion loss 0.2 dB
Back reflection –20 dB



APC = Angled Physical Contact
Insertion loss 0.2 dB
Back reflection –40 dB

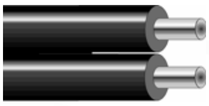
Optical cables for the lab

Simplex



Patch cords

Duplex

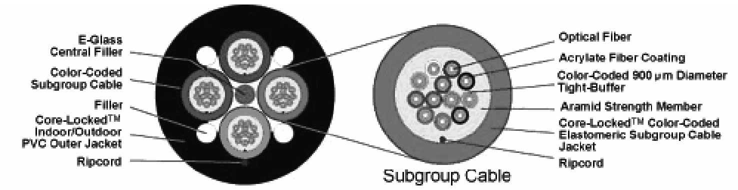


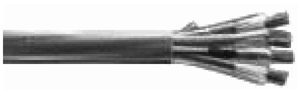
Duplex connectors

DSC

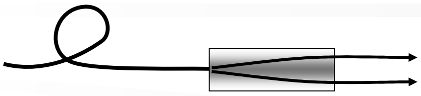
ESCON

Cables

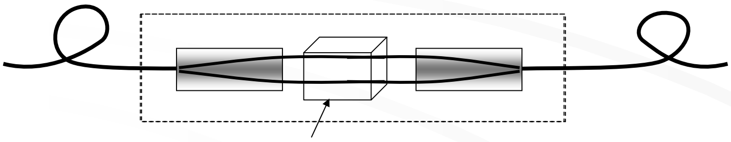




Collimator



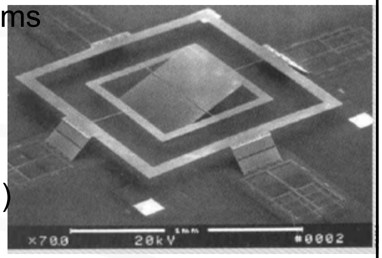
Fiber pigtail Grin lens Collimated light

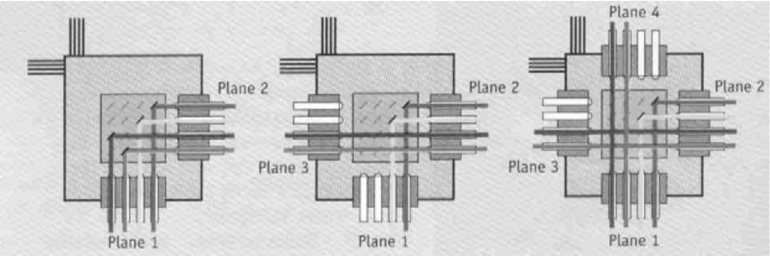


Miniature bulk optics (polarizer, isolator, filter, …anything)

MEMS

- Micro-Electro-Mechanical Systems
  - – Optical Switching
  - – Optical Cross Connect (OXC)

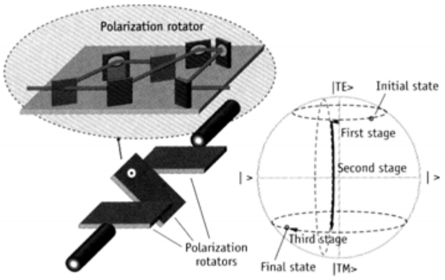




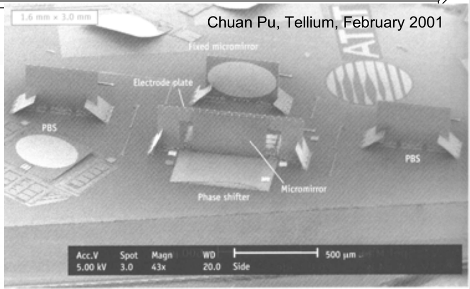
E. Kruglick, WDM, March 2001

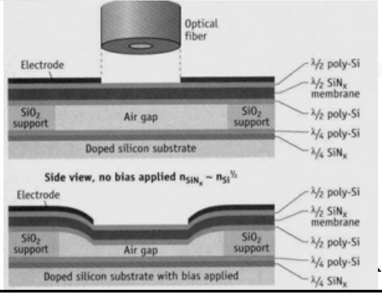
MEMS (2)

- Polarization Rotators



Chuan Pu, Tellium, February 2001





- **Variable reflectivity**

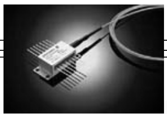
  Gain slope compensation of amplifiers

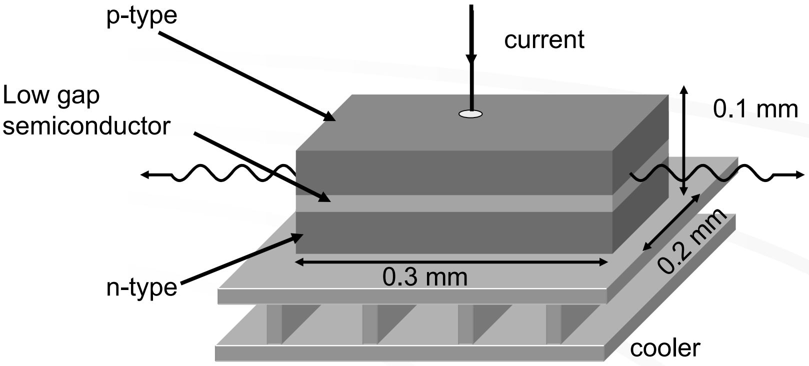
K.W. Goossen, Lucent, October 2000

Lasers for transmission

Semiconductor Diode Laser
Fabry-Perot Laser
DFB

Laser diode





p-type

current

Low gap semiconductor

0.1 mm

0.2 mm

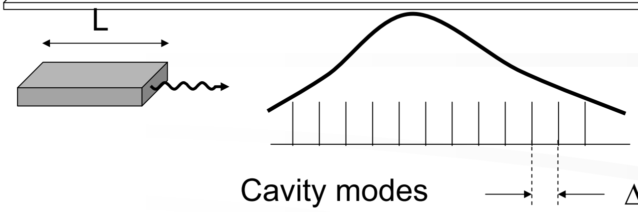
0.3 mm

n-type

cooler

Fabry-Perot (FP) laser cavity

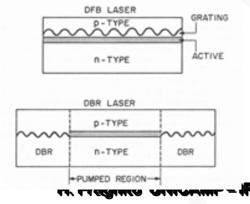
Cavity modes



Cavity modes $\Delta\nu = c/2nL$

Fabry-Perot lasers ~ 30 modes (2-10 nm linewidth)
Mode jumping – Mode partition noise

DFB and DBR lasers: ~ 50 MHz linewidth

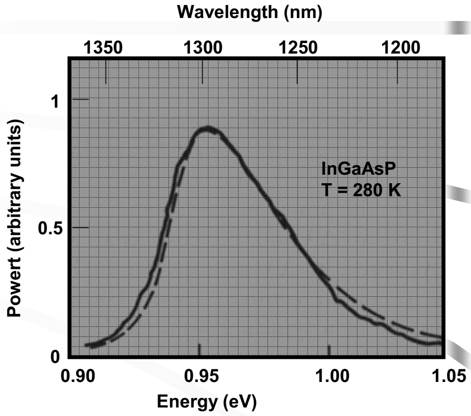


DFB: Distributed Feedback laser

DBR: Distributed Bragg Reflector

Spontaneous emission spectrum

Emission spectrum of LEDs
(Light Emission Diode)



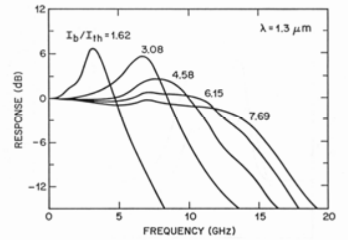
ASE or noise spectrum of Lasers
(Amplified Spontaneous Emission)

Modulation bandwidth and chirp

Direct Modulation

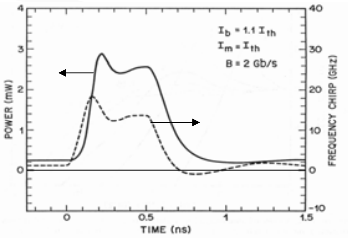
BW limited by

- **carrier diffusion**
- **RC of wiring, contacts, packaging**
- **Relaxation oscillations**



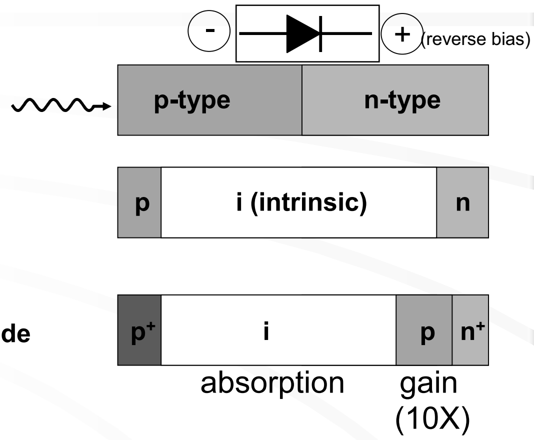
Instantaneous frequency varies (chirp)

- **Dependence of refractive index on injection current (changes effective length of optical cavity)**
- **Positive chirp**



Photodiodes

Photodiodes



- + (reverse bias)

p-n junction

p-type n-type

p-i-n

p i (intrinsic) n

APD avalanche photodiode

p^+ i p n^+

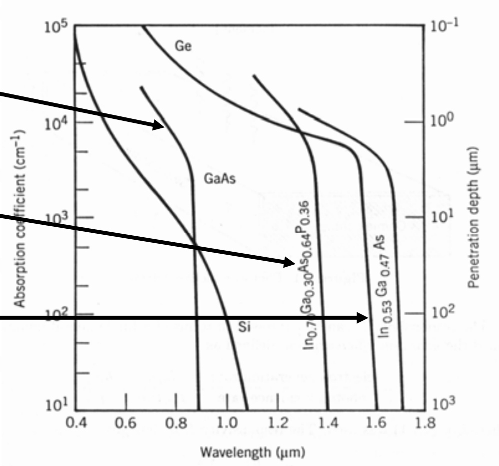
absorption gain (10X)

Materials for Photodiodes

First communications window (830 nm)

Second window (1300 nm)

Third window (1550 nm)



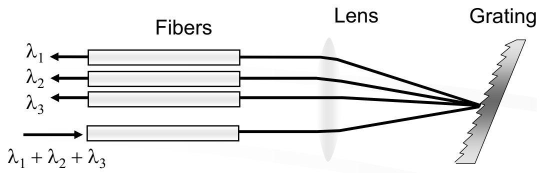
G.P. Agrawal, Fiber-Optic Communication Systems, Wiley, New York (1997)

Photodiode Characteristics

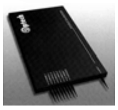
parameter	symbol	unit	**Si**	**Ge**	**InGaAs**
wavelength	λ	nm	400-1100	800-1800	1000-1700
Responsivity	R	A/W	0.5	0.6	0.8
Quantum eff.	η	%	85	50	65
Dark current	I_d	nA	1-10	50-500	1-20
Rise time	t_r	ps	20	100	20
Bandwidth	Δf	GHz	50	30	40
Bias (p-i-n)	V_b	V	50	10	6
Bias (APD)	V_b	V	250	40	30
Gain (APD)	M	-	500	200	10

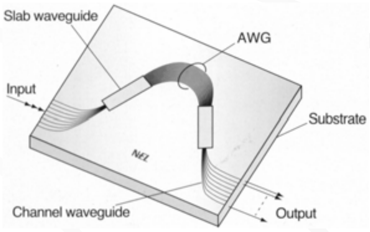
WDM Multiplexers

Free Space Grating MUX



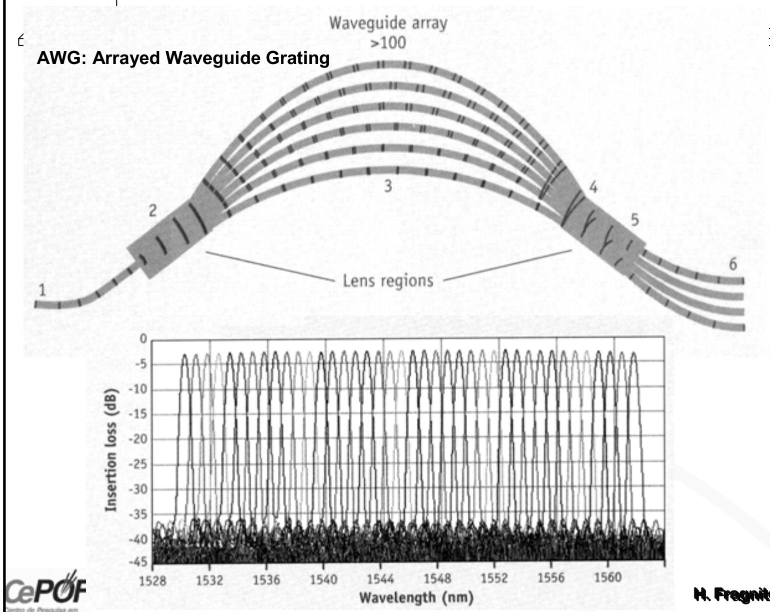
AWG: Arrayed Waveguide Grating





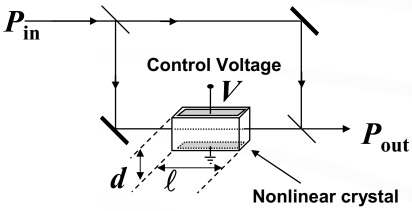
AWG

AWG: Arrayed Waveguide Grating



Modulators

Electro-Optic Switch



$P_{out} = P_{in}\,(1+\cos\Delta\phi)/2$

Refractive index change:

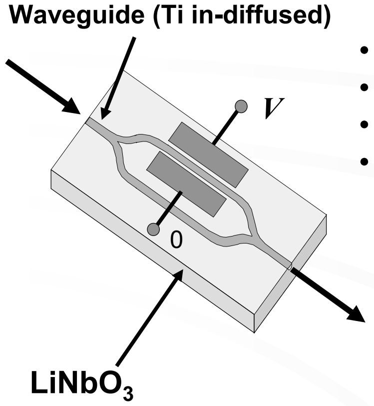
$$\Delta n = -\tfrac{1}{2} r n^3 (V/d)$$

r = EO - coefficient

$$\Delta\phi = \pi V / V_\pi$$

Switching voltage: $$V_\pi = \frac{\lambda d}{r n^3 \ell}$$

Waveguide Electro-Optic Switch



- Mach-Zehnder
- Switching voltage: 5 - 8 V
- Integrated optics
- Fiber pigtail

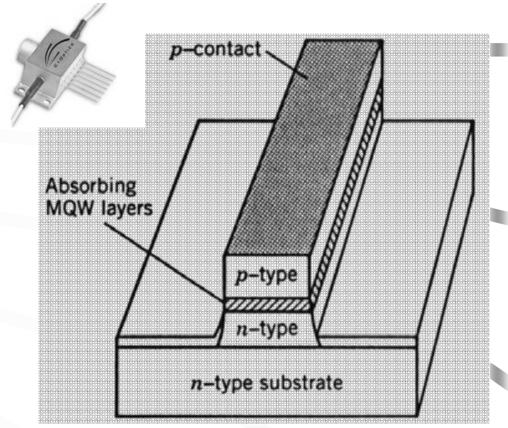
Electroabsorption modulator

Franz-Keldysh effect
50 GHz, 2V

Energy gap of semiconductors depends on applied electric field

Effect is enhanced in Multiple Quantum Wells

Integrated with laser in the same chip



G.P. Agrawal, Fiber-Optic Communication Systems, Wiley, New York (1997)

Direct versus External Modulation

Direct modulation

$I(t)$

laser

Broad spectral source

External modulation

$V(t)$

laser

modulator

Transform limited pulses

$$\sigma_t = LD\sigma_\lambda$$

Examples: D = 17 ps/nm/km; λ = 1550 nm

Fabry-Perot Laser:
σ_λ = 2 nm $\Rightarrow D\sigma_\lambda$ = 34 ps/km

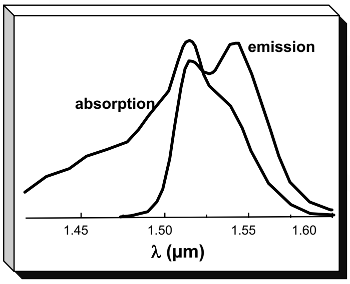
DFB Laser: (σ_ν = 20 MHz)
σ_λ = 0.16 pm $\Rightarrow D\sigma_\lambda$ = 0.003 ps/km
But frequency chirp at 2.5 Gb/s modulation is ~ 20 GHz:
σ_λ = 0.17 nm $\Rightarrow D\sigma_\lambda$ = 2.7 ps/km

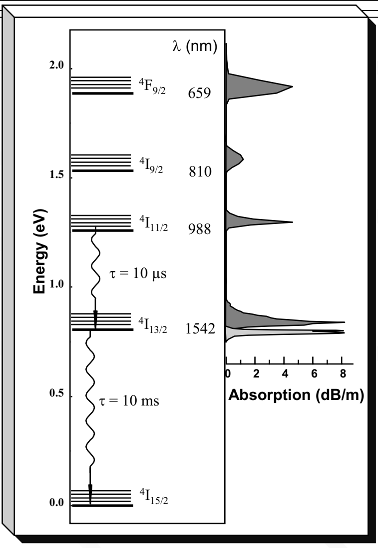
Bandwidth limited pulses:
B = 2.5 Gb/s $\Rightarrow D\sigma_\lambda$ = 0.34 ps/km
B = 10 Gb/s $\Rightarrow D\sigma_\lambda$ = 1.4 ps/km
B = 40 Gb/s $\Rightarrow D\sigma_\lambda$ = 5.5 ps/km

Optical Amplifiers

Er^{+3} energy levels

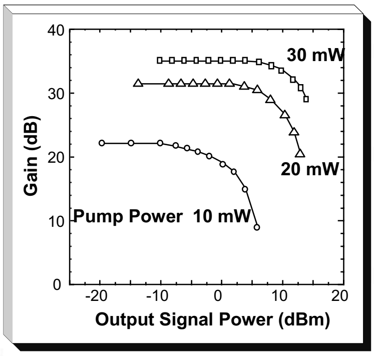
- Pump:
  - 980 nm or 1.48 µm
  - pump power > 5 mW
- Emission:
  - 1.52 - 1.57 µm
  - long living upper state (10 ms)
  - gain ≈ 30 dB

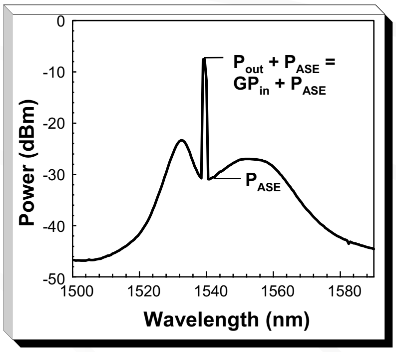




Gain Saturation and Noise of EDFA

- **Signal to Noise Ratio (SNR) degradation**
  Due to Amplified Spontaneous Emission (ASE)
- **Noise Figure: NF = SNR_{in}/SNR_{out} > 3 dB**





SOA

Semiconductor Optical Amplifier

Laser diode with antireflection coating

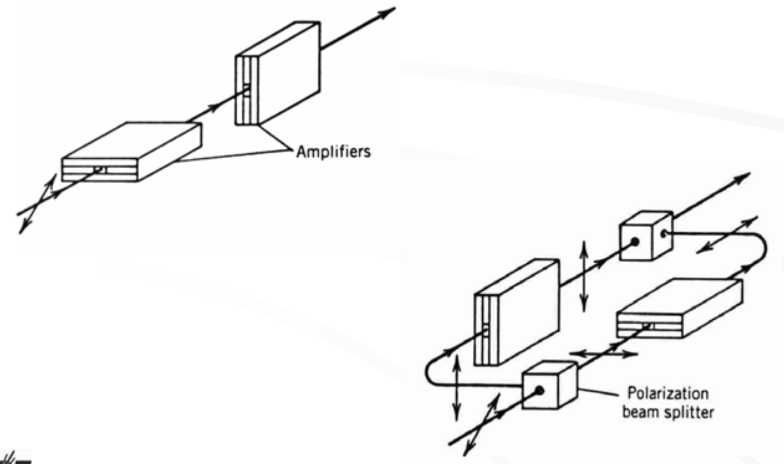
Fast response (recombination time) ~ ns

Very sensitive to light polarization
(PDG: polarization dependent gain)

Wide bandwidth

Operation in 1300 nm or 1500 nm windows

PDG compensation in SOAs



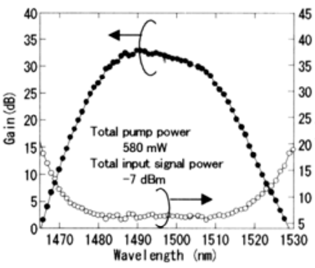
G.P. Agrawal, Fiber-Optic Communication Systems, Wiley, New York (1997)

Thulium Doped Fiber Amplifiers

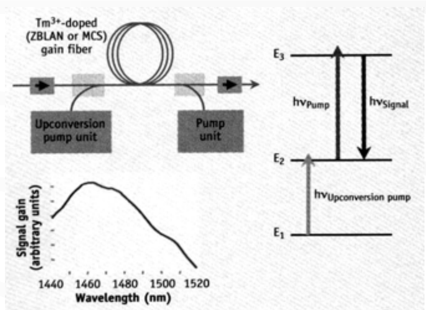
1440-1480 nm normal

1480-1510 nm gain shifted

Special host glass



A. Aozasa et. al., OFC´2001, PD1, March 2001



M. Islam and M. Nietubyct.WDM, March 2001

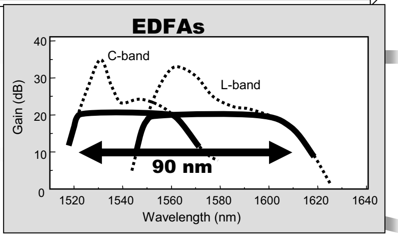
Optical Amplifiers

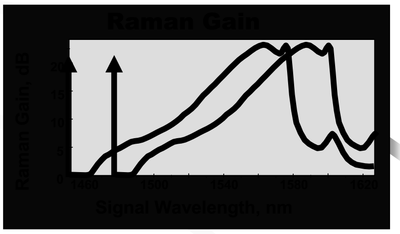
EDFA (1500-1620 nm) Erbium

TDFA (1440-1510 nm) Thulium

SOA (60 nm bandwidth)
Semiconductor Optical Amplifier

Raman Amplifiers (40 nm bandwidth; choice of spectral region)

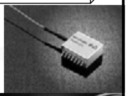


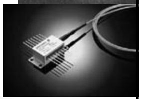


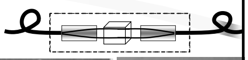
Limited by Nature to ~ 100 nm
Physics: Quantum energy levels
Chemistry: Special materials

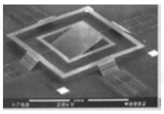
Components REVIEW

- **Lasers and photodiodes**
  - **Linewidth depends on laser type:**
    - **Fabry-Perot: 2-8 nm (1 THz)**
    - **DFB: 50 MHz (0.00005 nm)**
  - **Modulation bandwidth to 20 GHz but chirp may be a problem**
  - **Avalanche photodiodes provide gain**
  - **p-i-n photodiodes respond to 50 GHz**
- **integrated, waveguide devices (ex. AWG MUX)**
  - **Compact, highly stable devices**
- **High speed modulators:**
  - **electro-optic (Lithium Niobate)**
  - **electroabsorption (Semiconductor)**
- **Optical Amplifiers:**
  - **EDFA: 35 nm bandwidth, NF = 4-6 dB, τ = 10 ms**
  - **L-band EDFA: 1560-1610 nm**
  - **SOAs: Compact and inexpensive, but polarization dependent and τ = ns**
  - **Raman: 40-100 nm bandwidth, we can choose the gain region**
  - **Other Rare earths: Thulium (S-band), Praseodymium (1300 nm band),…**









System performance

Power Budget
Detection
BER and Q factor
Eye diagram

Power budget

System design

(dB units)

$$P_{RX} = P_{TX} - \alpha L - N_{\mathrm{splices}}\eta_{\mathrm{splice}} - \text{System margin}$$

Average splicing insertion loss

2 – 5 dB (aging)

Dispersion

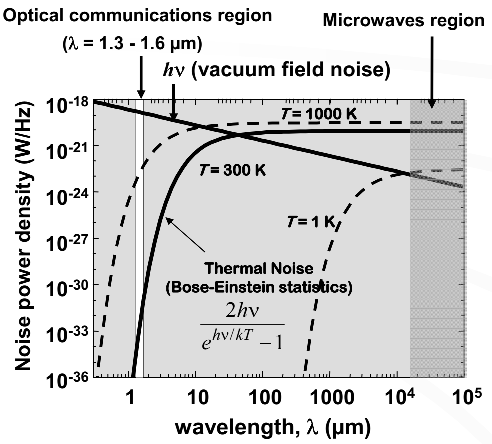
Keep pulse duration < 1.25 T (T = 1/B = “bit slot”)

$\sigma_{\lambda} D L B < 0.25$

Attenuation and dispersion can be compensated with optical amplifiers and dispersion compensators

What about noise?

Optical Field Noise



At optical telecom frequencies:

quantum fluctuations of vacuum field >> thermal noise (even at 1273 ºC)

In practice, thermal noise of electronic part of receiver dominates

---

Photodetection noise

Total current $$I_1 = \underbrace{(\eta e / h\nu)}_{\text{Responsivity (A/W)}} P + i_S + i_T + i_d$$

P = optical power (W)

Dark current

Thermal noise

Shot noise

Signal photocurrent

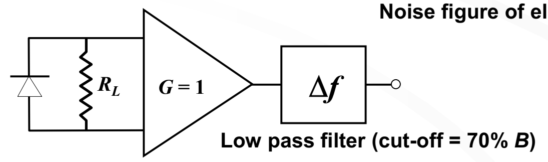
Shot noise $$\sigma_S^2 = \left\langle i_S^2 \right\rangle = 2eI_1\Delta f$$

Thermal noise $$\sigma_T^2 = \frac{4kT}{R_L} F_N \Delta f$$

Noise figure of electrical amplifier

In practice…

$\sigma_T >> \sigma_S$

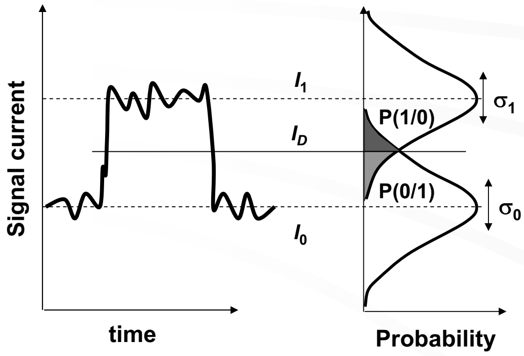


Low pass filter (cut-off = 70% *B*)

BER

Bit Error Rate

$$BER = p(1)\,P(0/1) + p(0)\,P(1/0)$$



Q parameter

$$Q = \frac{I_1 - I_D}{\sigma_1}$$

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$$

Q ~ Signal/Noise

I_D = decision threshold

$$I_D = \frac{\sigma_1 I_1 + \sigma_0 I_0}{\sigma_1 + \sigma_0}$$ **optimum**

BER for Gaussian random processes

IF fluctuations around I_1 and I_0 follow Gaussian distributions

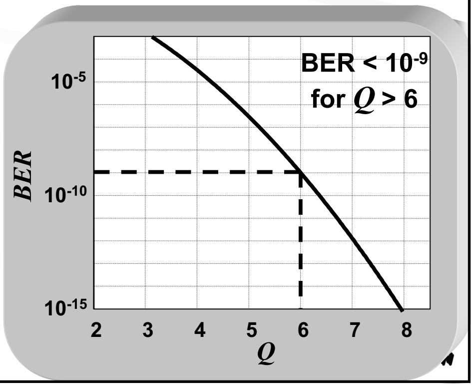
AND (optimum) decision threshold $I_D = \frac{\sigma_1 I_1 + \sigma_0 I_0}{\sigma_1 + \sigma_0}$

THEN

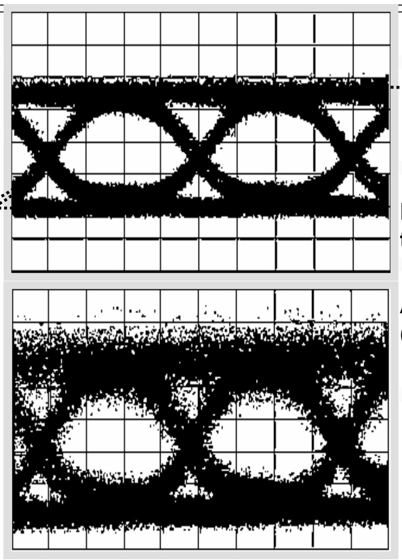
$$\mathrm{BER} \cong \frac{\exp(-Q^2/2)}{Q\sqrt{2\pi}}$$

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$$ **Q parameter**

$Q^2 \approx SNR/2$
(Electrical signal-to-noise ratio)



Eye diagram



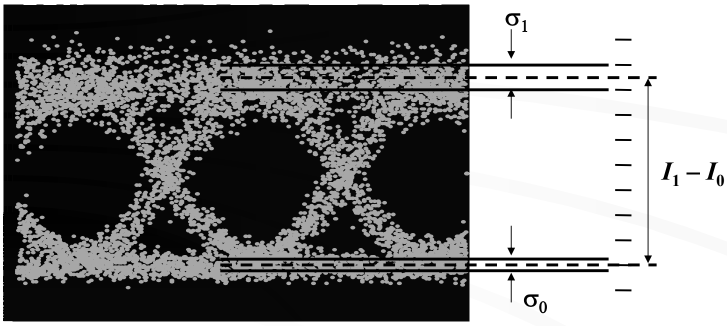
10 Gb/s NRZ
2^{15}-1 PRBS

Before transmission

After transmission (DSF 80 km)

25 ps/div

Using the eye diagram



$$Q = (I_1 - I_0)/(\sigma_1 + \sigma_0) \approx 7/(1+0.5) = 5 \quad (\Rightarrow BER \approx 10^{-7})$$

System Performance REVIEW

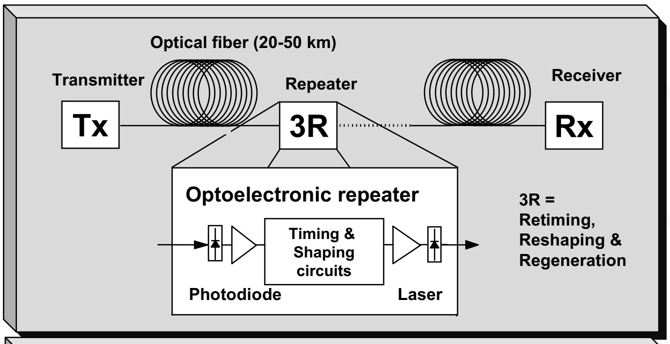
- **Noise in optical field gives shot noise, but in photodetected, electrical signals, thermal noise dominates**
- **Eye diagram is a powerful tool for system diagnostics**
  - **BER is determined by Q factor ($Q^2 \sim SNR/2$)**
  - **BER < 10^{-9} for Q > 6**
- **What are the physical limits of fiber optic transmission systems?**
  - **Attenuation?**
  - **Dispersion?**
  - **Nonlinearities?**

WDM Systems

Traditional Systems – 3R
Optically Amplified systems
WDM

Traditional Optical Communication System

Loss compensation: Repeaters at every 20-50 km

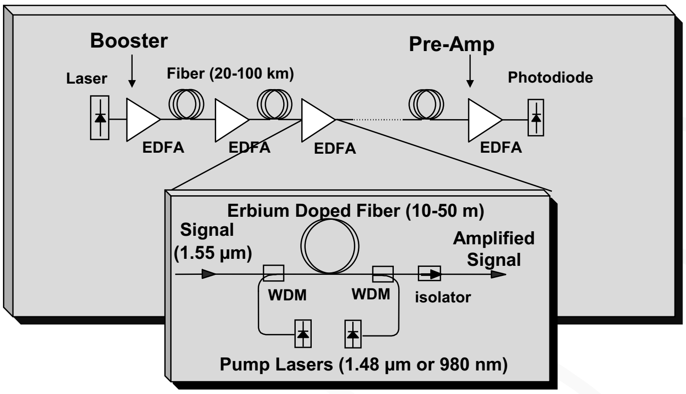


3R =
Retiming,
Reshaping &
Regeneration

System capacity limited by speed of electronic circuits

Optically Amplified Systems

EDFA = Erbium Doped Fiber Amplifier



Bits continue in photonic format

Characteristics of EDFA based Systems

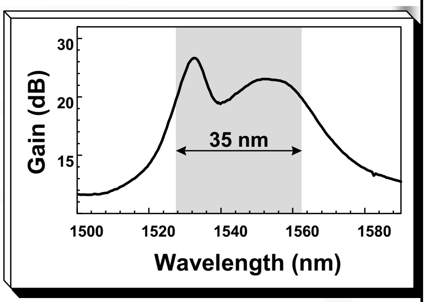
Bandwidth > 4 THz
depends on glass host
(100 nm in Telurite glass)

Low noise
NF ~ 4 – 7 dB

Optical power > 10 mW
larger distance between EDFAs

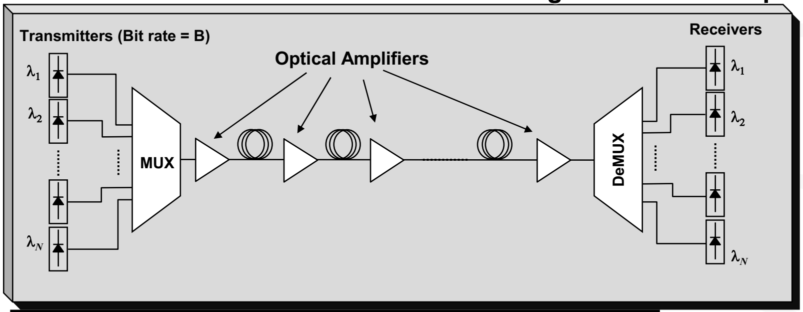
Transparent to bit rate, modulation format, and bit coding

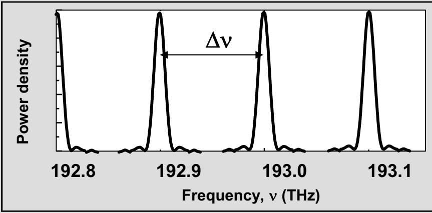
Ideal for WDM
(Wavelength Division Multiplexing)



DWDM Systems

DWDM = Dense Wavelength Division Multiplexing





$\Delta\nu$ = 100 GHz, 50 GHz, (up to 40 Gb/s) DWDM

25 GHz, or 12.5 GHz (up to 10 Gb/s) UDWDM (Ultra Dense)

ITU grid

$\nu_n = \nu_0 + n\Delta\nu$

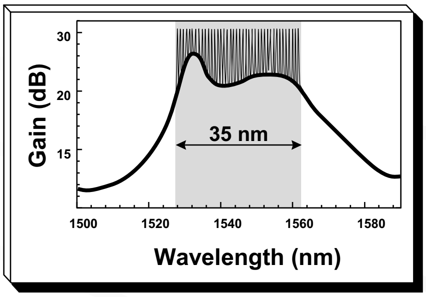
ν_0 = 193.1 THz (1552.52 nm)

($n = 0, \pm1, \pm2, \ldots$)

Bandwidth of WDM systems with EDFAs

EDFA = Erbium Doped Fiber Amplifier
C band (1530-1560 nm)

- **4 THz Optical Bandwidth**
- **80 WDM channels x 40 Gb/s**
  (50 GHz channel spacing)
- **Total capacity: 3.2 Tb/s**
- **Important issues:**
  - **Bandwidth**
  - **Gain flatness**
  - **Output power**



Capacity of DWDM systems determined by bandwidth of optical amplifiers

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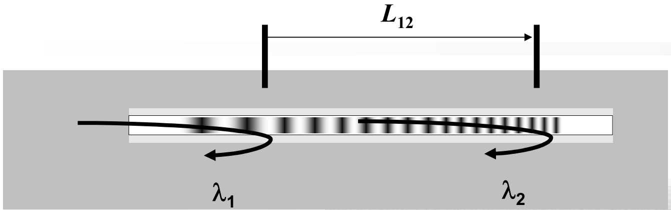
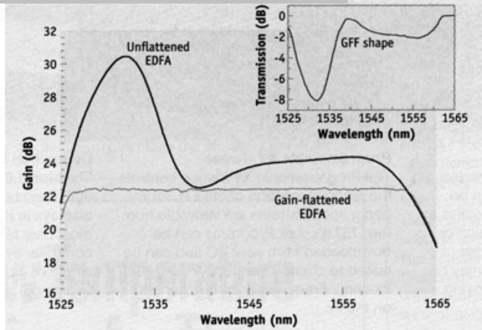
Chirped Fiber Bragg Gratings



- **Dispersion compensation**
  Optical Delay $\tau_{12} = nL_{12}/c$
- **Gain flattening**
  (varying index modulation)



M. Guy and F. Trépanier, WDM, March 2001

Systems Concepts REVIEW

- Optical Communication system use several Multiplexing techniques, all include TDM (Time Division Multiplexing)
  - TDM standards (SONET, SDH): ex. OC-192 = STM-64 = 10 Gb/s
  - Modulation is ISK – Intensity Shifted Keying and NRZ format
- DWDM systems use Gb/s lasers at different lambdas
  - Aggregated bit rate = NxB
  - Channel spacing 50-100 GHz; ITU grid
  - Total optical bandwidth limited by bandwidth of optical amplifiers
  - Total power NxP (nonlinear optical effects are important)

Where to get more information

- G.P. Agrawal, *Fiber-Optic Communication Systems*, 2nd ed., J. Wiley & Sons, New York (1998).
- *Lightwave Magazine*, PennWell, free subscription: http://lw.pennnet.com/home.cfm
- B.E.A. Saleh and M.C. Teich, *Fundamentals of Photonics*, Wiley, New York, 1991.
- K. Iizuka, *Elements of Photonics*, Vol. II: For fiber and integrated optics, Wiley, New York, 2002.
- G. Keiser, *Optical Fiber Communications*, 2nd ed., Mc Graw Hill, New York, 1991.
- J.A. Buck, *Fundamentals of optical Fibers*, Wiley, New York, 1995.
- *Journal of Lightwave Technology* 24(12), special issue, Dec. 2006.