全光通信网

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2006年秋

北京交通大学

参考资料

光纤通信技术 孙学康 张金菊，人民邮电出版社，2004

光传送网 顾畹仪等，机械工业出版社，2003

光纤通信系统 王秉钧 王少勇，电子工业出版社，2004

全光光纤通信网 杨淑雯，科学出版社，2004

全光网络 张宝富等，人民邮电出版社，2002

光纤通信技术 D.K.Mynbaev & L.L.Scheiner,科学出版社，2002

课程考核要求

平时成绩**30%,** 考试（或考察）**70**％。


TransPAC/10Gb

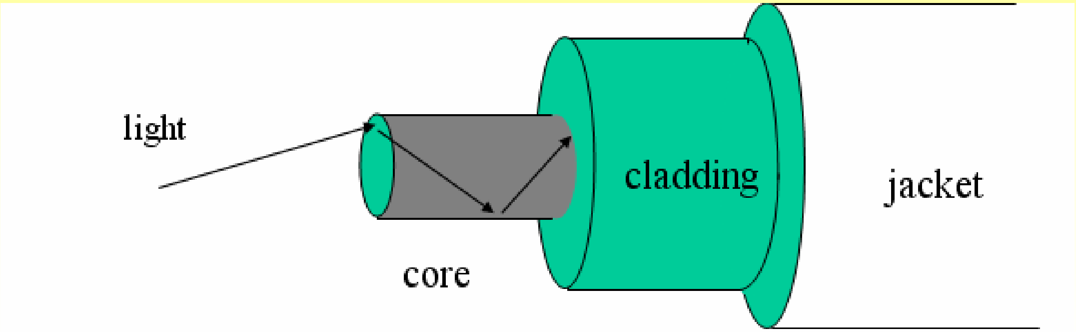
主要内容

- 光纤传输技术
- 光纤通信网
- 核心器件与功能模块
- 全光网实现方式

第一部分 光纤传输技术

- 光纤的传输特性
- 数字光纤传输技术

通信光纤



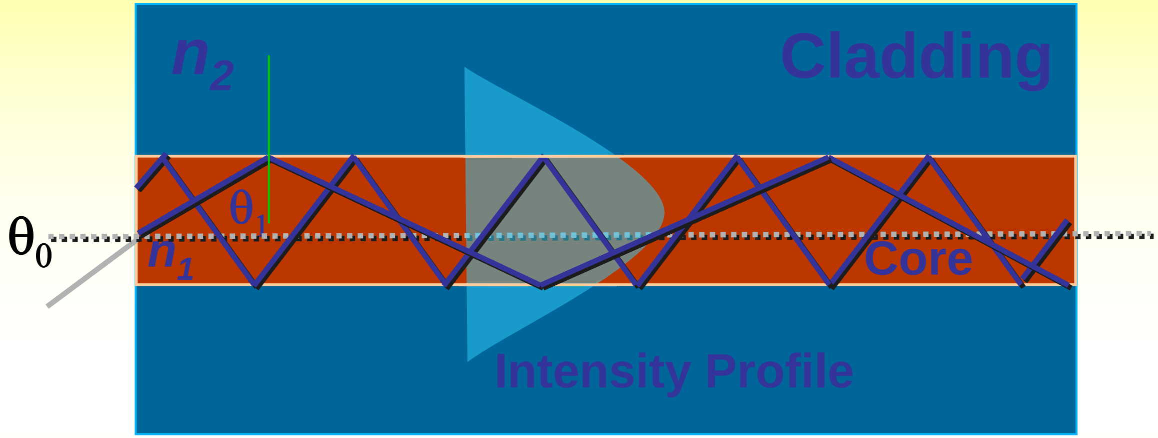
芯区：SiO_2:Ge，

直径：单模光纤9μm，多模光纤50～62.5μm

包层：纯SiO_2，直径125μm

涂覆层：树脂，直径250μm

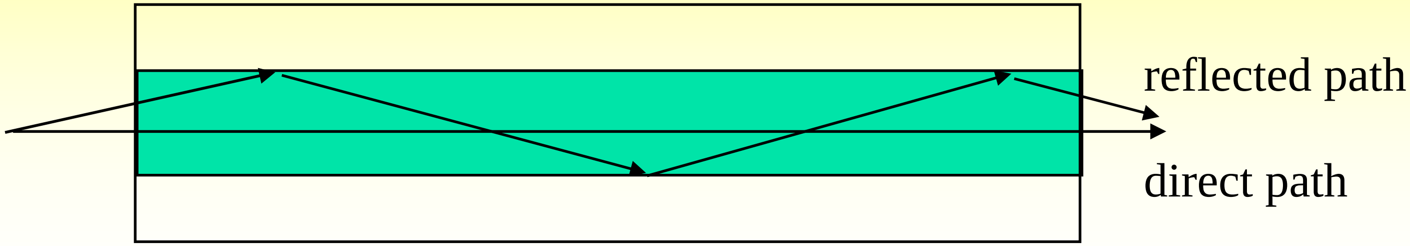
Propagation in Fiber



- Light propagates by total internal reflections at the core-cladding interface
- A light ray traveling in fiber must interfere constructively with itself to propagate successfully
- Each allowed ray is a mode

多模光纤和单模光纤

Multimode fiber: **multiple rays follow different paths**

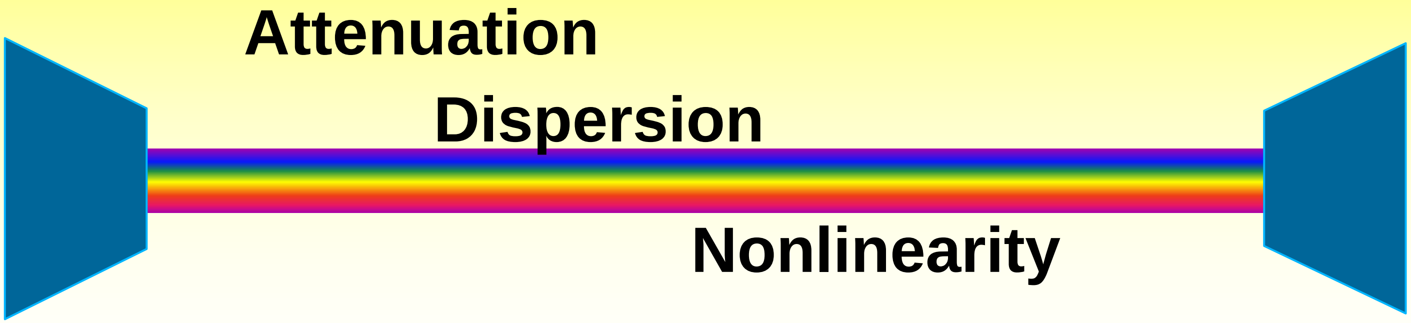


优点：芯径大，易于光耦合。缺点：模间色散。
BL～500 MHz-km，适用于低速短距离系统

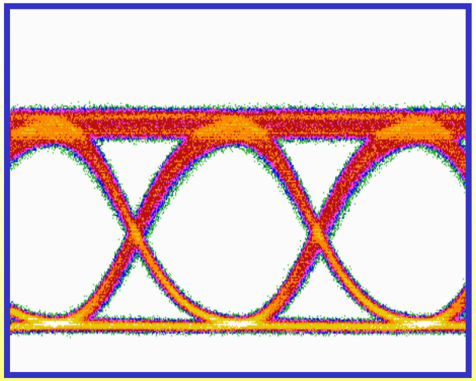
Single mode fiber: **only direct path propagates in fiber**

优点：无模间色散。缺点：不易于光耦合。
BL～100 THz-km，适用于高速信号的长距离传输

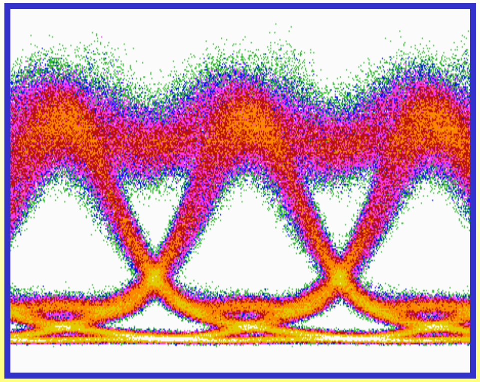
Fiber Fundamentals



Distortion

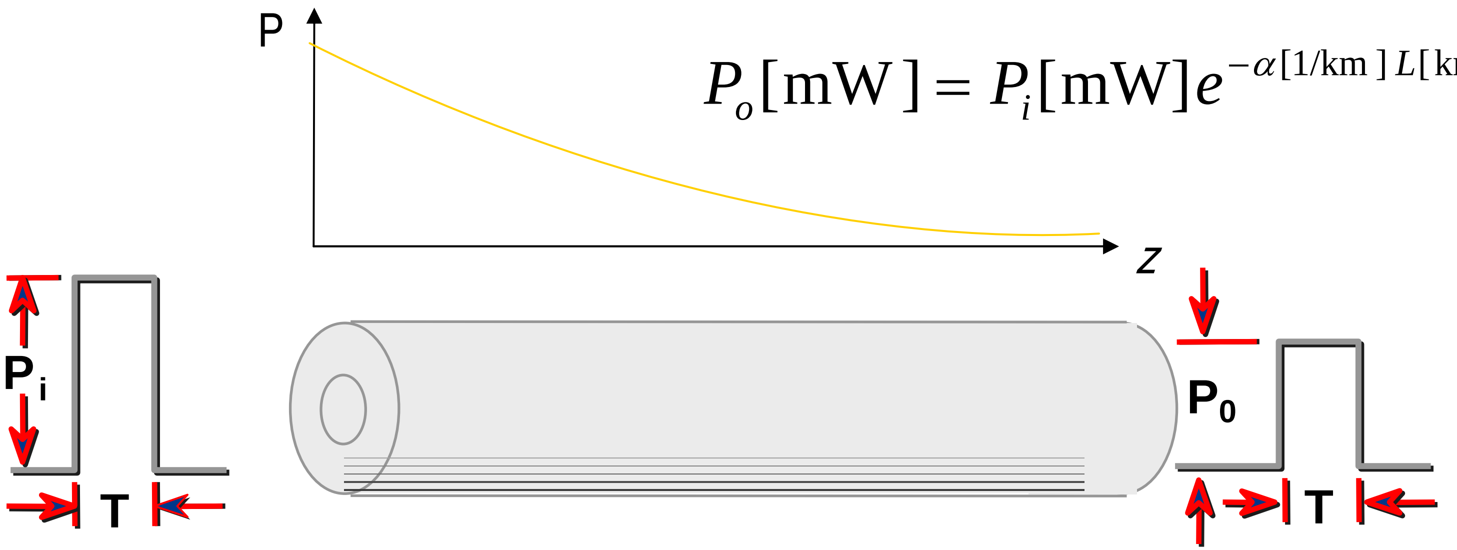


Transmitted Data Waveform



Waveform After 1000 Km

光纤损耗



$$P_o[\mathrm{mW}] = P_i[\mathrm{mW}]e^{-\alpha[1/\mathrm{km}]L[\mathrm{km}]}$$

以**1mW**为参考值的光功率分贝表示：$P[\mathrm{dBm}] = 10\lg P[\mathrm{mW}]$

$$P_o[\mathrm{dBm}] = P_i[\mathrm{dBm}] - (10\lg e)\alpha[1/\mathrm{km}]L[\mathrm{km}]$$

$$= P_i[\mathrm{dBm}] - \alpha[\mathrm{dB/km}]L[\mathrm{km}]$$

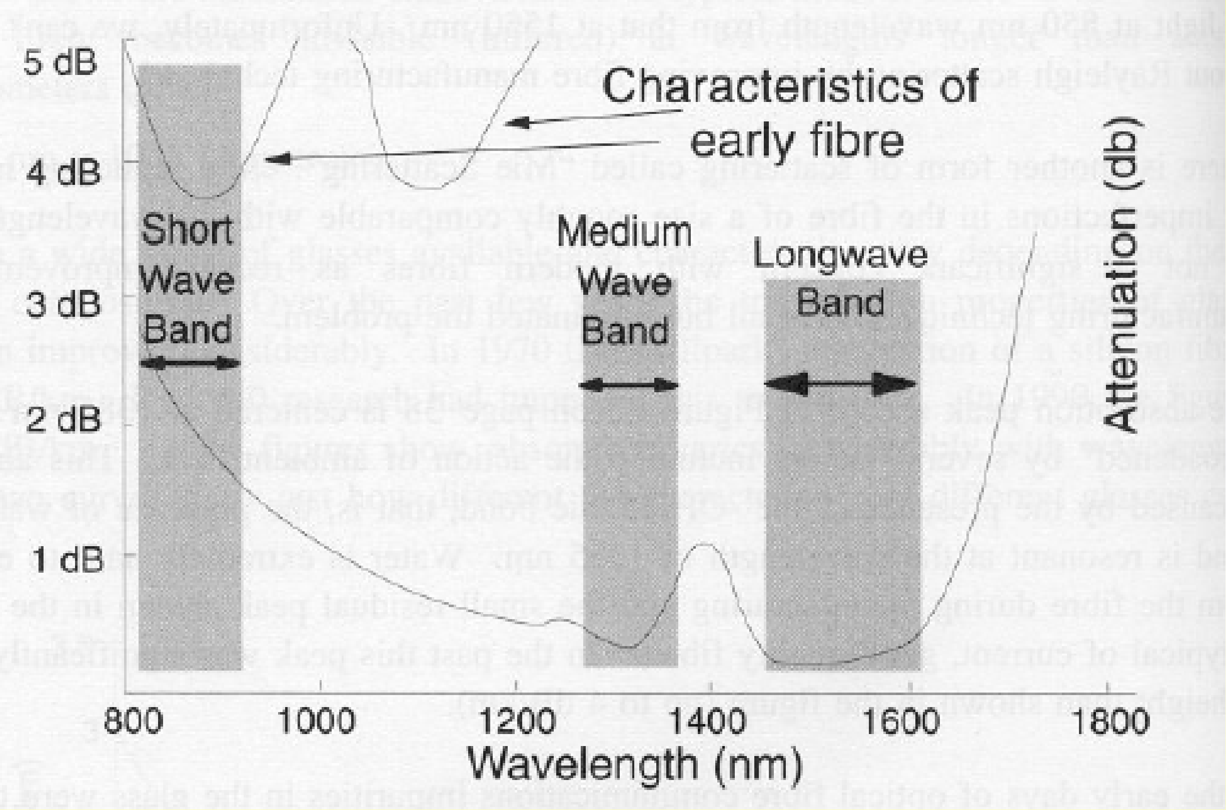
光纤损耗的分贝表示：

$$\alpha[\mathrm{dB/km}] = (10\lg e)\alpha[1/\mathrm{km}] = 4.343\alpha[1/\mathrm{km}]$$

Example

10dBm	10 mW
3dBm	5 mW
0 dBm	1 mW
-3 dBm	500 uW
-10 dBm	100 uW
-30 dBm	1 uW

光纤损耗谱



低损耗传输带宽超过**50THz**

新型的无水光纤和**O**同位素光纤带宽可达数百～上千**THz**

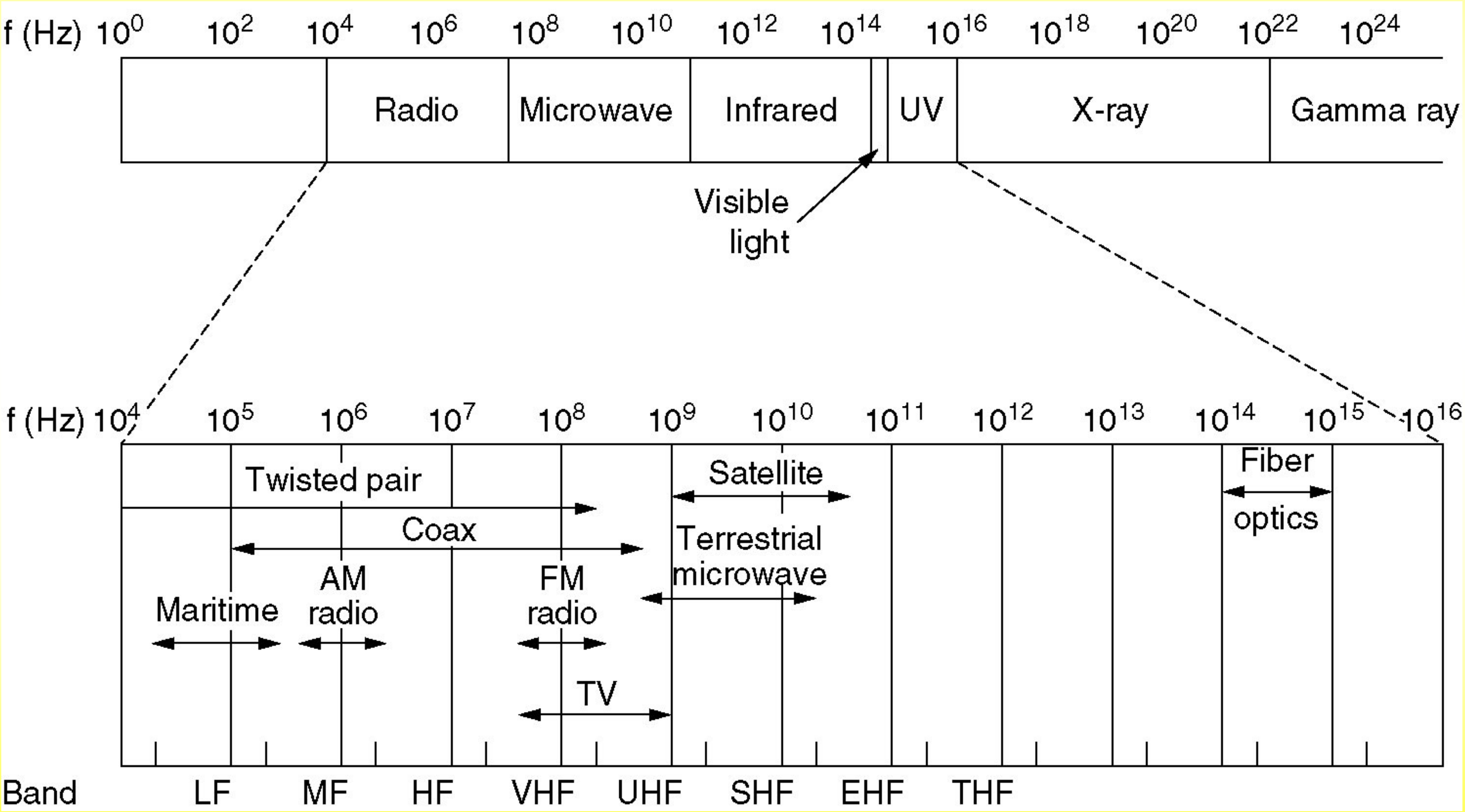
石英光纤的纯度Glass Purity

Fiber Optics Requires Very High Purity Glass

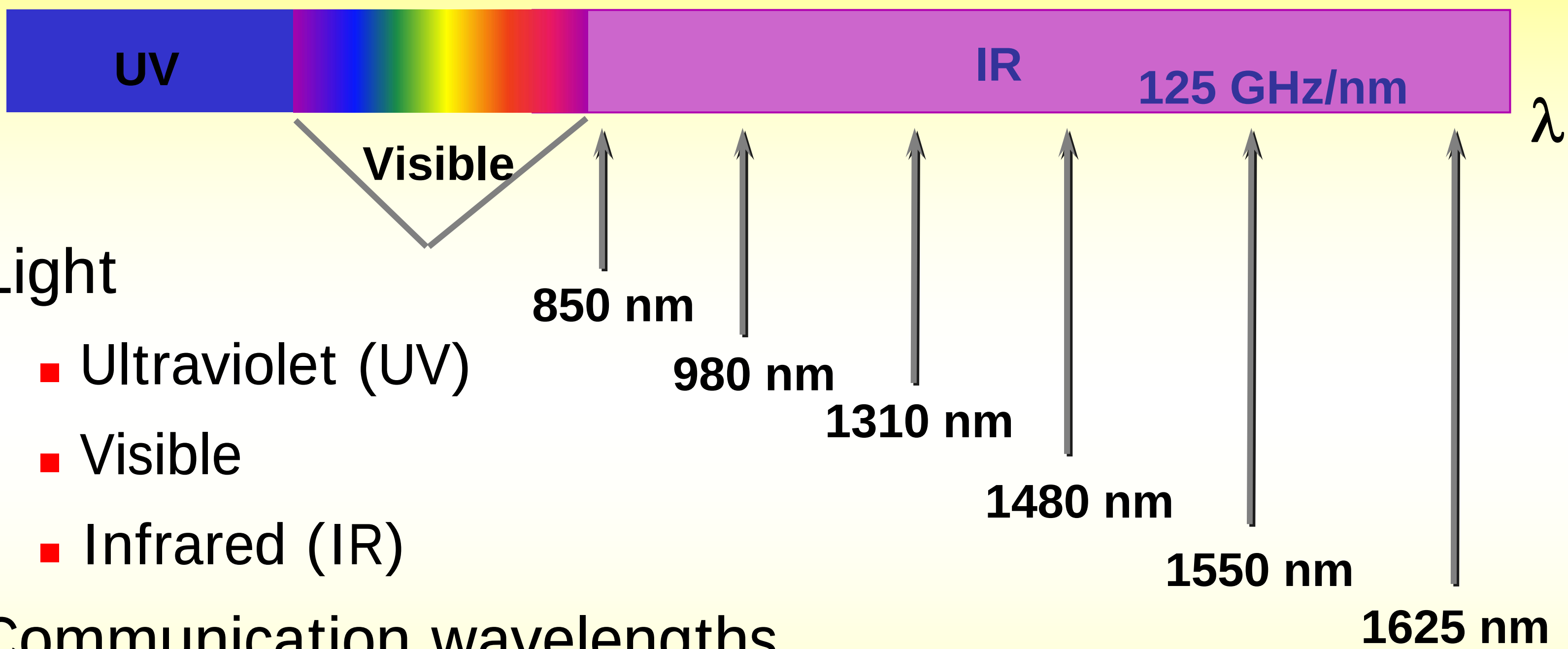
Window Glass	1 inch (~3 cm)
Optical Quality Glass	10 feet (~3 m)
Fiber Optics	9 miles (~14 km)

Propagation Distance Need to Reduce the Transmitted Light Power by 50% (3 dB)

The Electromagnetic Spectrum



Optical Spectrum



- Light
  - Ultraviolet (UV)
  - Visible
  - Infrared (IR)
- Communication wavelengths
  - 850, 1310, 1550 nm
  - Low-loss wavelengths
- Specialty wavelengths
  - 980, 1480, 1625 nm

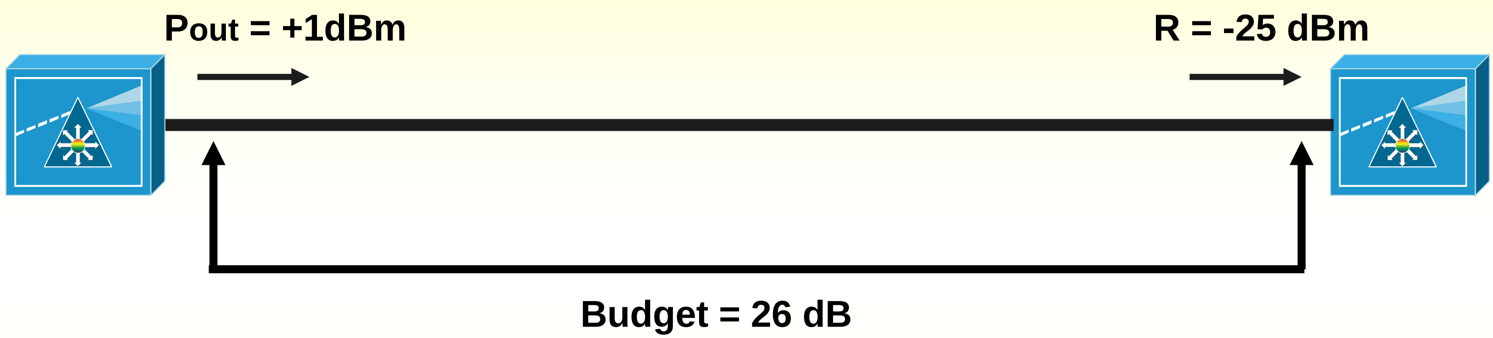
$C = f \times \lambda$

Wavelength: λ (nanometers)

Frequency: f (terahertz)

Optical Budget

Basic Optical Budget = Output Power – Input Sensitivity



Optical Budget is affected by:

- Fiber attenuation
- Splices
- Patch Panels/Connectors
- Optical components
- Bends in fiber
- Contamination (dirt/oil on connectors)

Example:

其它损耗**3dB**，系统富余度**5dB**

光纤损耗的功率预算为**18dB**

1.31um: L=18dB/(0.35dB/km)=51.4km

1.55um: L=18dB/(0.2dB/km)=90km

单模光纤色散

- **Chromatic Dispersion**
  - Different wavelengths travel at different speeds
  - Causes spreading of the light pulse

- **Polarization Mode Dispersion (PMD)**
  - Single-mode fiber supports two polarization states
  - Fast and slow axes have different group velocities
  - Causes spreading of the light pulse

色度色散的描述

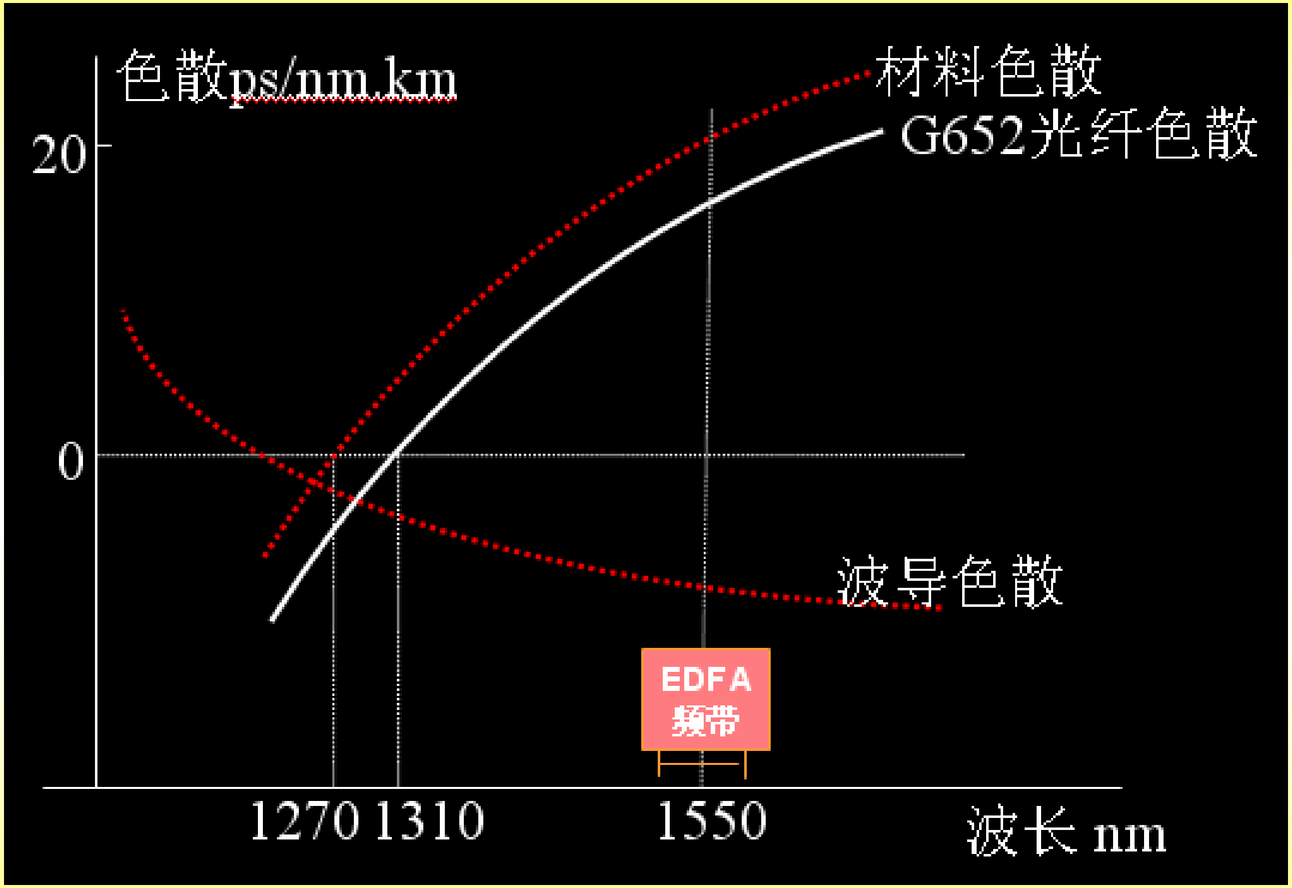
- 单位长度光纤上的群时延

$$\tau(\lambda)[\mathrm{ps/km}] = \frac{1}{v_g} = \frac{d\beta}{d\omega} = -\frac{\lambda^2}{2\pi c}\frac{d\beta(\lambda)}{d\lambda}$$

- 光纤色散D定义为群时延随波长的变化率

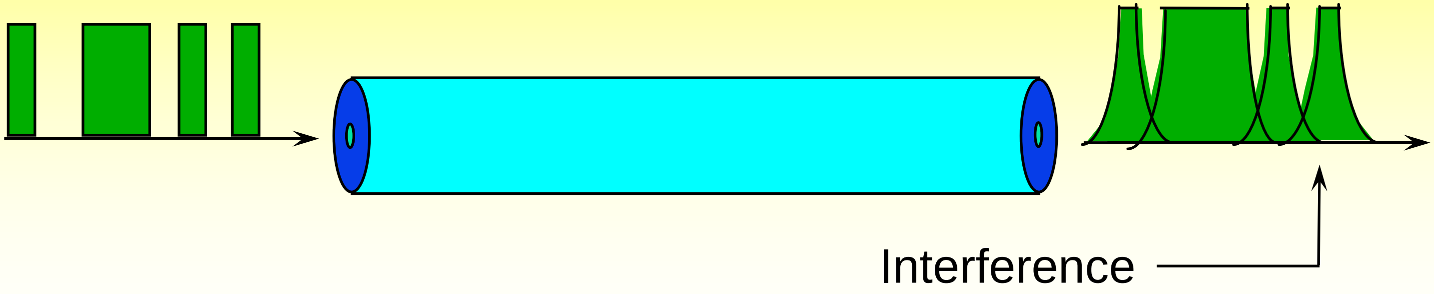
$$D[\mathrm{ps/km \cdot nm}] = \frac{d\tau(\lambda)}{d\lambda}$$

光纤色散曲线



色散补偿光纤、光纤光栅等多种技术可用于消除色散所造成的信号畸变

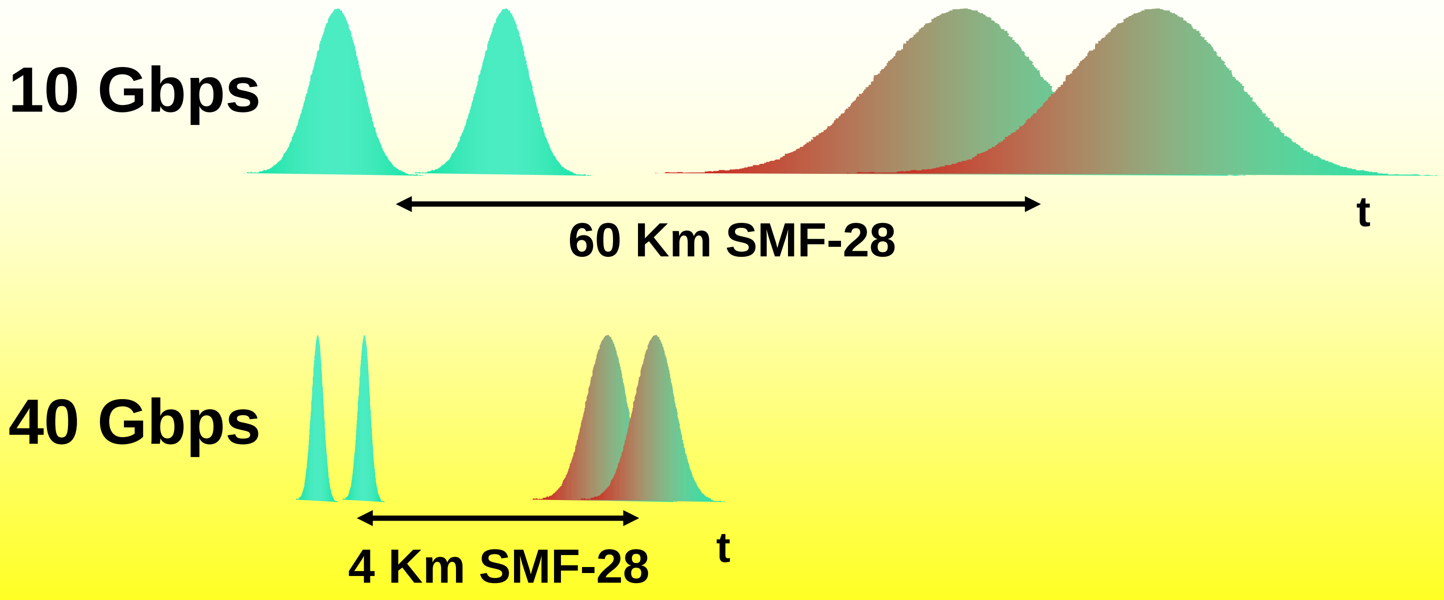
Dispersion Induced Dgradation



- A pulse spreads as it travels down the fiber
- Inter-symbol Interference (ISI) leads to performance impairments
- Degradation depends on:
  - laser used (source spectral width)
  - bit-rate (signal spectral width and temporal pulse separation)
  - Different fiber types

色散对传输速率和距离的限制

- **Dispersion causes pulse distortion, pulse "smearing" effects**
- **Higher bit-rates and shorter pulses are less robust to Chromatic Dispersion**
- **Limits "how fast“ and “how far”**



色散限制

在光源谱宽可以忽略的情况下

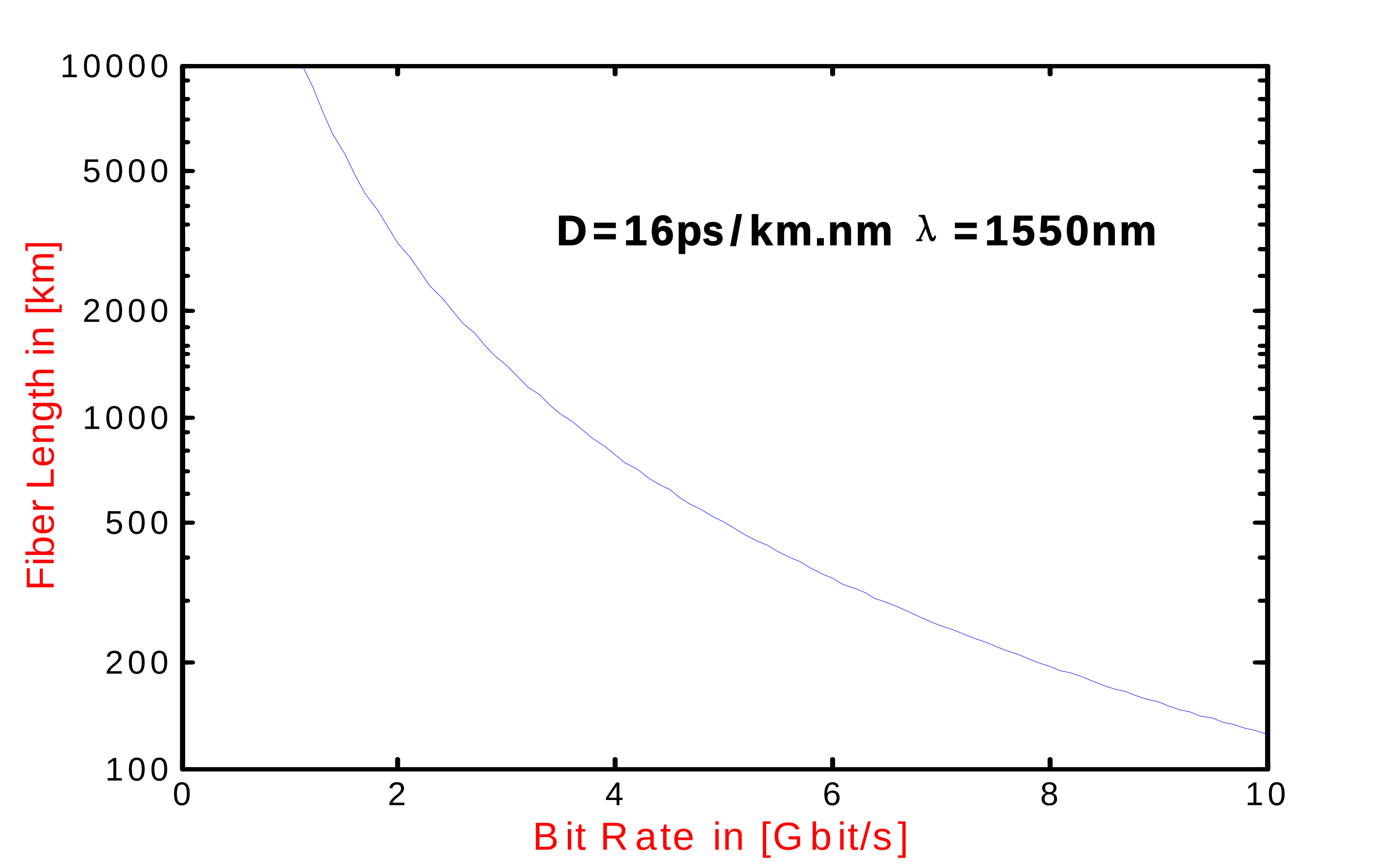
光纤的色散长度：$L_D = \frac{T_0^2}{|\beta_2|} = \frac{2\pi c}{\lambda^2}\frac{T_0^2}{|D|} \approx \frac{\pi c}{2\lambda^2}\frac{1}{|D|B^2}$

T_0为高斯脉冲的**1/e**功率点半宽度，**B**为比特率，经**L_D**距离传输后脉冲展宽为原来的约**1.4**倍

- **Limits "how fast“ and “how far”**

$$B^2 L \le \frac{\pi c}{2\lambda^2}\frac{1}{|D|}$$

Example



10000
5000
2000
1000
500
200
100
0
2
4
6
8
10
Fiber Length in [km]
Bit Rate in [Gbit/s]
D=16ps/km.nm λ =1550nm

光纤中的光学非线性

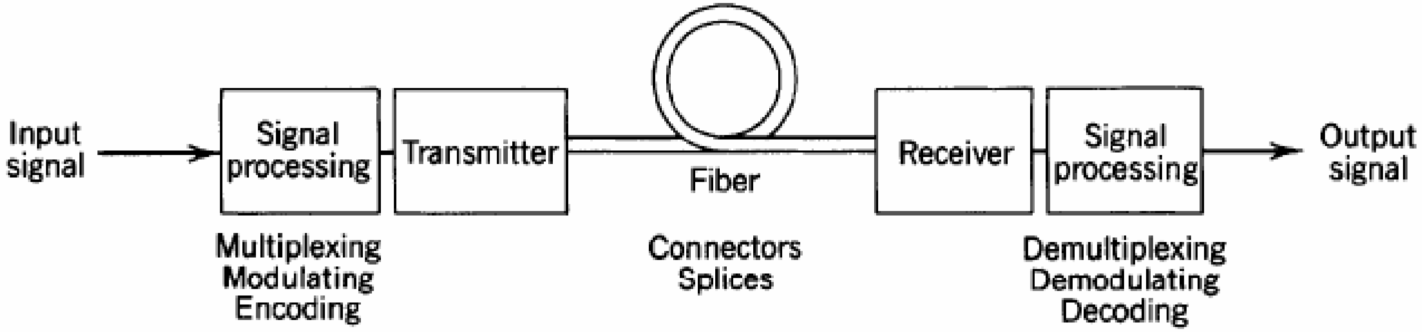
- Self-phase modulation (SPM)
  - **SPM**谱展宽，脉冲啁啾和畸变，光孤子
- Cross-phase modulation (XPM)
  - **XPM**双折射，功率损失、啁啾和畸变，波长串扰，时分解复用
- Four-Wave Mixing (FWM)
  - 功率损失，波长串扰，波长转换，光谱反转
- Stimulated Raman scattering (SRS)
  - 功率损失，波长串扰，分布式光放大，典型阈值**1~2W**
- Stimulated Brillouin scattering (SBS)
  - 功率损失，反向串扰，**Brillouin**陀螺，对高速信号无影响，阈值**2~5mW**

色散对非线性有明显的抑制作用

数字光纤传输技术

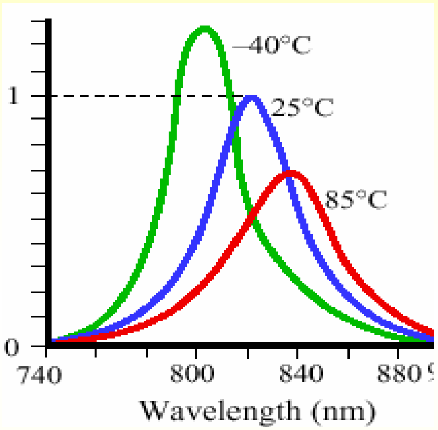
Optical Fiber Communication System

Wavelength λ_o (μm)	Fiber	Source		Detector	
0.87	Multimode step-index				Si
		LED	AlGaAs	*p-i-n*	
1.3	Multimode graded-index				Ge
		Laser	InGaAsP	APD	
1.55	Single-mode				InGaAs

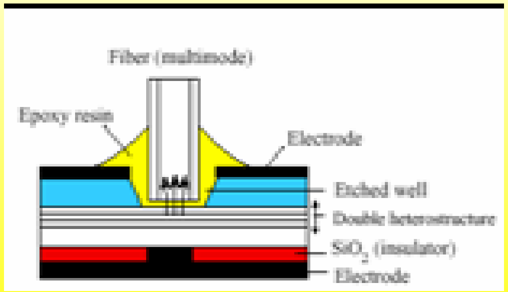


Light Source Characteristics

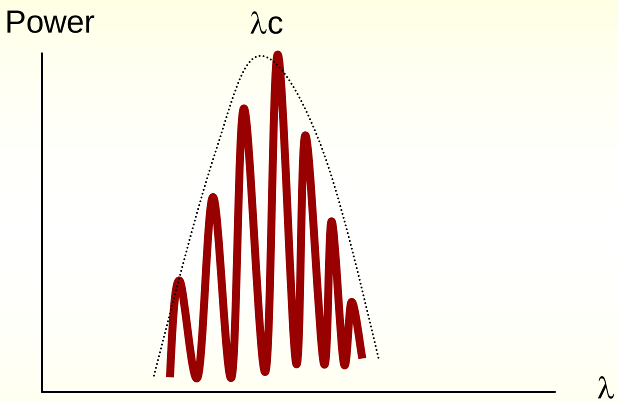
LED



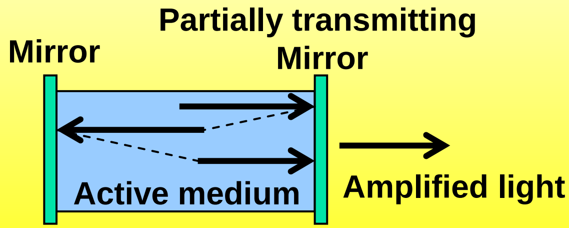
- Spectrally broad
- Unstable center/peak wavelength



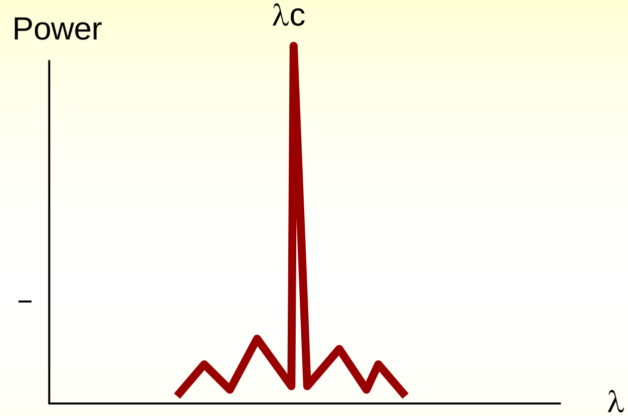
Fabry Perot Laser



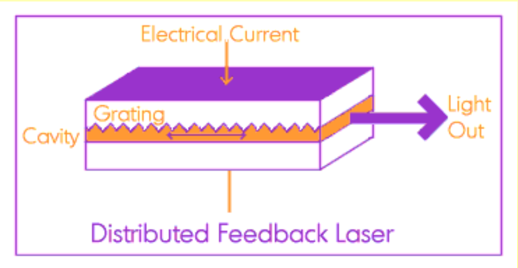
- Dynamic spectral broadening
- Unstable center/peak wavelength



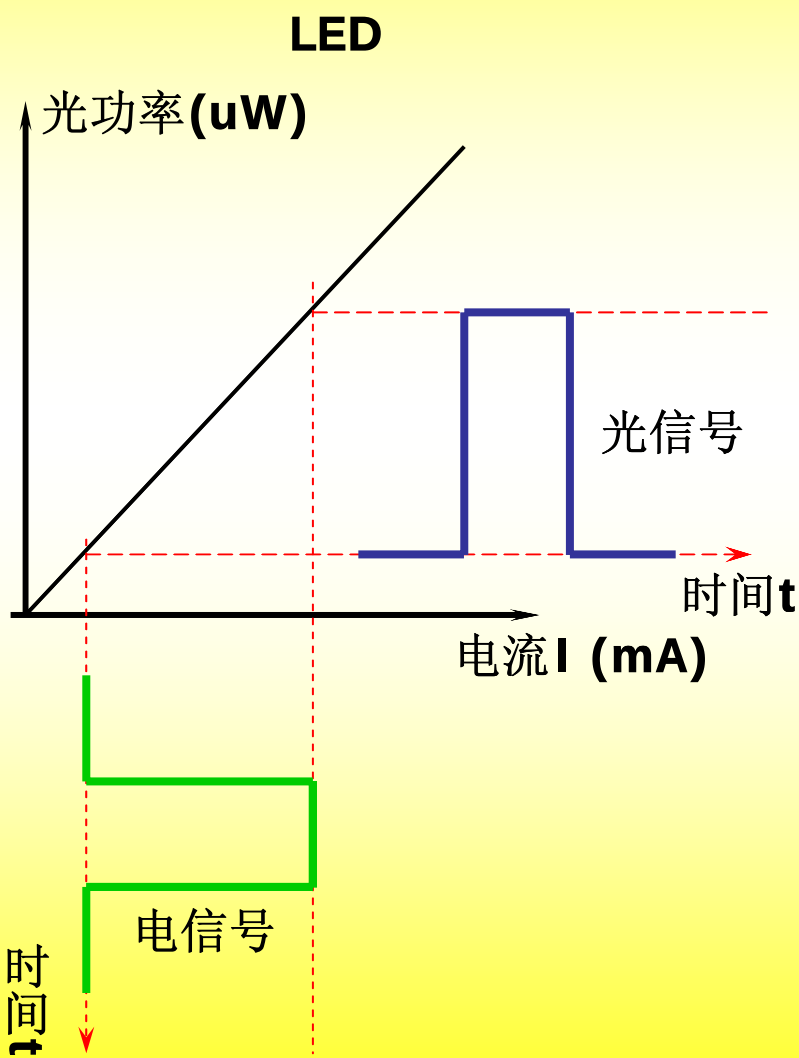
Distributed Feedback (DFB) Laser

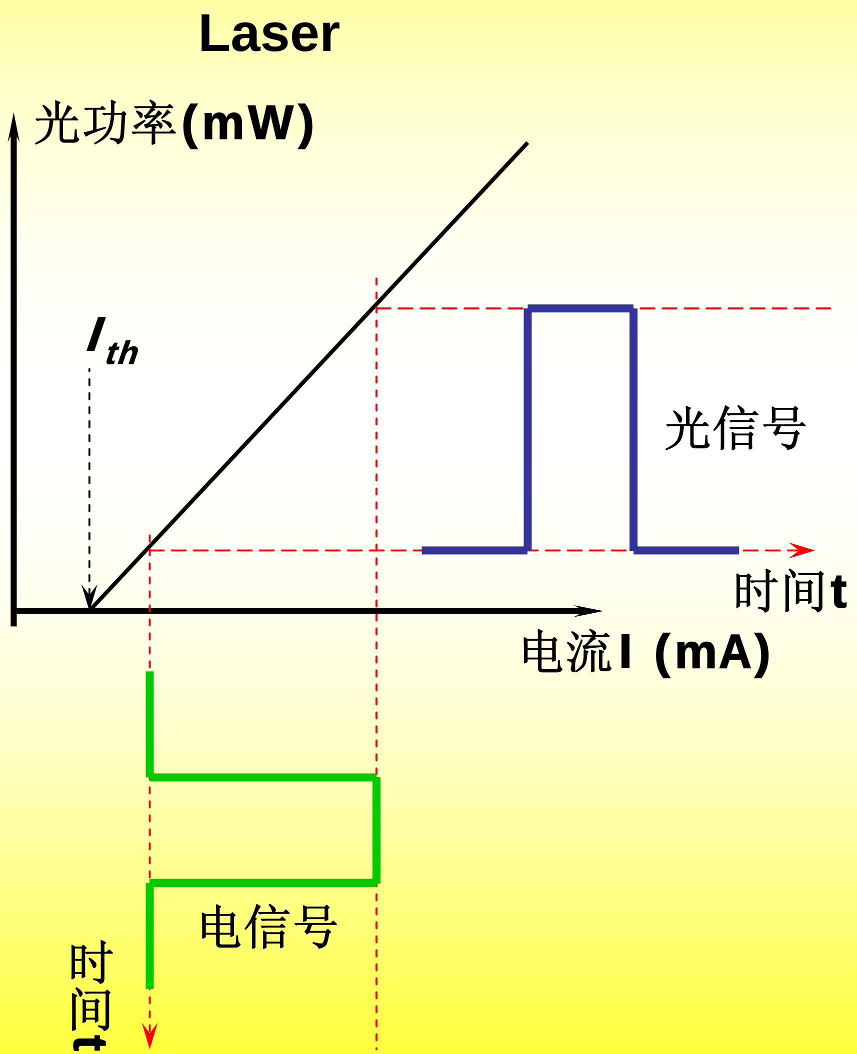


- **Dynamic single mode laser**
- **Tighter wavelength control**



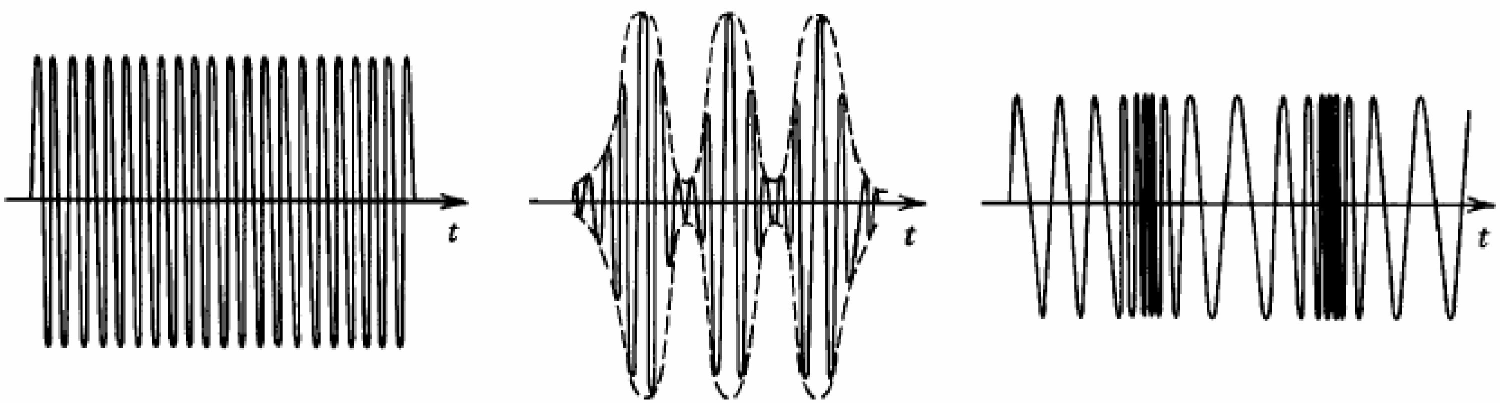
Light Source Characteristics





Modulation

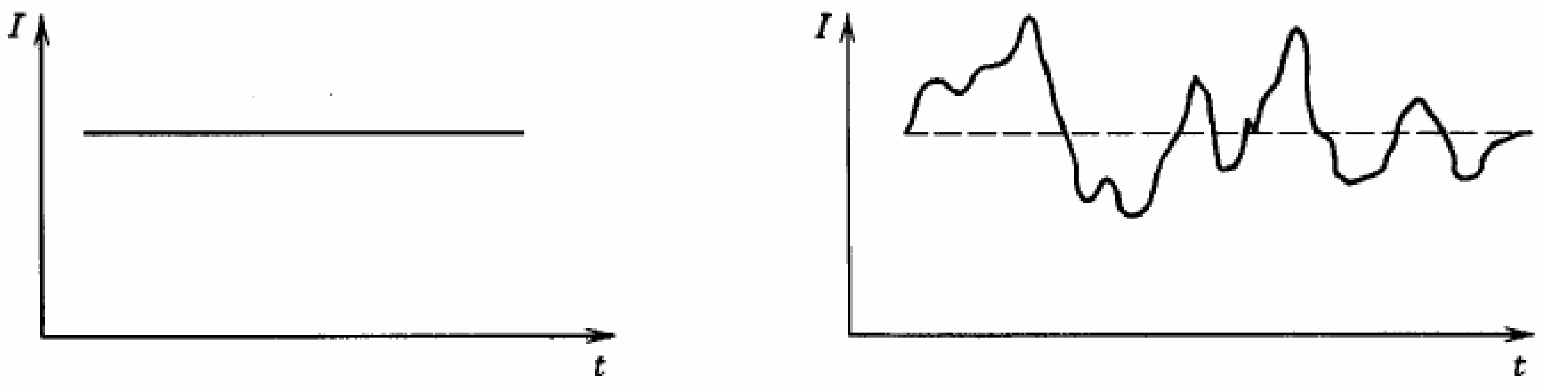
- Field Modulation
  - Amplitude modulation
  - Frequency modulation
- Difficult to implement in optical frequency band



(a) (b) (c)

Intensity Modulation

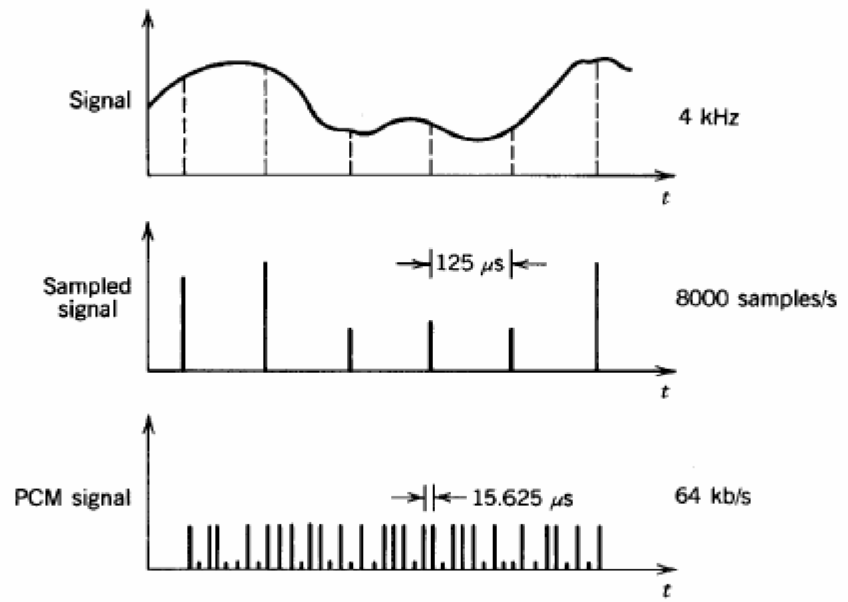
- Intensity Modulation
- Easy to implement



(a) (b)

Pulse Code Modulation (PCM)

- PCM – sampled, quantized and discretized in bits

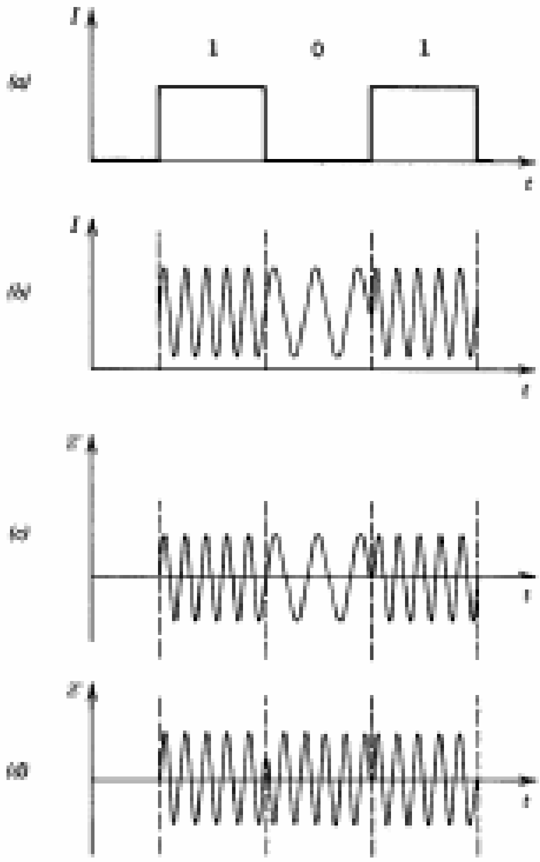


语声频段：300～3400Hz；取样频率：8kHz；8bit量化编码

一路电话：8bit×8kHz＝64kbit/s

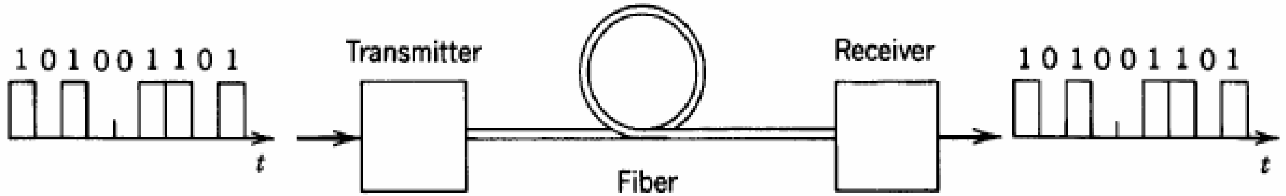
Keying of PCM Signals

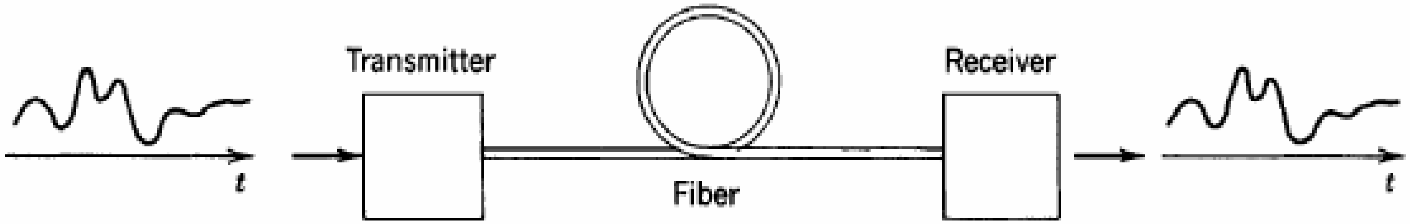
- OOK 适合于光通信
- FSK
- PSK



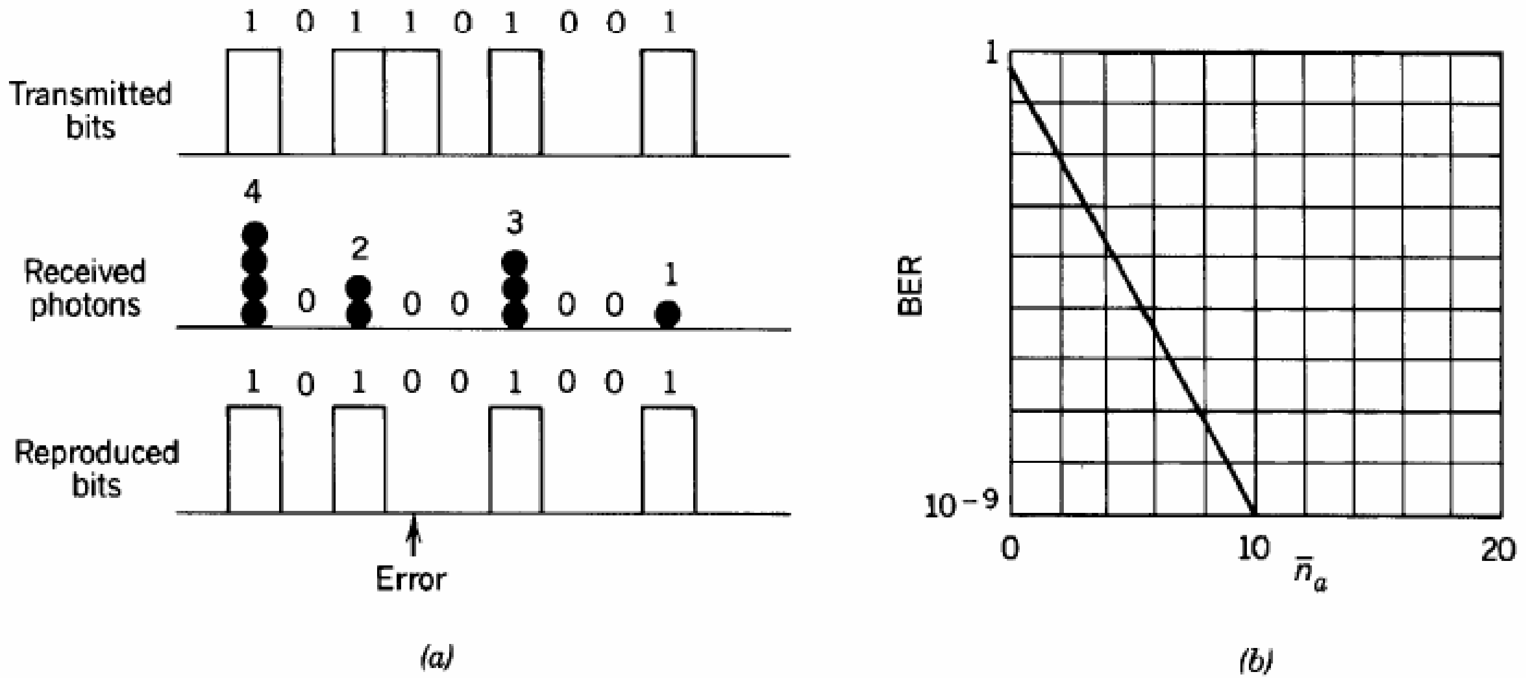
Digital Communication System

- Bit-rate-Distance product: LB_o
  - B_o : bit-rate in bits/s, L : distance
- Bit Error Rate (BER) $\mathrm{BER} = \frac{1}{2}p_1 + \frac{1}{2}p_0$
- Receiver Sensitivity $P_r = h\nu \bar{n}_0 B_0$



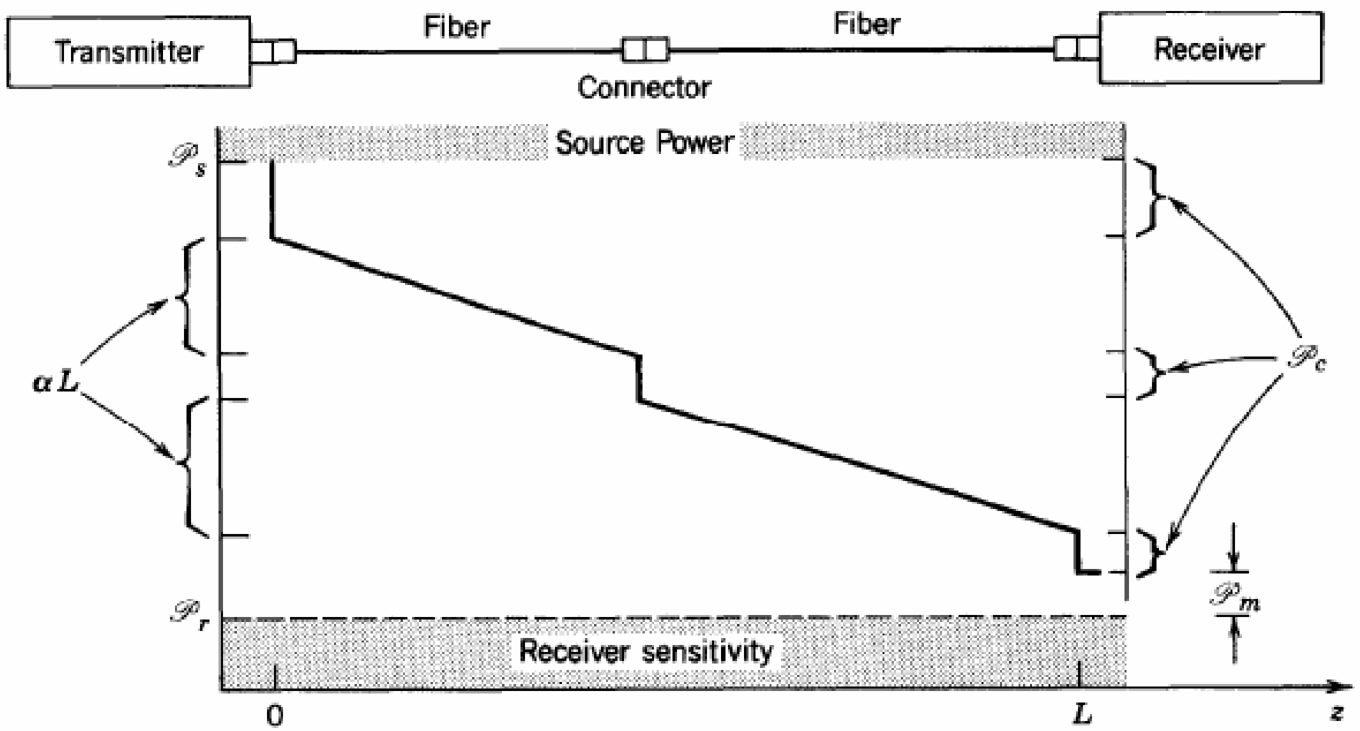


Receiver Sensitivity



Design Strategy

- Power budget



Design Strategy

- Power in dBm units

$$\mathscr{P} = 10\log_{10} P \qquad P \text{ in mW} \qquad \mathscr{P} \text{ in dBm}$$

- Power budget

$$\mathscr{P}_s - \mathscr{P}_c - \mathscr{P}_m - \alpha L = \mathscr{P}_r \qquad \text{(dB units)}$$

$\mathscr{P}_s$ is the power of the source (dBm)

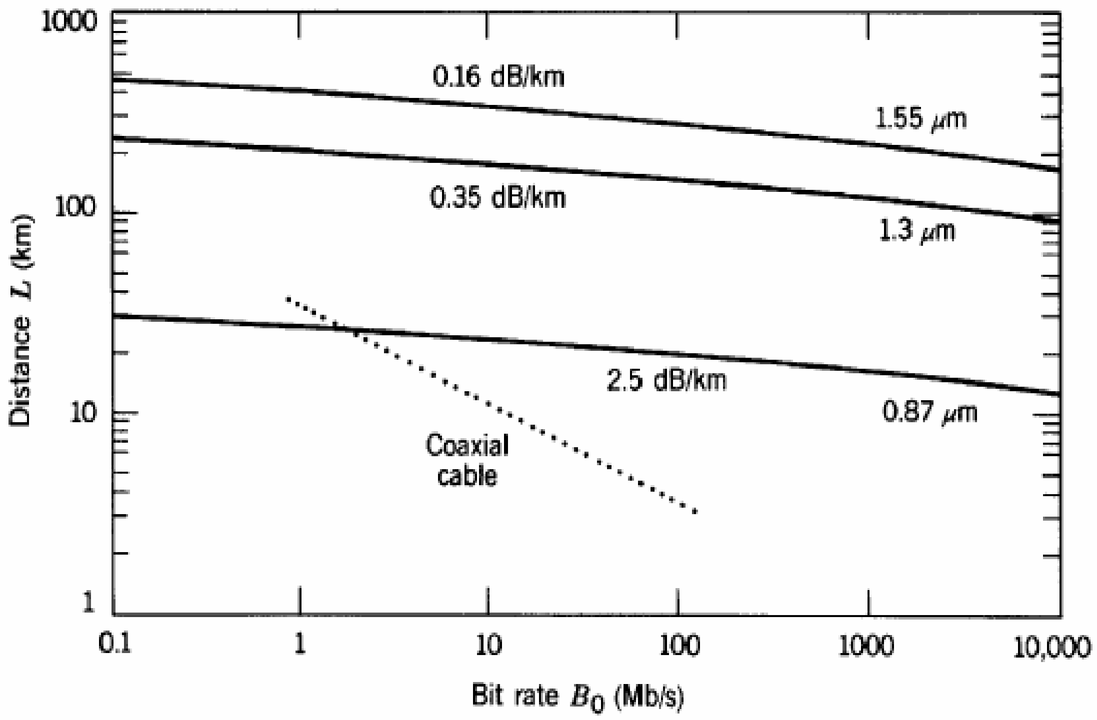
α is the fiber loss in dB/km

$\mathscr{P}_c$ is the splicing and coupling loss (dB)

$$\mathscr{P}_r = 10\log\frac{\bar{n}_0 h\nu B_0}{10^{-3}} \text{ dBm}$$

$$L_0 = \frac{1}{\alpha}\left(\mathscr{P}_s - \mathscr{P}_c - \mathscr{P}_m - 10\log\frac{\bar{n}_0 h\nu B_0}{10^{-3}}\right)$$

Under Attenuation-limit Conditions



Dispersion Limit

- For Multimode Step-Index Fiber

$$LB_0 = \frac{c_1}{2\Delta}$$

- For Multimode Graded-Index Fiber

$$LB_0 = \frac{c_1}{\Delta^2}$$

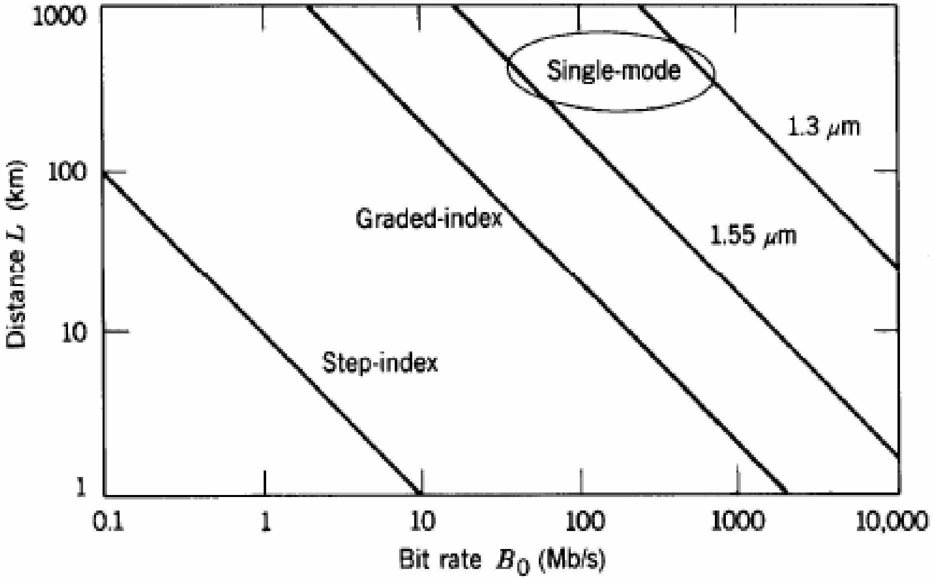
- For Single mode Step-Index Fiber

$$LB_0 = \frac{1}{4|D_\lambda|\sigma_\lambda}$$

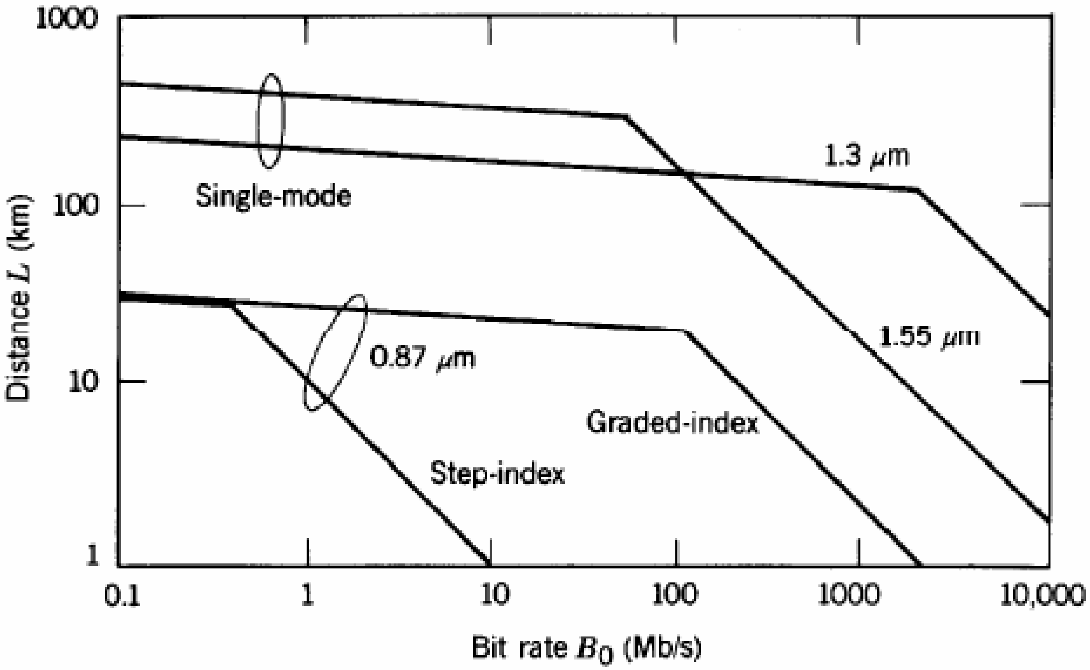
Dispersion Limit

- Dispersion-limited maximum length

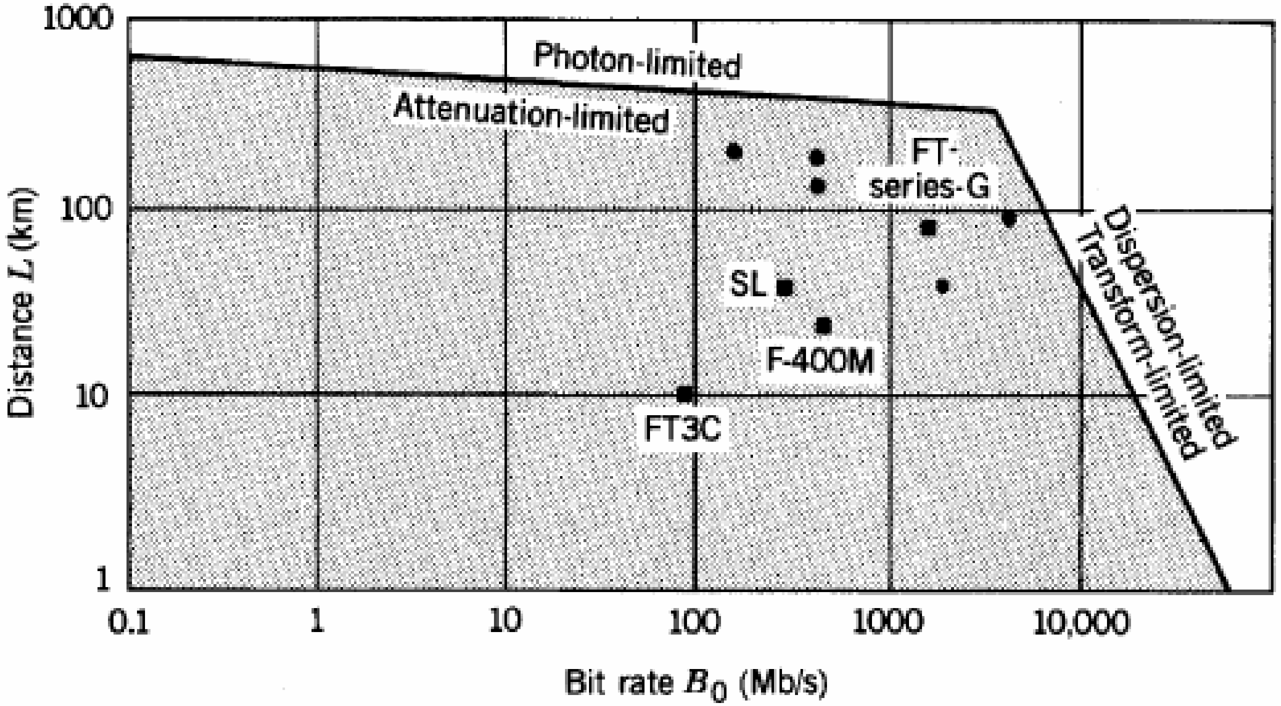
$\sigma_\lambda = 1\text{nm}$



Overall Consideration

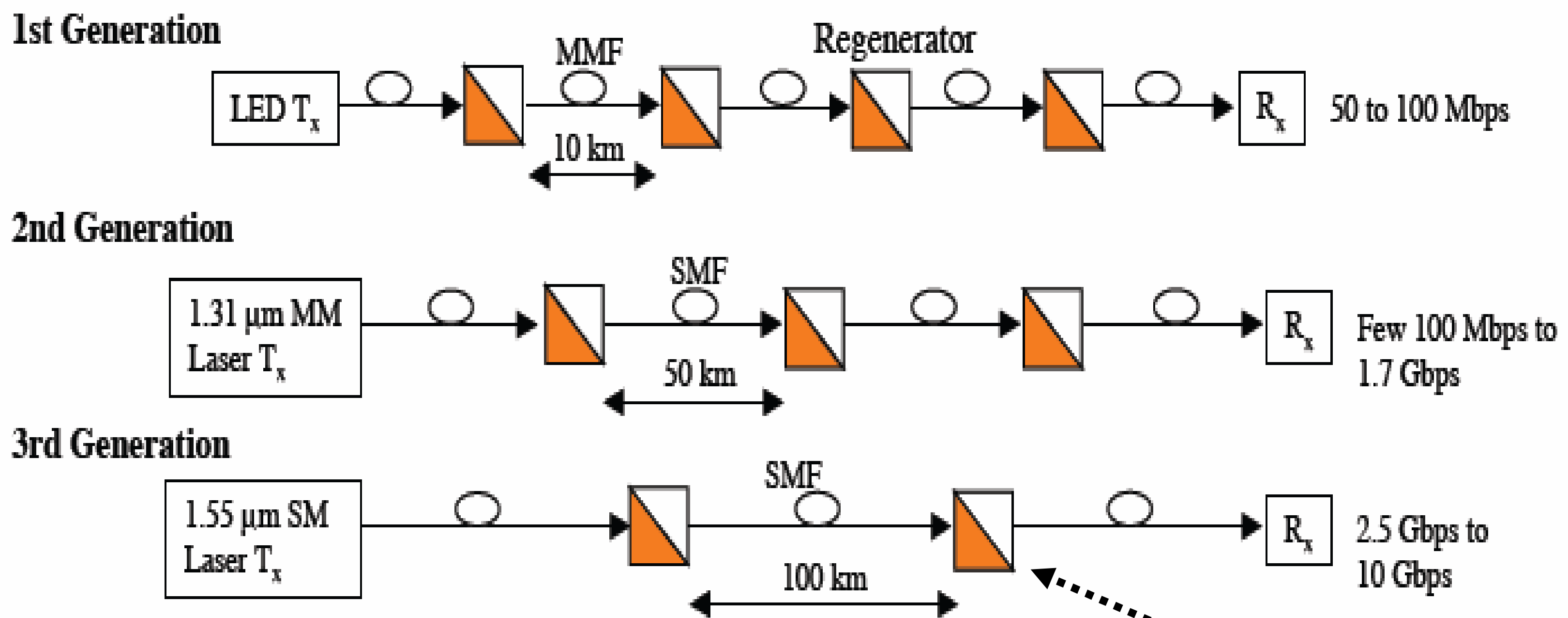


Existing Systems



单波长系统

Capacity and Repeater Spacing

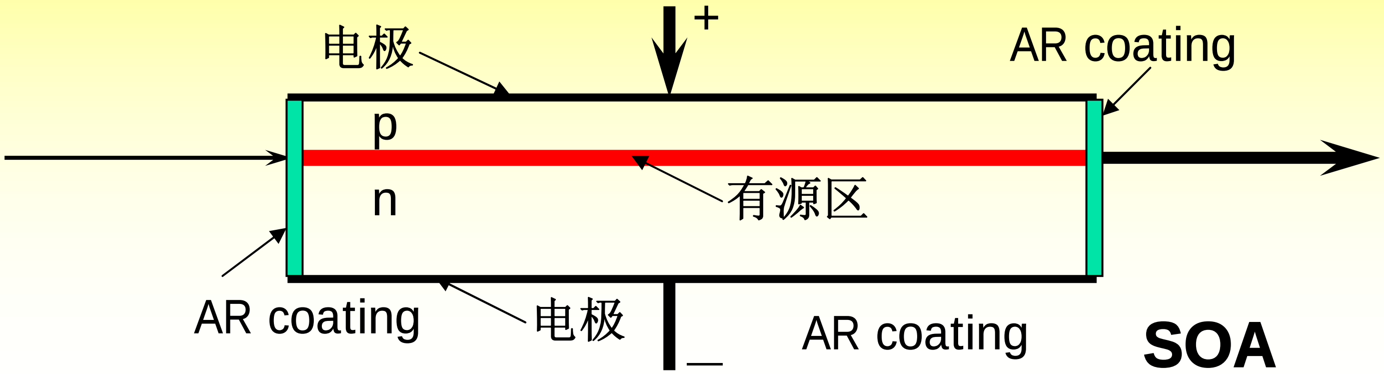


O-E-O电光再生中继

光放大技术—全光网关键技术

- 半导体光放大器（**SOA**）
- 掺铒光纤放大器（**EDFA**）
- 光纤**Raman**分布式放大器（**FRA**）

半导体光放大器（SOA）



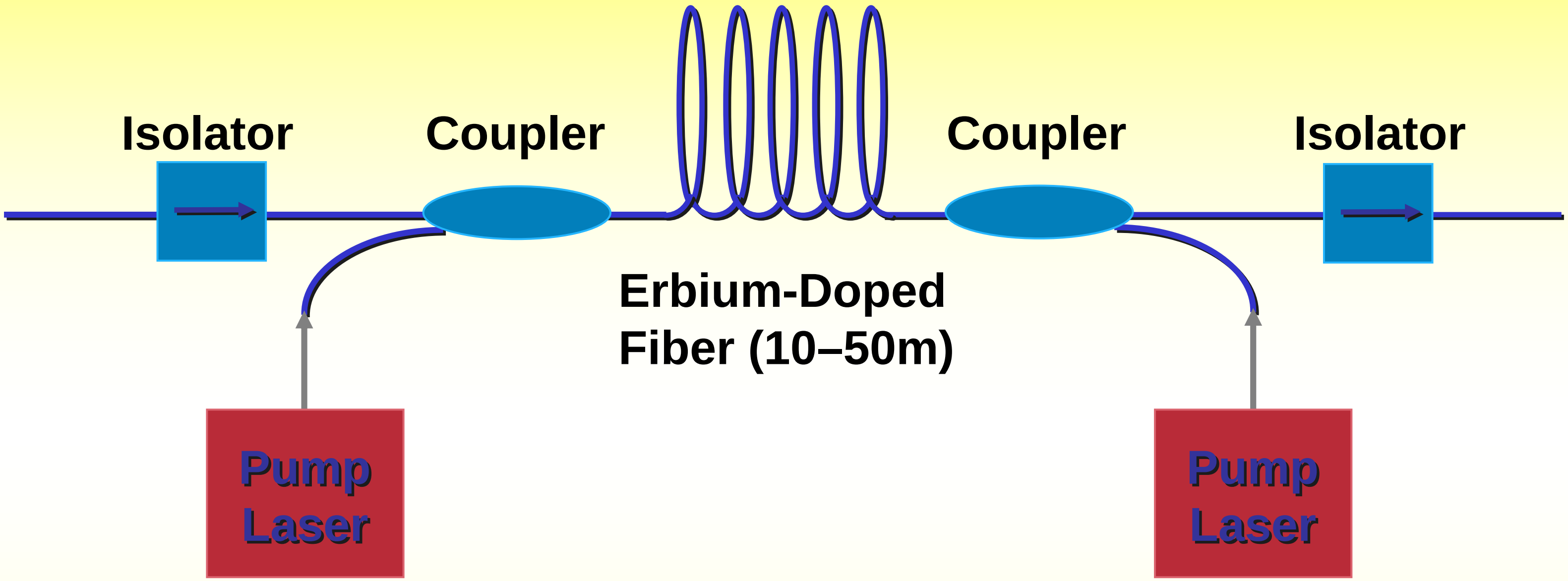
优点:

(1) 可在任意通信波段上实现;
(2) 单个器件放大带宽可达70～100nm（～12THz）
(3) 器件尺寸小（～1mm），易于集成化

缺点:

(1) 对抗反射膜的要求极高（～10^{-5}），制作难度大，成本高
(2) 输入输出端与光纤的耦合损耗较大（～3dB）
(3) 输入端的耦合损耗使放大器噪声因子增加（NF～7～9dB）
(4) 交叉增益调制（XGM）和非线性，不宜用于多波长放大

Erbium Doped Fiber Amplifier



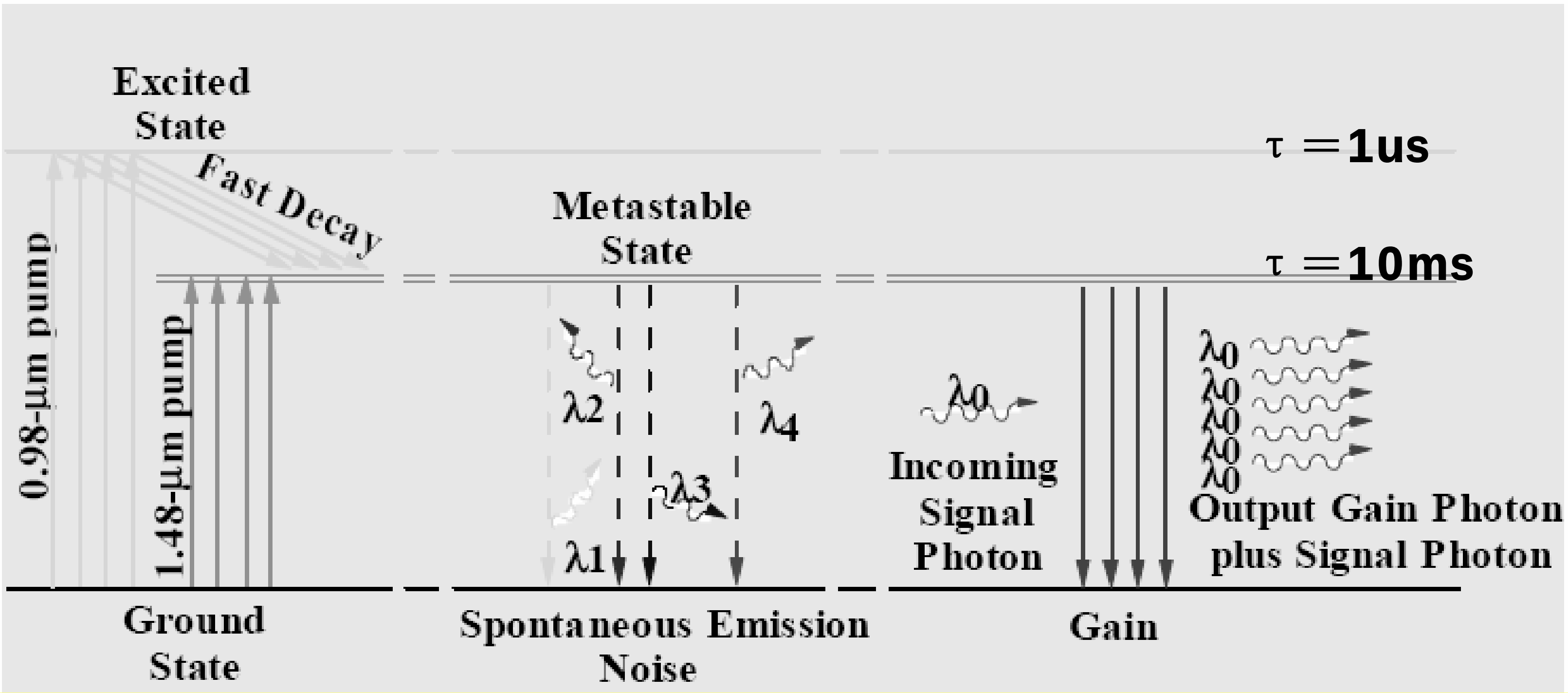
A “simple” device consisting of four parts:

- Erbium-doped fiber
- A pump laser (to invert the population).
- A coupler
- An isolator to cut off backpropagating noise

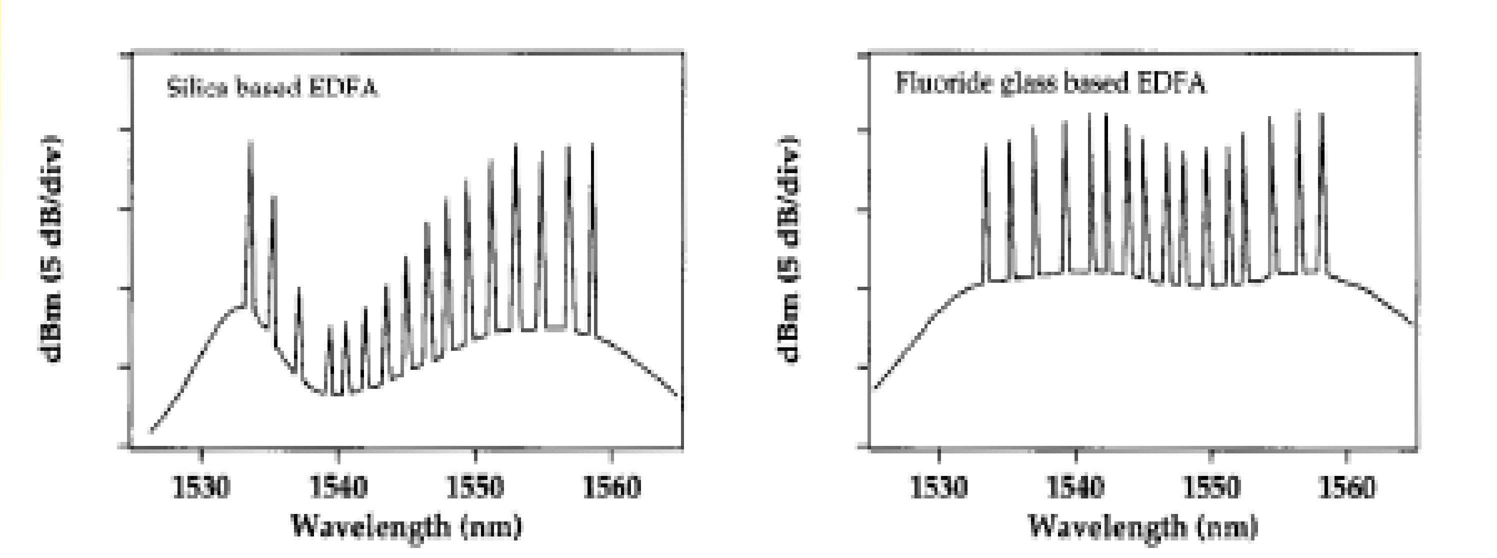
EDFA的突出优点

- **1530～1600nm**约**70nm**（～**9THz**）的放大带宽
- 与光纤系统完全匹配，无光耦合和镀膜问题
- 高增益（～**40dB**）
- 高饱和输出功率（～**200mW**）
- 低噪声因子（**NF**～**4dB**）
- 支持多波长放大，无**XGM**和非线性串扰问题
- 对比特率和调制格式等不敏感，完全透明

Energy Level Diagram of EDFAs



EDFA Gain－Flattening



- Passive equalization
  - Add dopant: fluoride based EDFA
  - Broadband filter (LPFG)
  - Hybrid pump (980nm, 1480nm pump)
- Active equalization
  - Acousto-Optic Tunable Filter (AOTF)

EDFA 噪声因子 (Noise Figure)

$$\mathrm{NF}=\frac{(\mathrm{SNR})_{\mathrm{in}}}{(\mathrm{SNR})_{\mathrm{out}}}=\frac{2n_{sp}(G-1)+1}{G}\approx 2n_{sp}$$

$$n_{sp}\approx\frac{N_2}{N_2-N_1}$$

为放大器自发辐射因子（粒子数反转因子）
N_2，N_1分别为处于上下能级的粒子数密度
通常**$n_{sp}>1$**，强泵浦条件下有**$n_{sp}\approx 1$**

在最理想情况下：

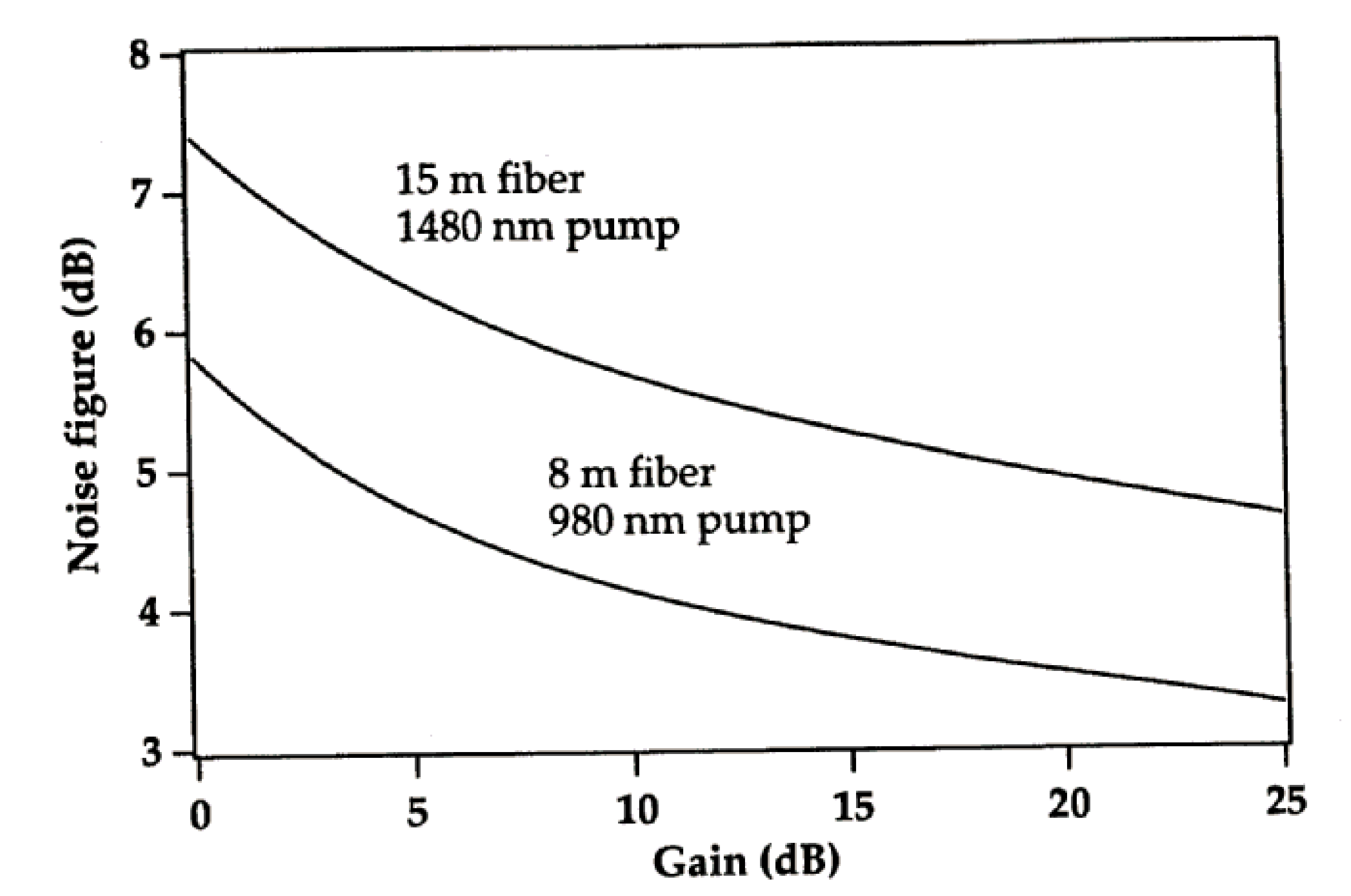
$$\mathrm{NF}=2,\qquad (3\mathrm{dB})$$

在实际当中：

$$n_{sp}\approx\frac{P_{ASE}}{2(G-1)h\nu B_o}$$

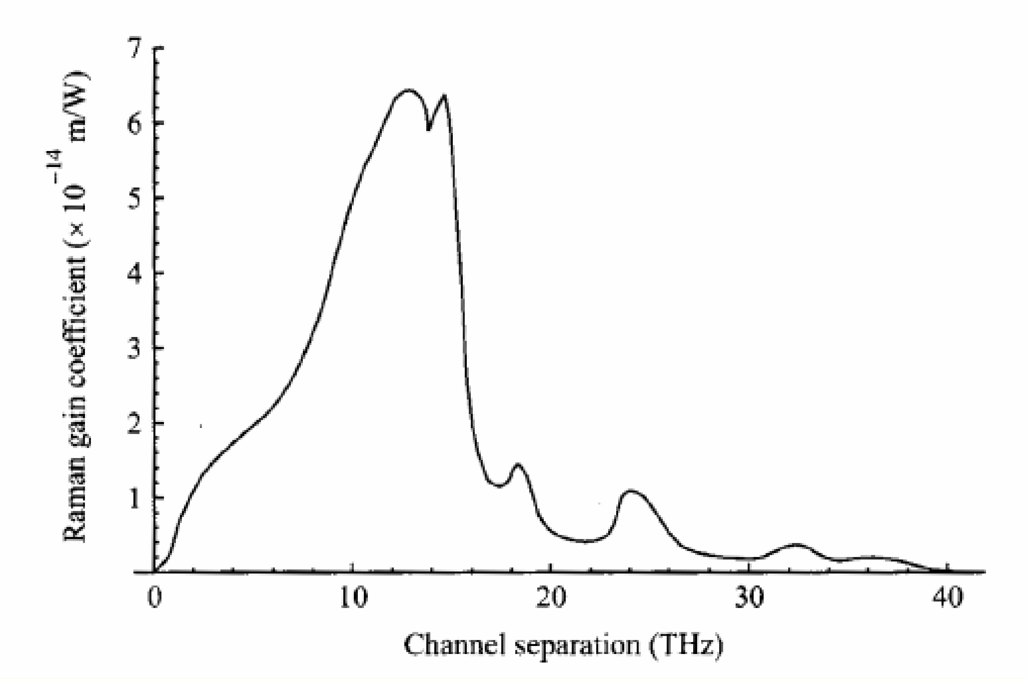
B_o：放大器输出端的光学滤波器带宽
G：放大器增益
P_{ASE}：通过滤波器的噪声功率

不同泵浦波长EDFA的NF



光纤Raman放大器

石英光纤的**Raman**增益谱



FRA的特点:

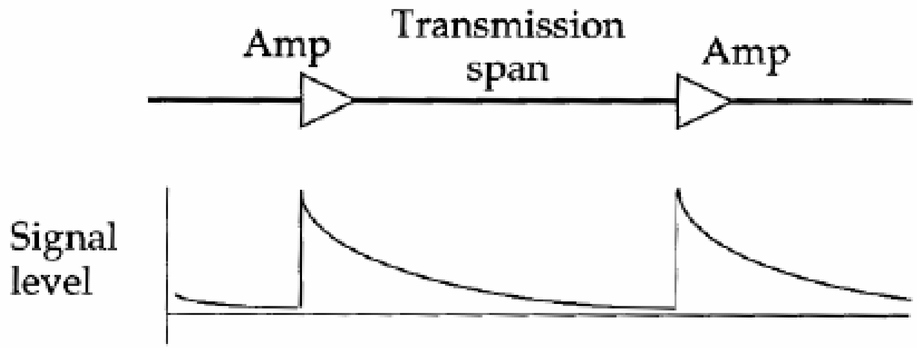
(1) 可在任意通信波段上实现;

(2) 放大带宽可达**15THz**

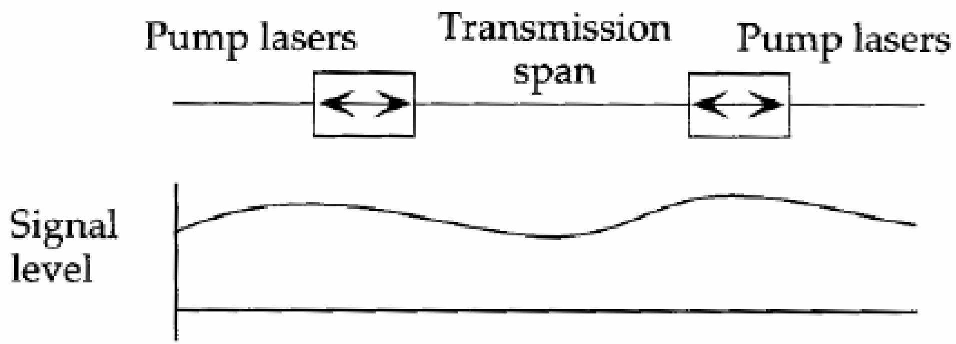
(3) 分布式放大

EDFA vs. Raman Amplifier

- EDFA - Lumped Amplification

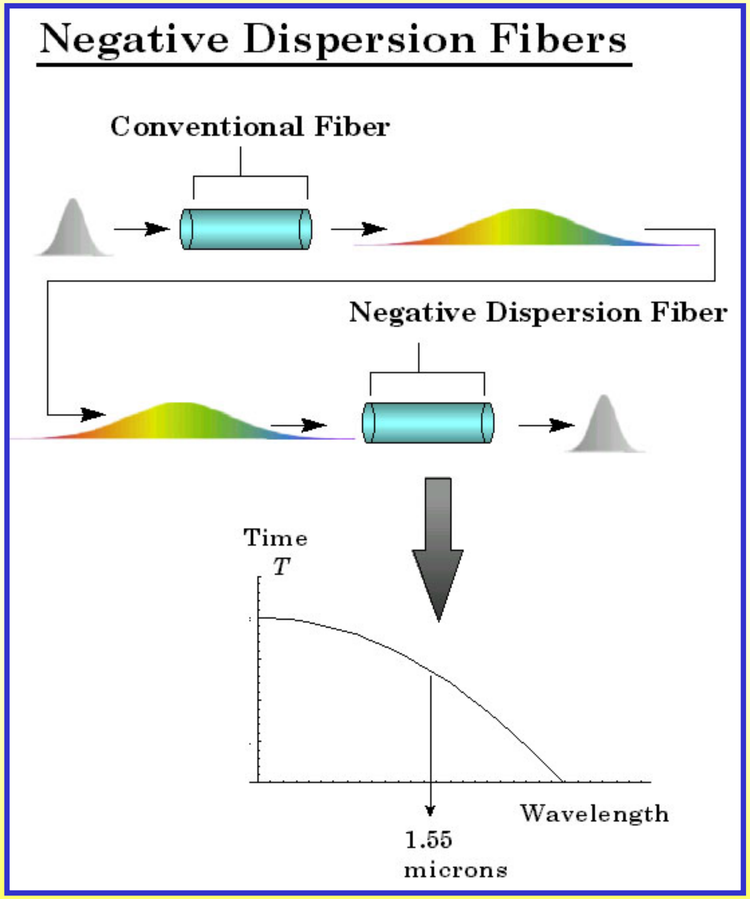


- Raman Amplifier - Distributed Amplification



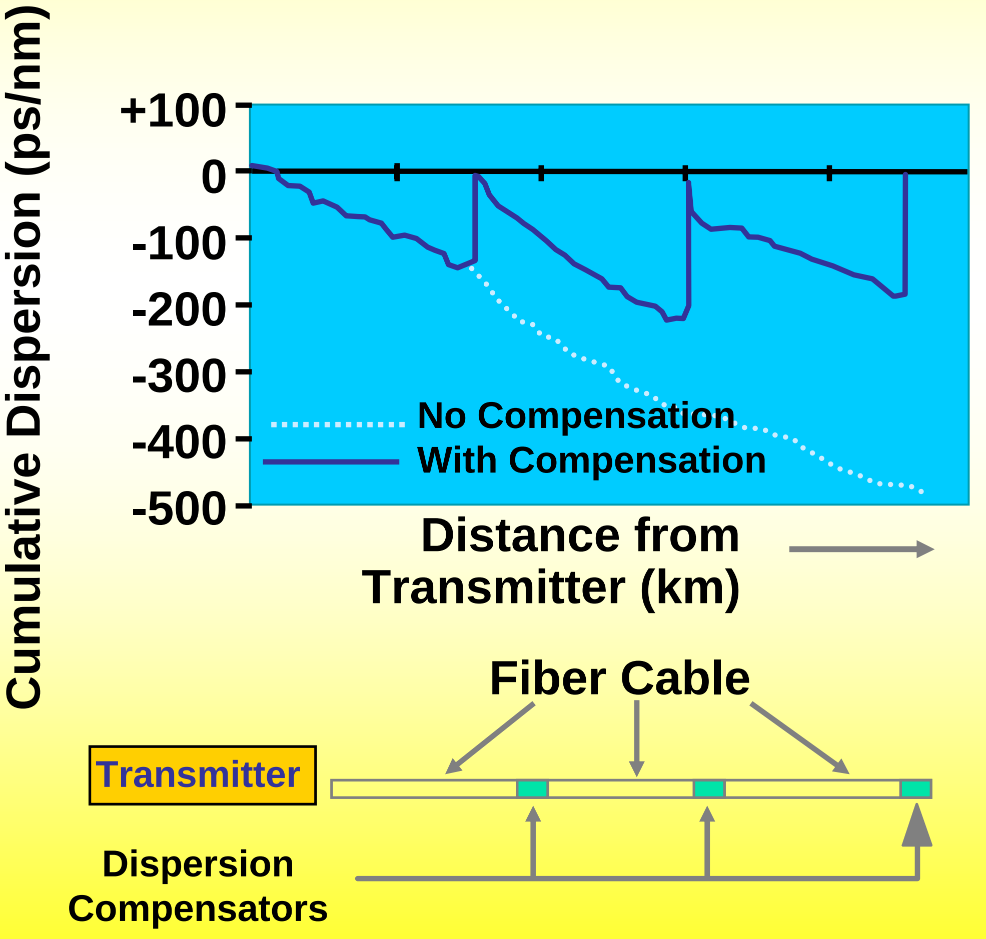
色散补偿—全光化关键技术之一

- Dispersion Compensation
  - By joining fibers with CD of opposite signs (polarity) and suitable lengths an average dispersion close to zero can be obtained; the compensating fiber can be several kilometers and the reel can be inserted at any point in the link, at the receiver or at the transmitter
  - Dispersion compensation devices (chirped fiber Bragg gratings)



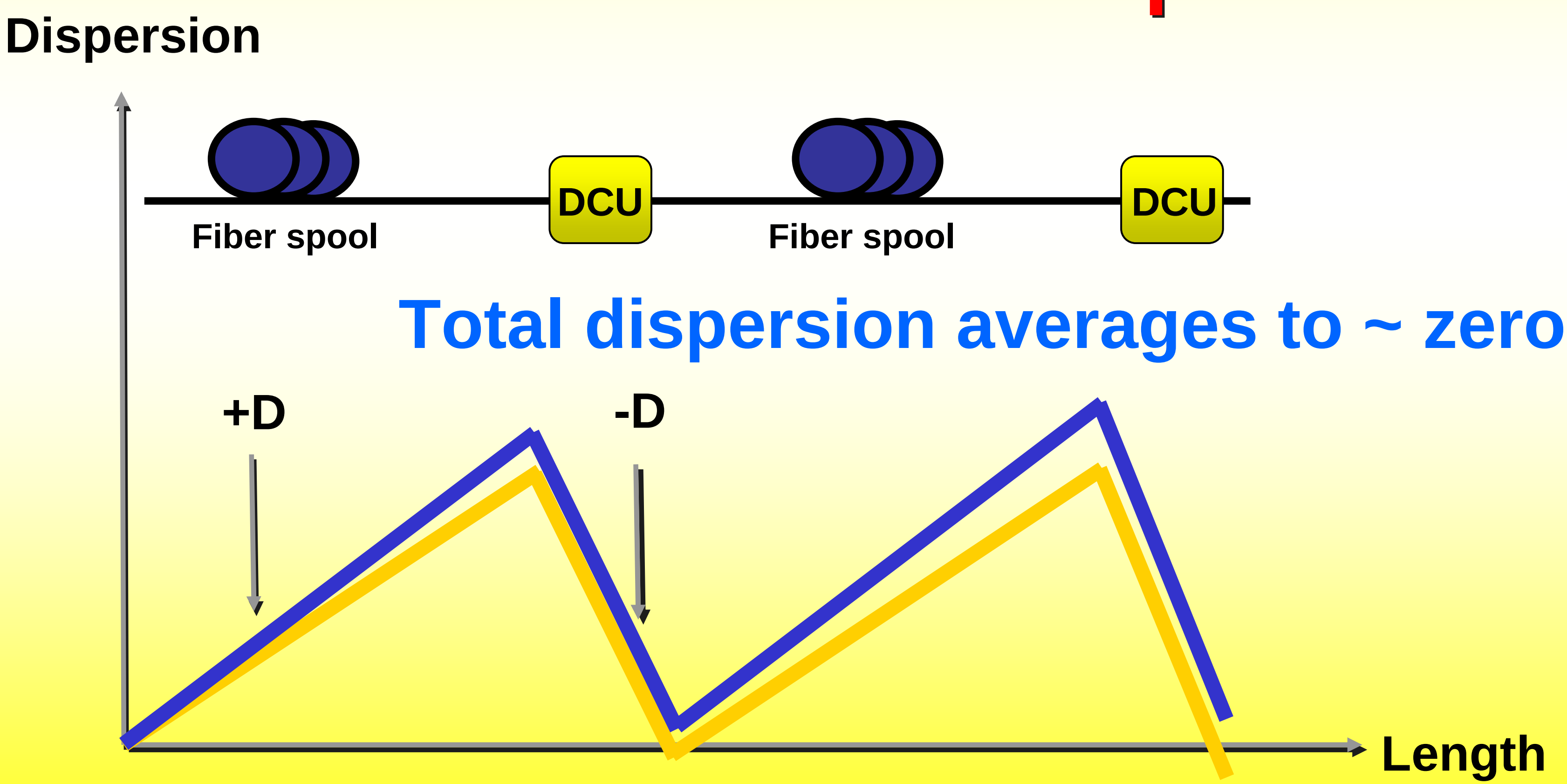
Dispersion Compensation

Total Dispersion Controlled

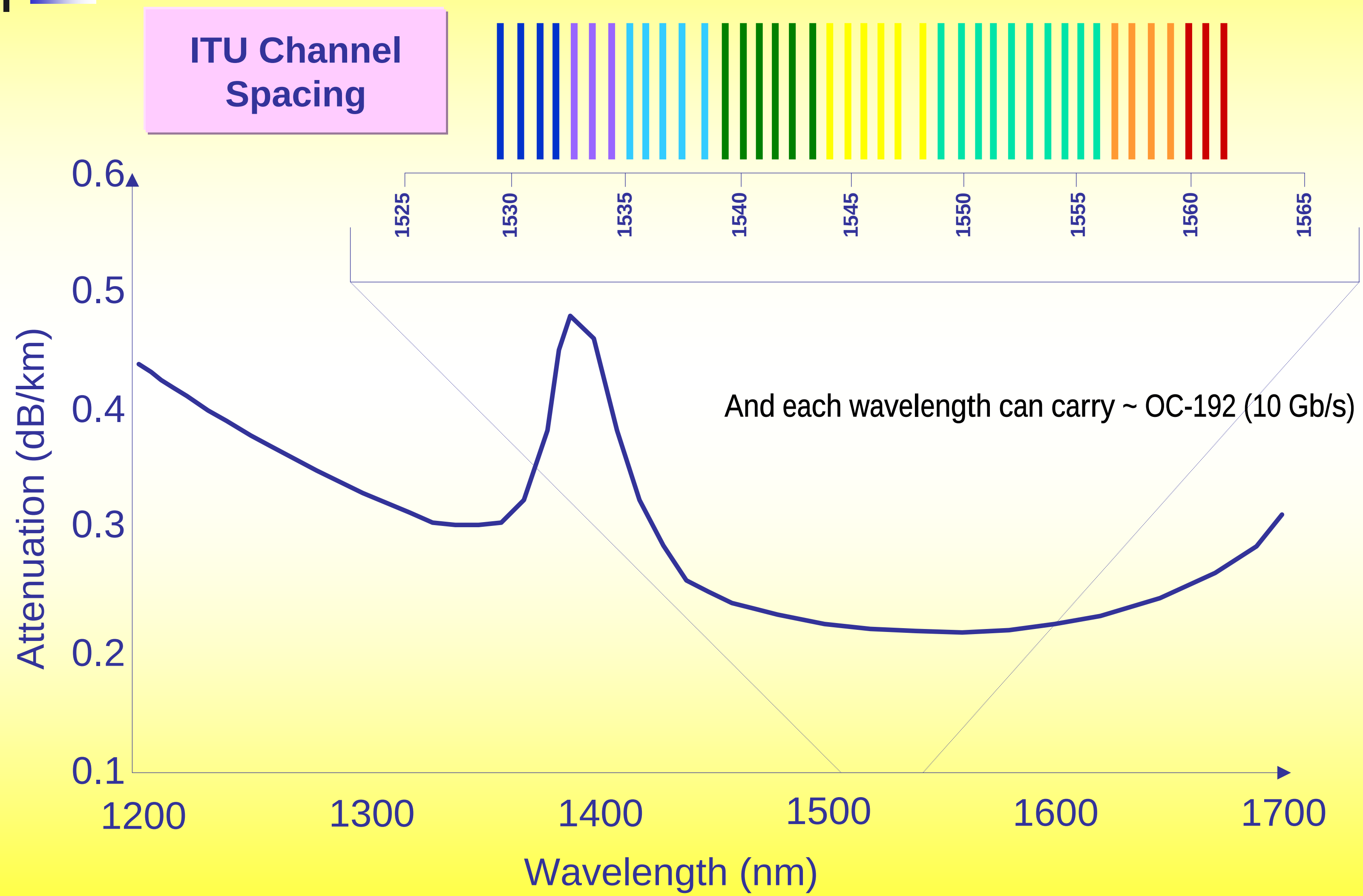


多波长色散补偿

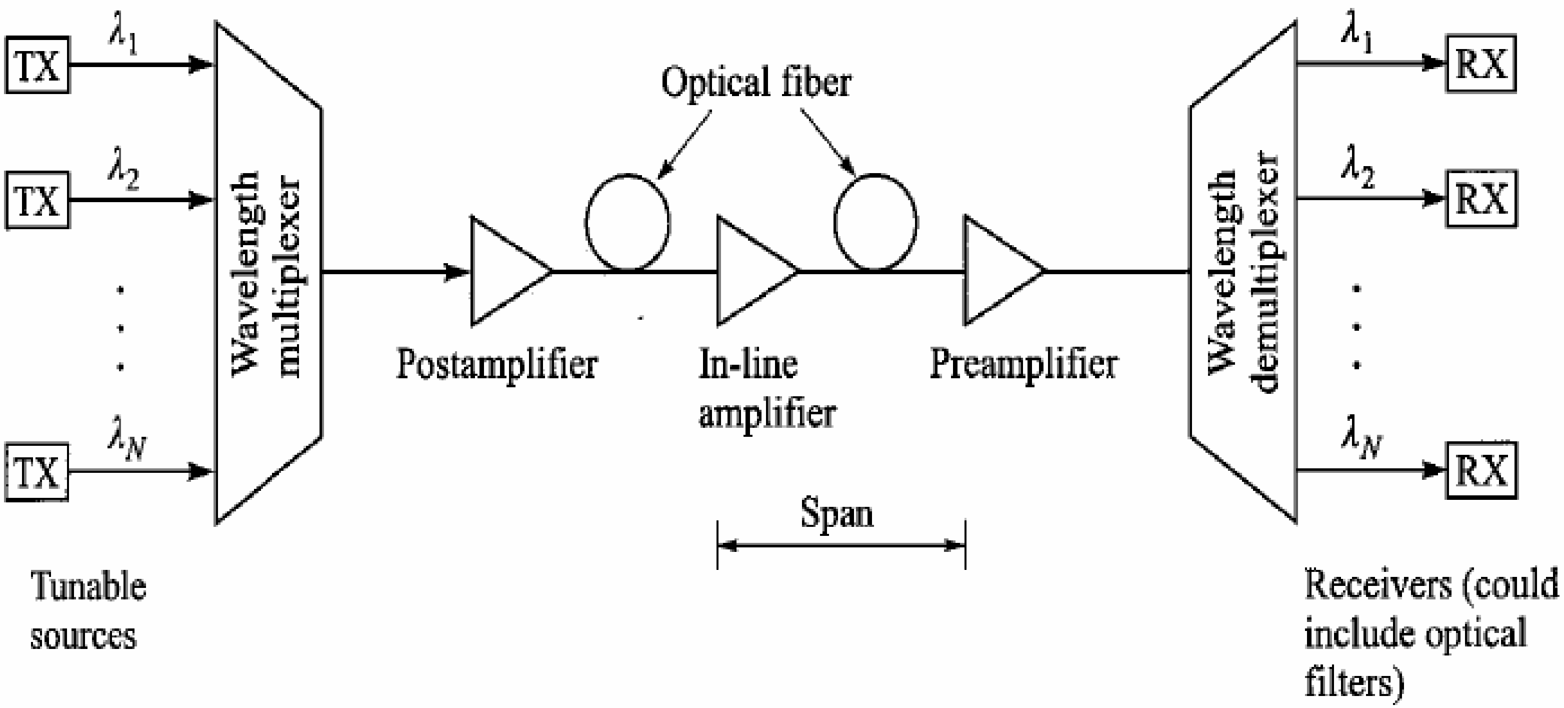
Dispersion → **Saw Tooth Compensation**



波分复用(WDM)—全光网关键技术



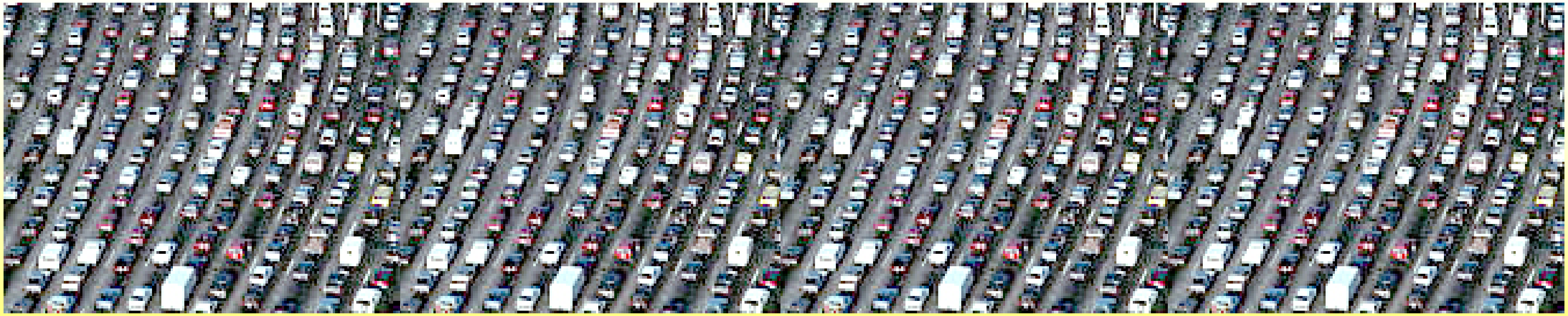
WDM Transmission System



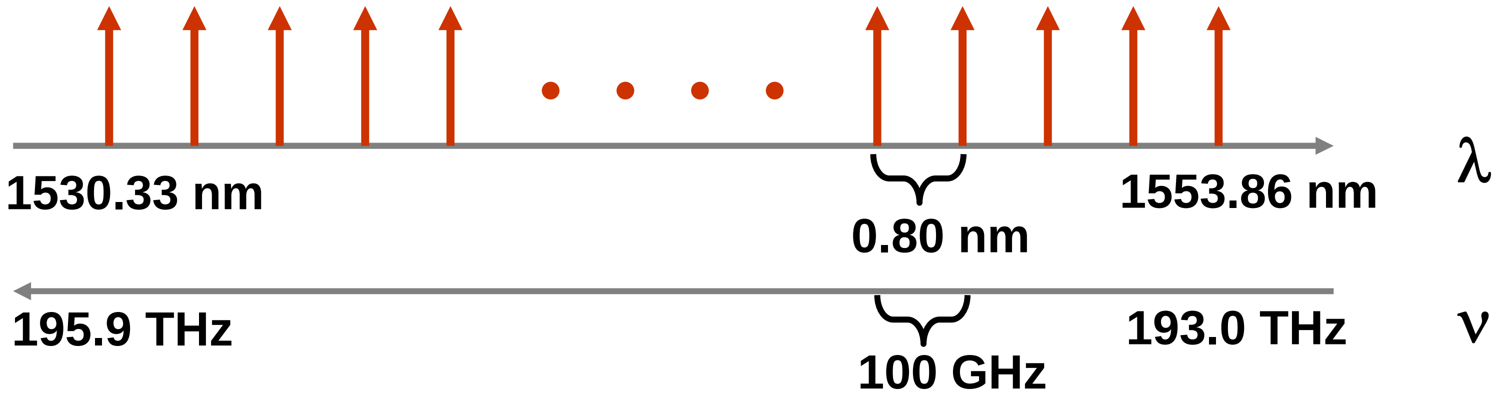
WDM的重要意义

If 64Kb/s = 1 lane

Then Based on today's WDM Technology, a single fiber would = 25 Million Lanes, or a Highway that was 60,000 Miles Wide



ITU Wavelength Grid



- ITU-T λ grid is based on 193.1 THz (1552.52nm) ± (25, 50, 100, 200) GHz
- It is a standard for laser in DWDM systems

Optical Transmission Bands

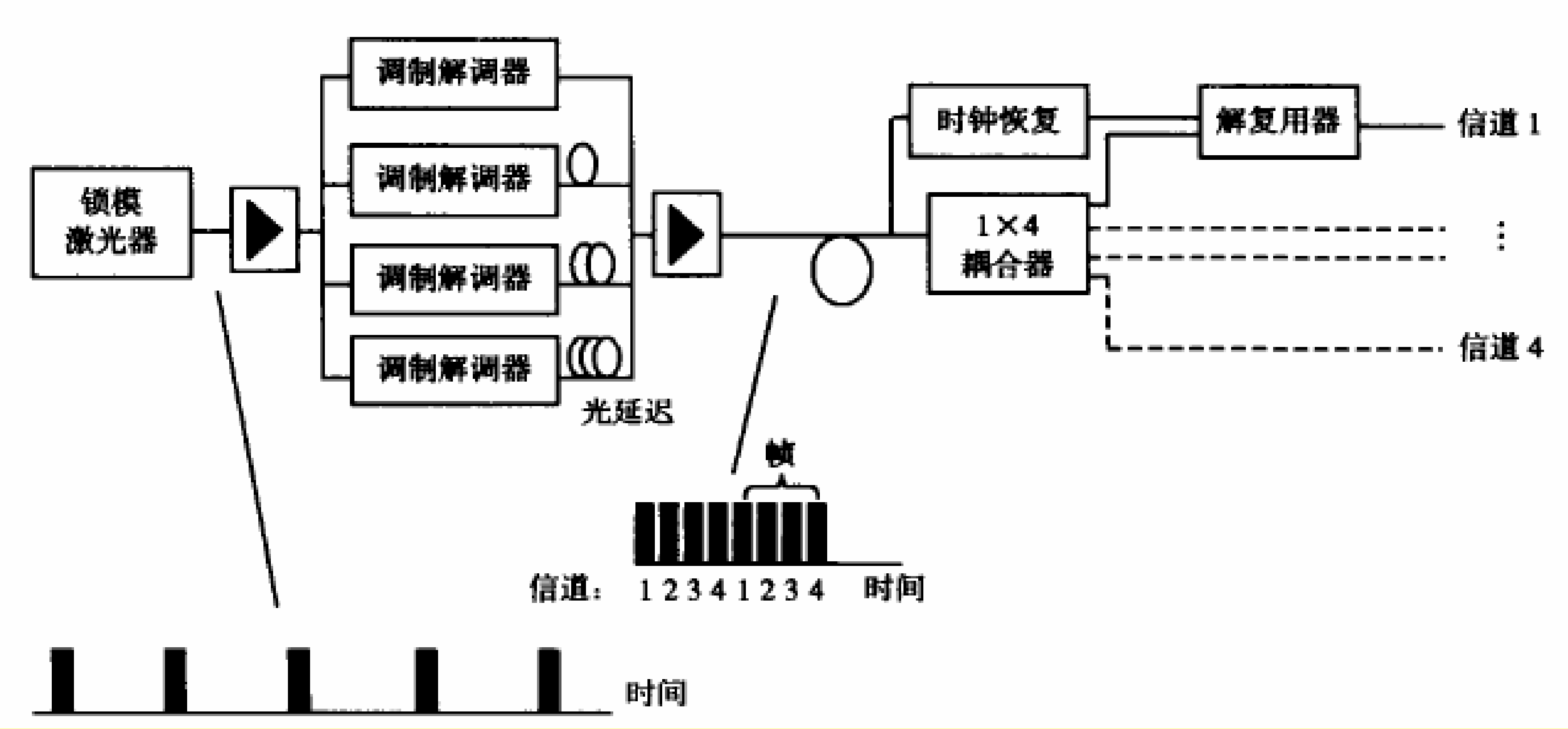
Band	Wavelength (nm)
	820 - 900
	1260 – 1360
“New Band”	1360 – 1460
S-Band	1460 – 1530
C-Band	1530 – 1565
L-Band	1565 – 1625
U-Band	1625 – 1675

WDM技术前沿研究热点

- 符合ITU-T标准的宽带可调谐激光器技术
- 适用于不同波段的掺杂光纤放大器技术
- 分布式Laman放大技术
- 各种高性能波分复用/解复用器件技术
- 动态波长转换技术
- 静态和动态全光波长上下话路（分插复用）器件（OADM）和交叉连接（OXC）技术
- 基于WDM的无源光网络（PON）和有源光网络（AON）技术

光时分复用(OTDM)—全光网关键技术

- **10Gbit/s**以上的高速电子设备实现困难且价格昂贵
- 采用**OTDM**技术可以方便地获得**40～160Gbit/s**的高速光信号

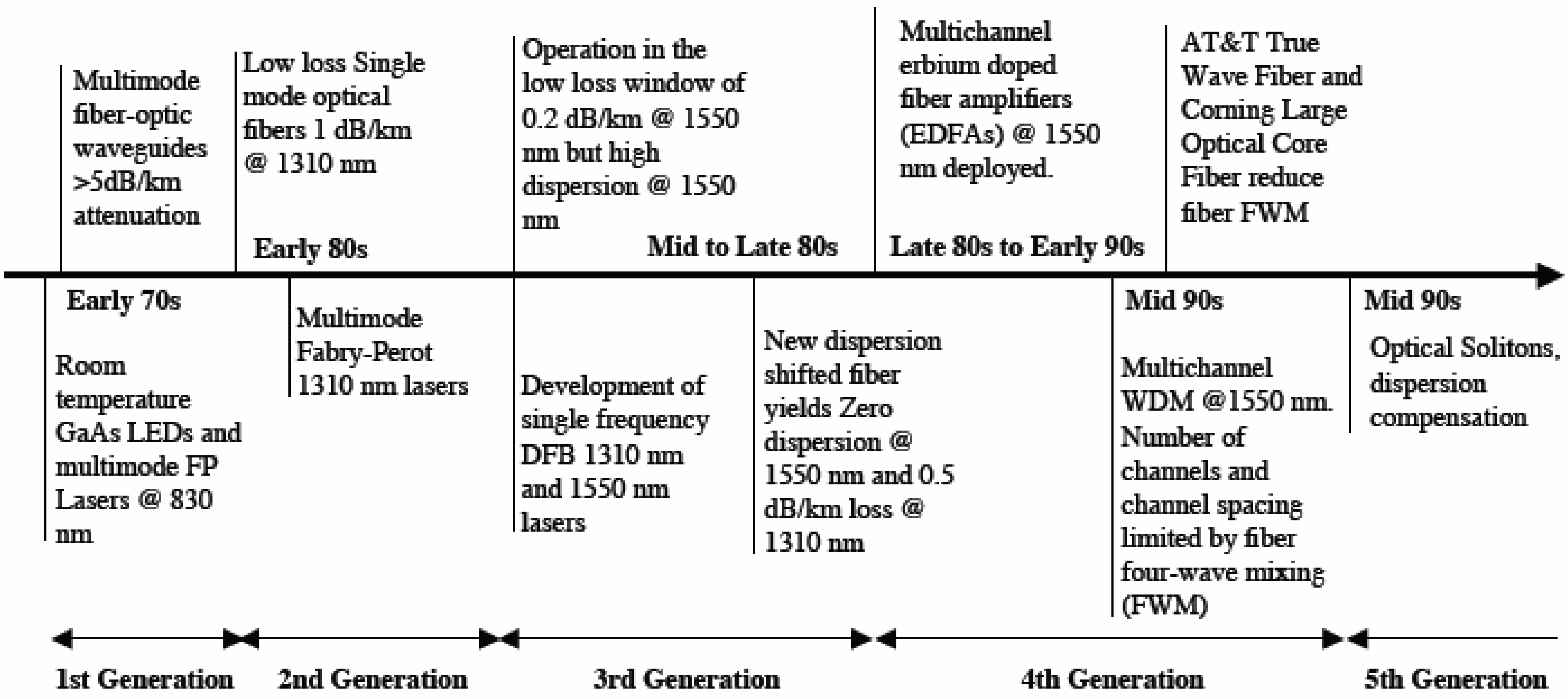


- 目前**40Gbit/s**以上的高速外调制器和高速**ETDM**技术发展迅速
- **OTDM**解复用技术尚不成熟

WDM+OTDM？

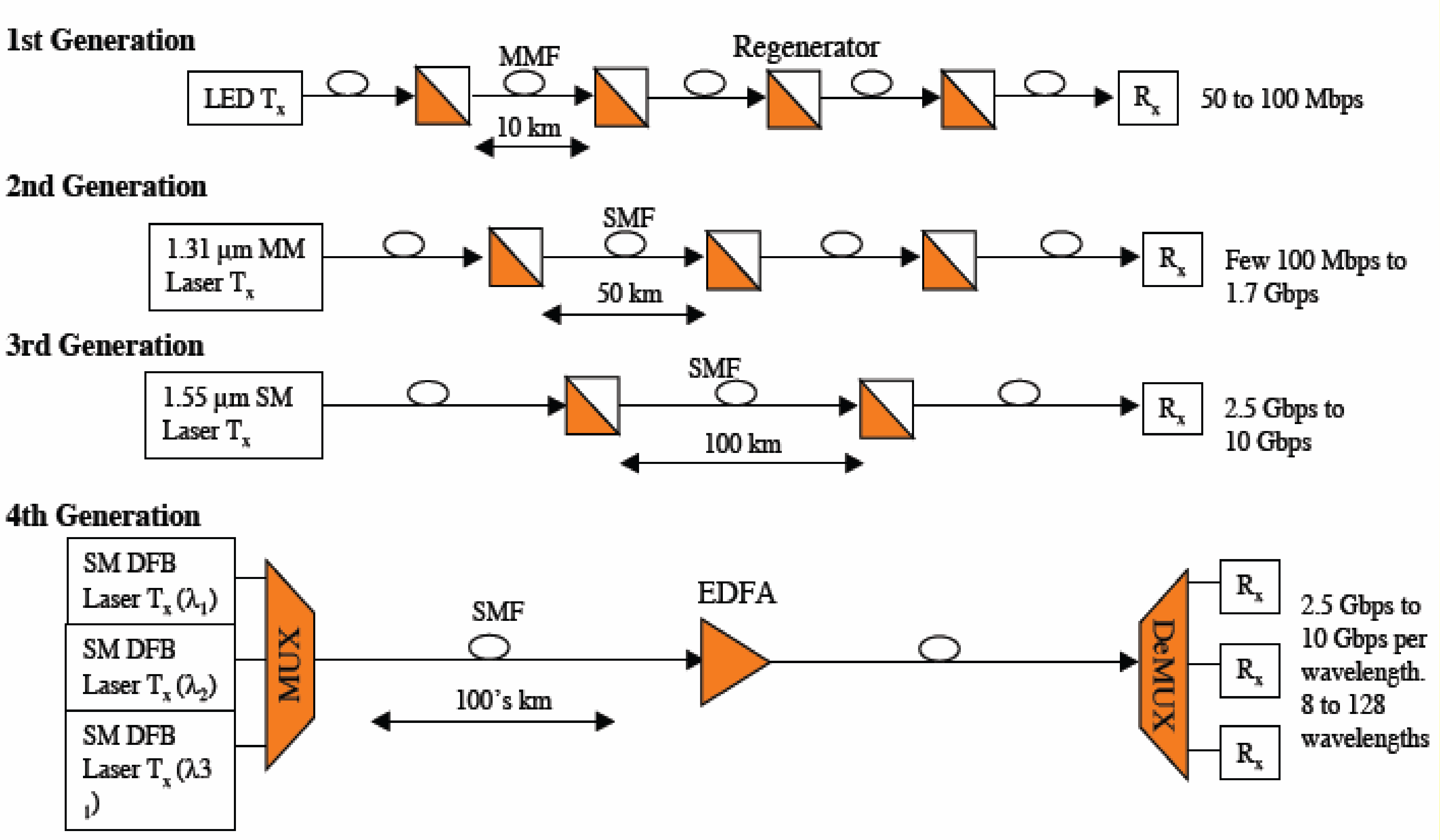
- WDM属于频域复用技术
- OTDM为时域复用技术
- 表面上看二者没有冲突，同时应用OTDM和WDM技术可以增加光纤的传输容量
- 然而，OTDM速率的提高将增加信号所占用的频带，因此将增大WDM的波长通道间隔
- 例如160Gbit/s的OTDM信号要求波长通道间隔至少为200GHz
- 具体采用何种技术，取决于技术的成熟度、系统的复杂性和系统造价

Summary

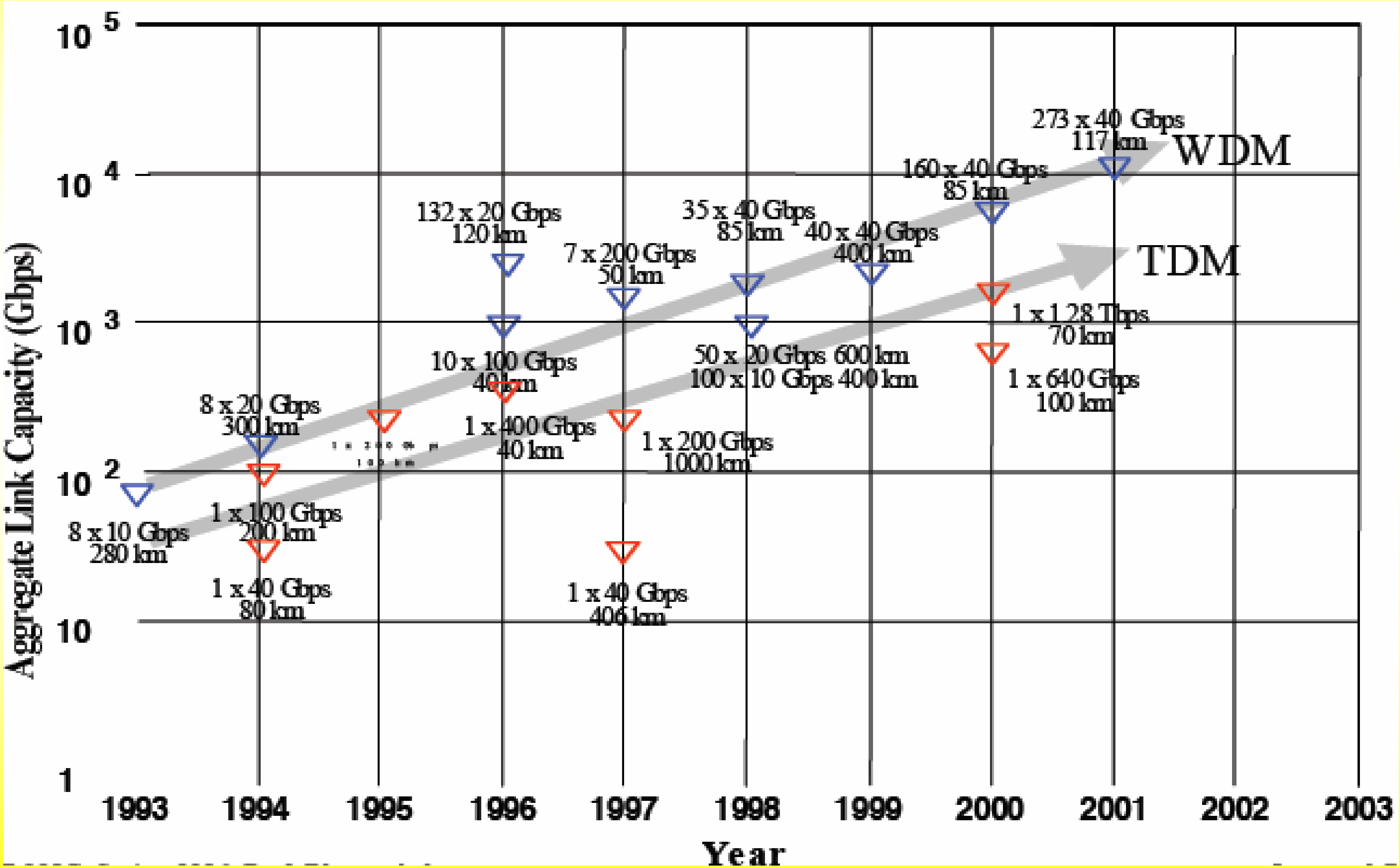


Multimode fiber-optic waveguides >5dB/km attenuation
Low loss Single mode optical fibers 1 dB/km @ 1310 nm
Early 80s
Operation in the low loss window of 0.2 dB/km @ 1550 nm but high dispersion @ 1550 nm
Mid to Late 80s
Multichannel erbium doped fiber amplifiers (EDFAs) @ 1550 nm deployed.
Late 80s to Early 90s
AT&T True Wave Fiber and Corning Large Optical Core Fiber reduce fiber FWM
Early 70s
Room temperature GaAs LEDs and multimode FP Lasers @ 830 nm
Multimode Fabry-Perot 1310 nm lasers
Development of single frequency DFB 1310 nm and 1550 nm lasers
New dispersion shifted fiber yields Zero dispersion @ 1550 nm and 0.5 dB/km loss @ 1310 nm
Mid 90s
Multichannel WDM @1550 nm. Number of channels and channel spacing limited by fiber four-wave mixing (FWM)
Mid 90s
Optical Solitons, dispersion compensation
1st Generation
2nd Generation
3rd Generation
4th Generation
5th Generation

Summary


1st Generation
LED Tx
MMF
10 km
Regenerator
Rx
50 to 100 Mbps
2nd Generation
1.31 μm MM Laser Tx
SMF
50 km
Rx
Few 100 Mbps to 1.7 Gbps
3rd Generation
1.55 μm SM Laser Tx
SMF
100 km
Rx
2.5 Gbps to 10 Gbps
4th Generation
SM DFB Laser Tx (λ1)
SM DFB Laser Tx (λ2)
SM DFB Laser Tx (λ3 i)
MUX
SMF
100's km
EDFA
DeMUX
Rx
Rx
Rx
2.5 Gbps to 10 Gbps per wavelength. 8 to 128 wavelengths

Summary


WDM
TDM
273 x 40 Gbps
117 km
160 x 40 Gbps
85 km
132 x 20 Gbps
120 km
35 x 40 Gbps
85 km
40 x 40 Gbps
400 km
7 x 200 Gbps
50 km
1 x 1.28 Tbps
70 km
50 x 20 Gbps 600 km
100 x 10 Gbps 400 km
10 x 100 Gbps
40 km
1 x 640 Gbps
100 km
8 x 20 Gbps
300 km
1 x 400 Gbps
40 km
1 x 200 Gbps
1000 km
1 x 100 Gbps
200 km
8 x 10 Gbps
280 km
1 x 40 Gbps
80 km
1 x 40 Gbps
406 km
Aggregate Link Capacity (Gbps)
10 5
10 4
10 3
10 2
10
1
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Year