ECSE-6660 Optical Networking Components: Part I

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Or

http://www.ecse.rpi.edu/Homepages/shivkuma/

Shivkumar Kalyanaraman

Rensselaer Polytechnic Institute

shivkuma@ecse.rpi.edu

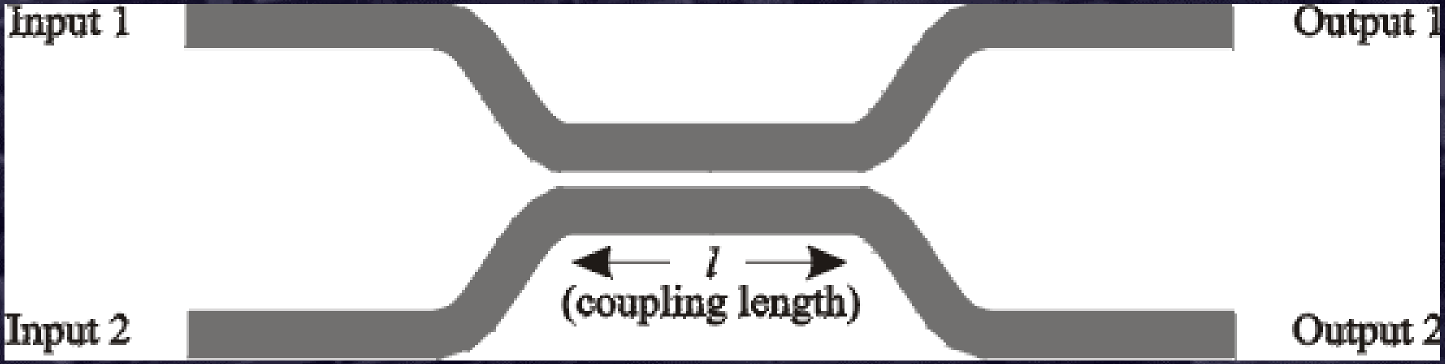
Based in part on textbooks of S.V.Kartalopoulos (DWDM) and H. Dutton (Understanding Optical communications), and slides of Partha Dutta

Overview

- Couplers, Splitters, Isolators, Circulators
- Filters, Gratings, Multiplexors
- Optical Amplifiers, Regenerators
- Light Sources, Tunable Lasers, Detectors
- Modulators
- Chapter 2 and 3 of Ramaswami/Sivarajan

Couplers, Splitters

Optical Couplers

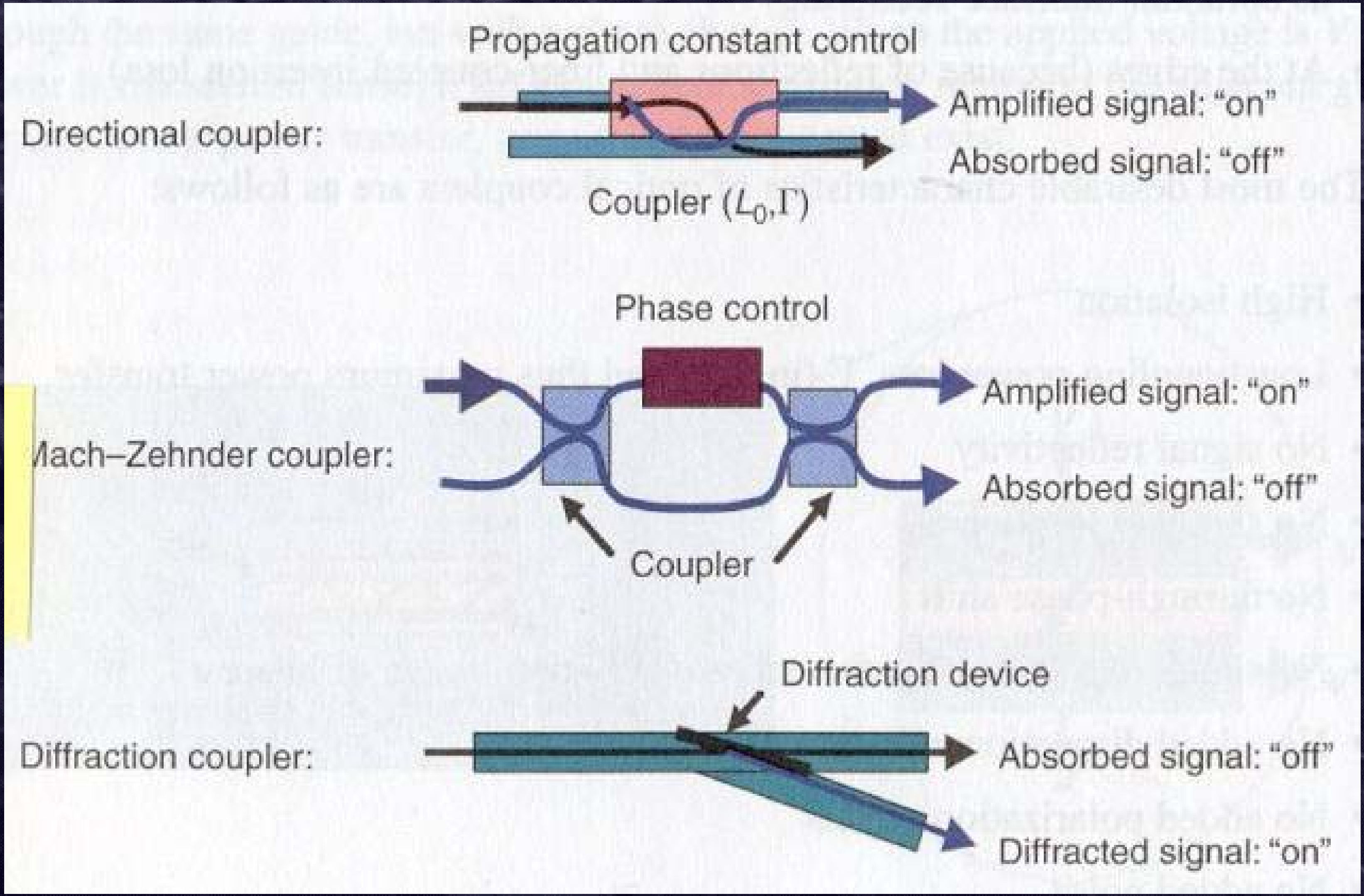


- Combines & splits signals
- Wavelength independent or selective
- Fabricated using waveguides in integrated optics
- α = *coupling ratio*
- Power(Output1) = α Power(Input1)
- Power(Output2) = (1- α) Power(Input1)
  - Power splitter if α=1/2: 3-dB coupler
  - Tap if α close to 1
  - λ-selective if α depends upon λ (used in EDFAs)

Couplers (contd)

- Light couples from one waveguide to a closely placed waveguide because the propagation mode overlaps the two waveguides
- Identical waveguides => complete coupling and back periodically ("coupled mode theory")
- Conservation of energy constraint:
  - Possible that electric fields at two outputs have same magnitude, but will be 90 deg out of phase!
  - Lossless combining is not possible

Couplers (Contd)



8-port Splitter Made by Cascading Y-Couplers

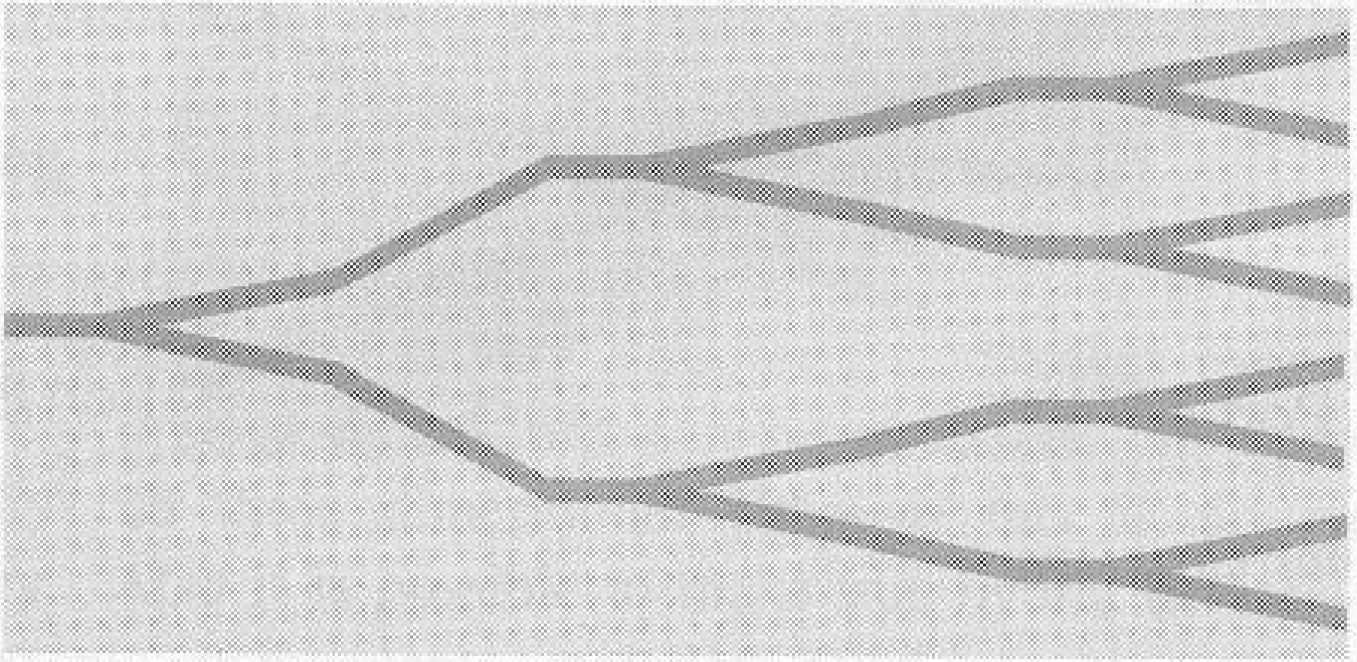
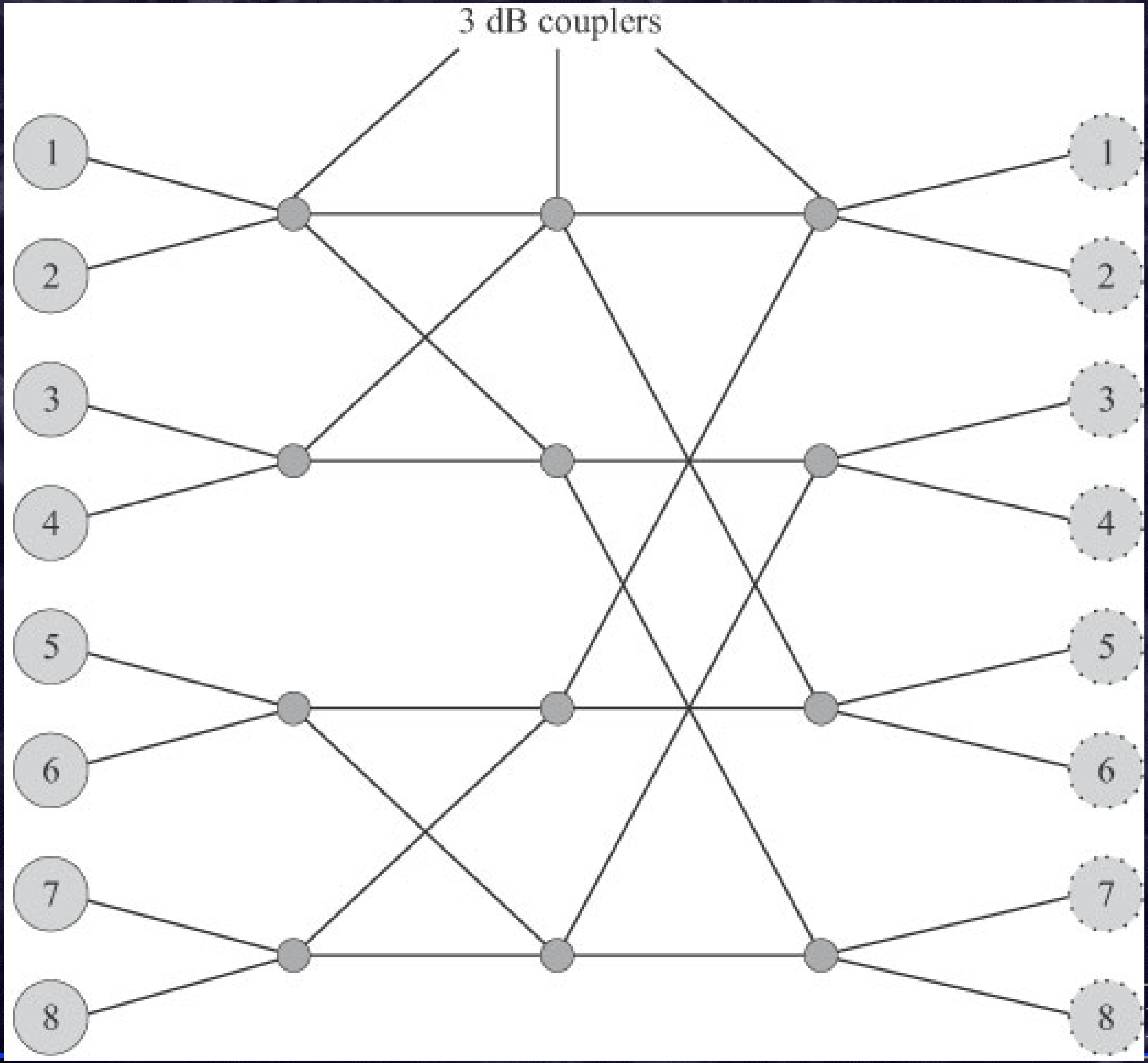


Figure 109. An 8-Port Splitter Made by Cascading Y-Couplers

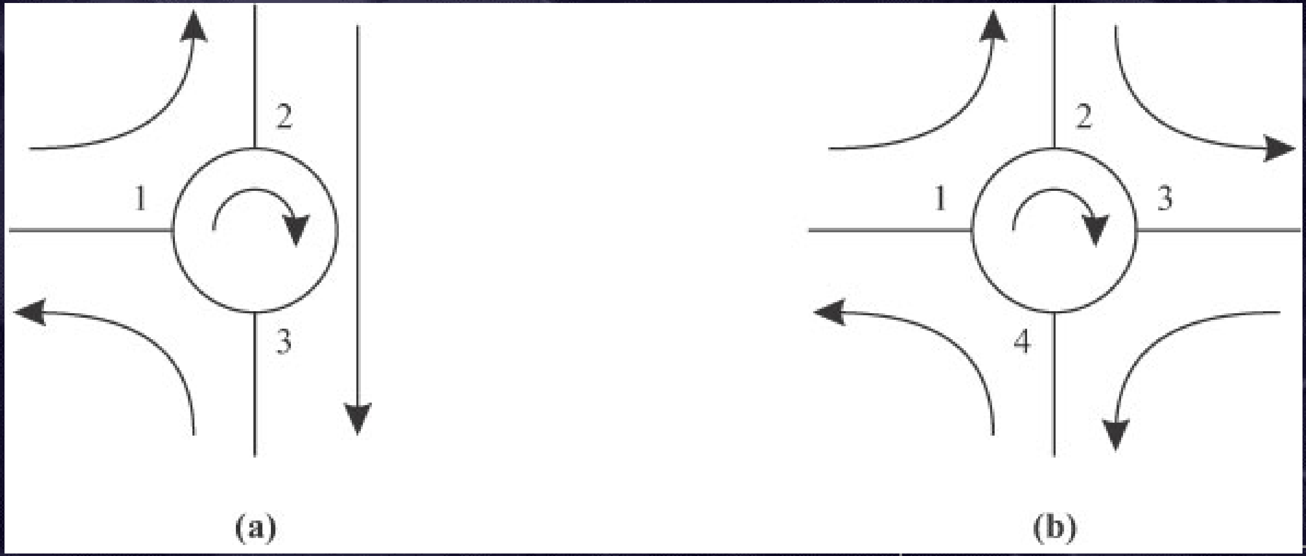
8x8 Star Coupler



Power from all inputs equally split among outputs

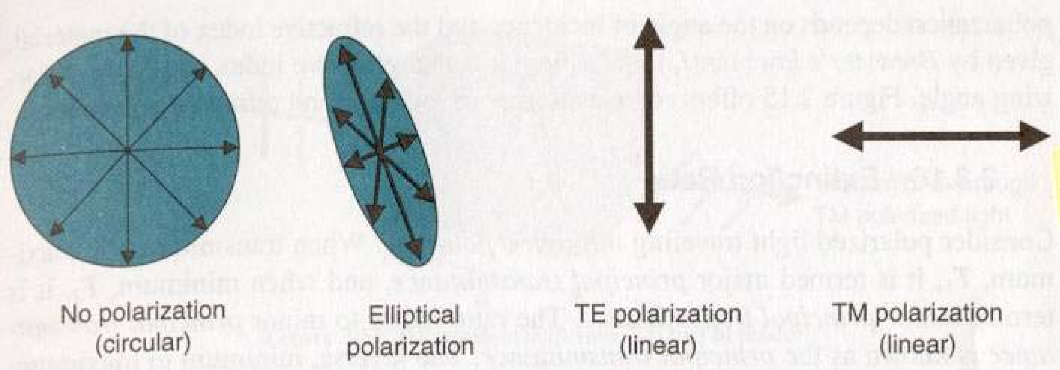
Isolators and Circulators

- *Extension of coupler concept*
- *Non-reciprocal* => will not work same way if inputs and outputs reversed
- Isolator: allow transmission in one direction, but block all transmission (eg: reflection) in the other
- Circulator: similar to isolator, but with multiple ports.



Recall: Polarization

- Polarization: Time course of the direction of the electric field vector
  - Linear, Elliptical, Circular, Non-polar
- Polarization plays an important role in the interaction of light with matter
  - Amount of light reflected at the boundary between two materials
  - Light Absorption, Scattering, Rotation
  - Refractive index of anisotropic materials depends on polarization (Brewster's law)



Polarizing Filters

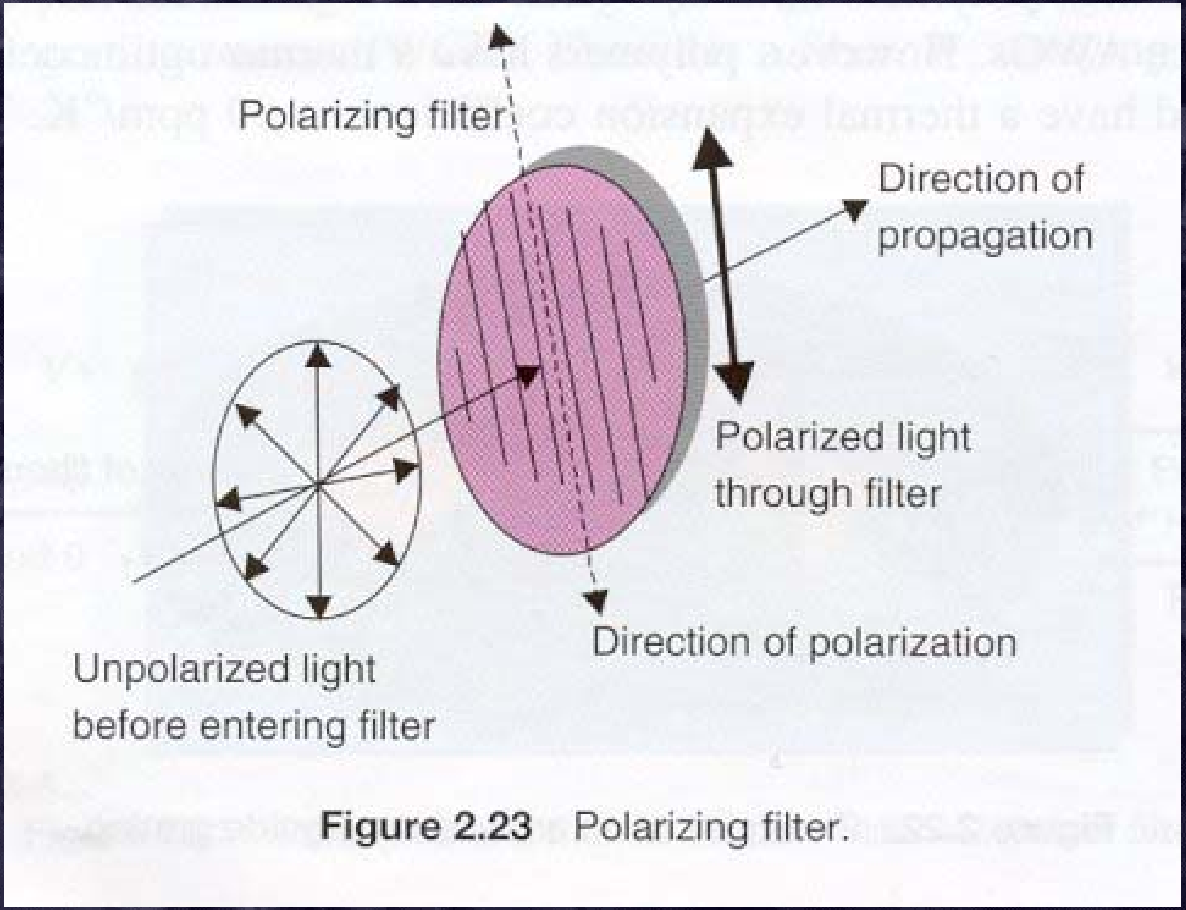


Figure 2.23 Polarizing filter.

Done using crystals called dichroics

Rotating Polarizations

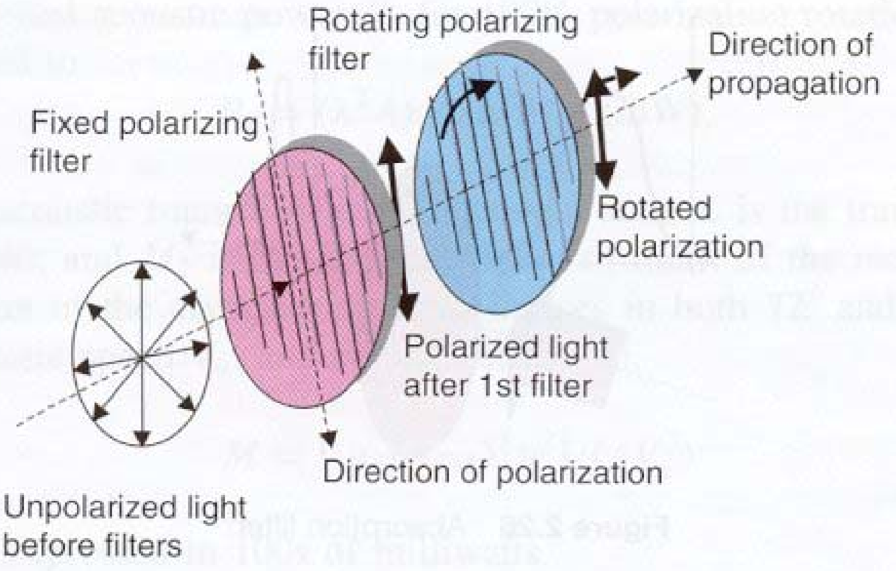


Figure 2.24 An assembly of a fixed and a rotating polarizing filter to rotate the polarization direction.

Crystals called "Faraday Rotators" can rotate the polarization without loss!

Optical Isolator

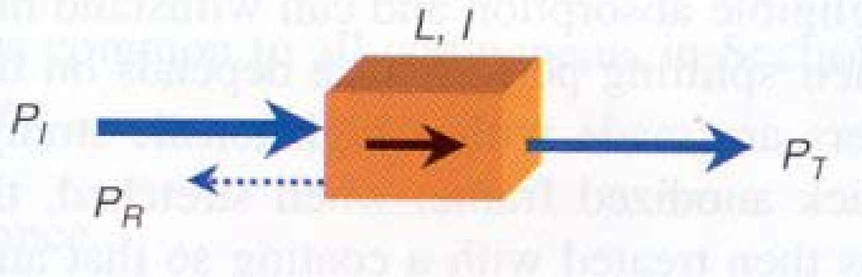
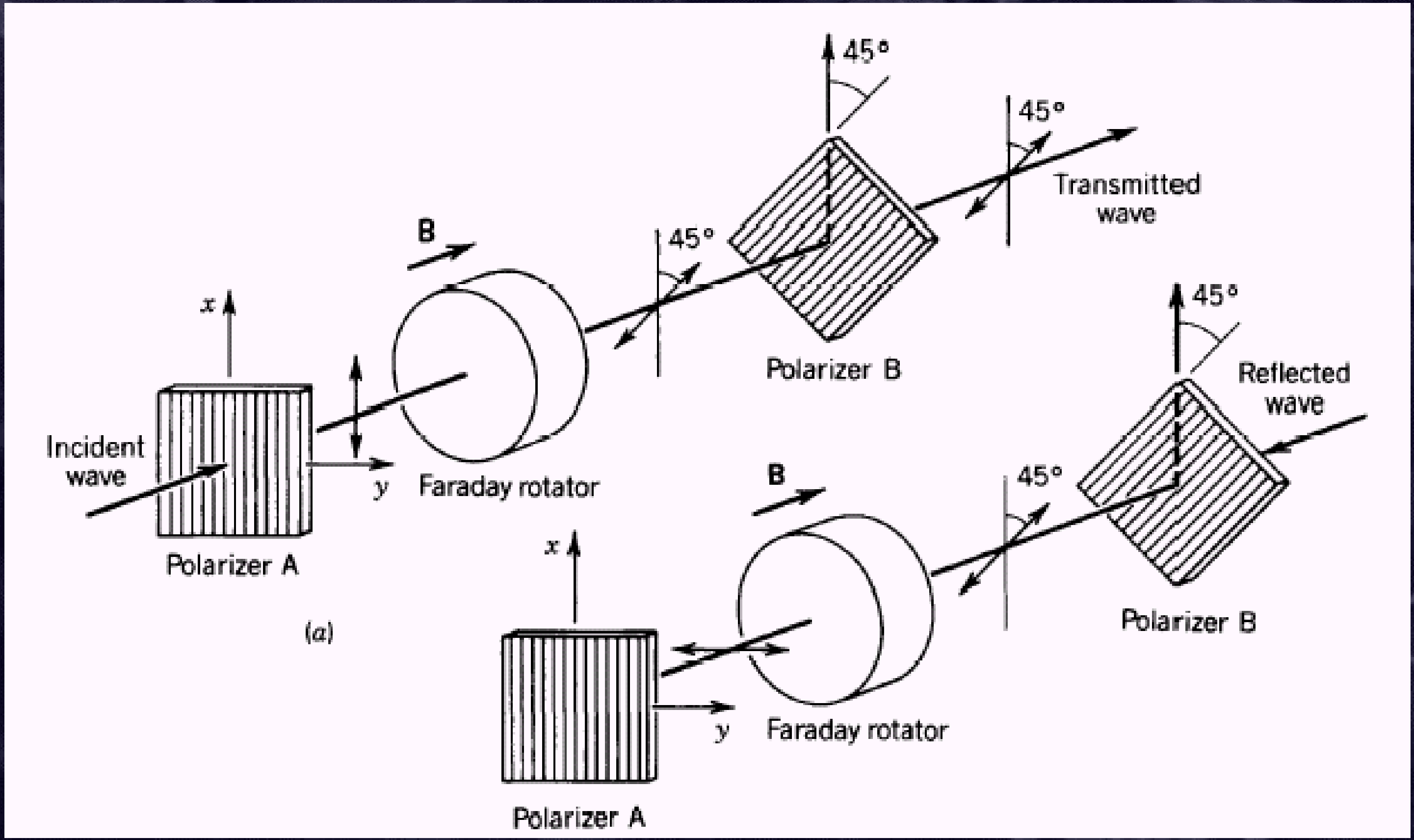
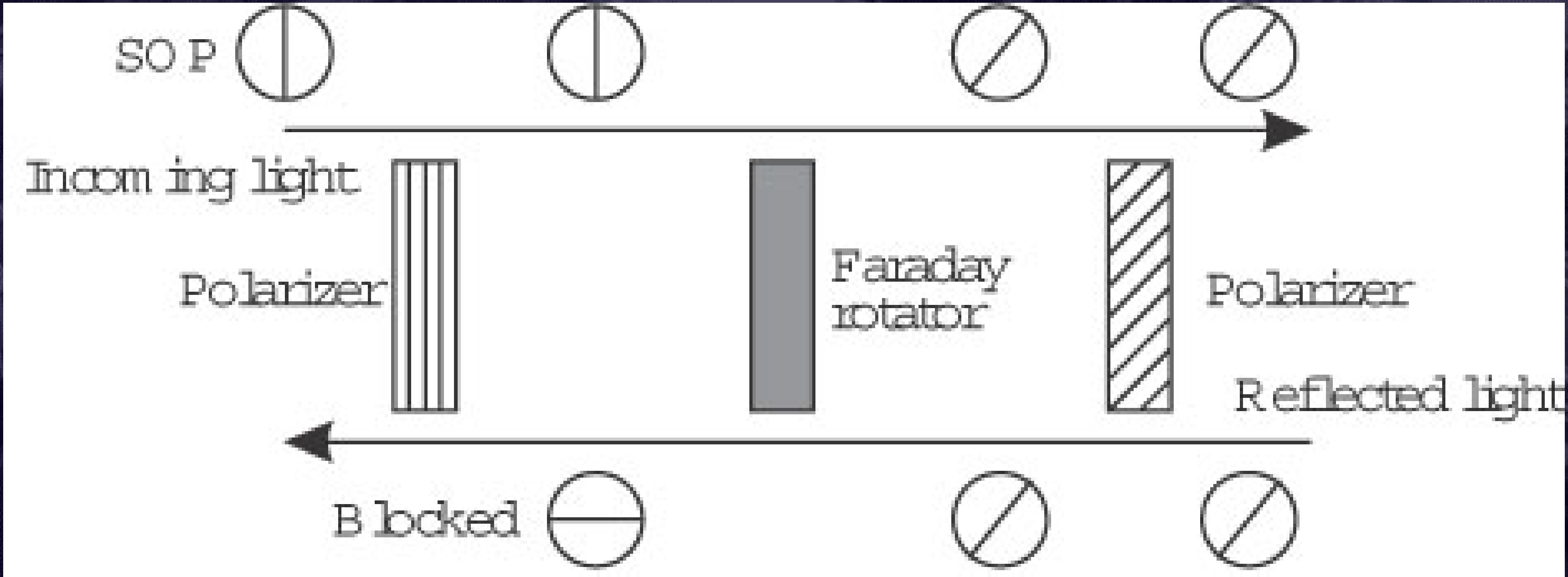


Figure 2.30 Model of an optical isolator.

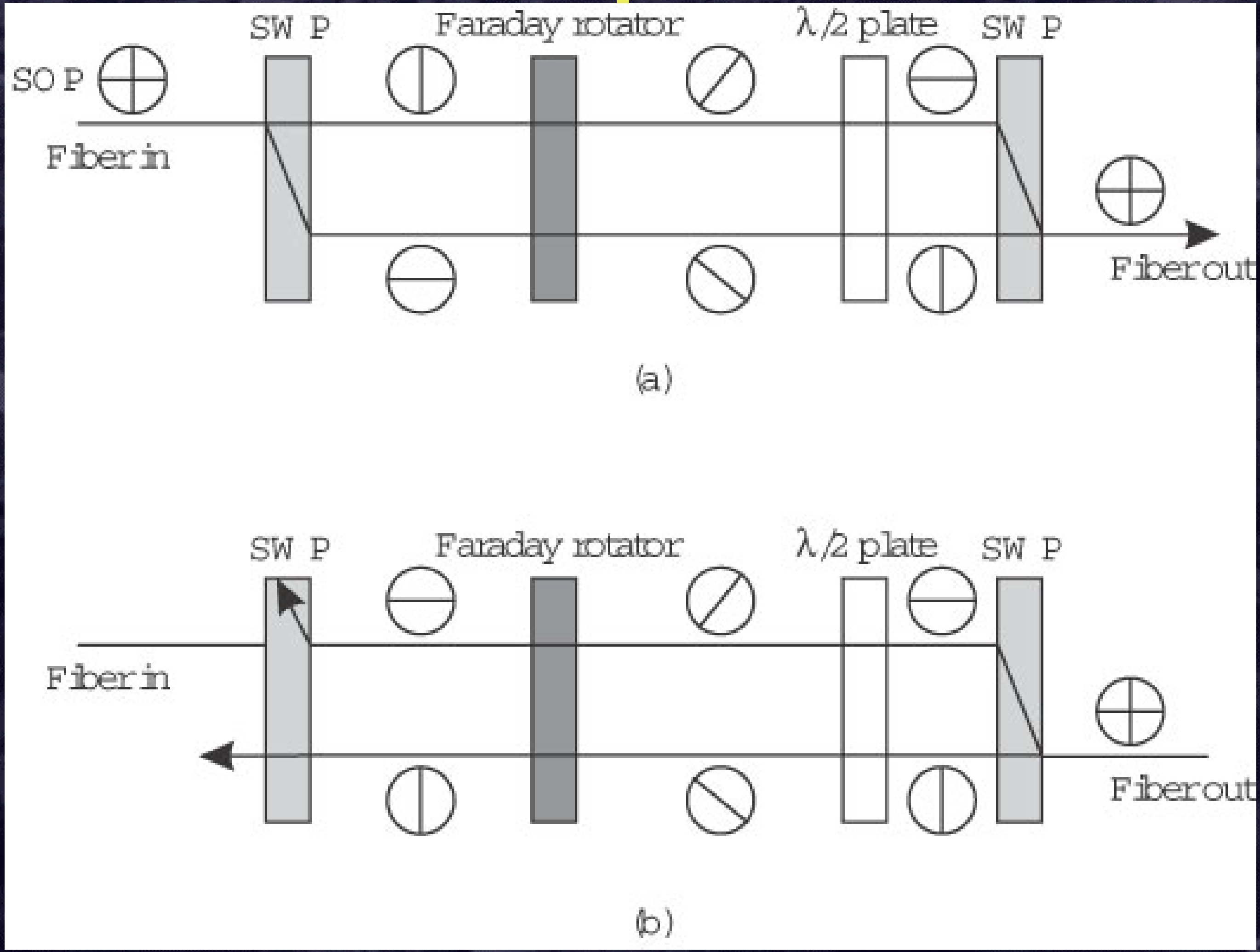


Polarization-dependent Isolators



Limitation: Requires a particular SOP for input light signal

Polarization-independent Isolators

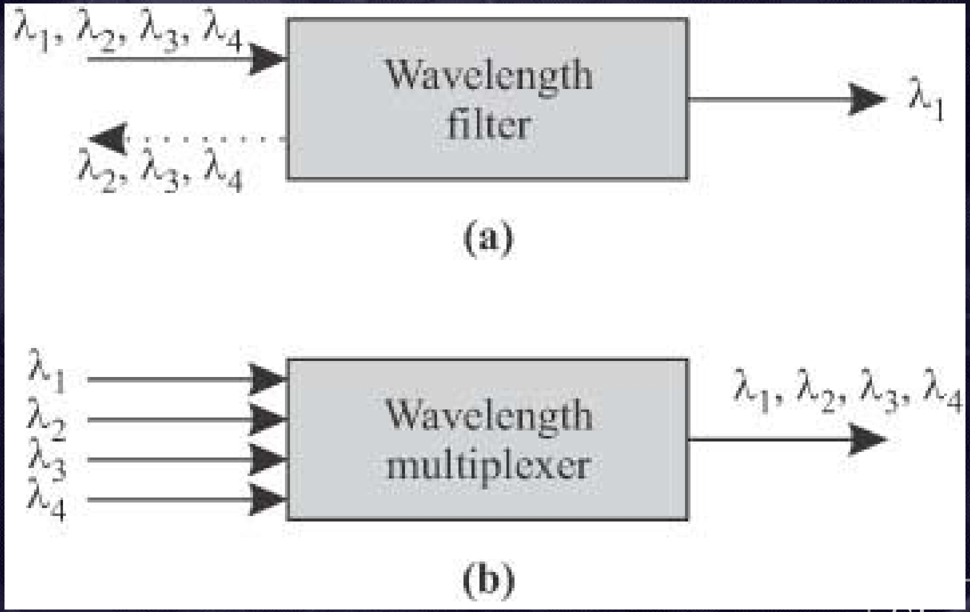


SWP: *Spatial Walk-off Polarizer (using birefringent crystals)*

Splits signal into orthogonally polarized components

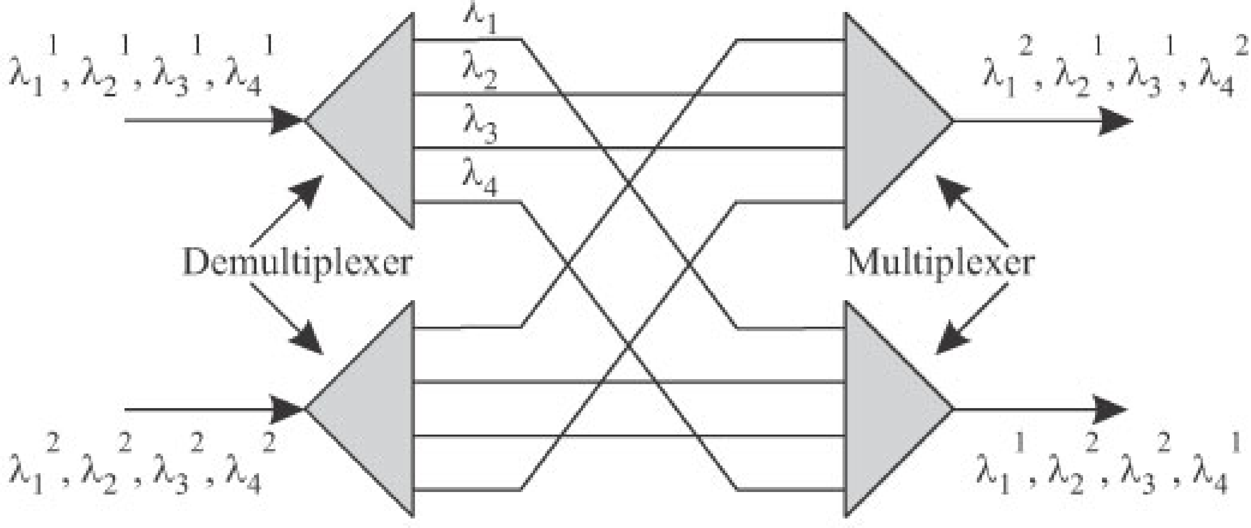
Multiplexers, Filters, Gratings

Wavelength selection technologies…



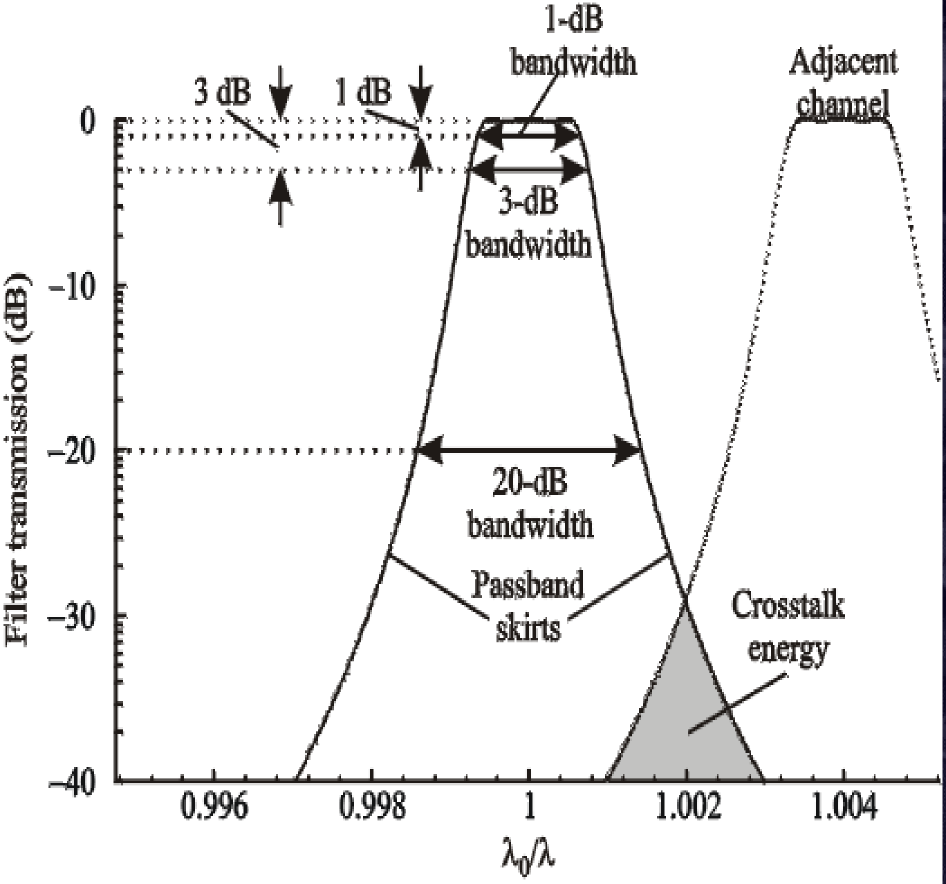
Applications

- Wavelength (band) selection,
- Static wavelength crossconnects (WXCs), OADMs
- Equalization of gain
- Filtering of noise
- Ideas used in laser operation
- Dispersion compensation modules



Characteristics of Filters

- Low insertion (input-to-output) loss
- Loss independent of SOP: geometry of waveguides
- Filter passband independent of temperature
- Flat passbands
- Sharp "skirts" on the passband & crosstalk rejection
- Cost: integrated optic waveguide manufacture
- Usually based upon interference or diffraction



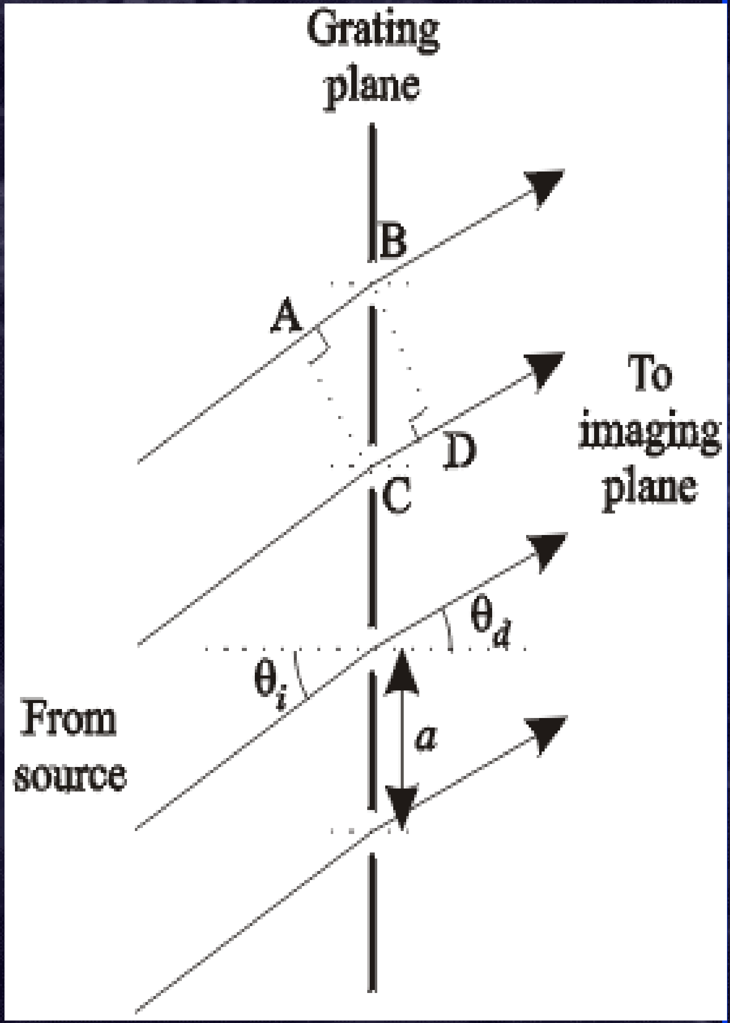
Gratings

- Device using interference among optical signals from same source, but with diff. relative phase shifts (I.e. different path lengths)

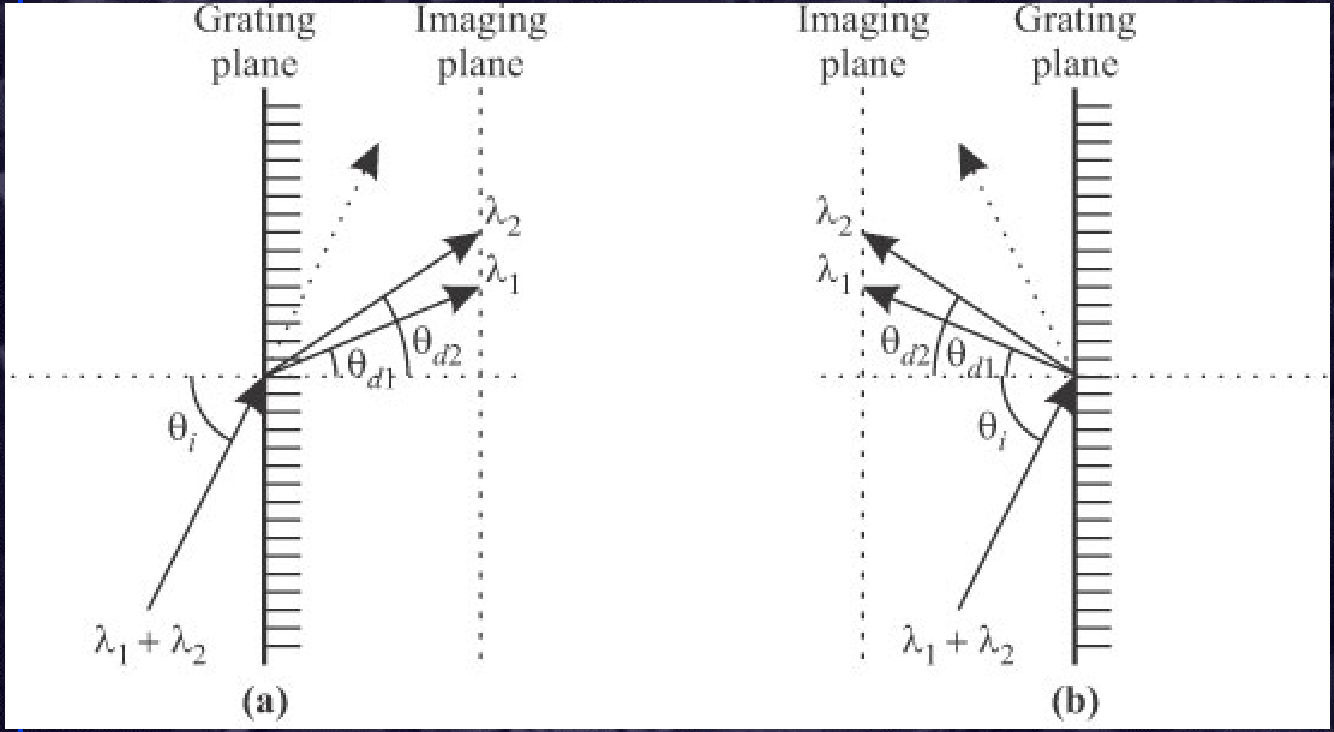
- Constructive interference at wavelength λ and grating pitch, a, if

  $a[\sin(\theta_i) - \sin(\theta_d)] = m \lambda$

- m = order of the grating



Transmission vs Reflection Grating



- Narrow slits (tx) vs narrow reflection surfaces (rx)
- Majority of devices are latter type (rx)

- Note: *etalon* is a device where multiple optical signals generated by repeated traversals of a single cavity

Diffraction Gratings

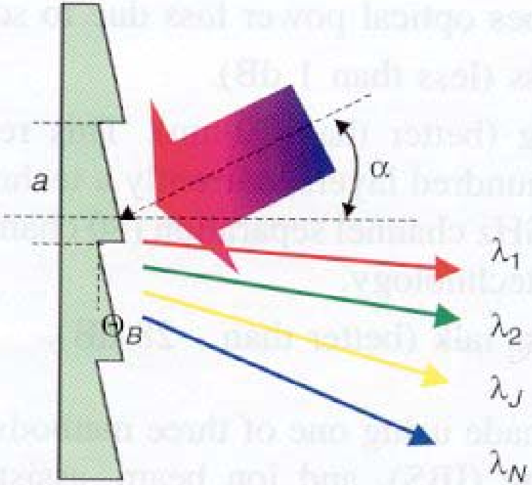


Figure 2.12 A diffraction grating.

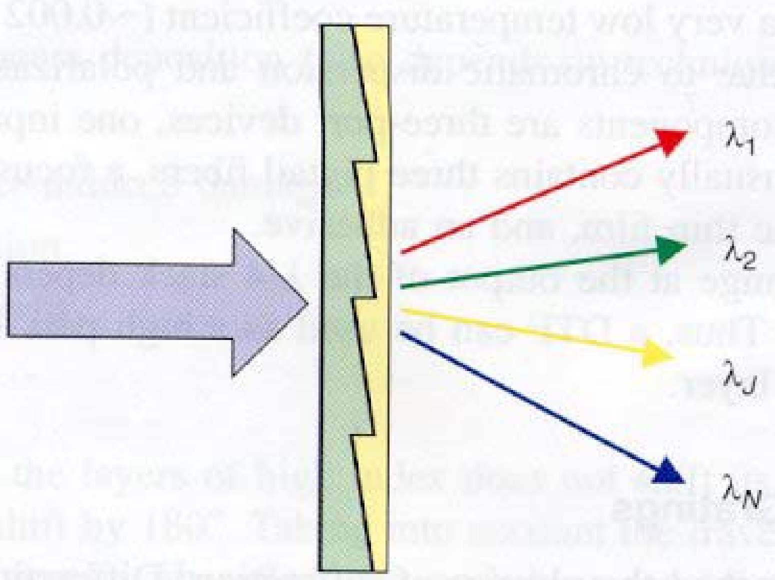
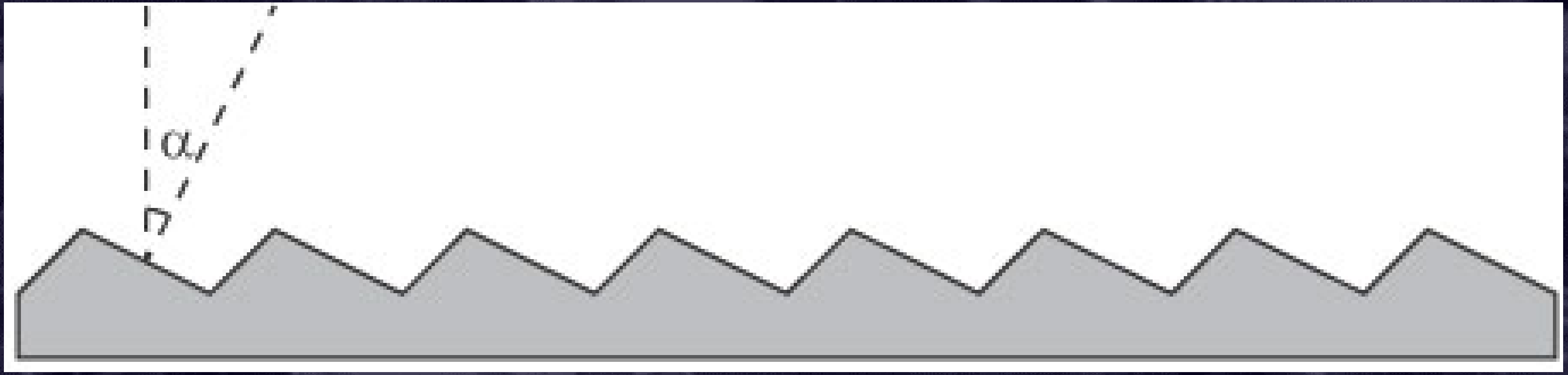


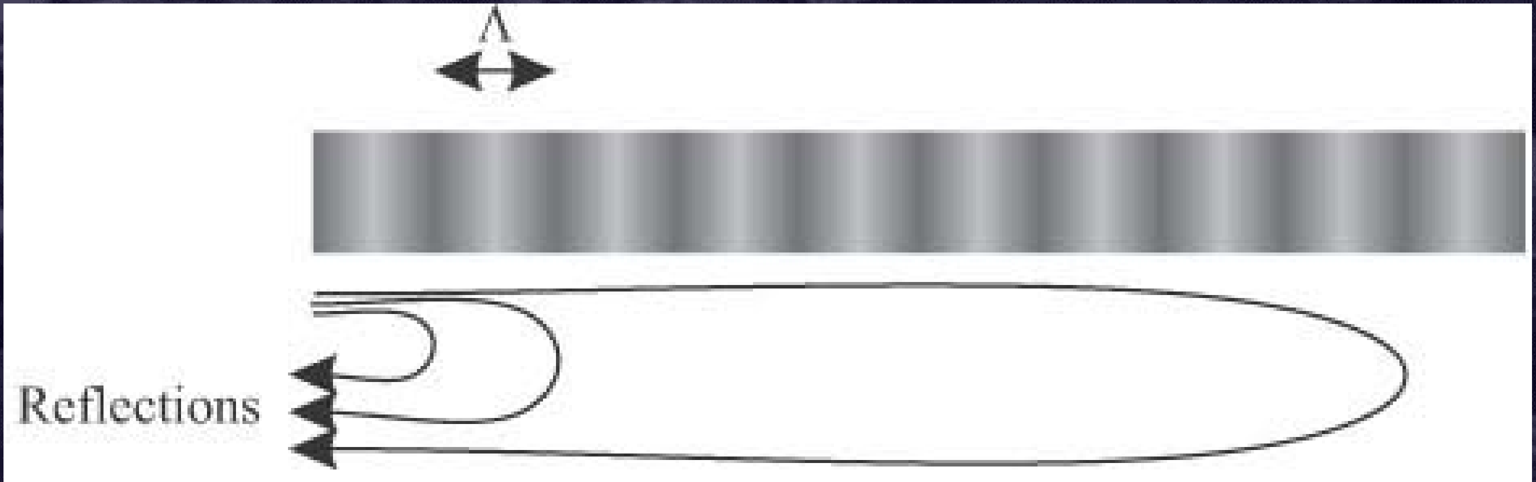
Figure 2.13 A pass-through grating diffracts each wavelength in different angle

Grating principles (contd)



- Blazing: concentrating the refracted energies at a different maxima other than zero-th order
- Reflecting slits are inclined at an angle to the grating plane.

Bragg Gratings



- Periodic perturbation (eg: of RI) "*written*" in the propagation medium
- Bragg condition: Energy is coupled from incident to scattered wave if wavelength is

$$\lambda_0 = 2\, n_{eff} \Lambda$$

where Λ is period of grating

- If incident wave has wavelength λ_0, this wavelength is *reflected by Bragg grating*

Bragg Grating Principles

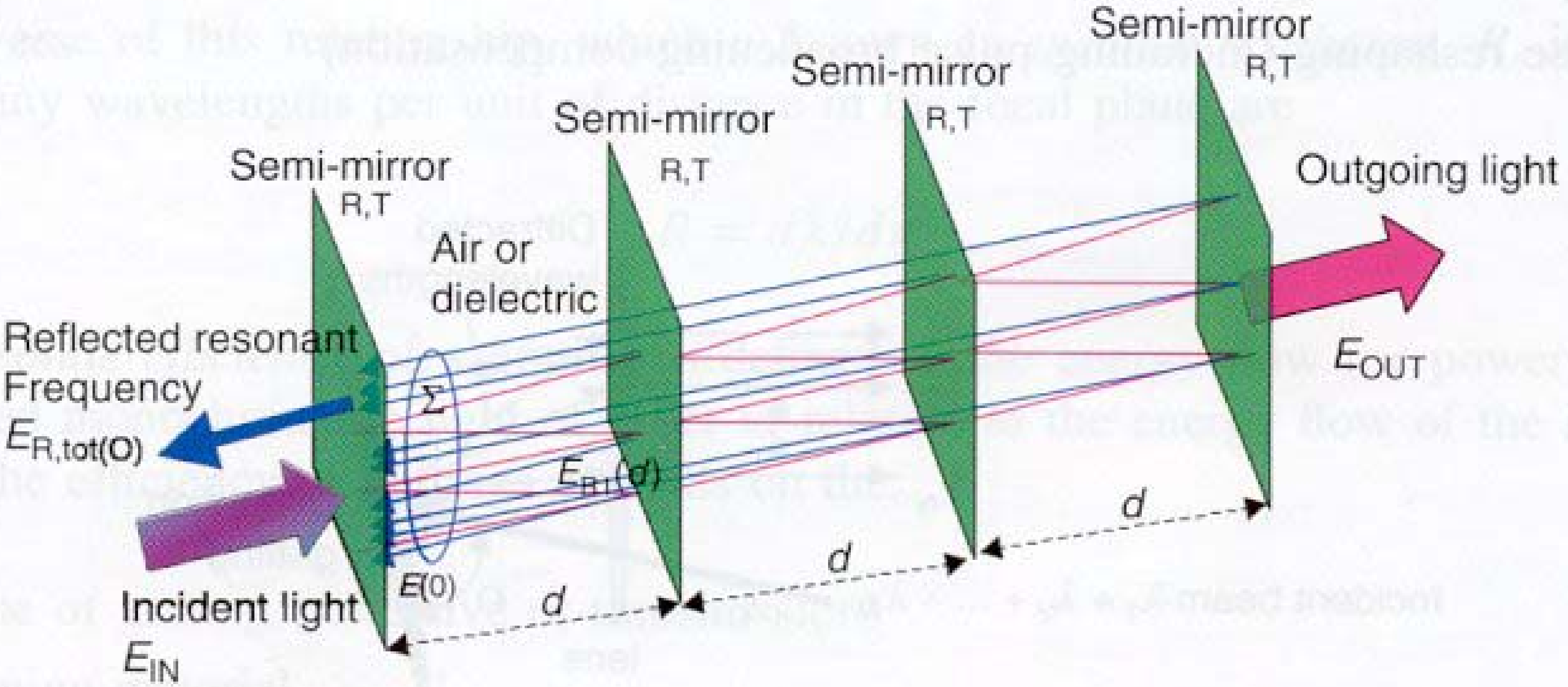
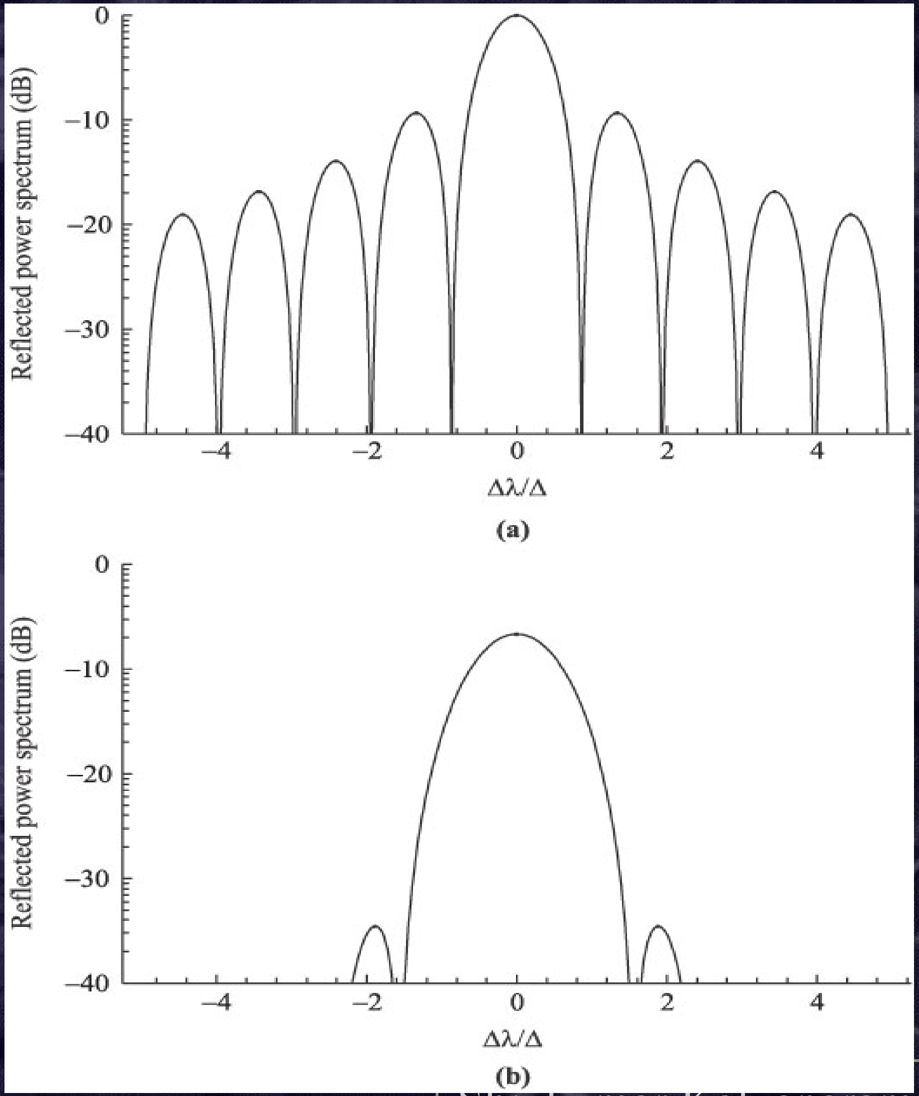


Figure 2.17 Principles of the Bragg grating.

Bragg Gratings (contd)

- Uniform vs apodized index profile
- Apodized: side lobes cut off, but width of main lobe increased
- Reflection spectrum is the F-transform of RI-distribution
- B/w of grating (1 nm) inversely proportional to grating length (few mm)
- Note: Lasers use Bragg gratings to achieve a single frequency operation



Fiber Gratings

- Very low-cost, low loss, ease of coupling (to other fibers), polarization insensitivity, low temp coeff and simple packaging
- "Writing" Fiber Gratings:
  - Use *photosensitivity* of certain types of fibers (eg: Silica doped with Ge, hit with UV light => RI change)
  - Use a "*phase mask*" (diffractive optical element)
- *Short-period* (aka Bragg, 0.5μm) or *long-period* gratings (upto a few mm)
  - Short-period (Fiber Bragg): low loss (0.1dB), λ-accuracy (0.05nm)
  - Long-period fiber gratings used in EDFAs to provide gain compensation

Fiber Bragg Grating

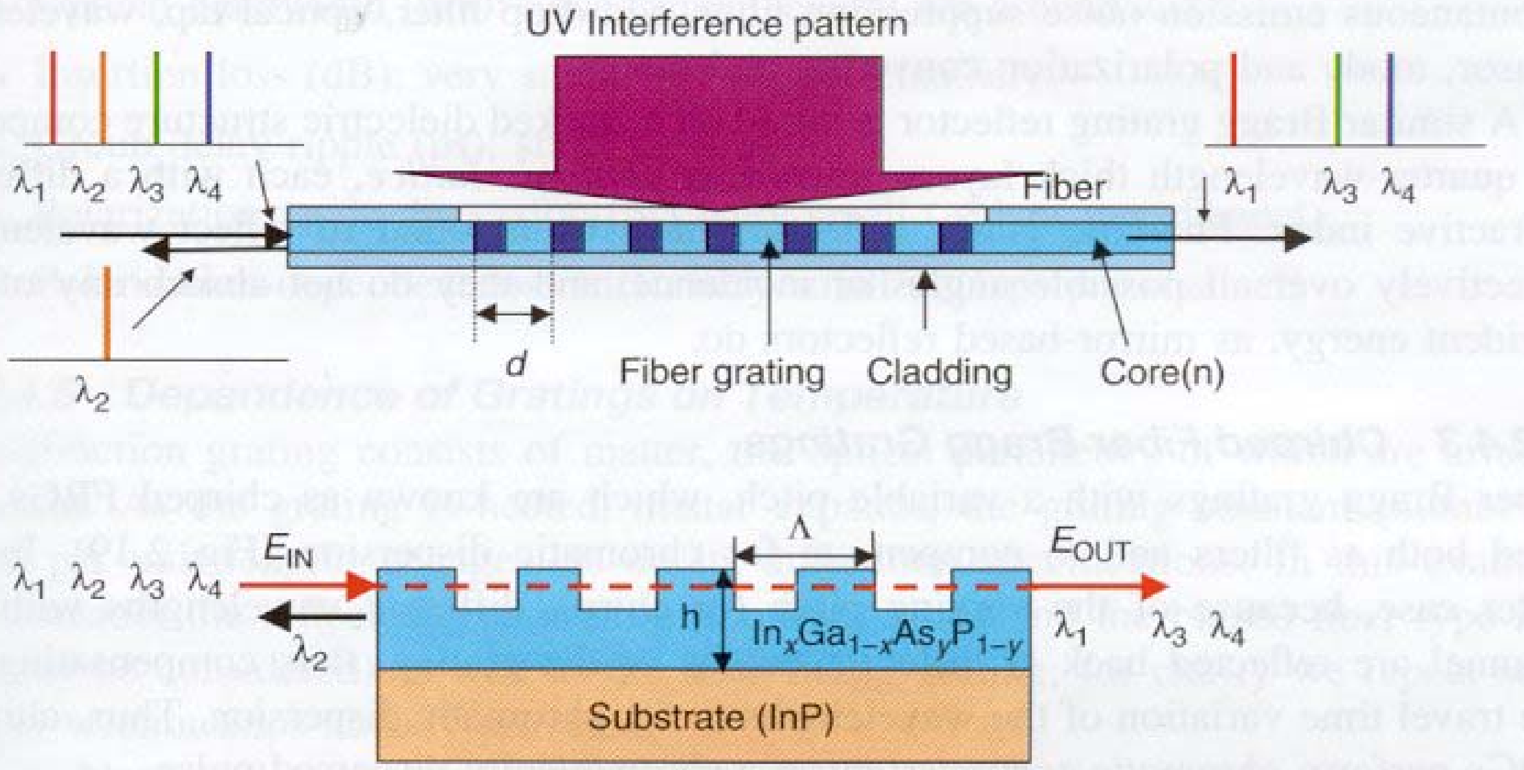
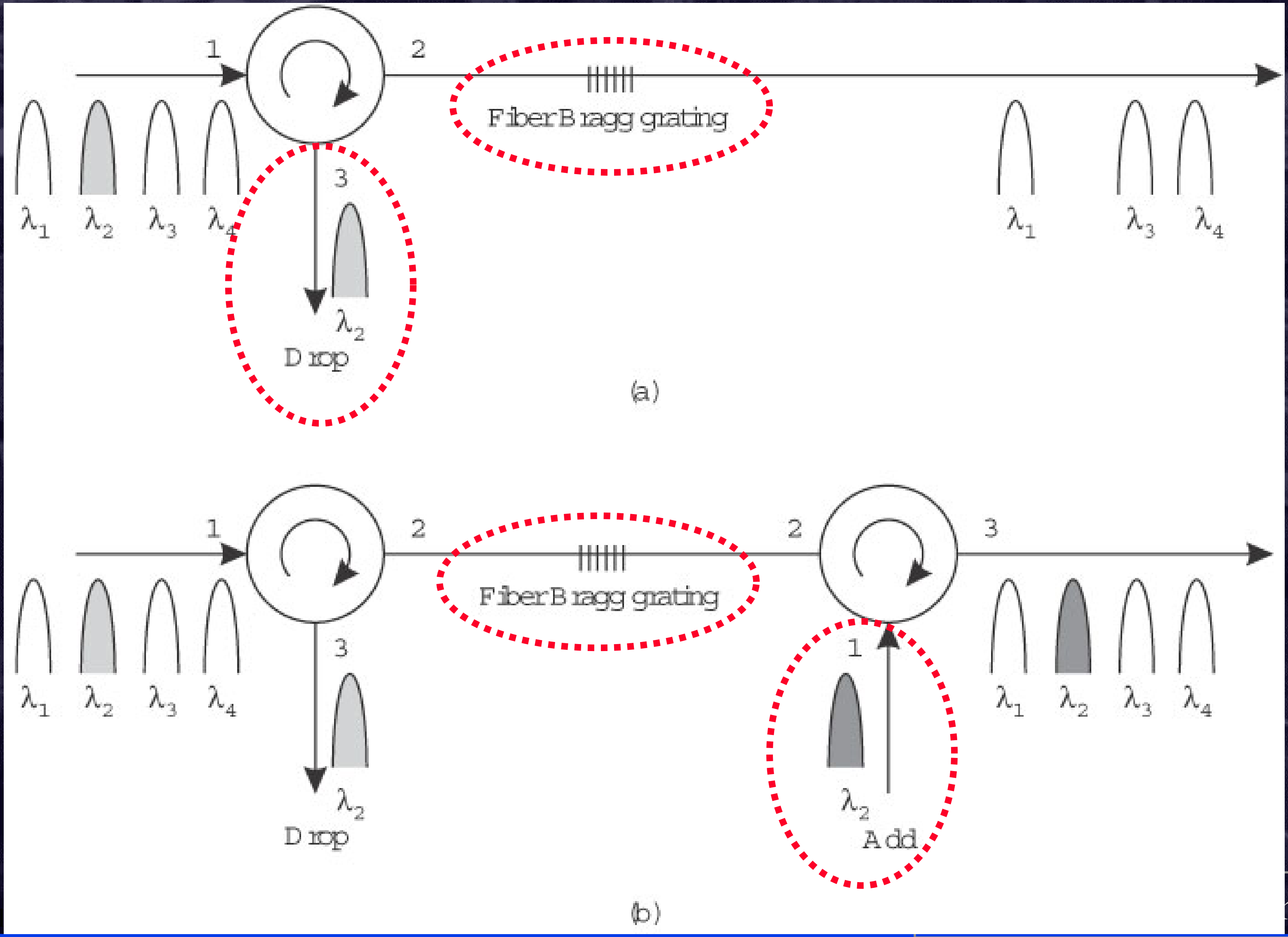


Figure 2.18 A fiber Bragg grating is made by exposing the core with a UV pattern and a monolithic one is made with corrugated InGaAsP over InP substrate.

OADM Elements with F-B Gratings



Fiber Bragg *Chirped* Grating

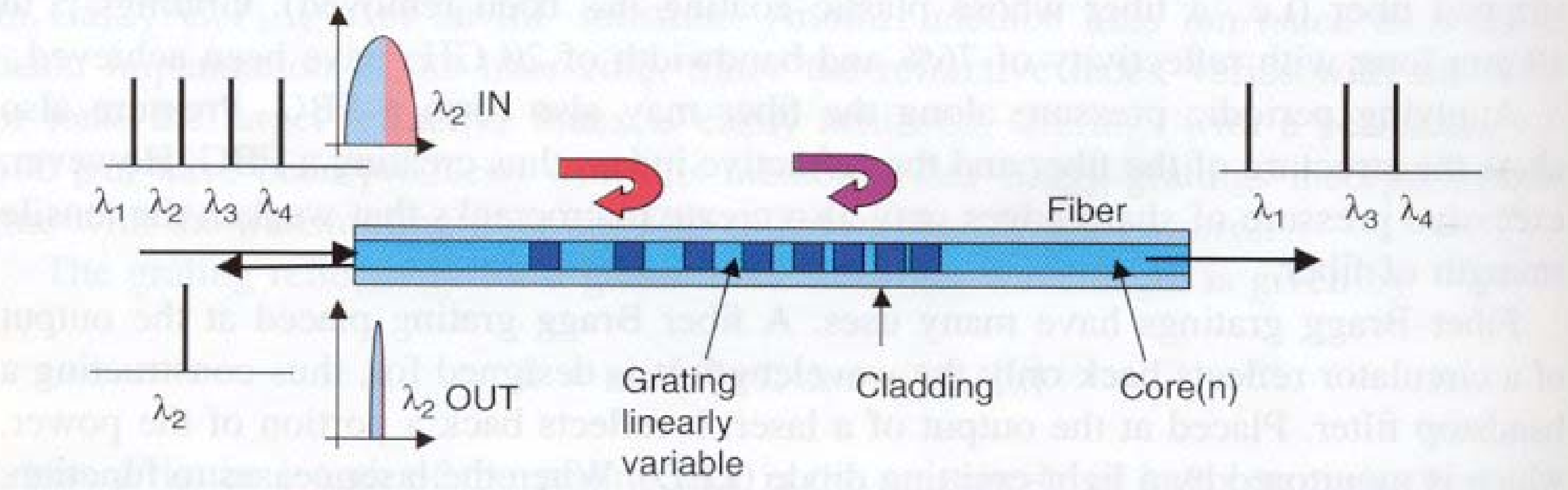
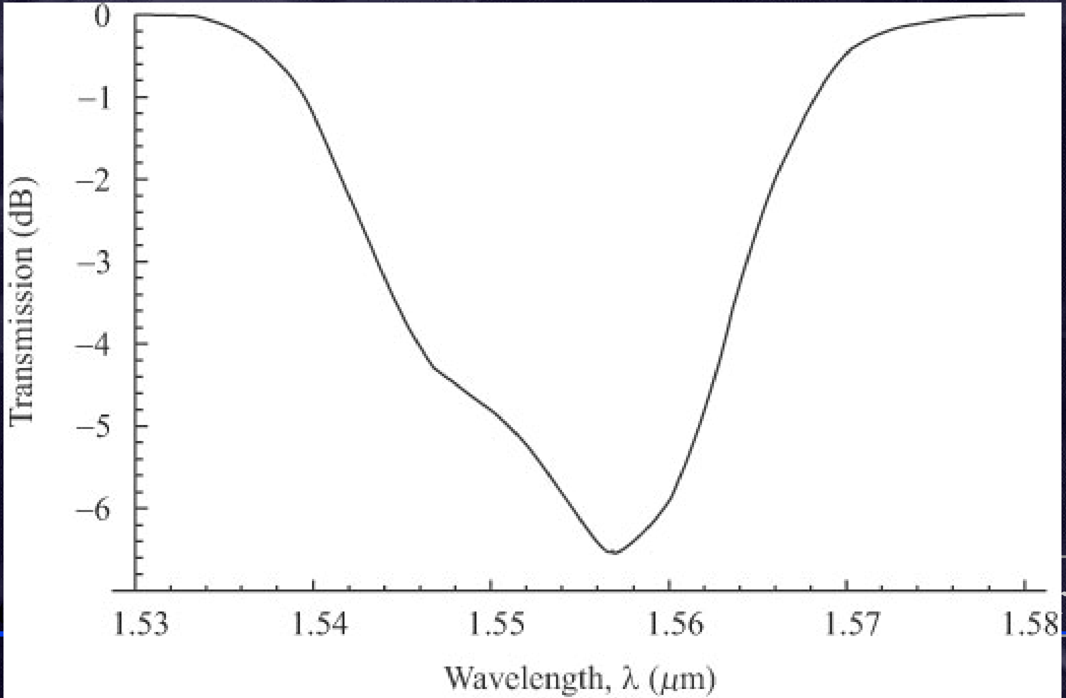


Figure 2.19 A fiber Bragg chirped grating reflects dispersed wavelengths of a channel at different depths, thus restoring the spectral width.

- Used in dispersion compensation (it tightens the pulse width)

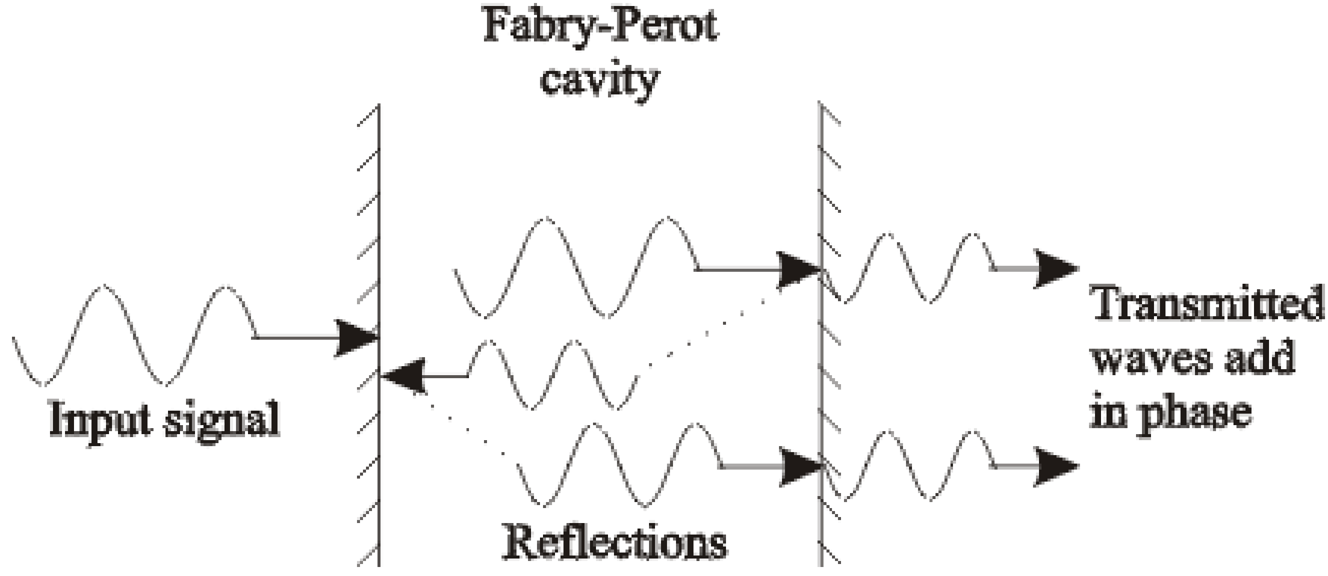
Long-period Fiber Gratings

- Principle of operation slightly different from fiber Bragg
  - Energy after grating interaction is coupling into *other forward propagating modes in the __cladding__*
  - …instead of being fully reflected as in Fiber Bragg
- Cladding modes very lossy and quickly attenuated
  - => Couple energy __OUT__ of a desired wavelength band



Fabry-Perot (FP) Filters

- Fabry-Perot filter also called F-P interferometer or *etalon*
- Cavity formed by parallel highly reflective mirrors
- **Tunable**: w/ cavity length or RI within cavity!
  - Eg: Piezoelectric material can "compress" when voltage is applied



Fabry-Perot (FP) Interferometer

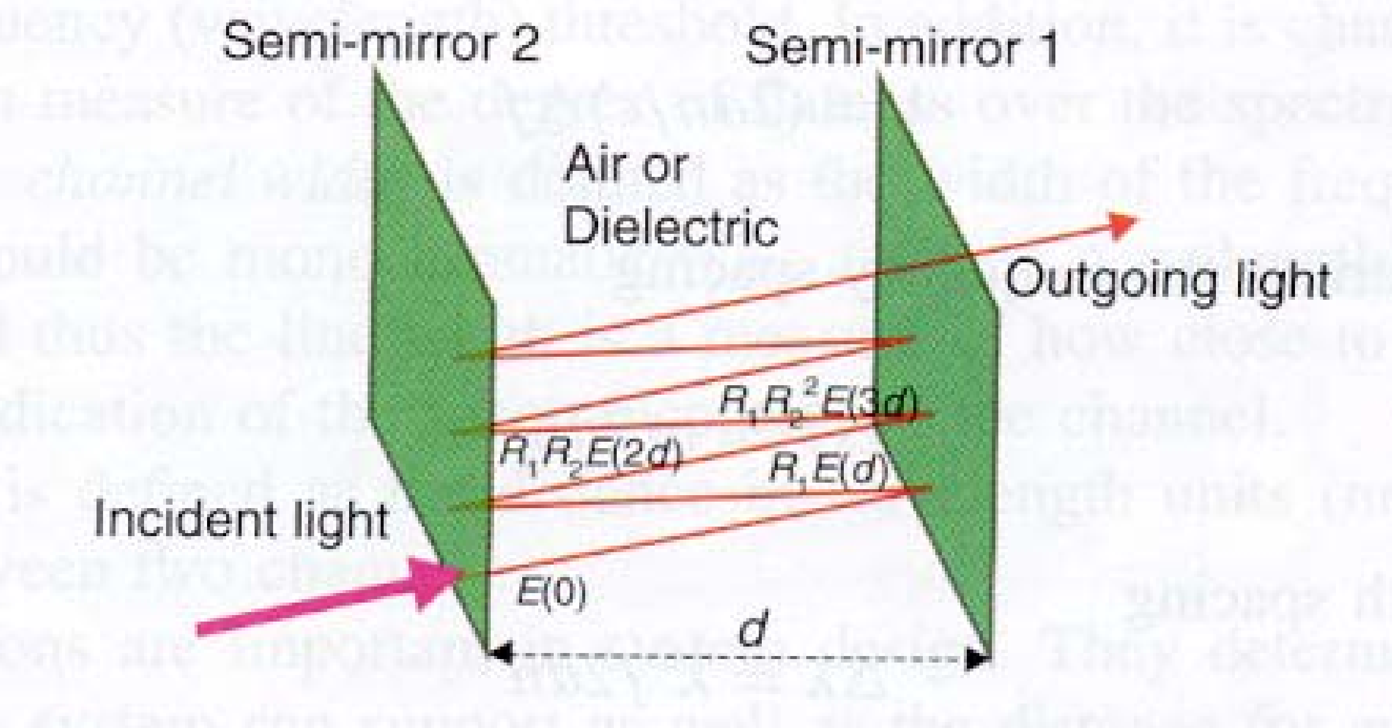


Figure 2.4 Principles of a Fabry–Perot interferometer.

- The outgoing λs for which d = k λ/2, add up in phase (resonant λs)

Interferometer Sharpness & Line Width

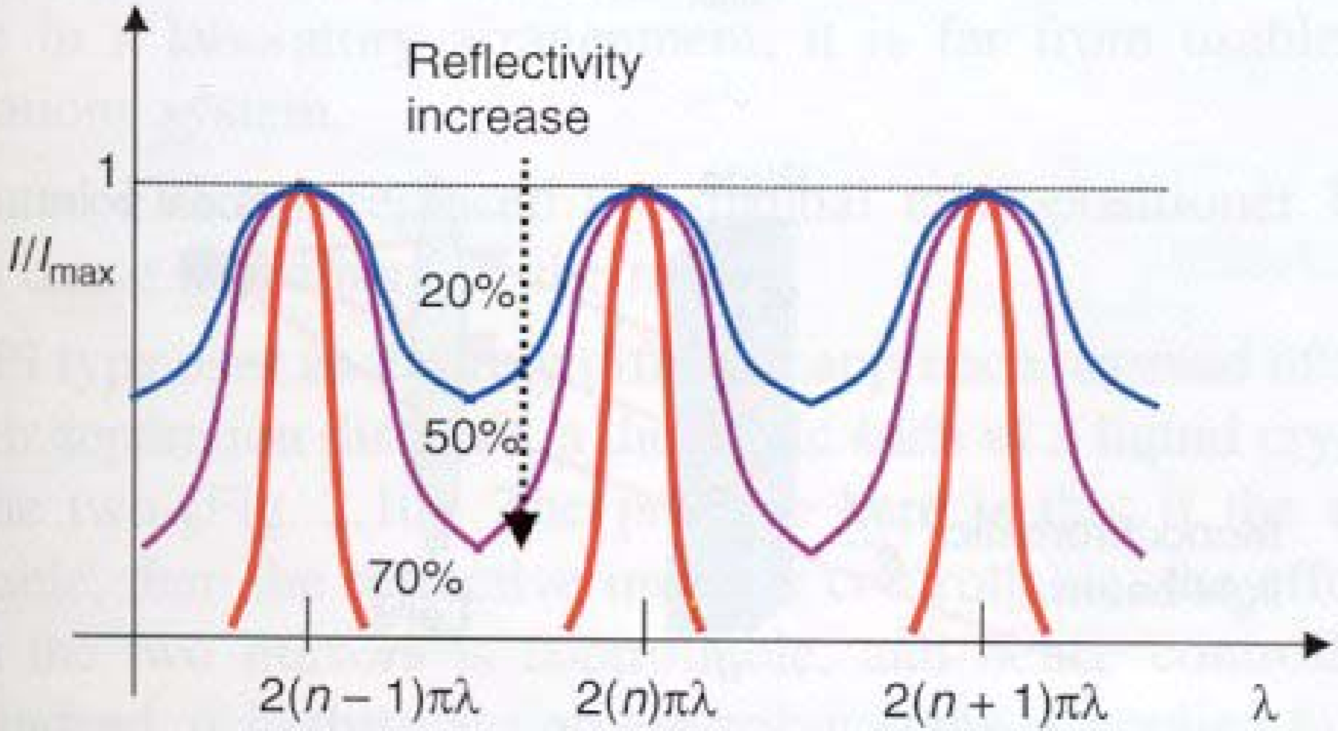
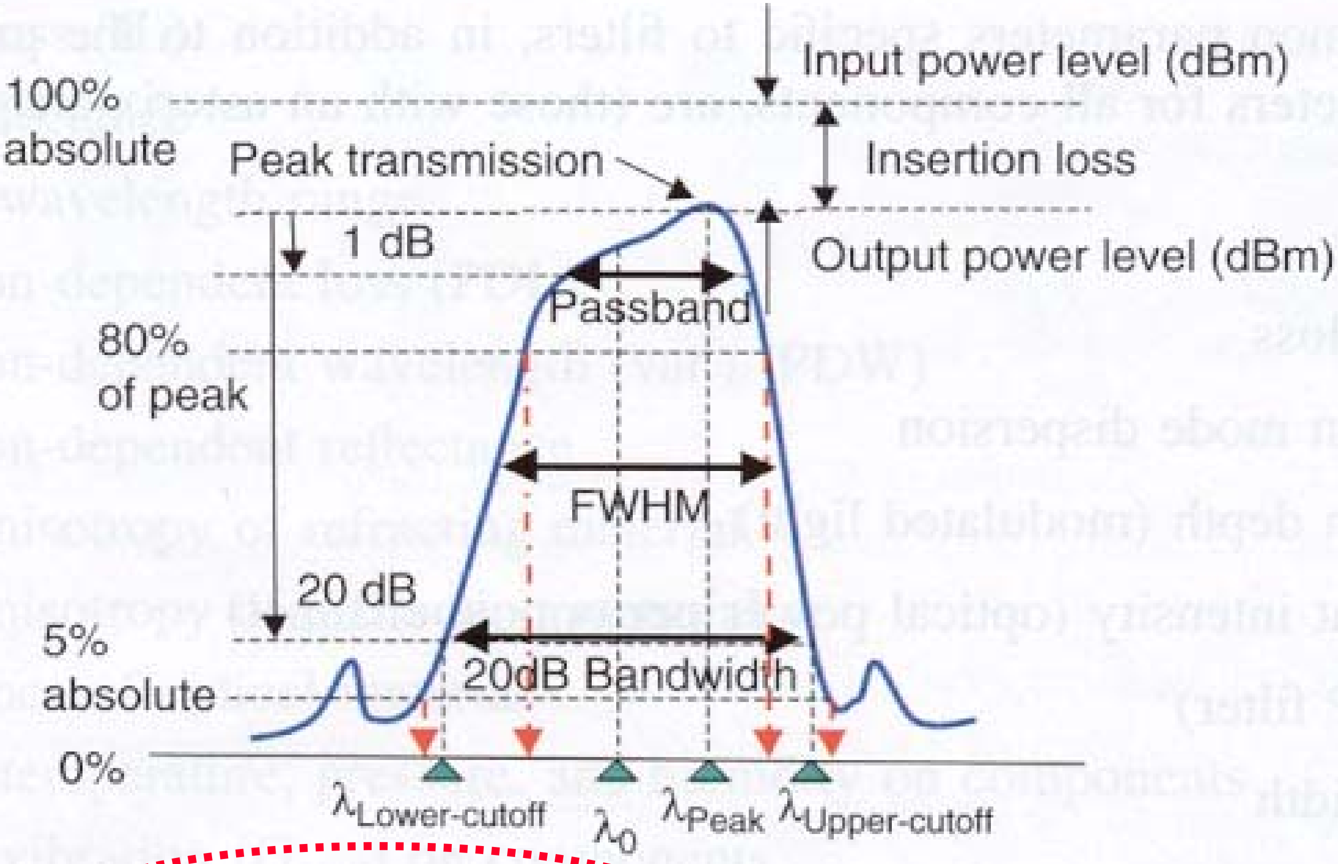


Figure 2.7 As reflectivity increases, the interferometer sharpness increases.

- Different DWDM λs can coincide with the passbands.
- FSR = free-spectral-range between the passbands

Filter Parameters



FWHM = Full-width half-maximum

Figure 2.3 Filter parameter definition.

Spectral Width, Linewidth, Line Spacing

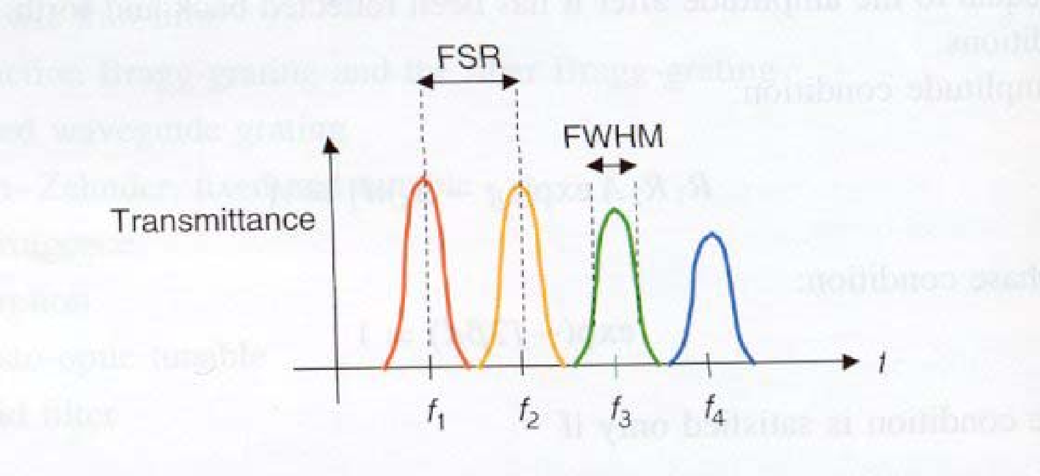


Figure 2.5 A typical transmittance profile of a Fabry–Perot resonator.

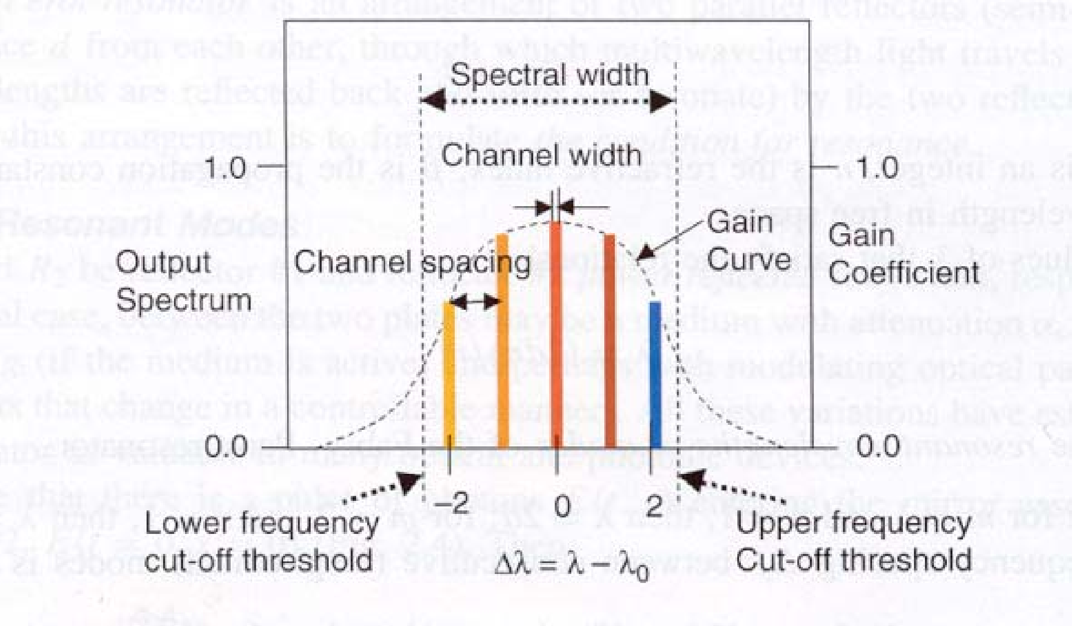
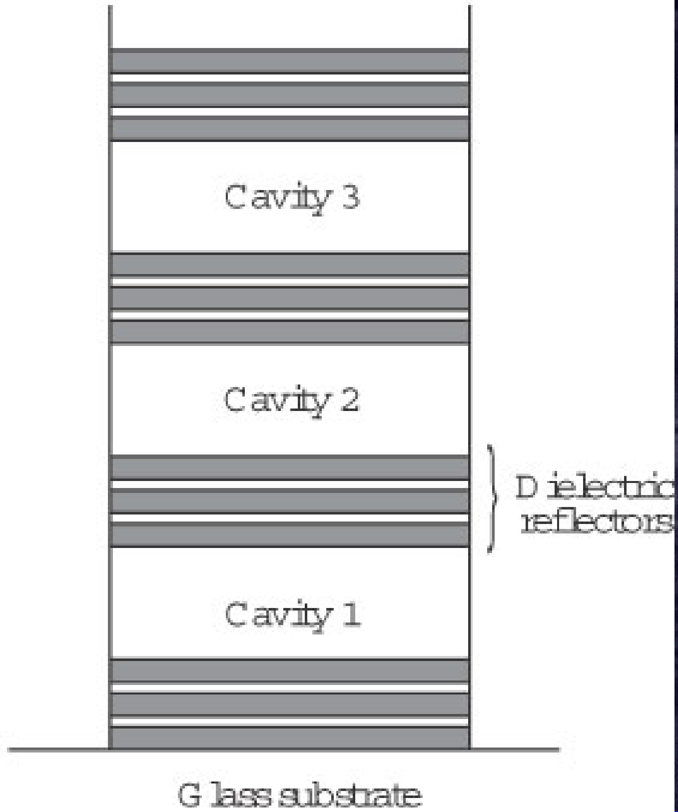
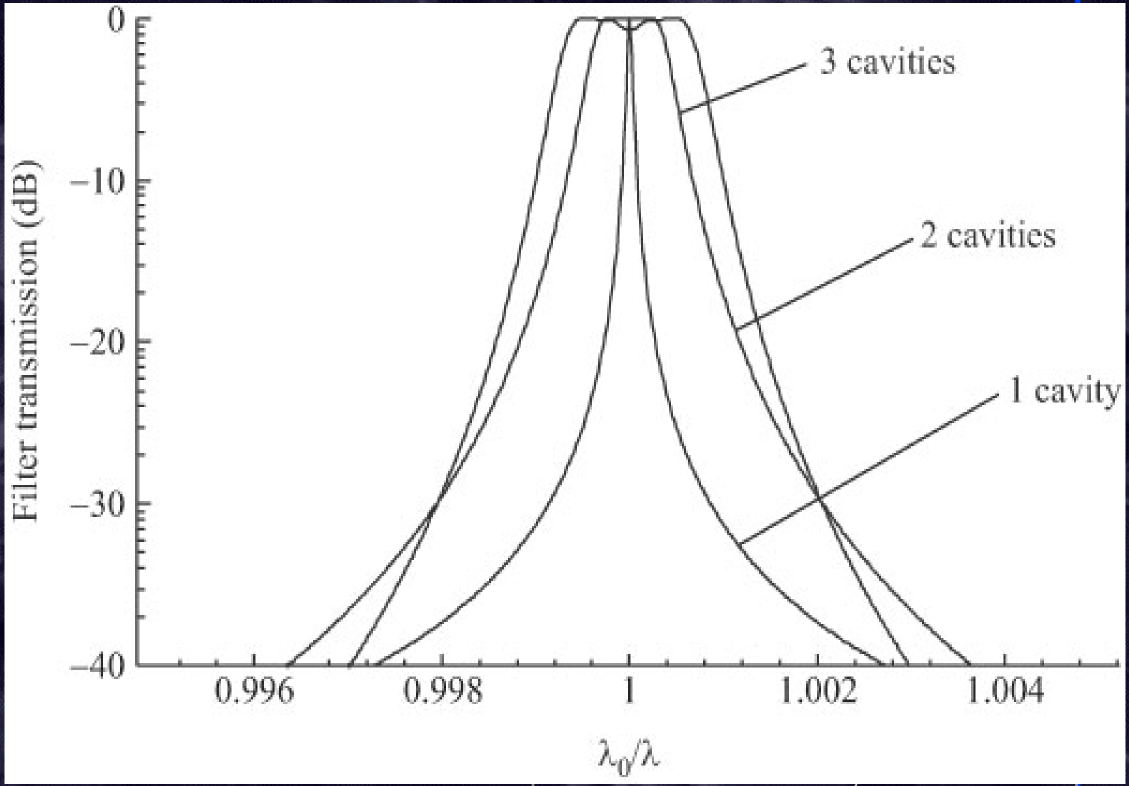


Figure 2.6 Definition of gain, spectral, channel and spacing width.

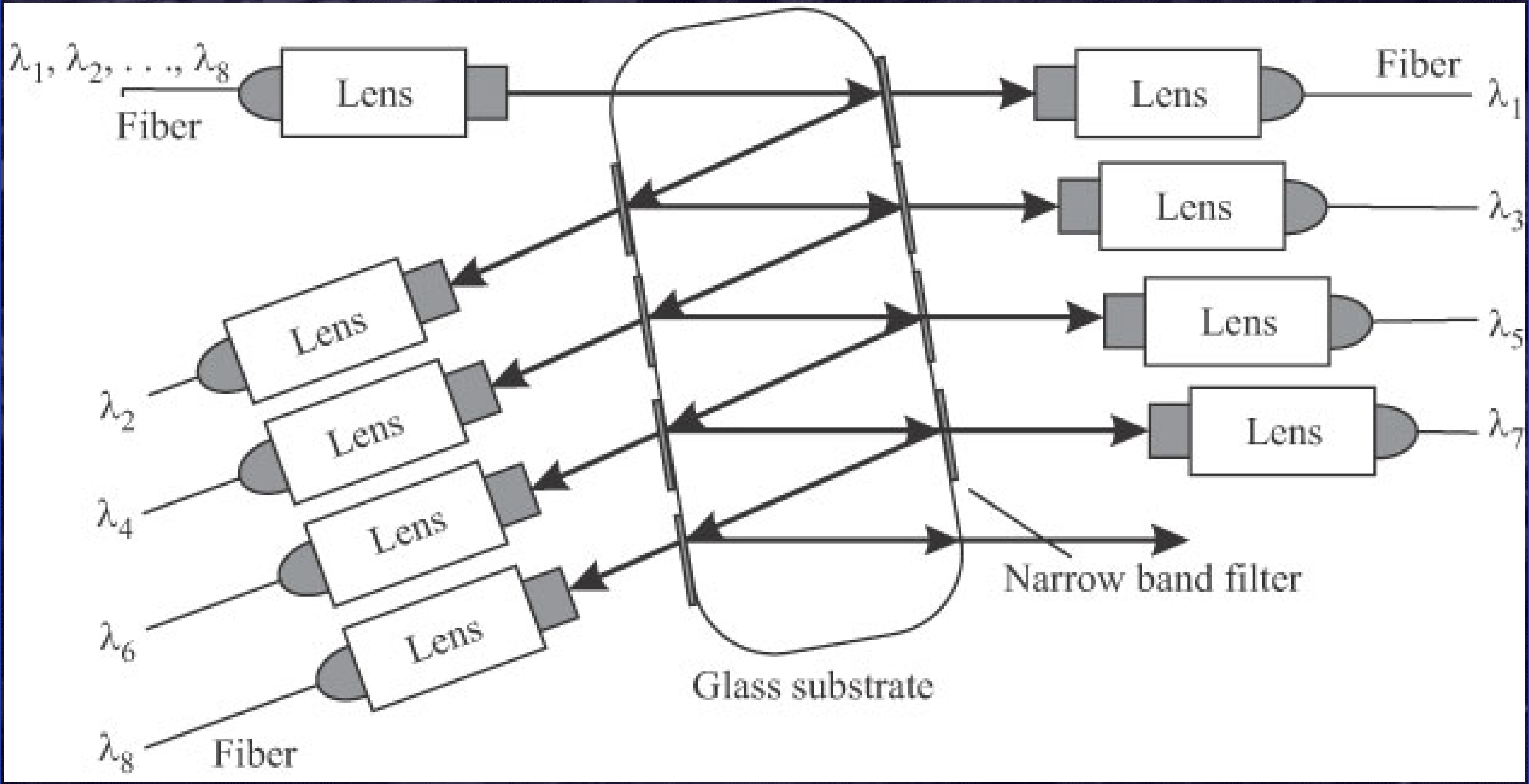
Thin-Film Multilayer Filters (TFMF)

- TFMF is an FP etalon where mirrors are realized using a <u>multiple</u> reflective dielectric thin-film layers (I.e. multiple cavities >= 2)





Mux/Demux Using Cascaded TFMFs



- Each filter passes one λ and reflects the other λs
- Very flat top and sharp skirts

Cascaded TFMFs (contd)

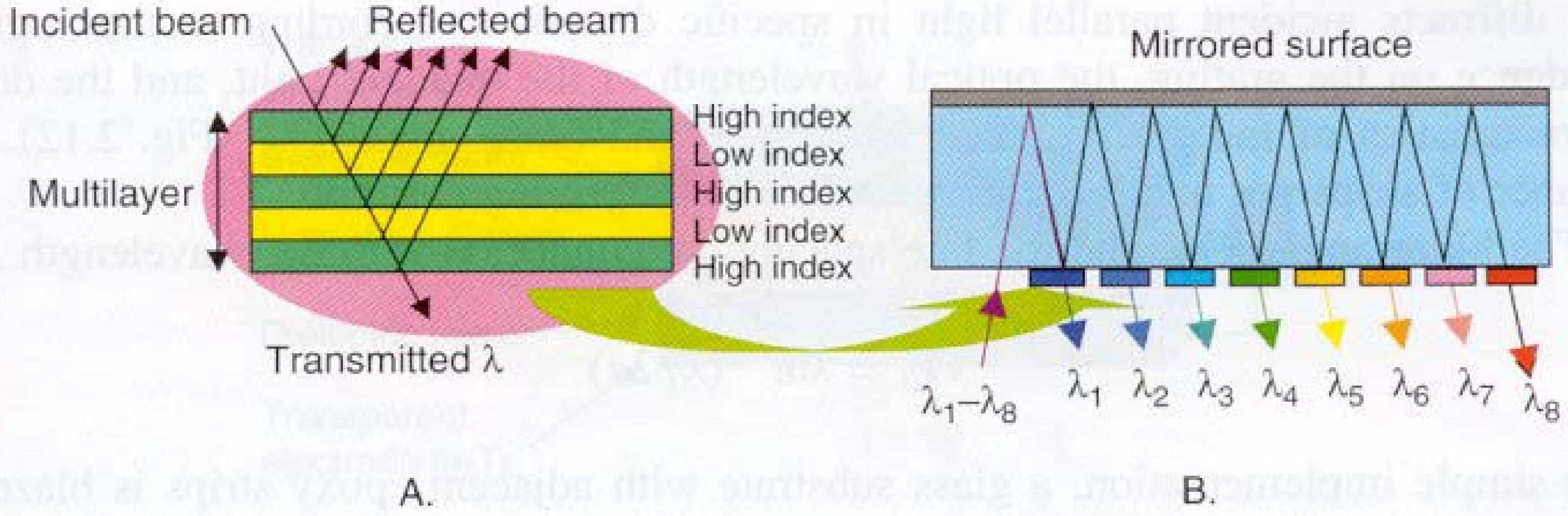


Figure 2.11 A dielectric interference filter is made with alternating layers of high/low refractive inde each l/4 thick, A. Using such filters at one side of a mirrored plate, a demultiplexer is built, B.

Mach-Zehnder Filter/Interferometer (MZI)

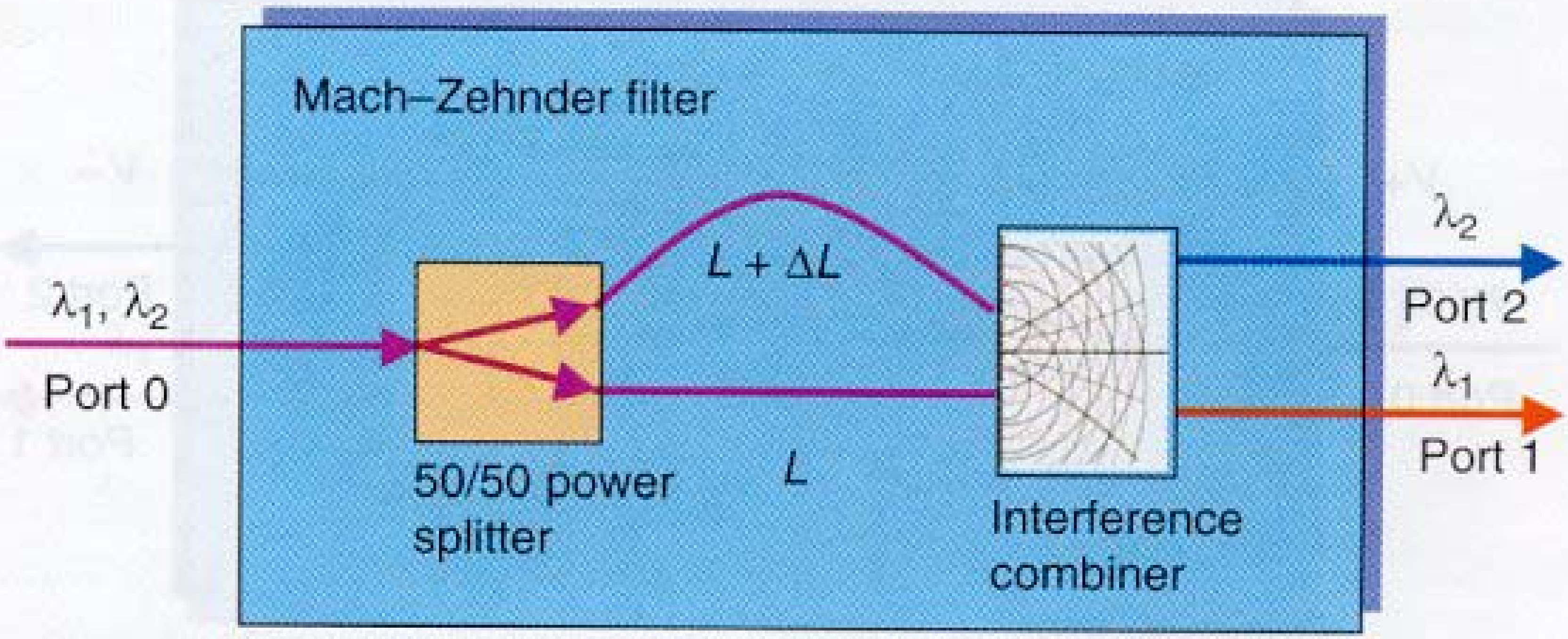
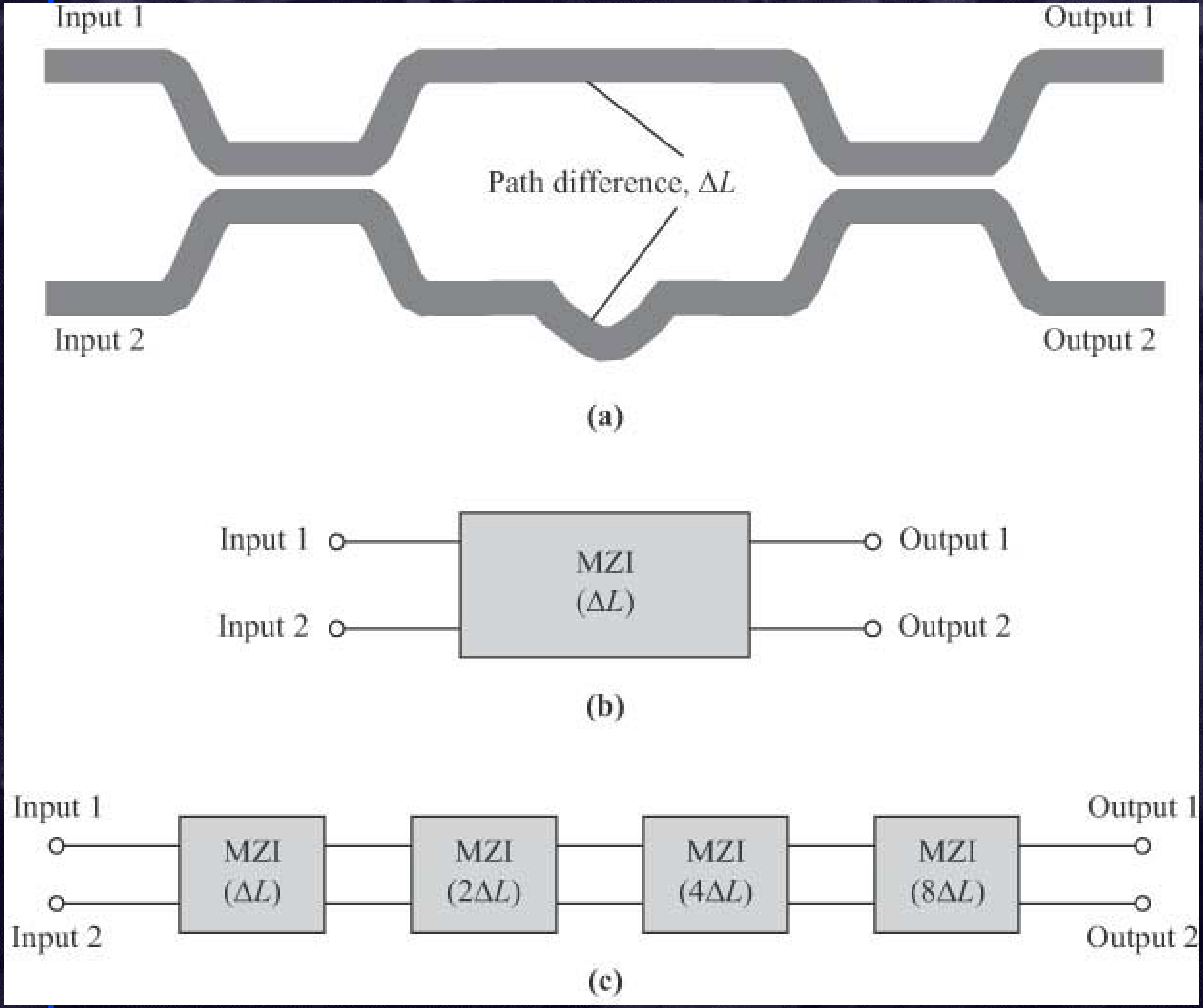


Figure 2.20 Principles of a Mach–Zehnder filter.

Mach-Zehnder (Contd)



- Reciprocal device
- Phase lag + interference
- Used for broadband filtering
- Crosstalk, non-flat spectrum, large skirts…
- Tunability: by varying temperature (~ few ms)

Thermo-Tunable M-Z Filter

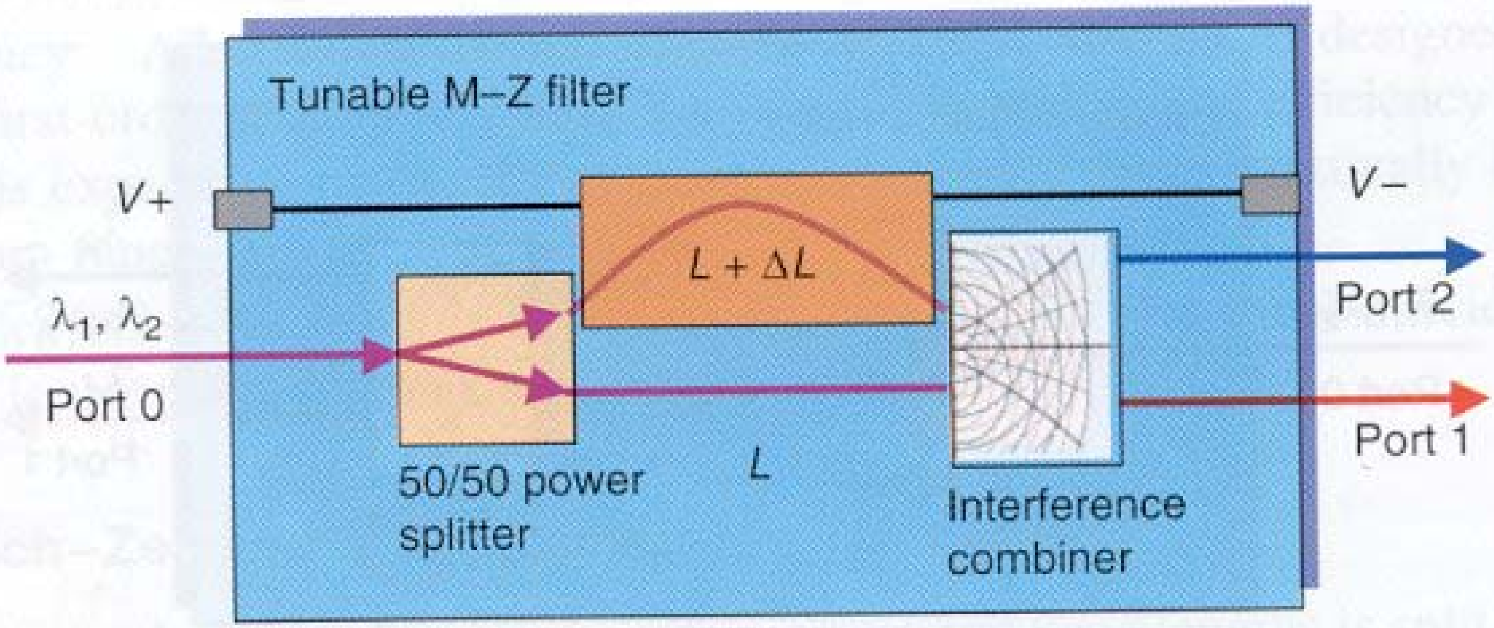
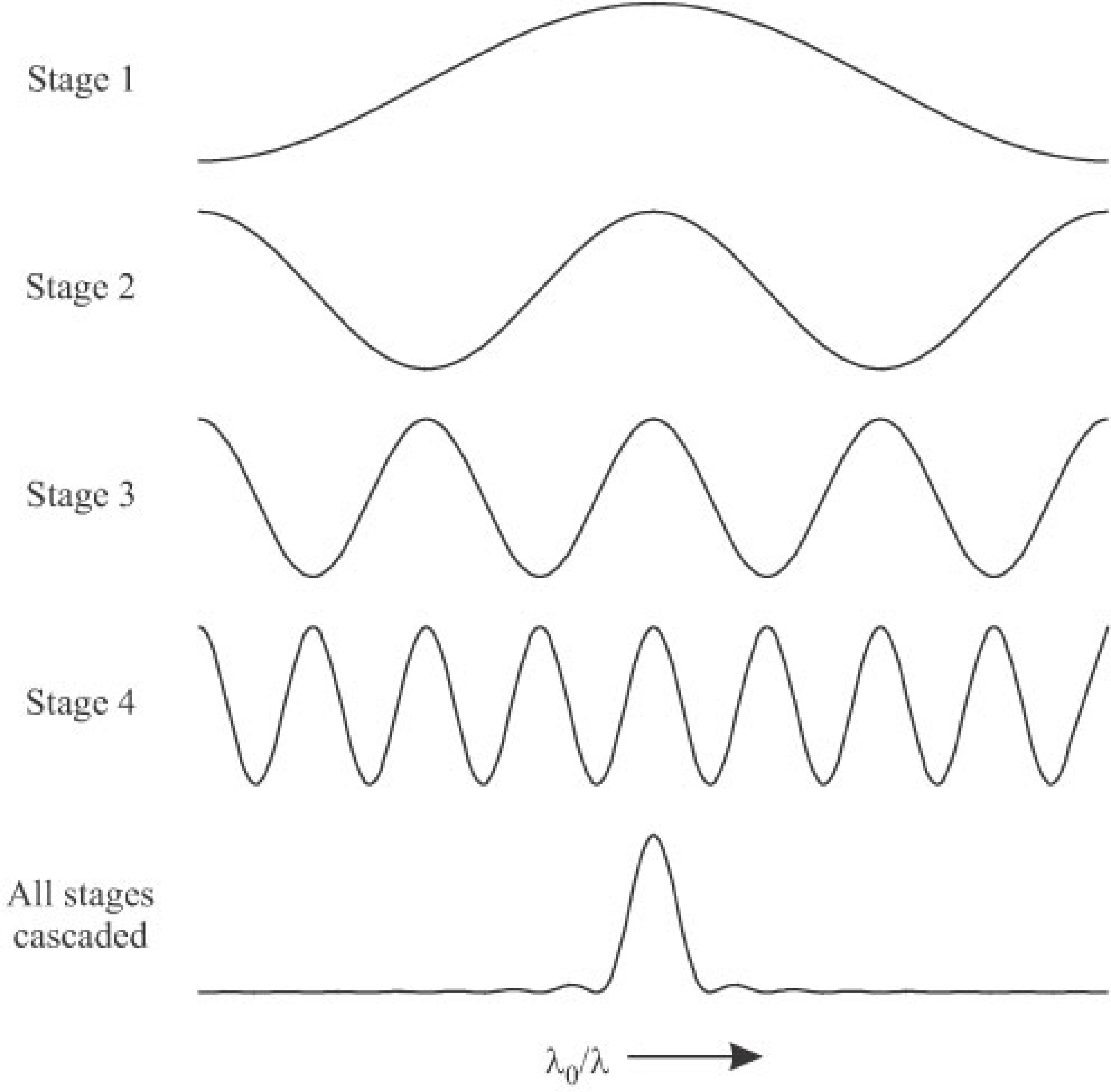


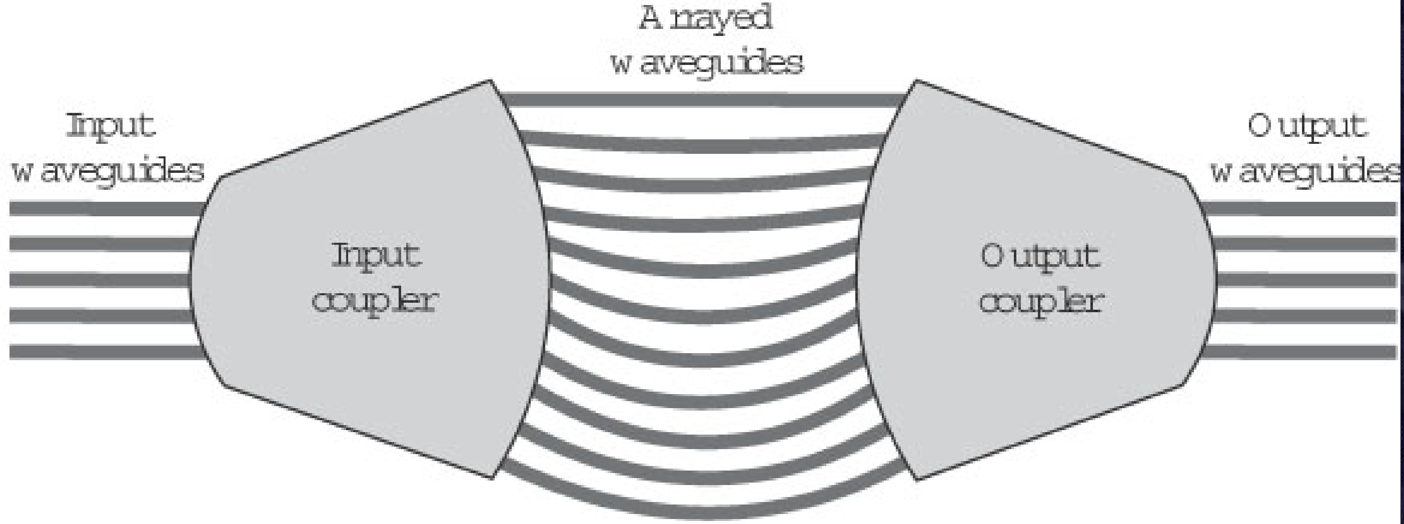
Figure 2.21 Principles of a thermo-tunable Mach–Zehnder filter.

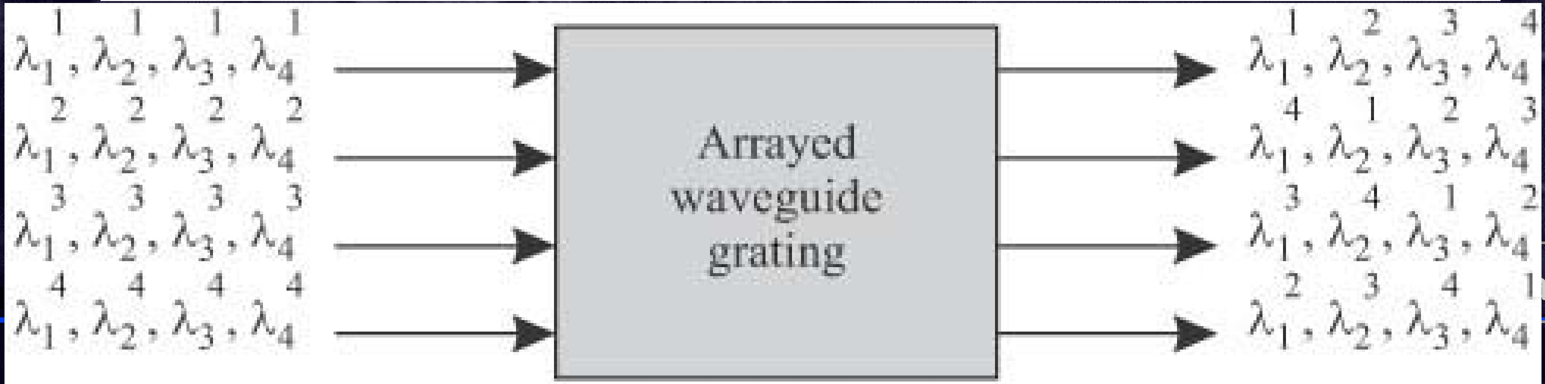
Multi-stage MZI Transfer Function



Arrayed Waveguide Grating (AWG)

- Generalization of MZI: several copies of signal, phase shifted differently and combined => 1xn, nx1 elements
- Lower loss, flatter passband compared to cascaded MZI
- Active temperature control needed





Arrayed Waveguide Grating

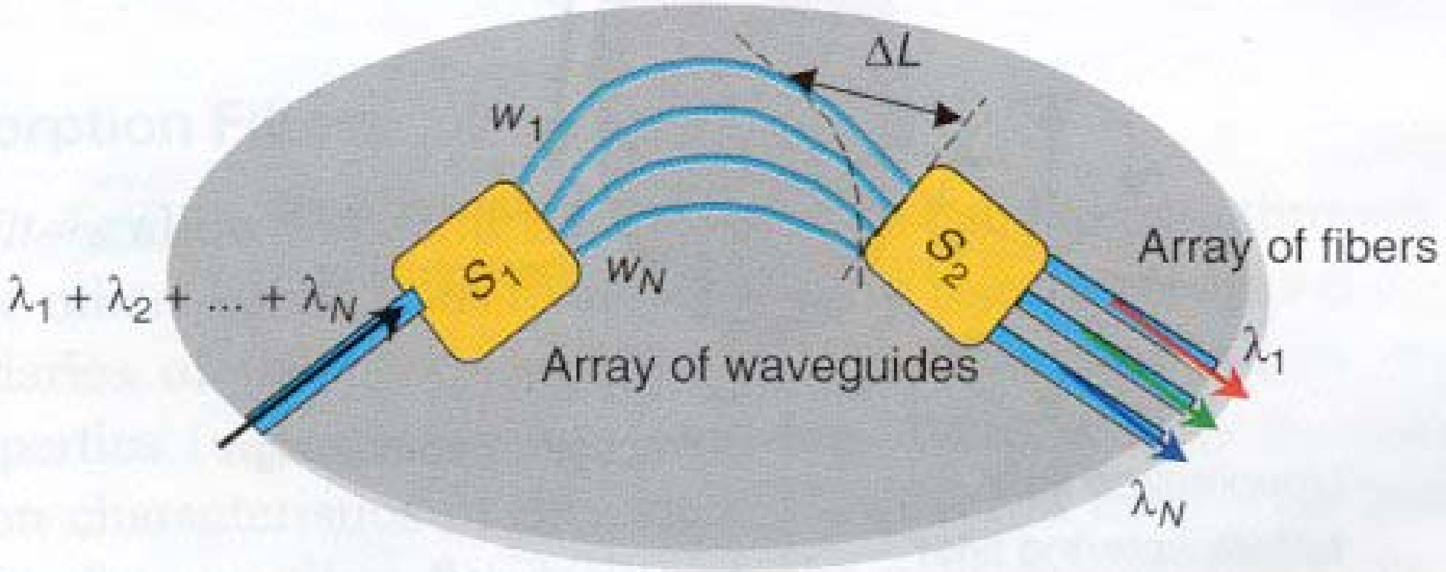
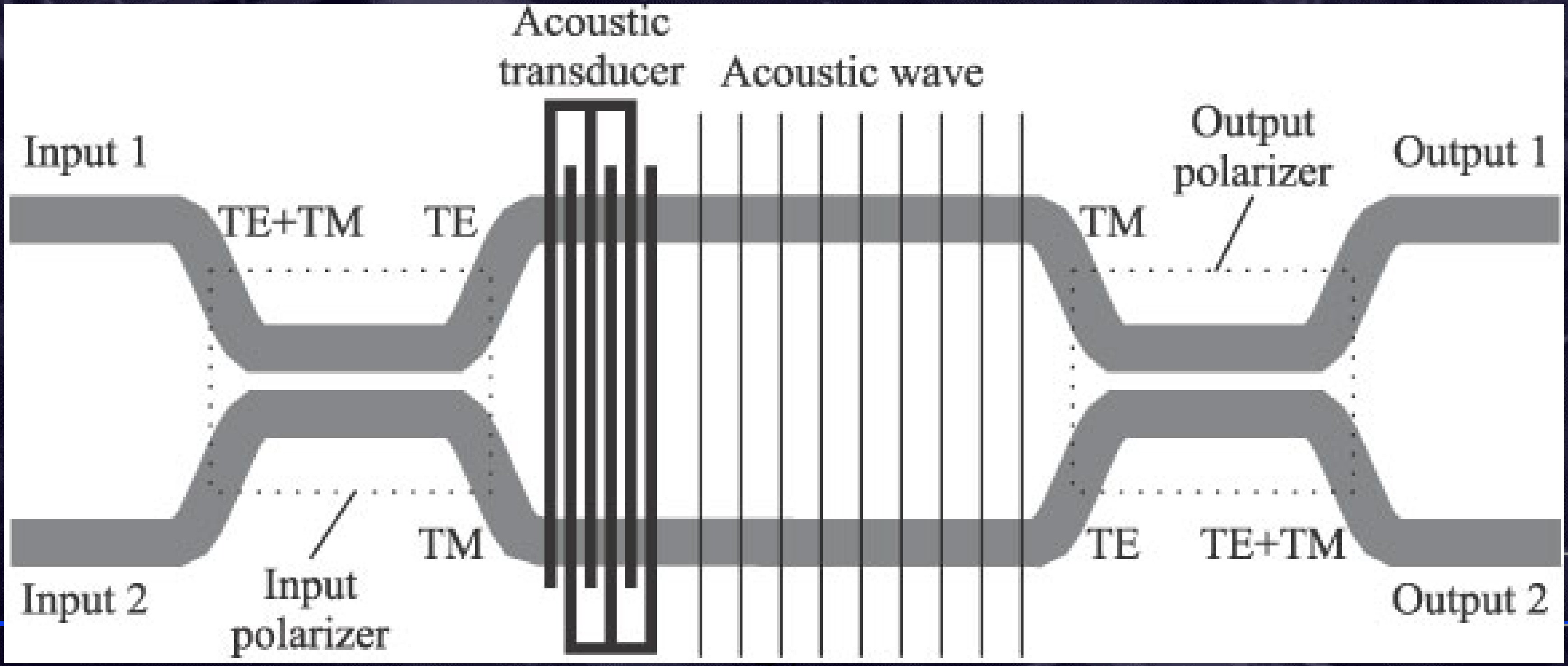


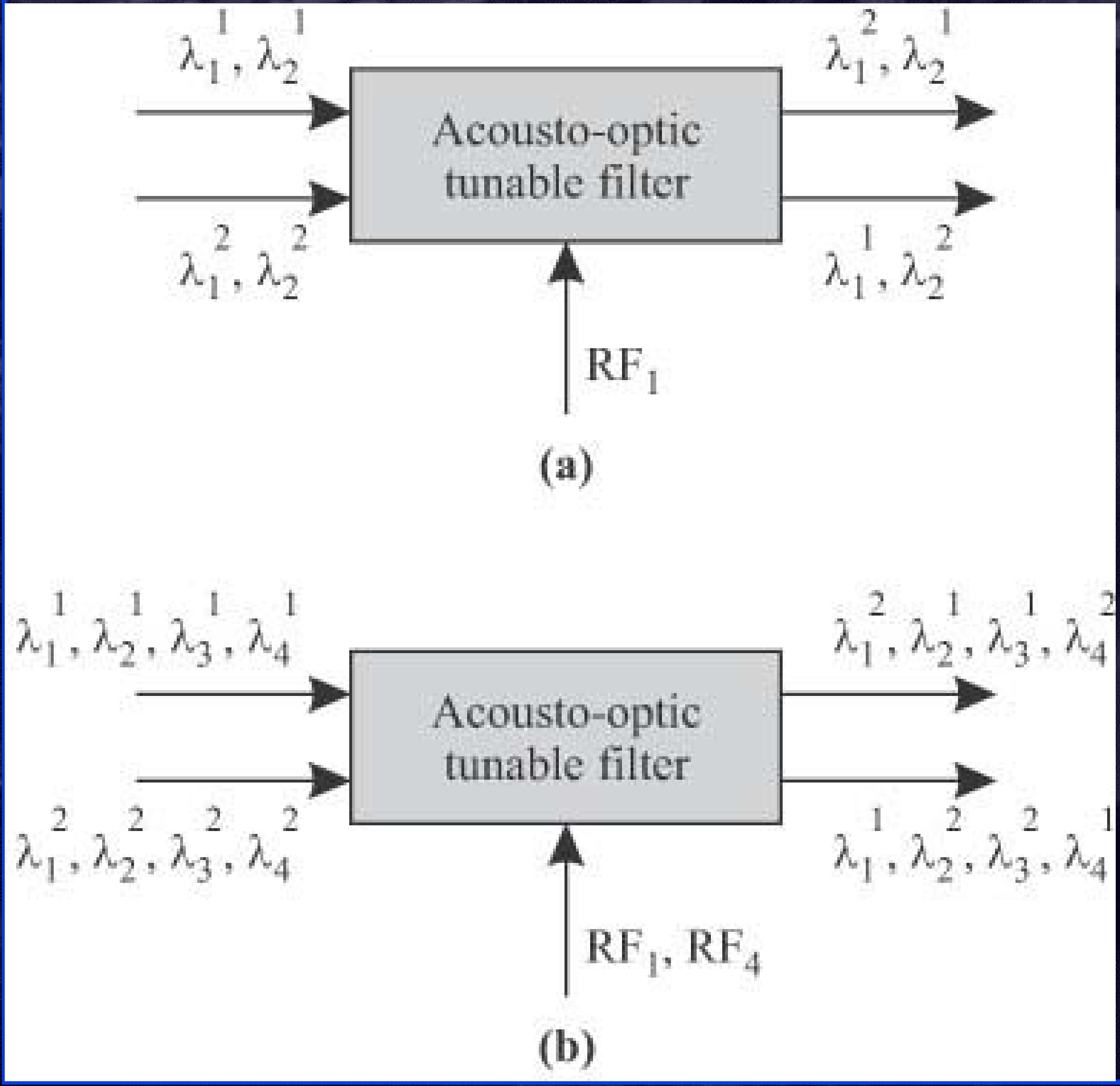
Figure 2.22 Principles of an arrayed waveguide grating.

Acousto-Optic Tunable Filter (AOTF)

- Interaction between sound and light: Sound is used to create a Bragg grating in a waveguide
- Acoustic wave in opposite direction to optical signal
- Density variations depend on acoustic RF freq lead to RI variations: RF frequency can be easily tuned
- Polarization dependent or independent designs…



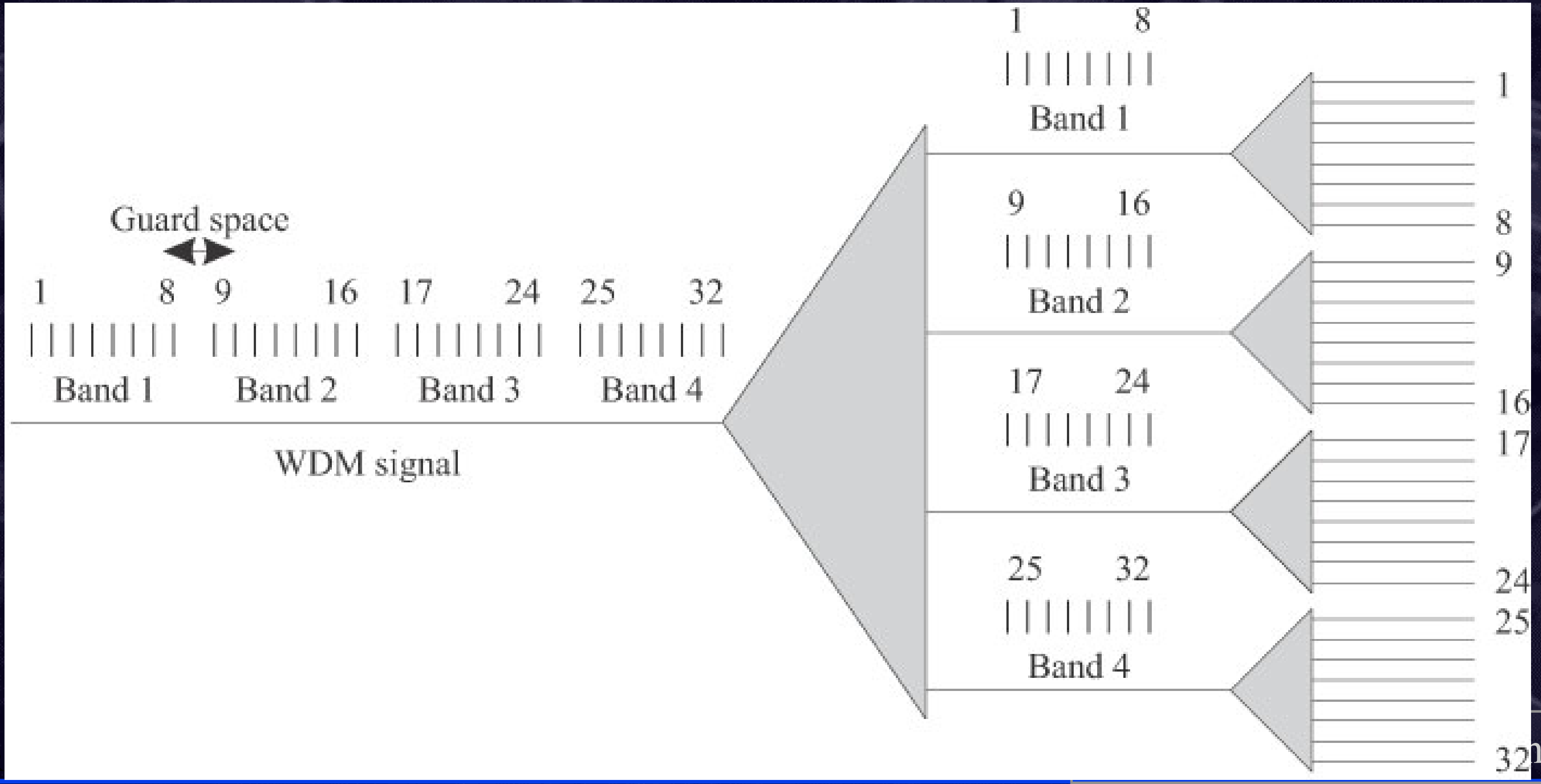
Dynamic Wavelength Crossconnects



- Multiple acoustic waves can be launched simultaneously
- The Bragg conditions for multiple λs can be satisfied simultaneously!
- => Dynamic crossconnects!
- Lots of crosstalk & wide passbands

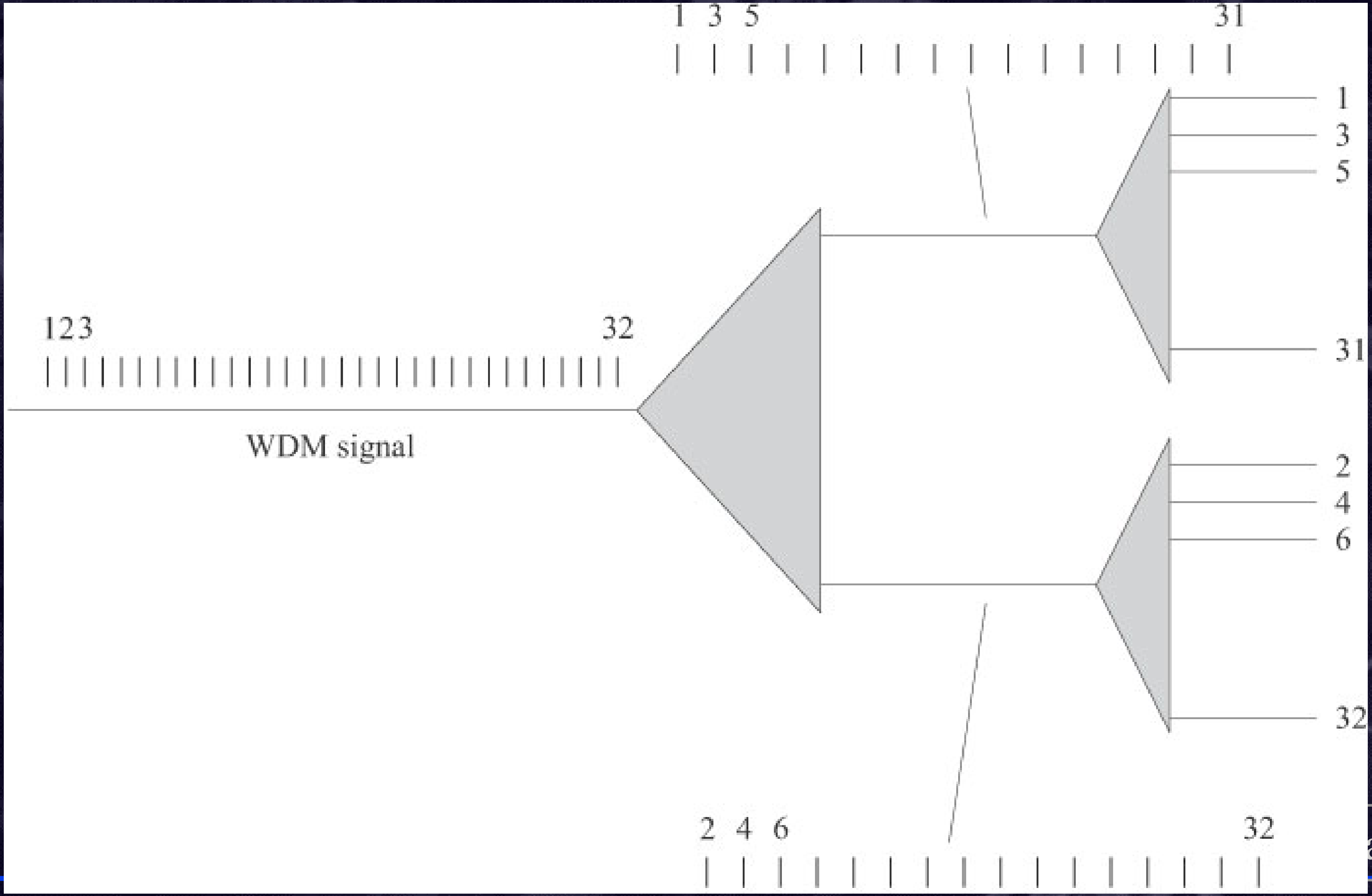
High Channel Count Multiplexers

- Multi-stage *Banded* multiplexers



Multi-stage Interleaving

- Filters in the last stage can be much wider than each channel width



Amplifiers, Regenerators

Amplification

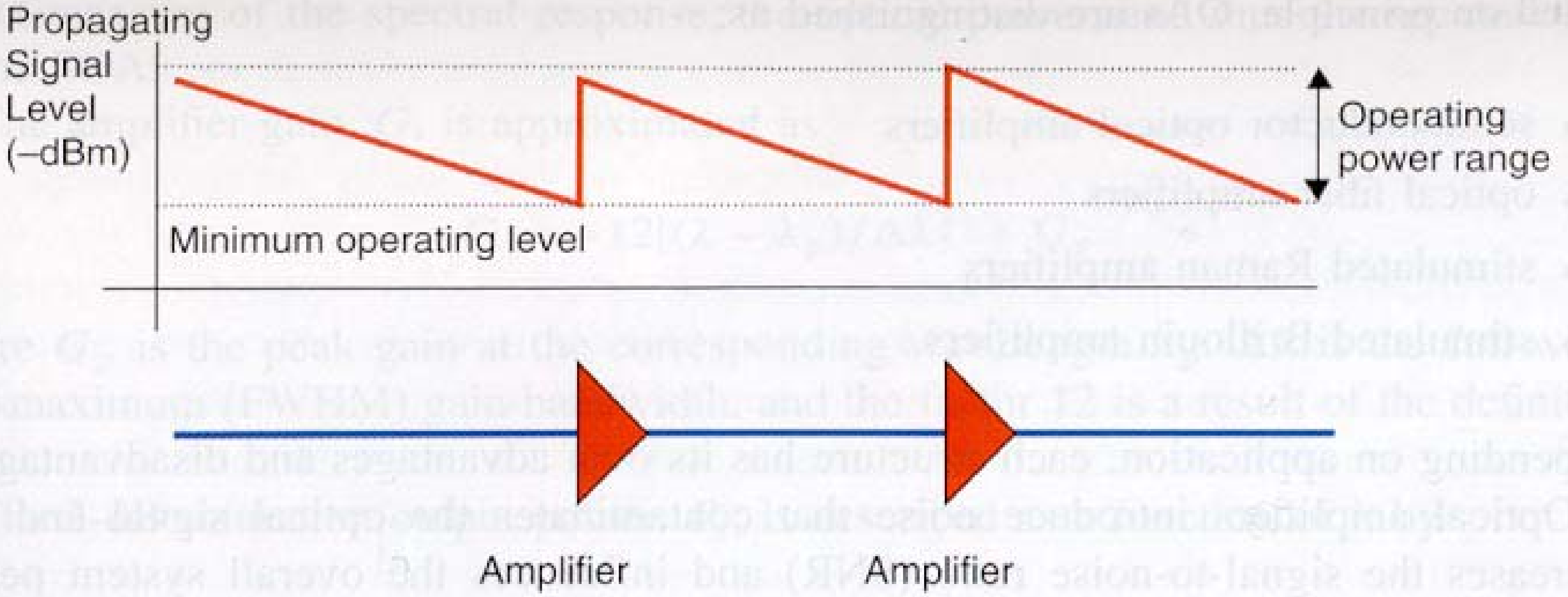
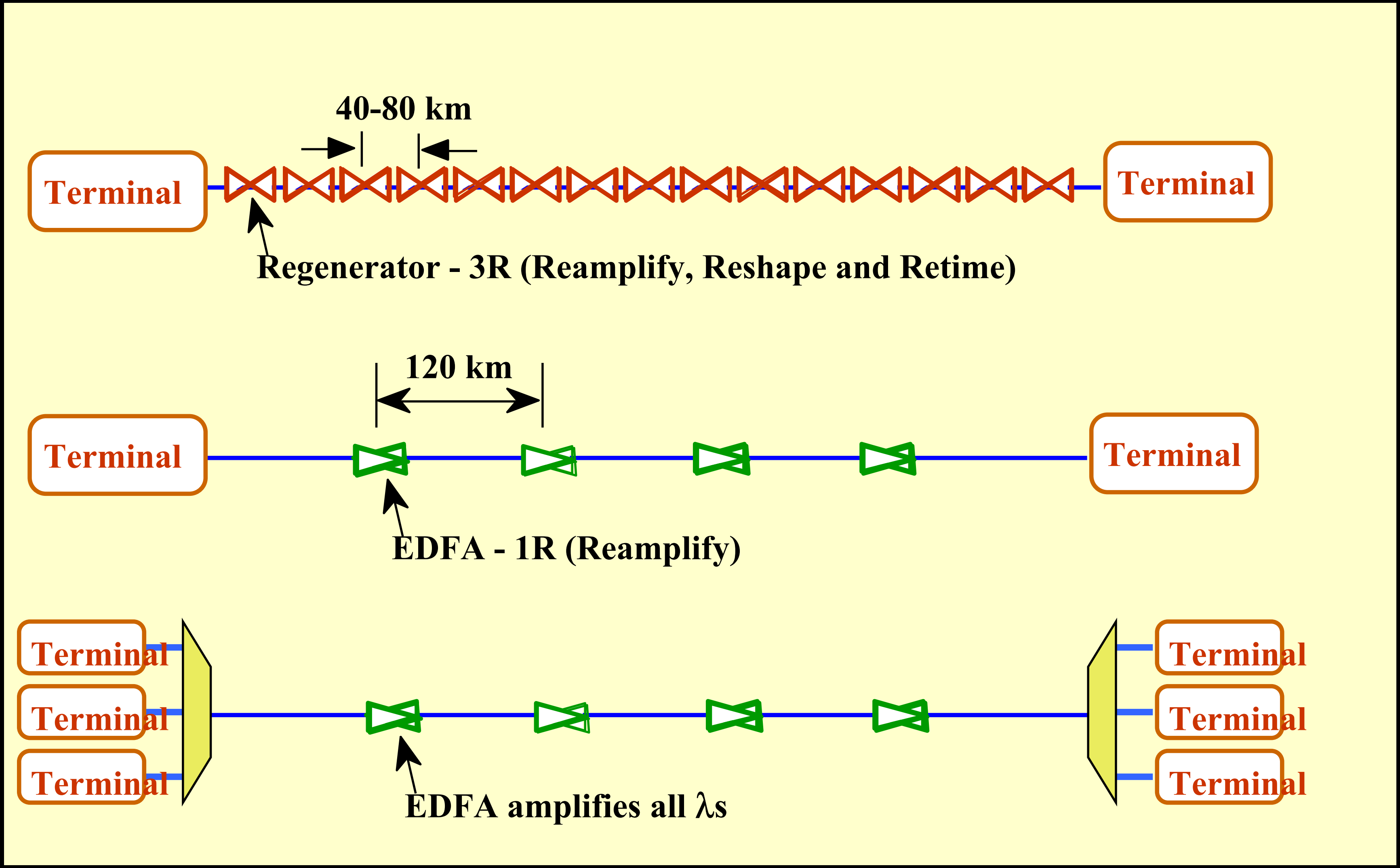


Figure 2.66 Signal attenuation and amplification action.

Optical Amplifiers vs Regenerators



OEO Regenerator

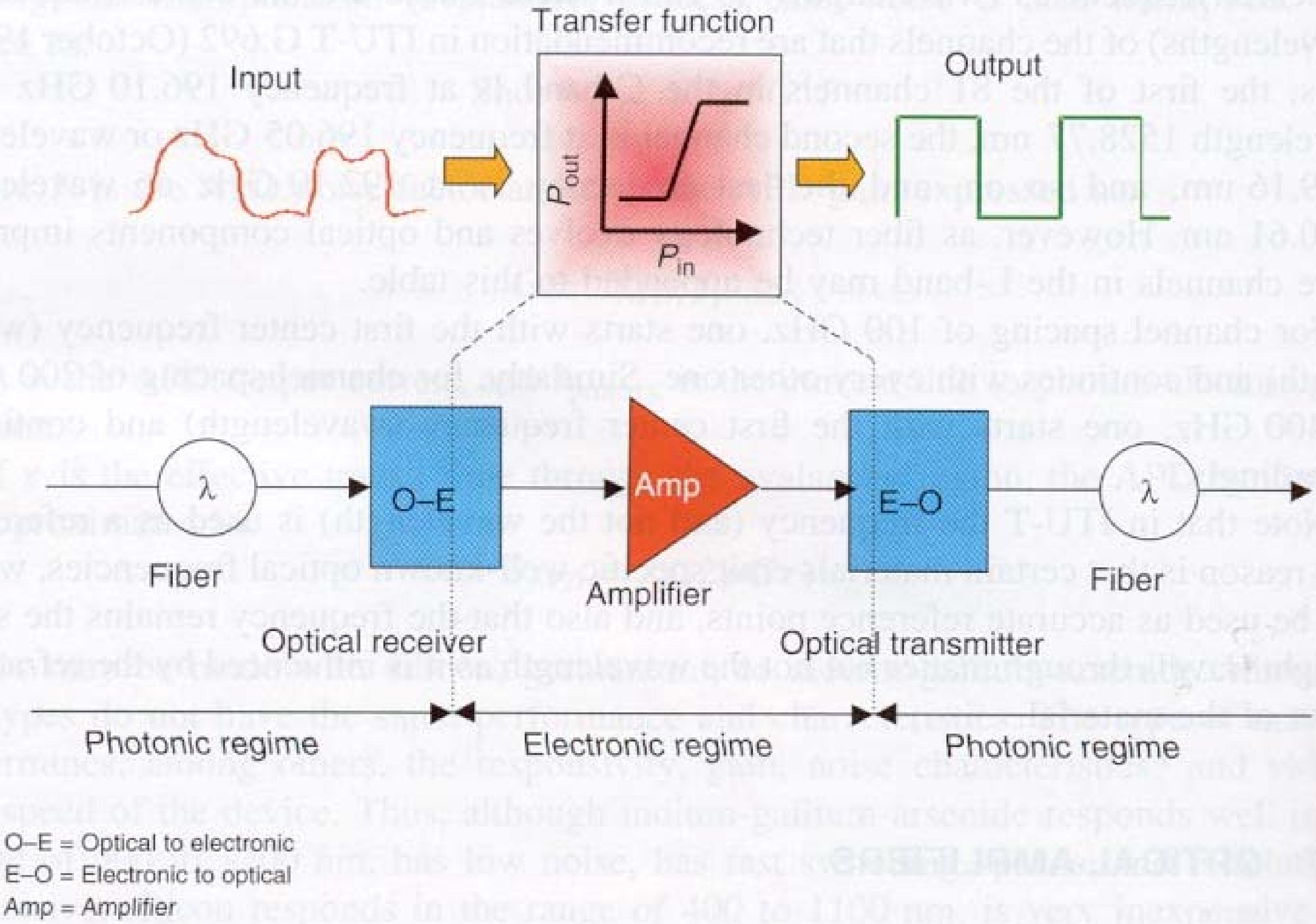
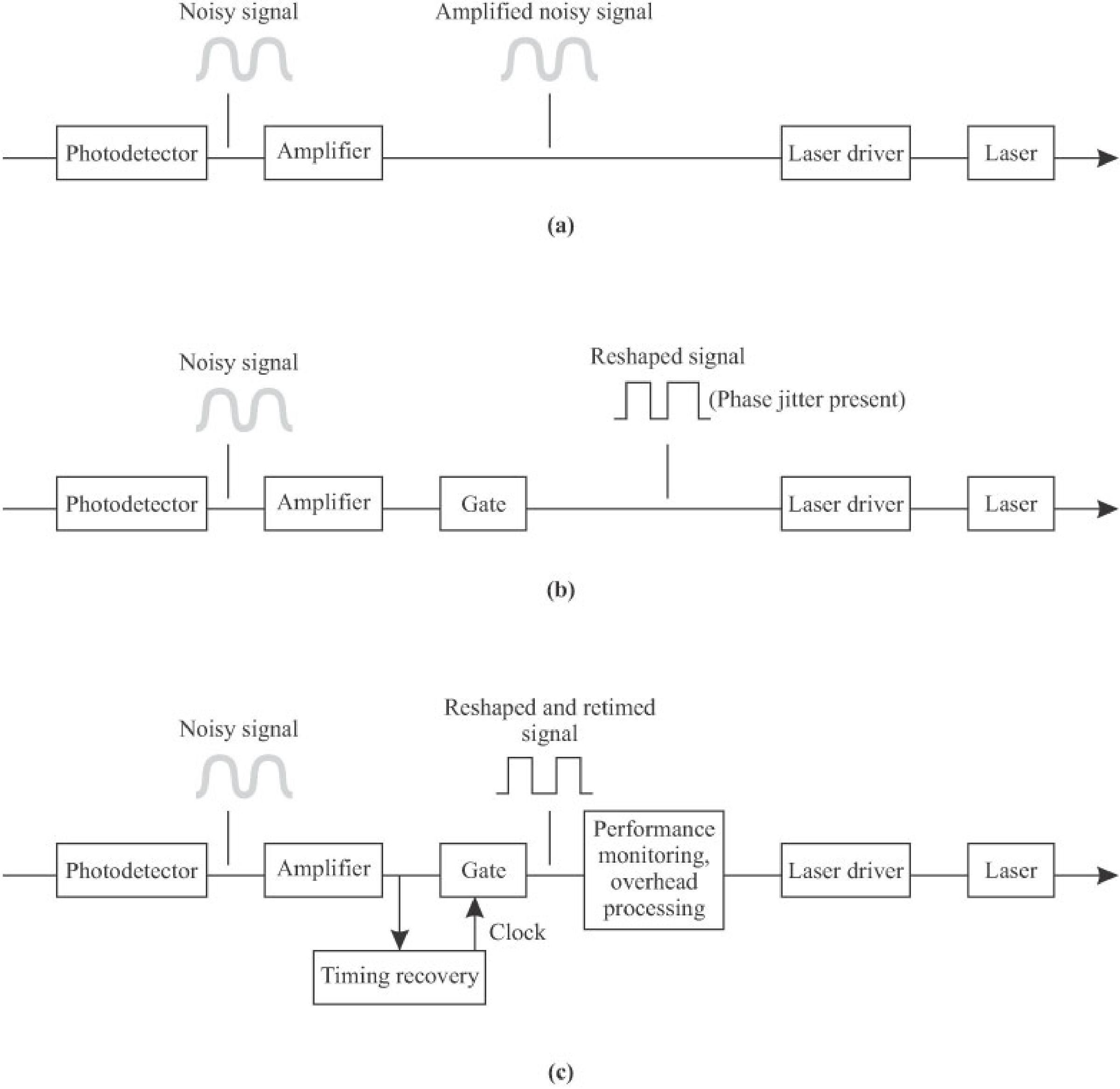


Figure 2.65 The model of a regenerator and the three major functions, optical receiver, electronic amplifier, and optical transmitter.

1R, 2R and 3R Regeneration

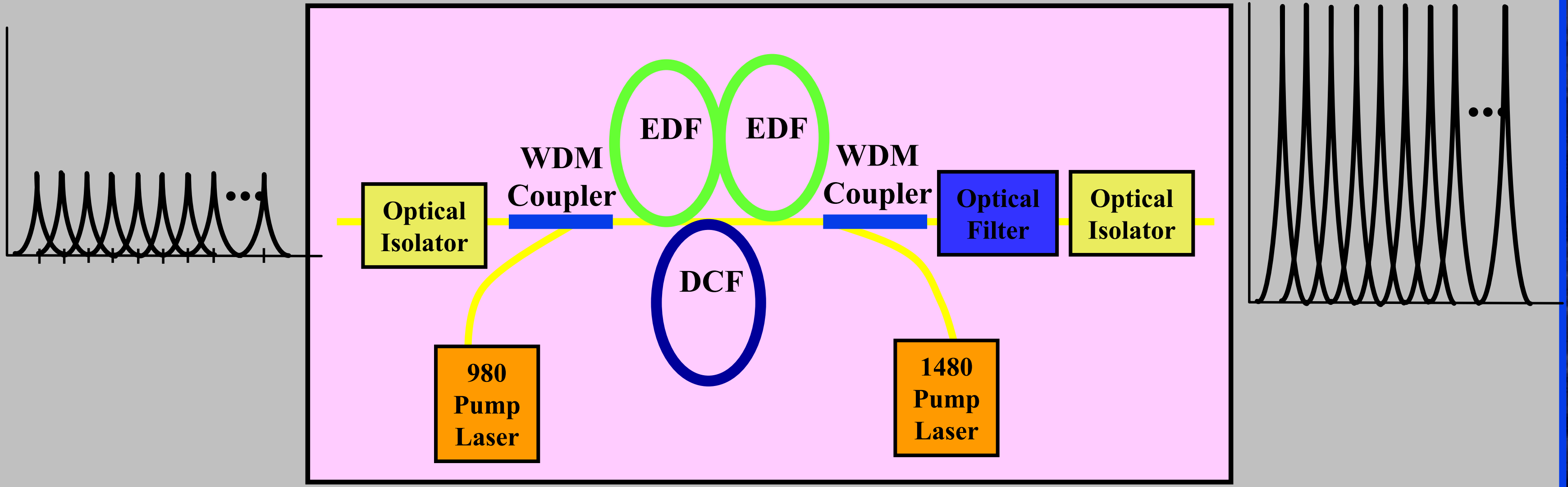


Regenerators vs O-Amplifiers

- Regenerators specific to bit rate and modulation format used; O-Amps are insensitive (I.e. *transparent*)
- A system with optical amplifiers can be more *easily upgraded* to higher bit rate w/o replacing the amplifiers
- Optical amplifiers have *large gain bandwidths* => key enabler of DWDM

- Issues:
  - Amplifiers introduce additional noise that accumulates
  - Spectral shape of gain (flatness), output power, transient behavior need to be carefully designed

EDFA Enables DWDM!



- EDFAs amplify all λs in 1550 window simultaneously
- Key performance parameters include
  - Saturation output power, noise figure, gain flatness/passband

Optical Amplifier Varieties

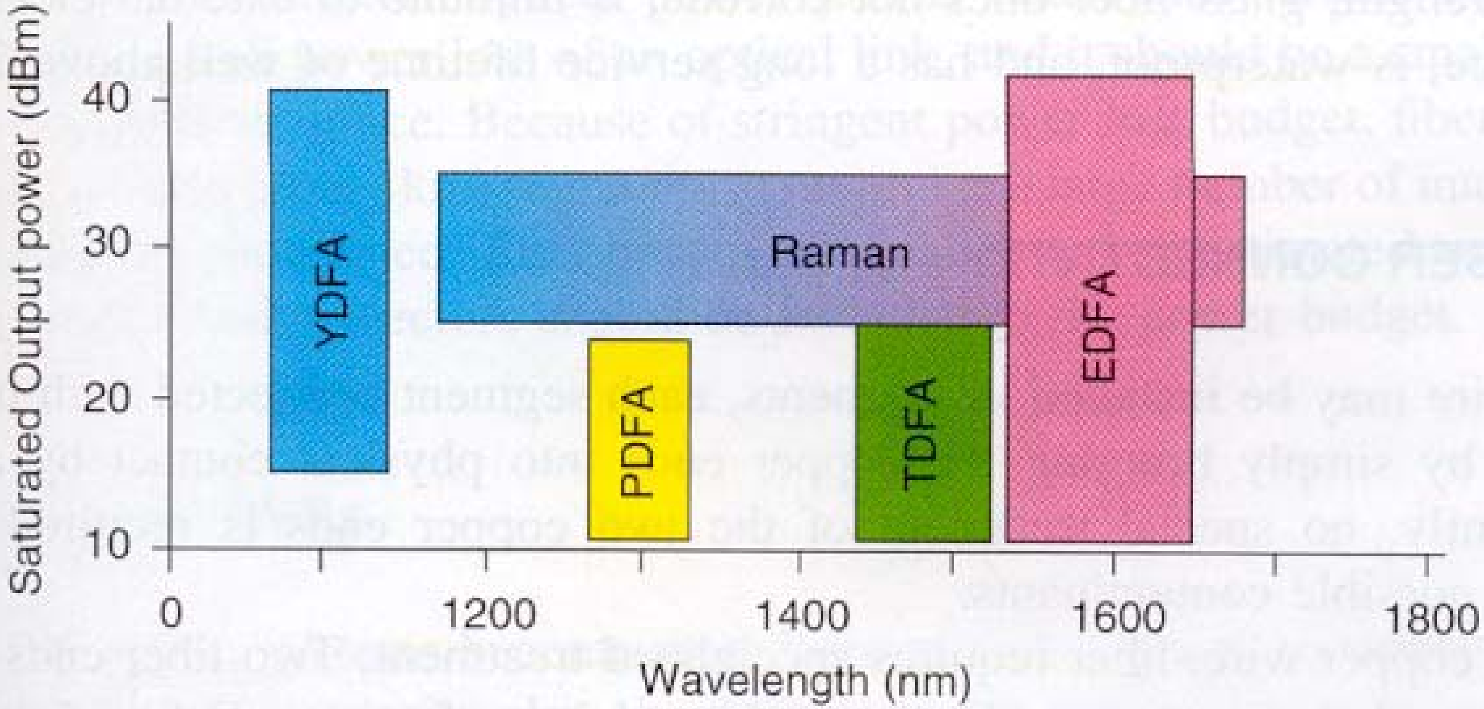
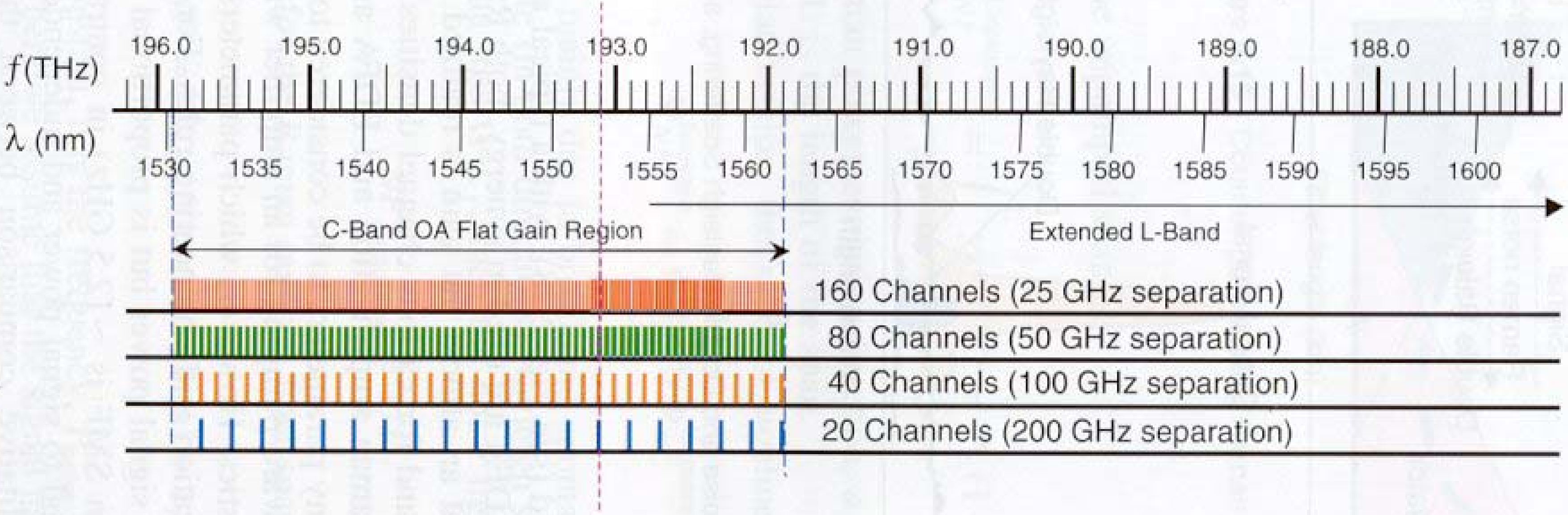


Figure 1.66 Optical amplifiers are many, each suitable for a different spectral range.

Optical Amplifier Flat Gain Region

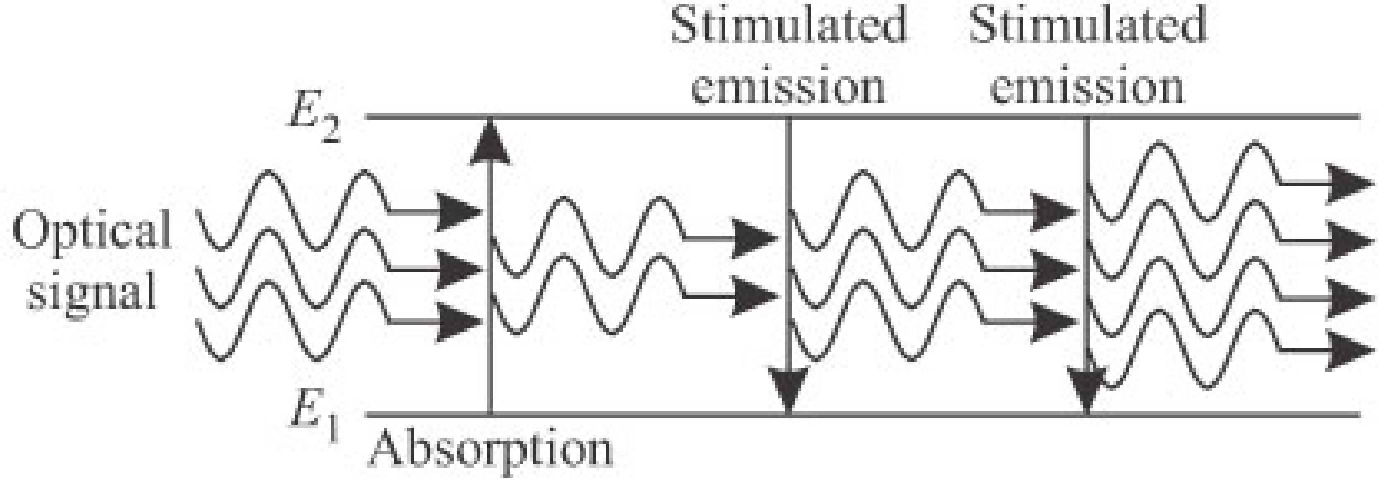


(ITU reference frequency 193.1 THz)

Figure 4.17 Optical amplifier flat gain region in C-band.

Principles: Stimulated Emission

- Transitions between discrete energy levels of atoms accompanied by *absorption* or *emission* of photons
- $E_2 \rightarrow E_1$ can be stimulated by an optical signal
- Resulting photon has *same energy, direction of propagation, phase, and polarization (a.k.a coherent!)*
- If stimulated emission dominates absorption, then we have amplification of signal
- Need to create a "*population inversion*" ($N_2 > N_1$) through a *pumping* process



Spontaneous Emission

- $E_2 \rightarrow E_1$ transitions can be spontaneous (I.e. *independent* of external radiation)
  - The photons are emitted in random directions, polarizations and phase (I.e. incoherent)!

- *Spontaneous emission rate* (or its inverse, spontaneous emission lifetime) is a characteristic of the system
  - Amplification of such incoherent radiation happens along with that of incident radiation
  - A.k.a. amplified spontaneous emission (ASE): appears as noise
  - ASE could saturate the amplifier in certain cases!

Optical Amplification: mechanics

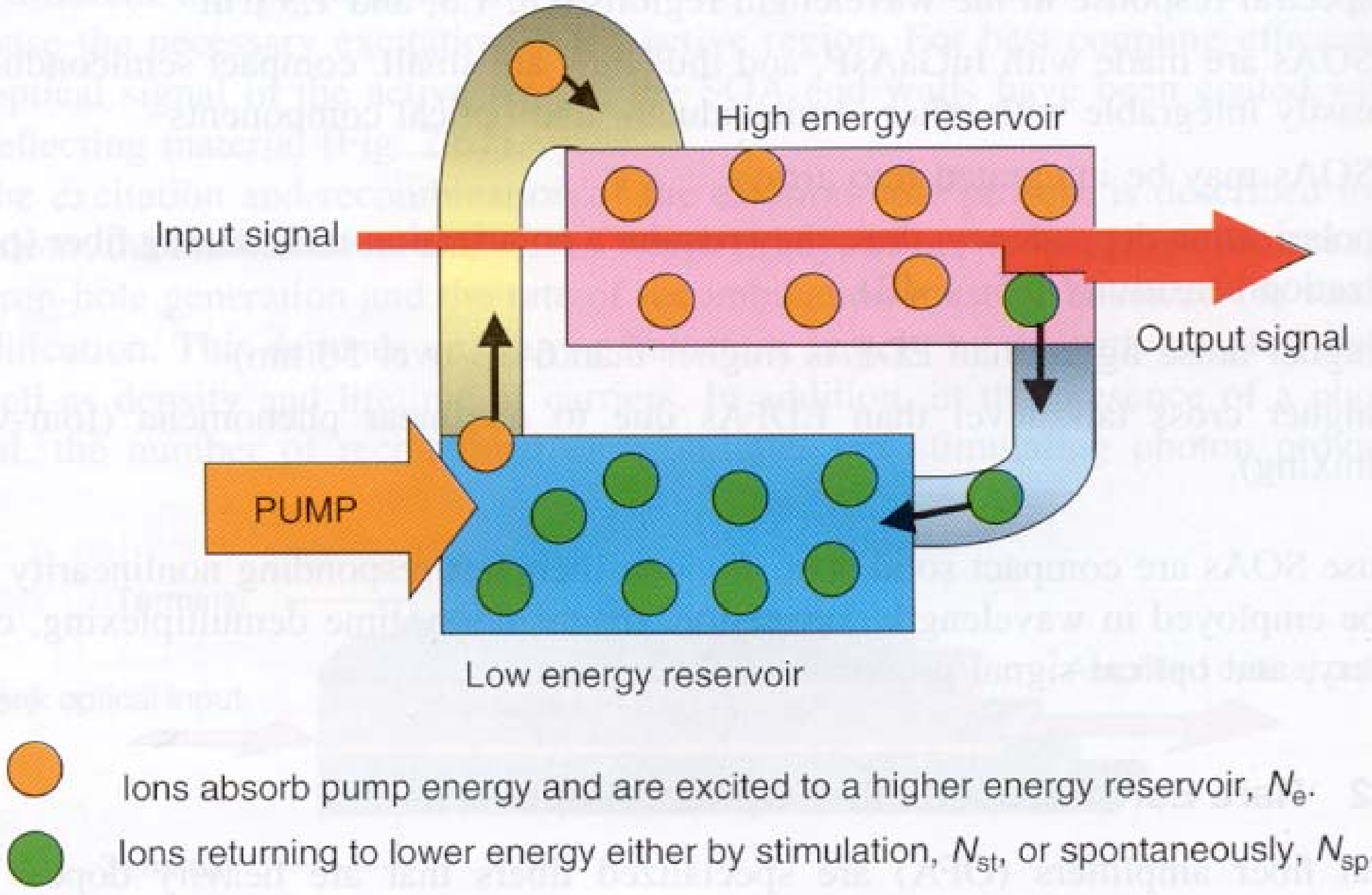
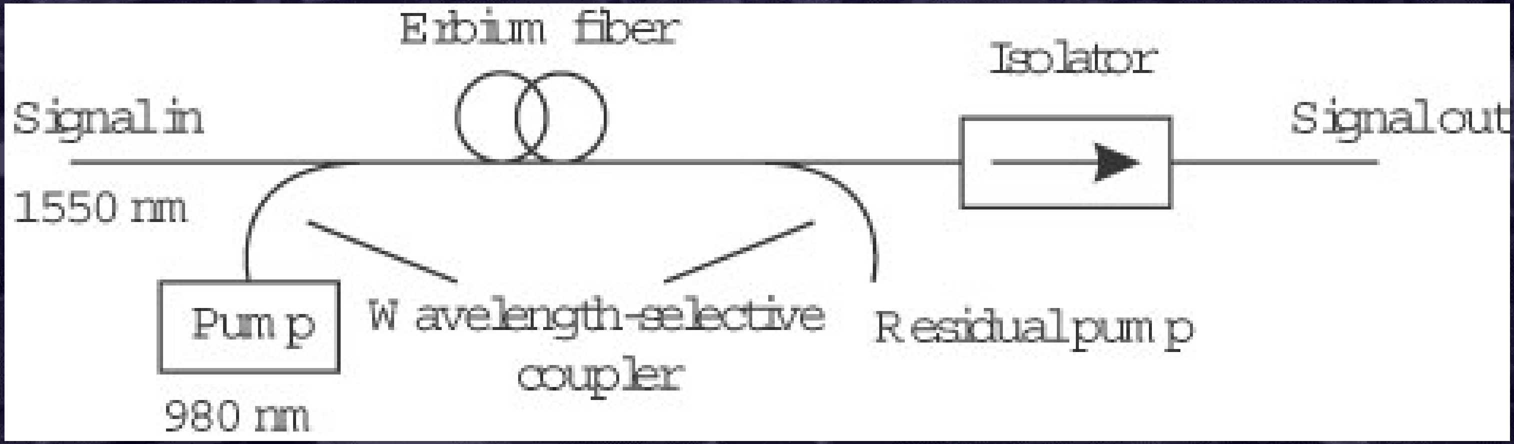


Figure 2.68 For sustained amplification, the rate of excitation should be less or equal to the rate of stimulation + the rate of spontaneous emission.

Erbium-Doped Fiber Amplifier (EDFA)



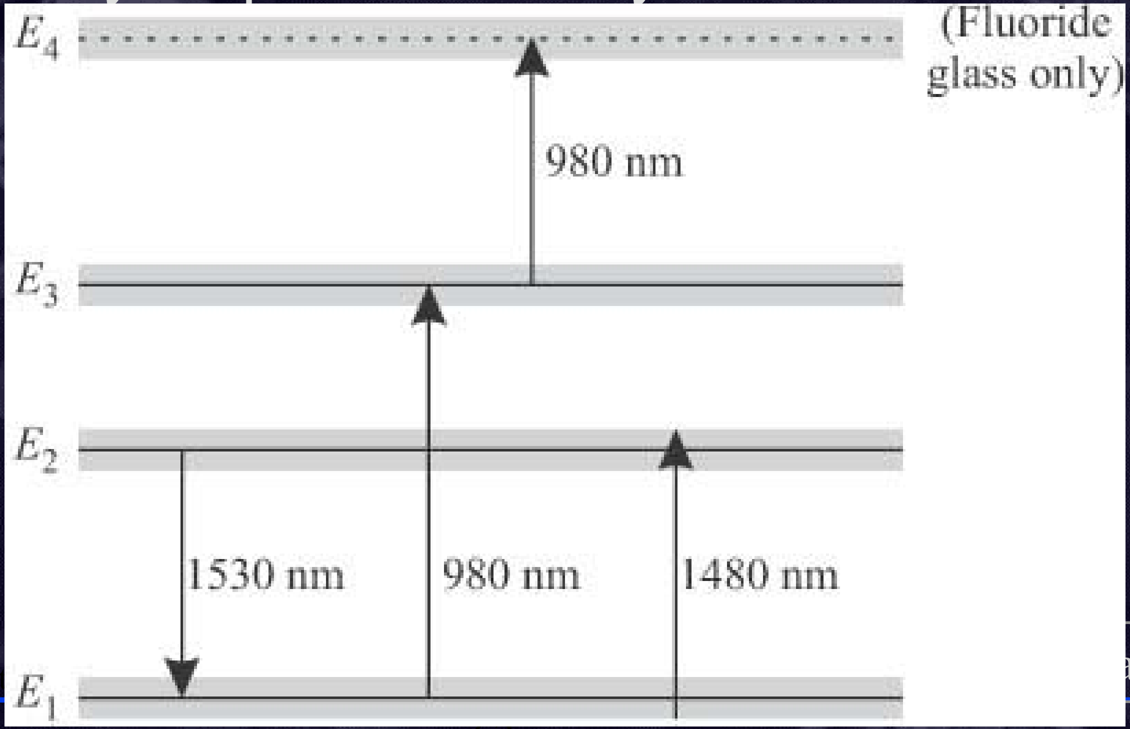
- Length of fiber: core doped with (rare earth) erbium ions **Er^{3+}**
- Fiber is pumped with a laser at 980 nm or 1480nm.
- Pump is coupled (in- and out-) using a λ-selective coupler
- An isolator is placed at the end to avoid reflections (else this will convert into a laser!)

EDFA success factors

- 1. Availability of compact and reliable high-power semiconductor pump lasers
- 2. EDFA is an all-fiber device => polarization-independent & easy to couple light in/out
- 3. Simplicity of device
- 4. No crosstalk introduced while amplifying!

EDFA: Operation

- When **Er^{3+}** ions introduced in silica, electrons disperse into an *energy band* around the lines E_1, E_2, E_3 (Stark splitting)
- Within each band, the ion distribution is non-uniform (thermalization)
- Due to these effects, a large λ range (50 nm) can be simultaneously amplified & luckily it is in the 1530nm range



EDFA: Operation (Contd)

- 980 nm or 1480nm pumps are used to create a population inversion between E_2 and E_1
- 980 nm pump => $E_1 \rightarrow E_3$ (absorption) & $E_3 \rightarrow E_2$ (spontaneous emission)
- 1480 nm pump => $E_1 \rightarrow E_2$ (absorption, less efficient)
- Lifetime in E_3 is 1μs, whereas in E_2 it is 10ms

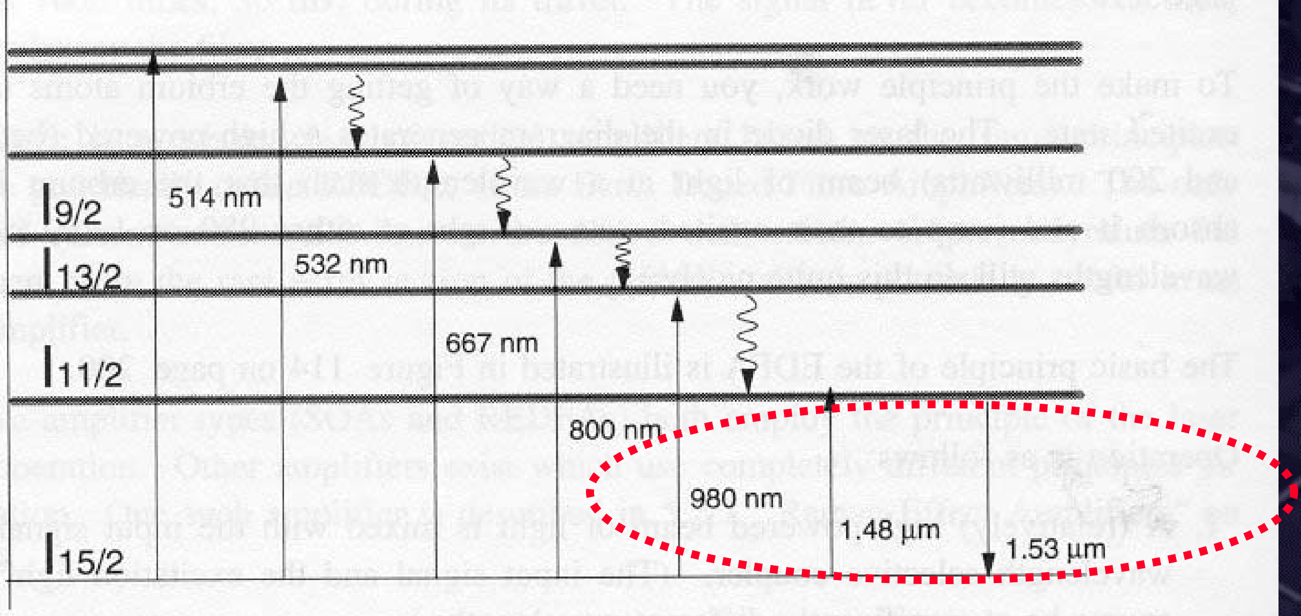


Figure 115. *Energy Level States of Erbium. While the energy states are represented as horizontal lines, they are really "energy bands" centred around a specific energy state. This distribution of energy states is called a "Fermi-Dirac Distribution".*

EDFA Pumping Issues

- *Higher power* 1480nm pumps *easily available* compared to 980 nm pumps
- Higher power 1480nm pumps may be *used remotely*!
- Degree of population inversion with 1480nm is less => *more noise*
- Fluoride fiber (EDFFAs) produce *flatter spectrum than EDFAs*, but they must be pumped at 1480nm (see pic earlier) due to “excited state absorption” ($E_3 \rightarrow E_4$)

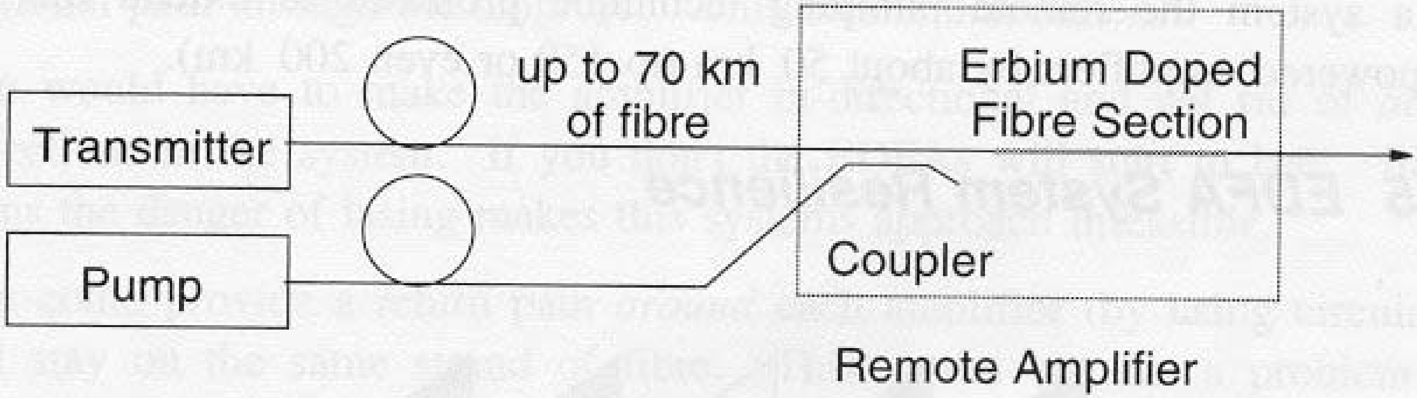
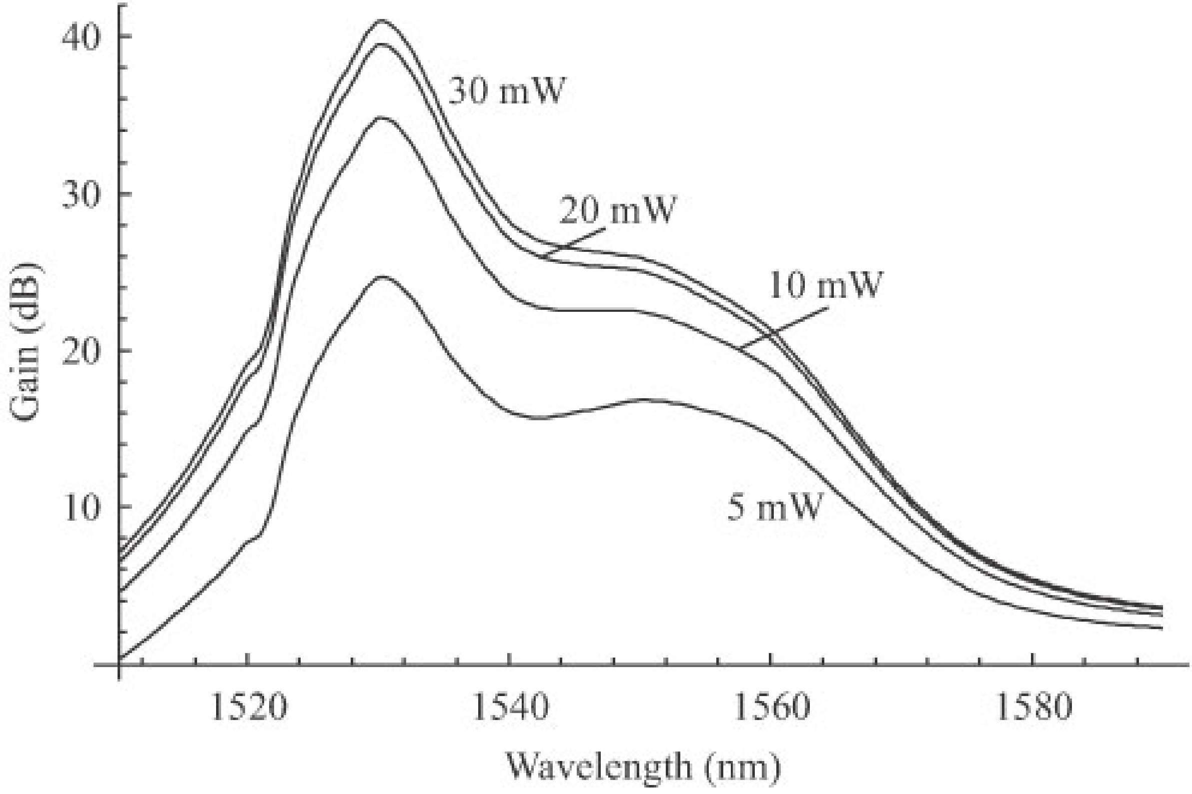


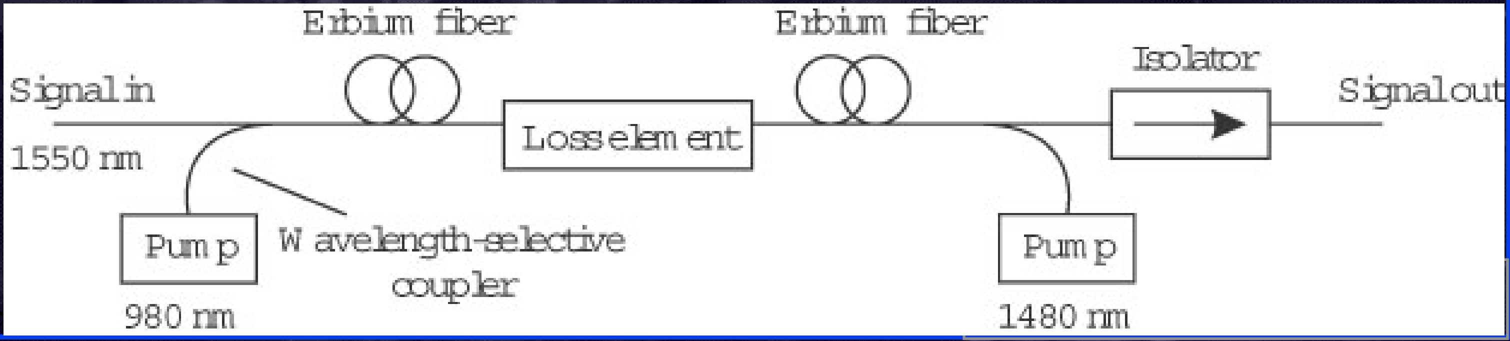
Figure 124. Remote Pumping

Towards Flat EDFA Gain

- Long period fiber-grating used to add some “loss” in the peaks of the curve

  (see →)





Reducing EDFA Gain Ripples

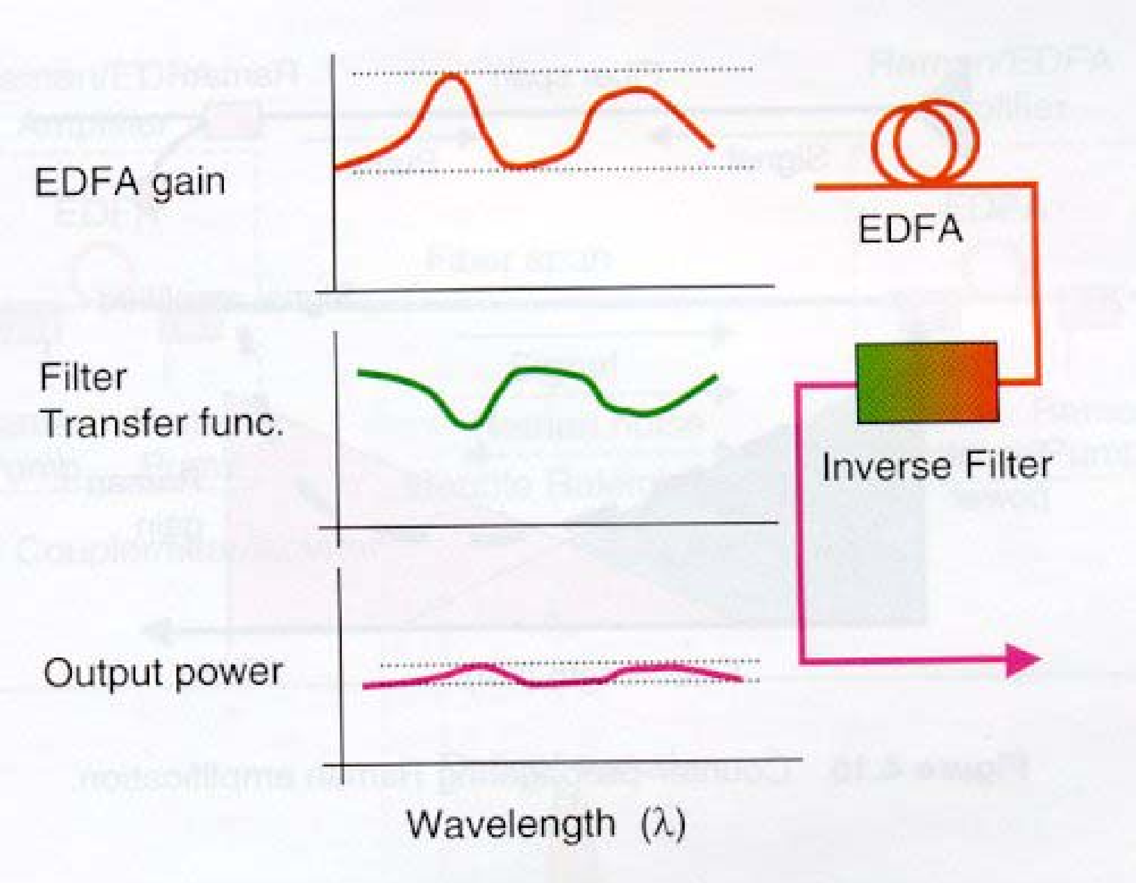


Figure 4.14 Inverse filters reduce EDFAs gain ripple.

EDFA: Summary

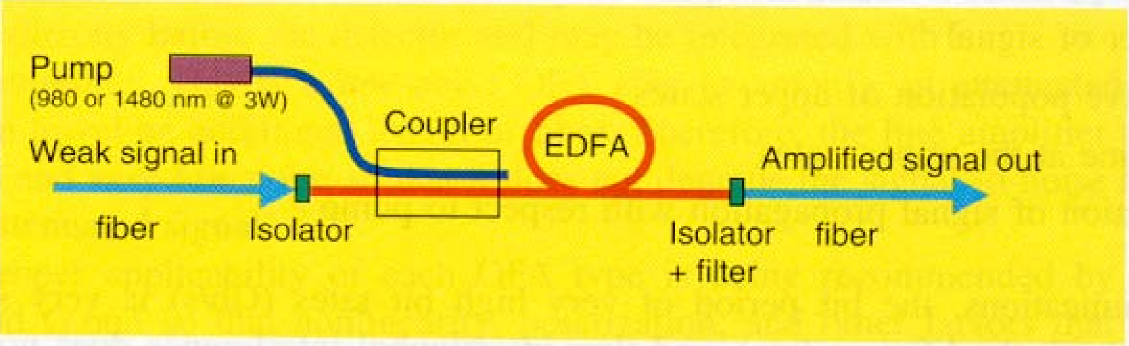


Figure 2.71 An EDFA amplifier consists of an erbium-doped silica fiber, an optical pump, a coupler and isolators at both ends.

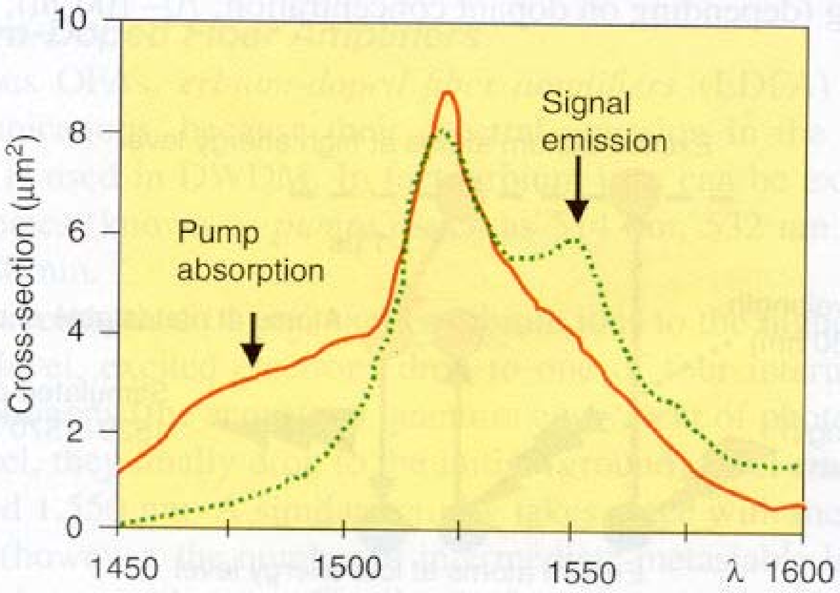


Figure 2.72 Pump absorption and signal emission spectra of EDFA.

Semiconductor Optical Amplifiers (SOA)

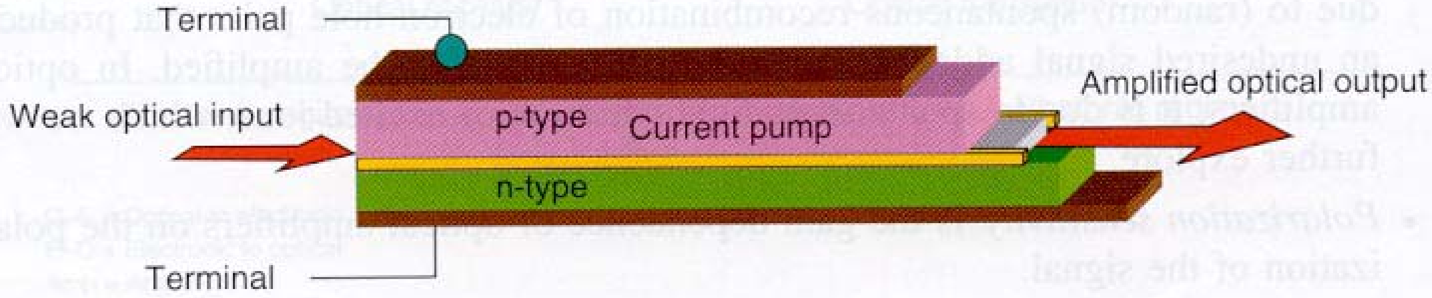
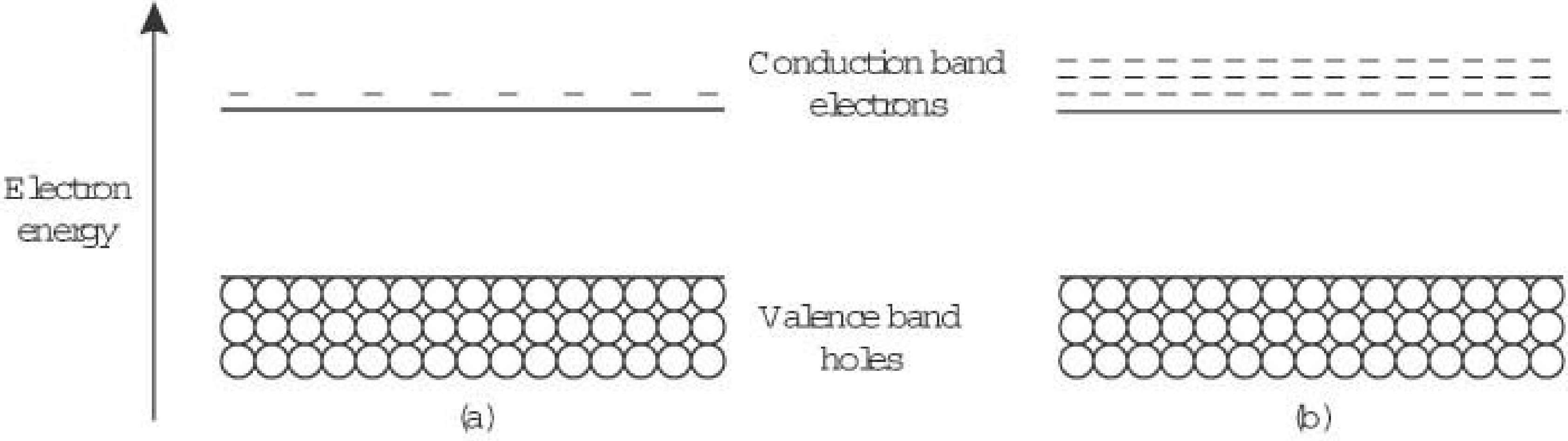
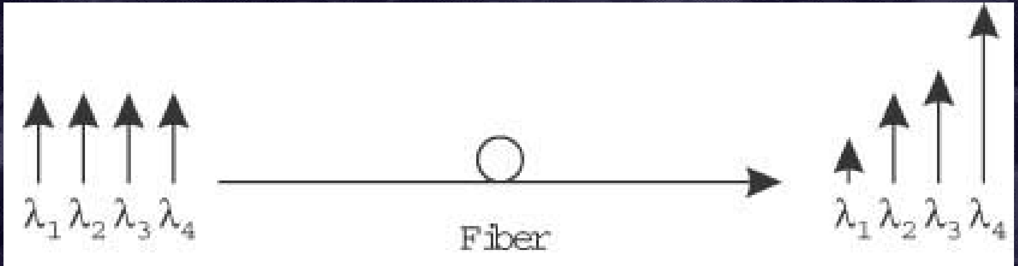


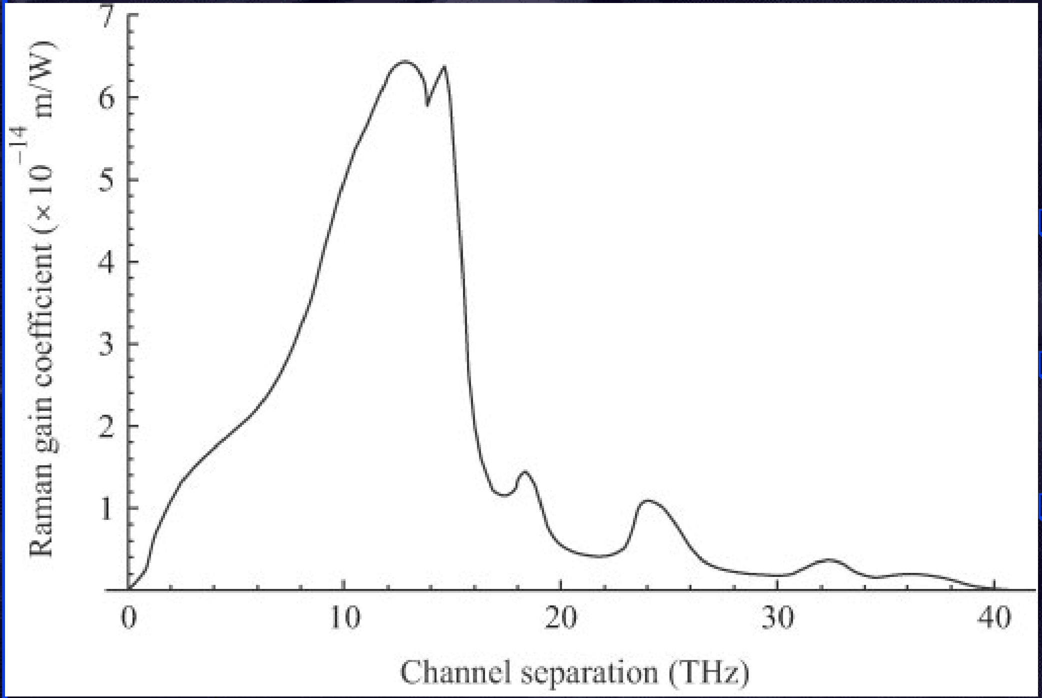
Figure 2.67 Semiconductor optical amplifiers (SOA) are devices based on conventional laser principles.



- SOAs have severe crosstalk problems, besides others
- But used in switches etc

Recall: SRS and Raman Amplifiers





- Power transferred from lower-λ to higher-λ channels (about 100nm)
- Eg: 1460-1480nm pump => amplification at 1550-1600nm
- Gain can be provided at ANY wavelength (all you need is an appropriate pump λ!)
- Multiple pumps can be used and gain tailored!
- Lumped or distributed designs possible
- Used today to complement EDFAs in ultra-long-haul systems

Raman Amplification

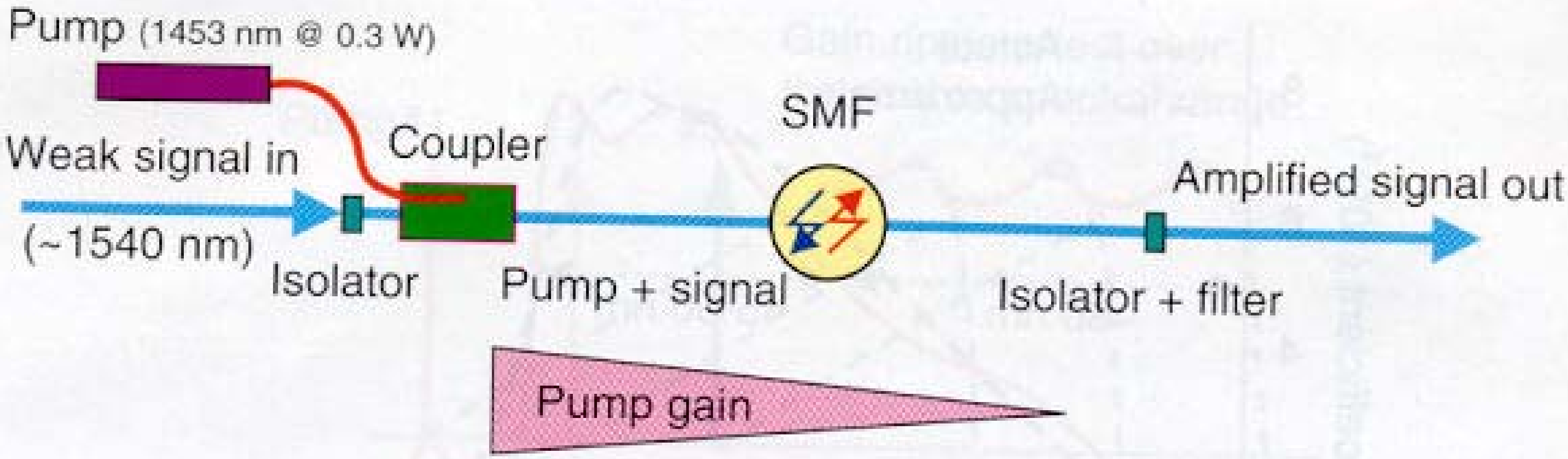


Figure 2.78 Principles of Raman amplification.

Raman Amplification (contd)

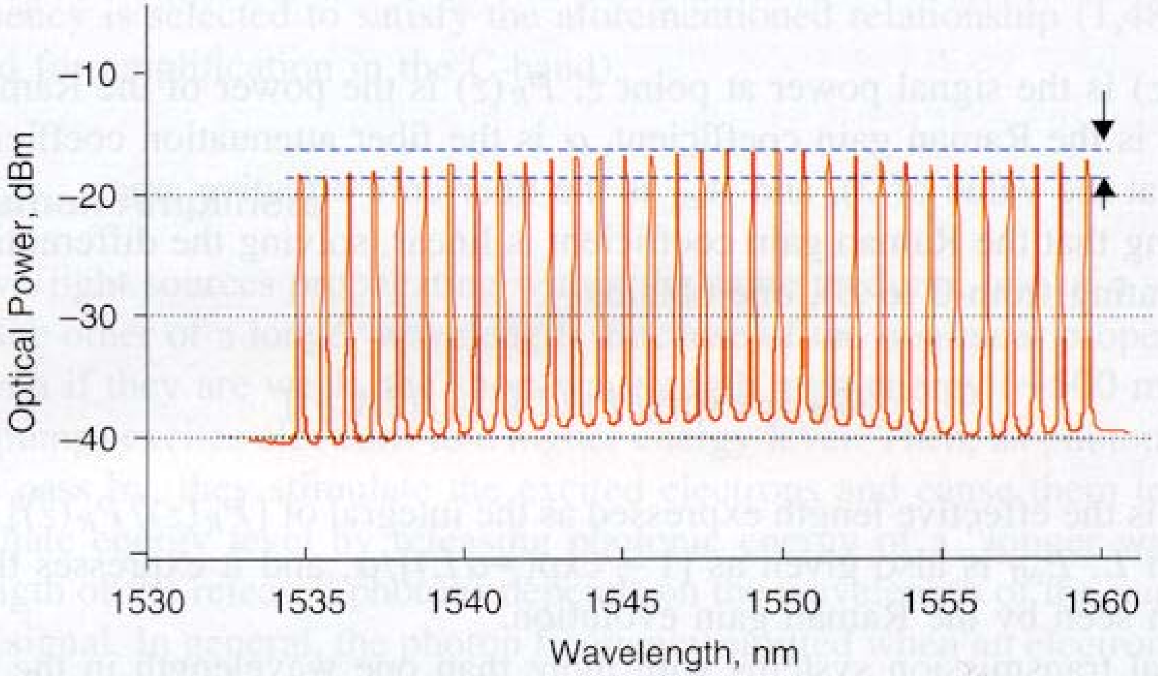


Figure 2.80 Typical Raman amplification over a 35 nm range (notice the peak-to-peak amplitude variation).

Counter-pumped Raman Amplification

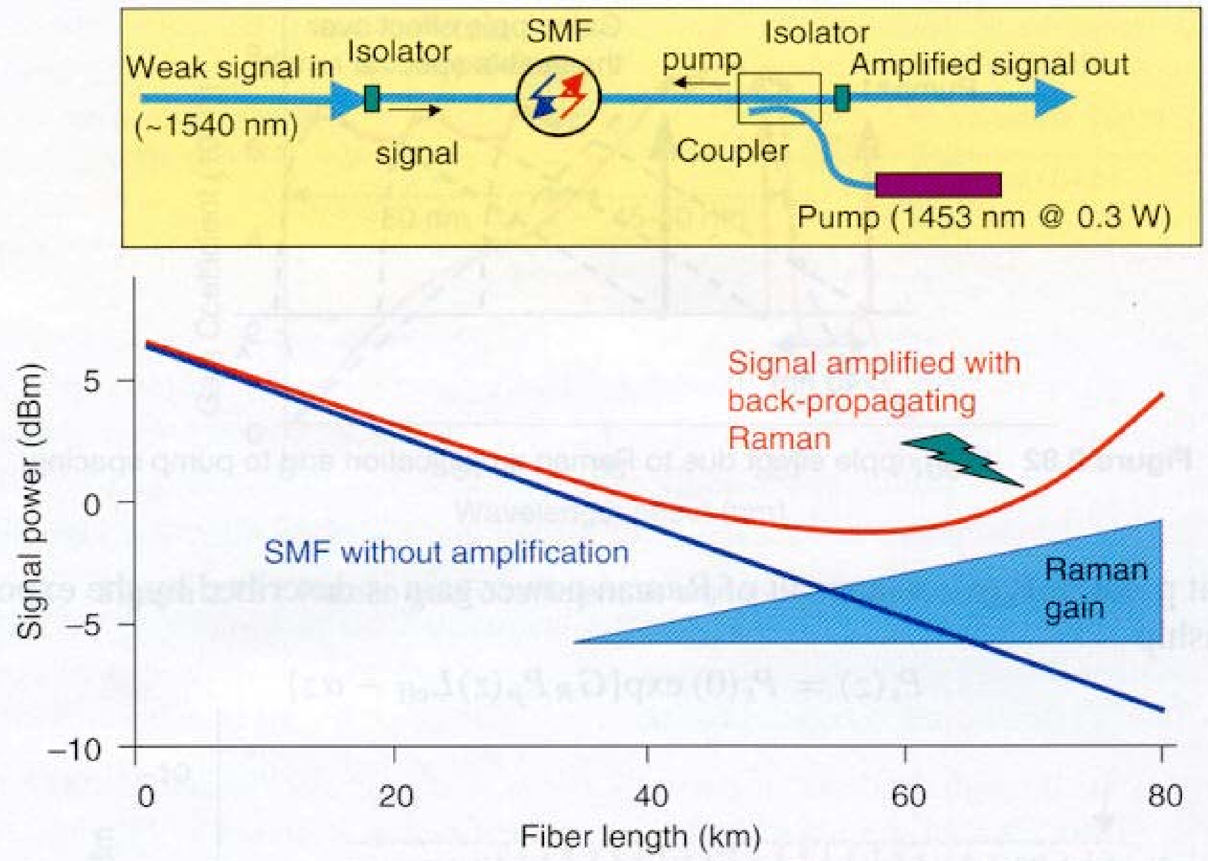
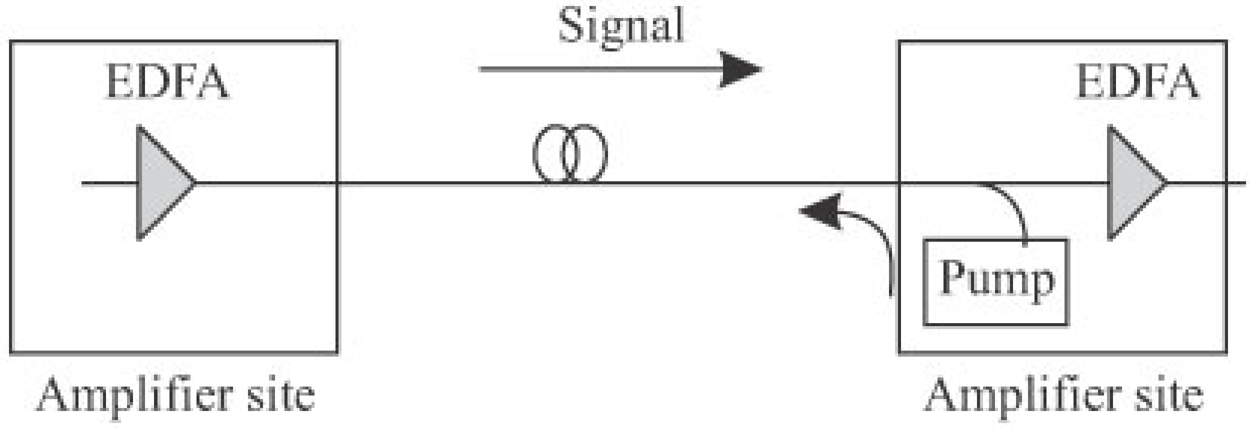


Figure 2.83 Counter-pumped Raman amplification.

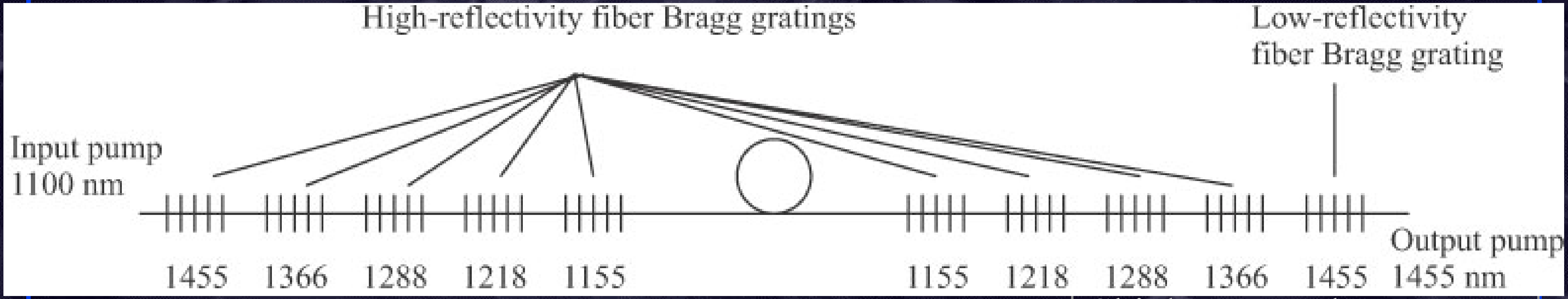
Distributed Raman Amplifiers

- Complement EDFAs in ultra-long-haul systems
- Challenge: need high-power pumps
- Pump power fluctuation => crosstalk noise!
- Counter-pumping: (dominant design) pump power fluctuations are averaged out over the propagation time of fiber; other crosstalk sources also reduced



Practical Raman Pumps

- Use a conveniently available (eg: 1100 nm) pump and use Raman effect itself, in combination with a series of FP-resonators (created through λ-selective mirrors, I.e. matched Bragg gratings)
- Eg: 1100nm →1155nm → 1218nm →1288nm → 1366nm → 1455 nm
- The final stage (1455nm) has low-reflectivity=> output pump at 1455nm which produces gain at 1550nm!
- 80% of the power comes to the output!



Recall: Optical Amplifier Varieties

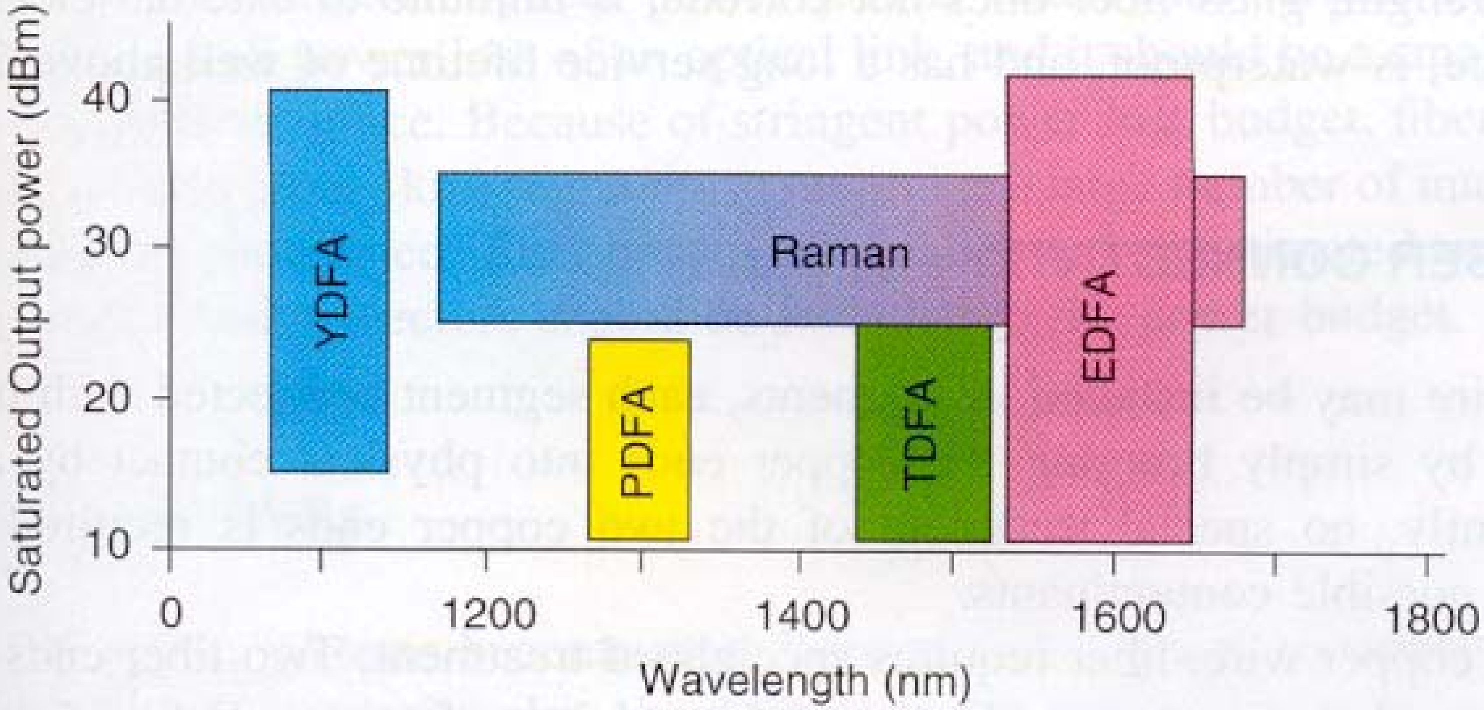


Figure 1.66 Optical amplifiers are many, each suitable for a different spectral range.

Raman vs OFAs

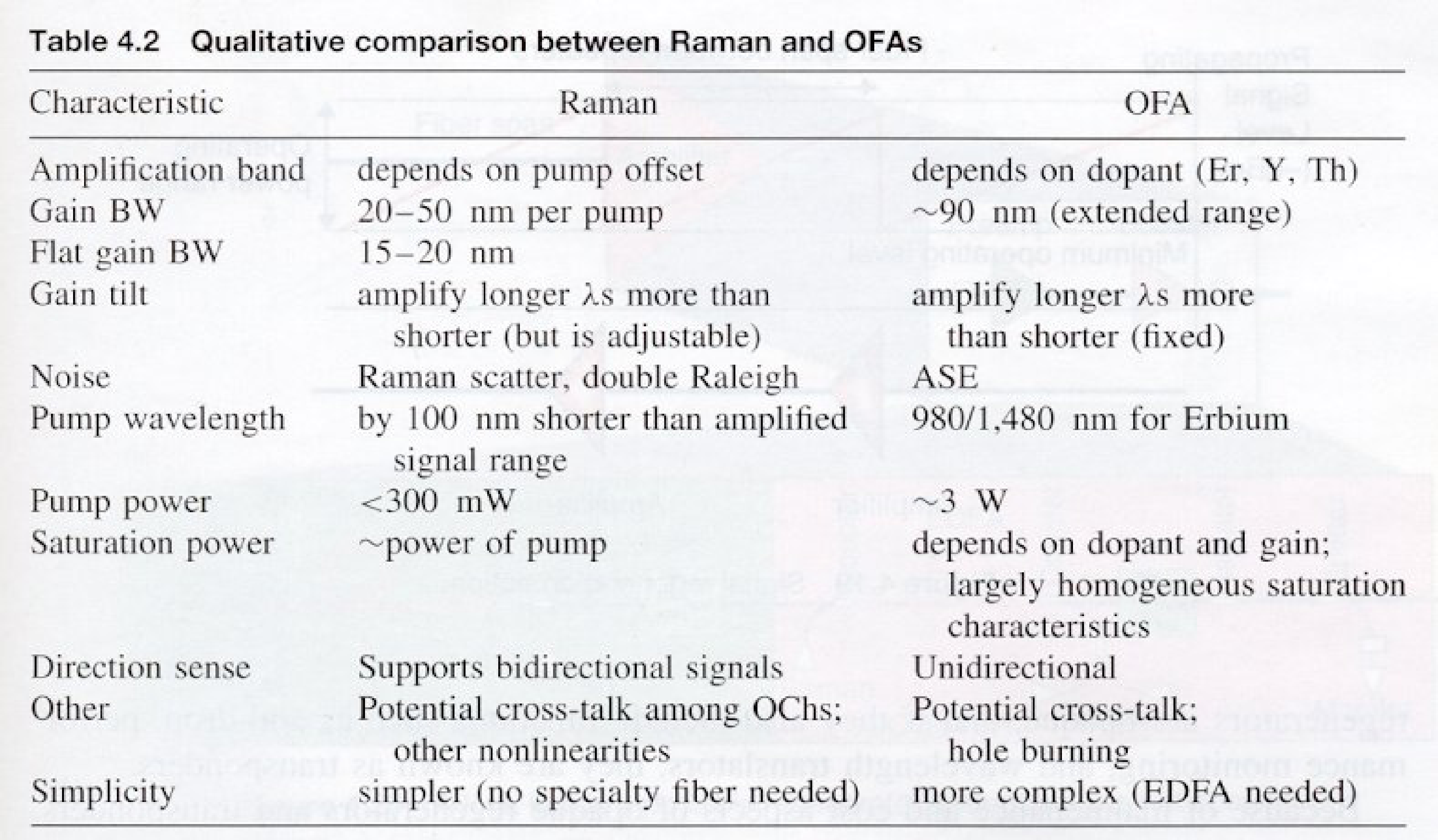


Table 4.2 Qualitative comparison between Raman and OFAs

Characteristic	Raman	OFA
Amplification band	depends on pump offset	depends on dopant (Er, Y, Th)
Gain BW	20–50 nm per pump	~90 nm (extended range)
Flat gain BW	15–20 nm	
Gain tilt	amplify longer λs more than shorter (but is adjustable)	amplify longer λs more than shorter (fixed)
Noise	Raman scatter, double Raleigh	ASE
Pump wavelength	by 100 nm shorter than amplified signal range	980/1,480 nm for Erbium
Pump power	<300 mW	~3 W
Saturation power	~power of pump	depends on dopant and gain; largely homogeneous saturation characteristics
Direction sense	Supports bidirectional signals	Unidirectional
Other	Potential cross-talk among OChs; other nonlinearities	Potential cross-talk; hole burning
Simplicity	simpler (no specialty fiber needed)	more complex (EDFA needed)

Long-Haul All-optical Amplification

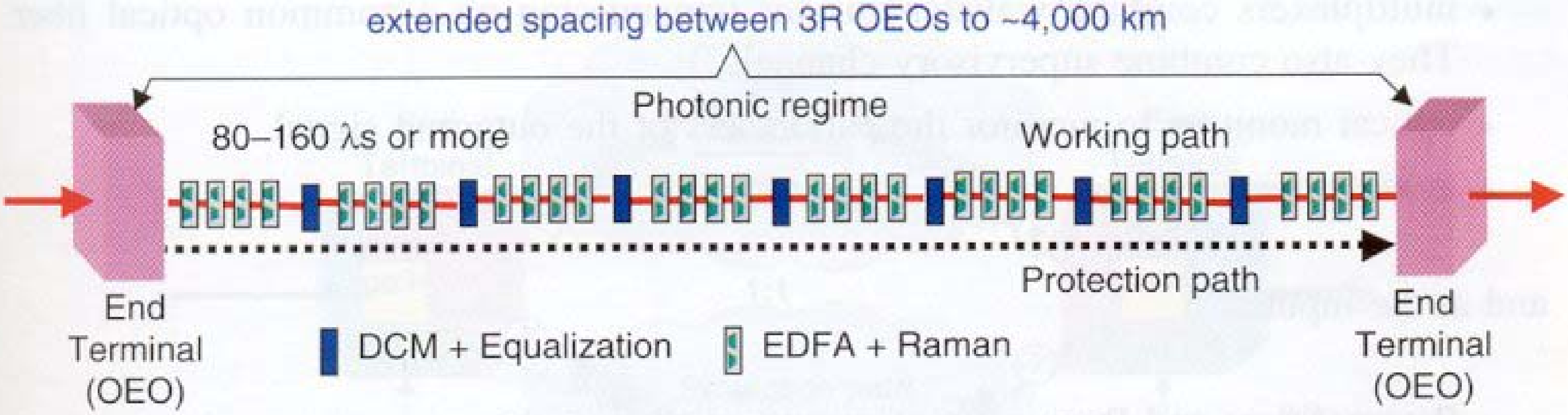


Figure 4.46 All optical amplification (EDFA + Raman) and dispersion compensation modules (DCM) enable the optical signal to reach ultra long distances (~4,000 km) between end terminals.

Optical Regenerator

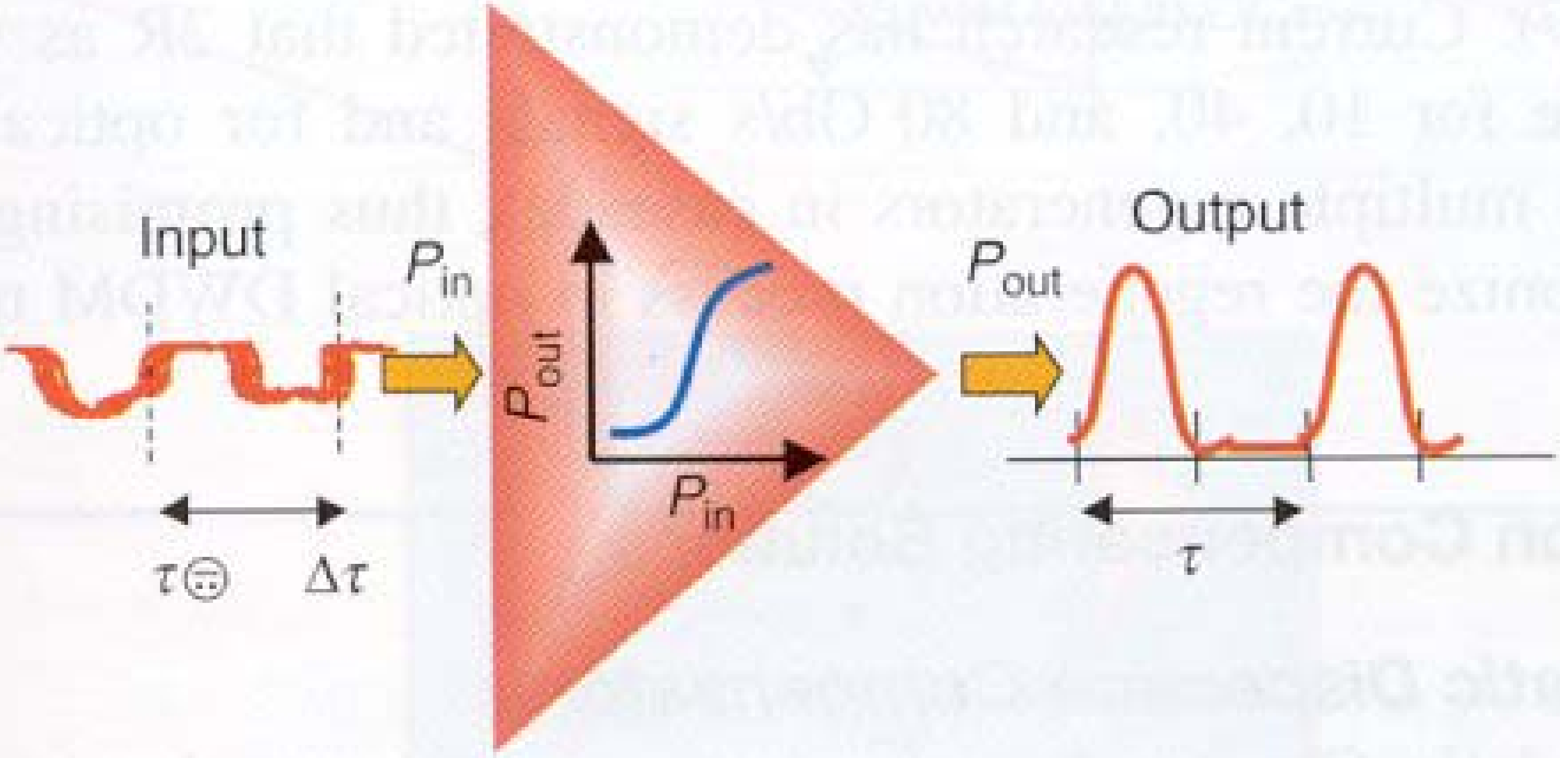


Figure 4.18 Model of an optical regenerator.

Regenerator

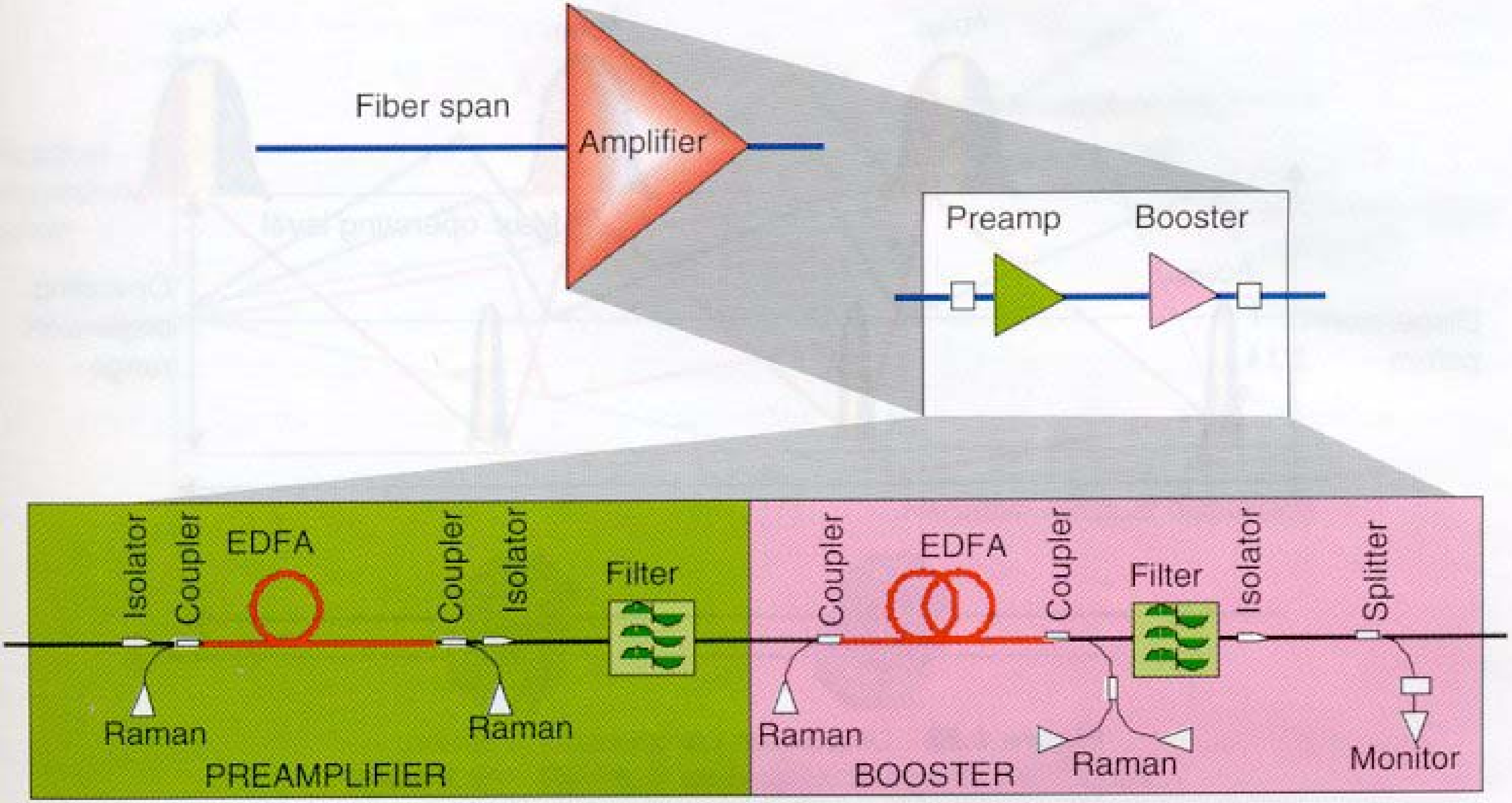


Figure 4.20 A look inside a possible regenerator (redundancy is not shown).

Regen w/ Dispersion Compensation and Gain Equalization

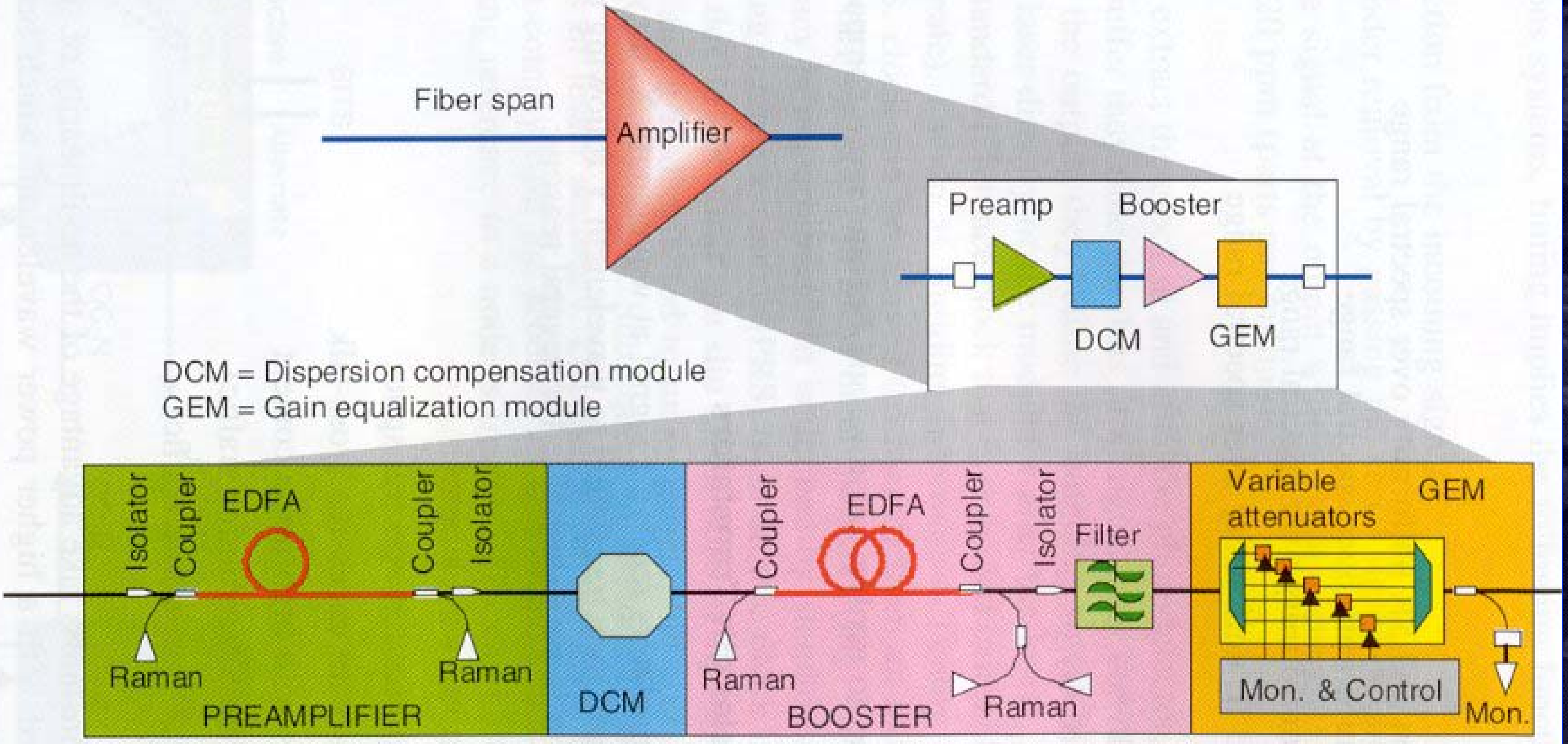


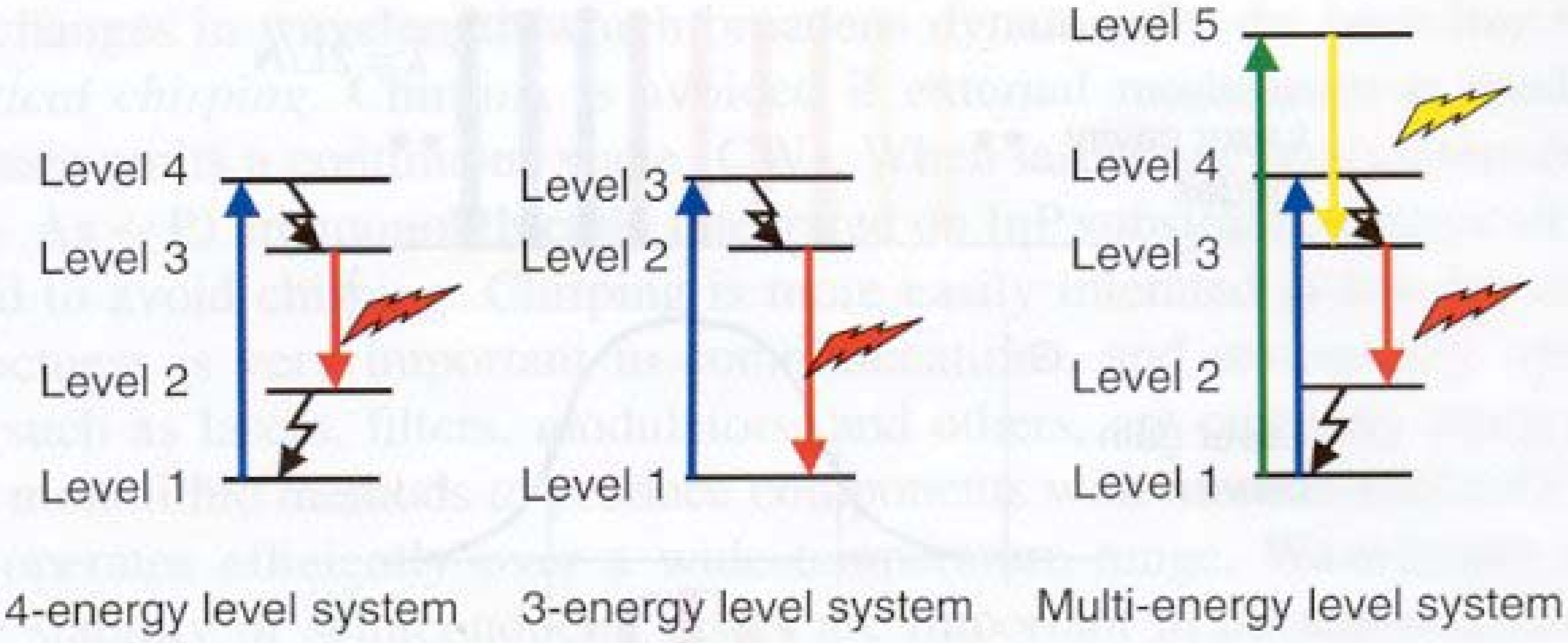
Figure 4.25 A regenerator with dispersion compensation and gain equalization modules.

Light Sources: LEDs, Lasers, VCSELs, Tunable Lasers

Lasers: Key Target Characteristics

- Laser: an optical amplifier enclosed in a reflective cavity that causes it to oscillate via positive feedback
- High output power (1-10 mW normal, 100-200mW EDFA pumps, few Ws for Raman pumps)
  - Threshold Current: drive current beyond which the laser emits power
  - Slope Efficiency: ratio of output optical power to drive current
- Narrow spectral width at specified λ
  - Side-mode suppression ratio
  - Tunable laser: operating λs
- λ-stability: drift over lifetime needs to small relative to WDM channel spacing
- Modulated lasers: low (accumulated) chromatic dispersion

Recall: Energy Levels & Light Emission



4-energy level system 3-energy level system Multi-energy level system

Figure 2.51 A four, three and multi-energy level system.

Spontaneous Emission, Meta-Stable States

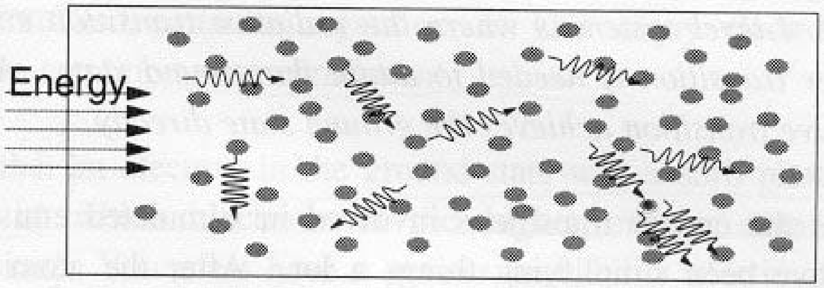


Figure 63. Spontaneous Emission

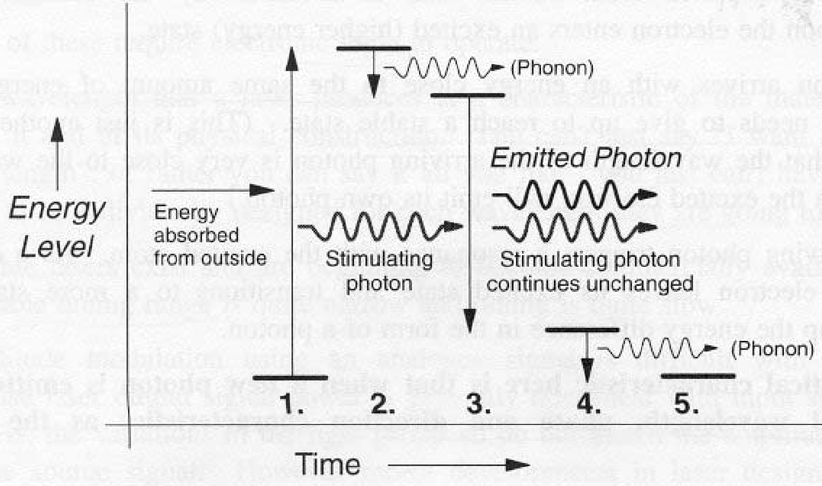
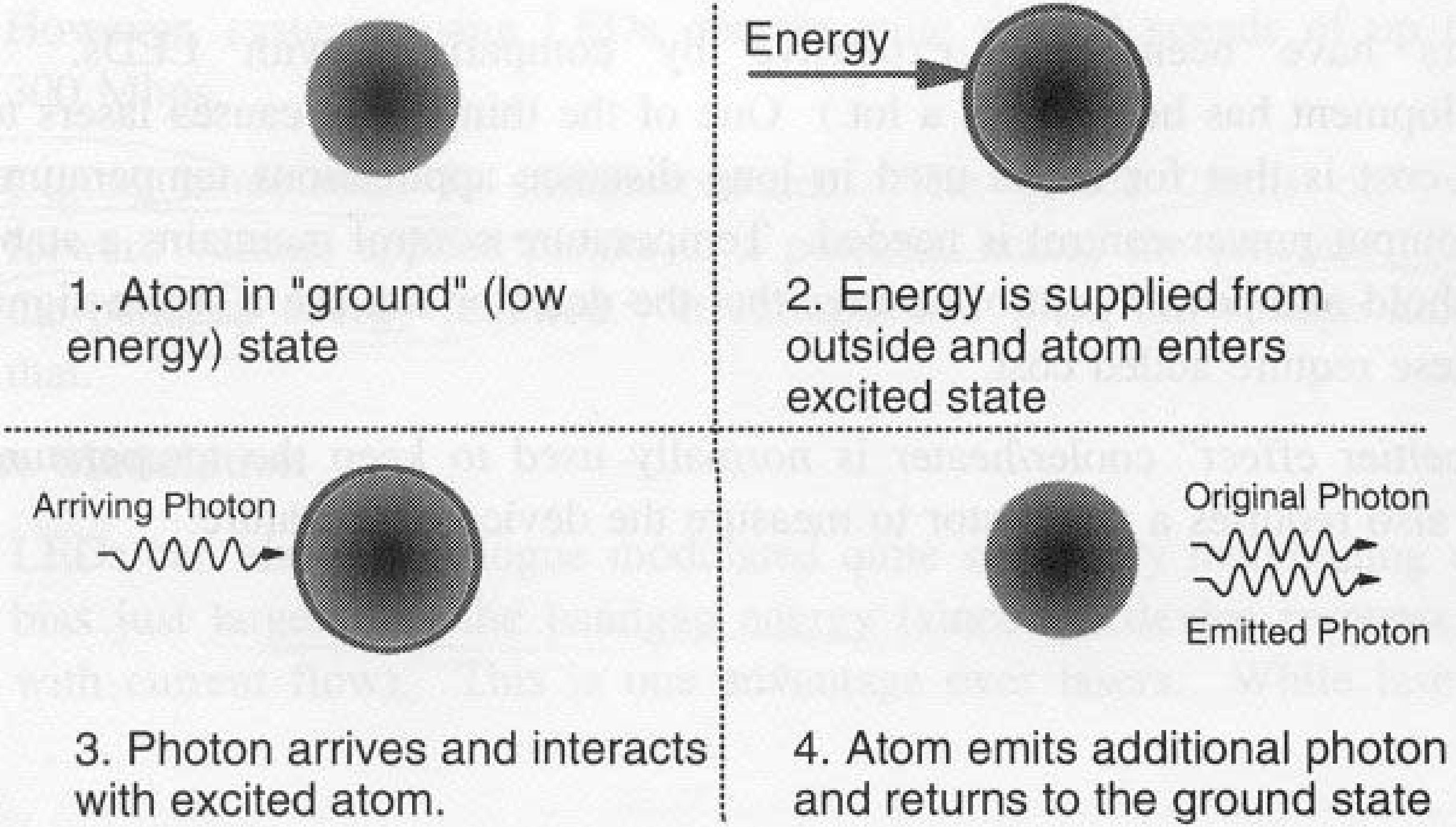


Figure 64. Energy States of a typical 4-Level Material. A material which has 4 energy levels involved in the lasing process is significantly more efficient than one with only 3 levels. A 4-level system is where the radiative transition ends in an unstable state and another transition is needed to attain the ground state. A 3-level system is where the radiative transition achieves the ground state directly.

Recall:Stimulated Emission



1. Atom in "ground" (low energy) state

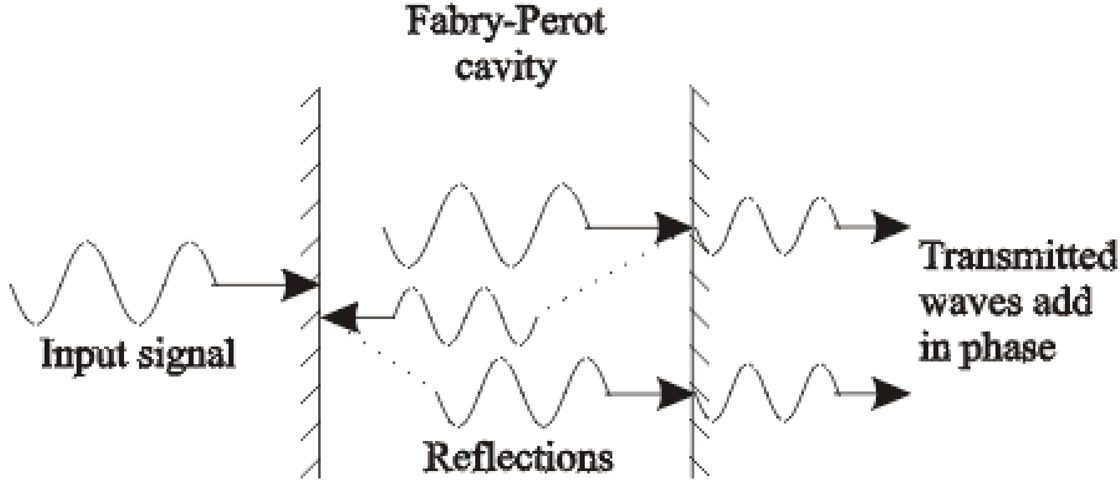
2. Energy is supplied from outside and atom enters excited state

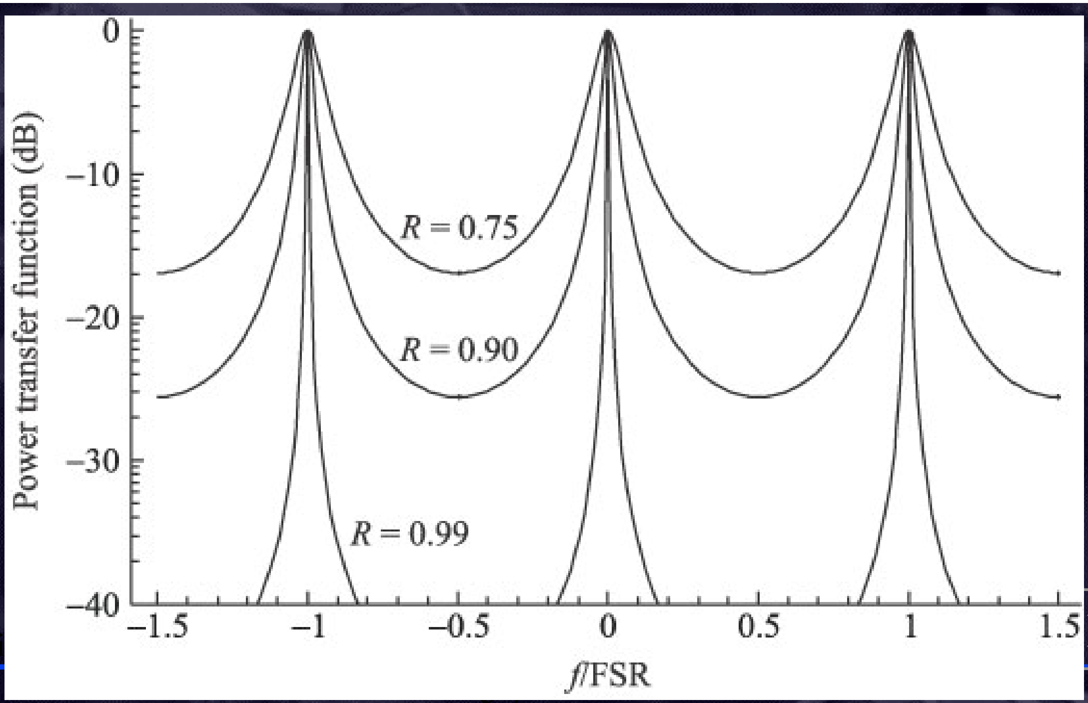
3. Photon arrives and interacts with excited atom.

4. Atom emits additional photon and returns to the ground state

Figure 62. Stimulated Emission

Recall: Fabry-Perot Etalon





Laser vs LEDs

- LED: Forward-biased pn-junction (~low R etalon)
  - Recombination of injected minority carriers by spontaneous emission produces light
  - Broad spectrum (upto gain b/w of medium)
  - Low power: -20dBm
  - Low internal modulation rates: 100s of Mbps max
  - LED slicing: LED + filter (power loss)
- Laser:
  - Higher power output
  - Sharp spectrum (coherence): ↓ chromatic dispersion
  - Internal or External modulation: ↑ distance, ↑ bit rates
  - Multi-longitudinal mode (MLM): larger spectrum (10s of nm) with discrete lines (unlike LEDs)

Simple LEDs: p-n junction, bandgap

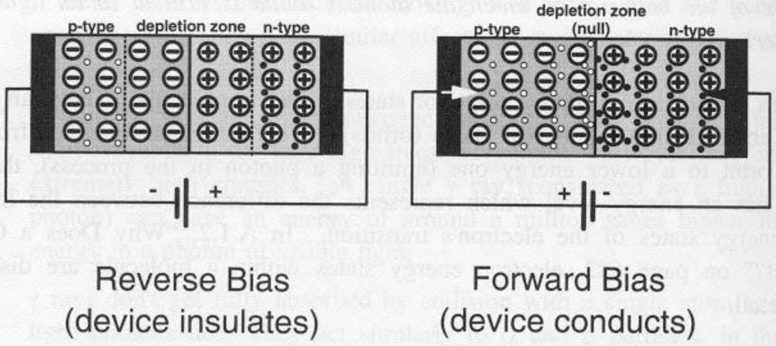


Figure 53. Electrical Potentials across a p-n Junction

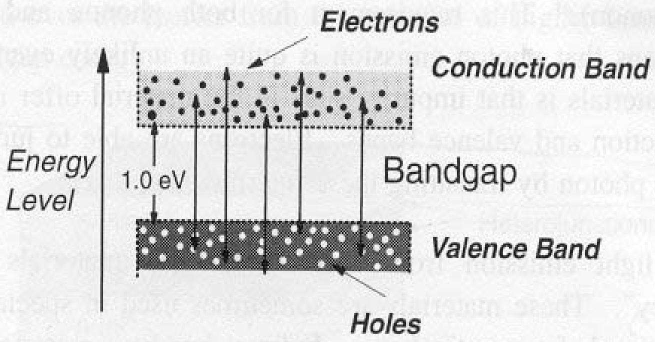


Figure 54. Bandgap Energy

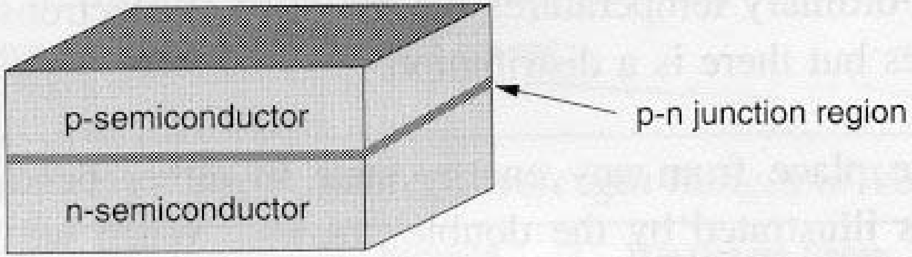


Figure 55. Simple P-N Junction LED

Double Heterojunction LED

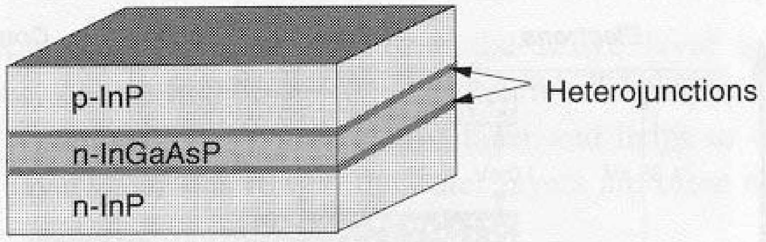
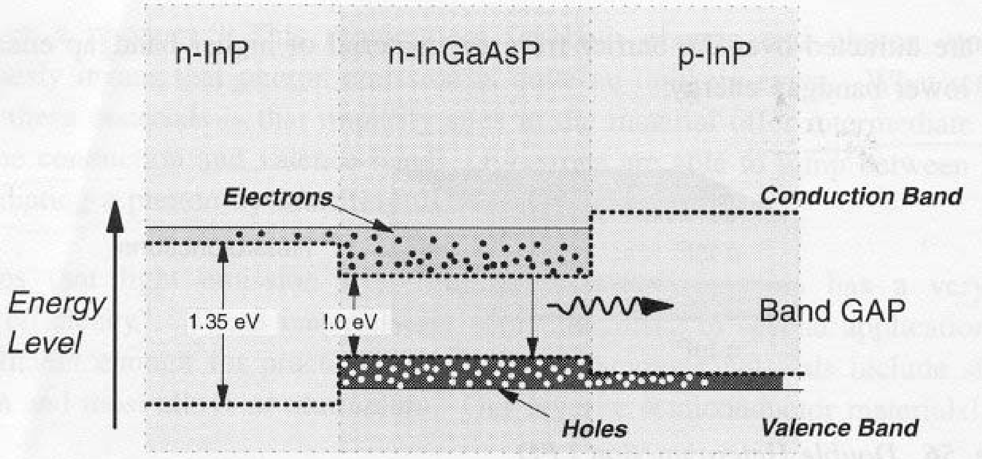


Figure 56. Double Heterojunction LED



Bandgap boundaries are denoted by dotted lines

Figure 57. Energy Bands in a Double Heterojunction

- Light produced in a more localized area in double heterojunction LEDs
- Heterojunction: junction between two semiconductors with different bandgap energies
- Charge carriers attracted to lower bandgap (restricts region of e-hole recombinations)

Effect of Temperature on λ and I

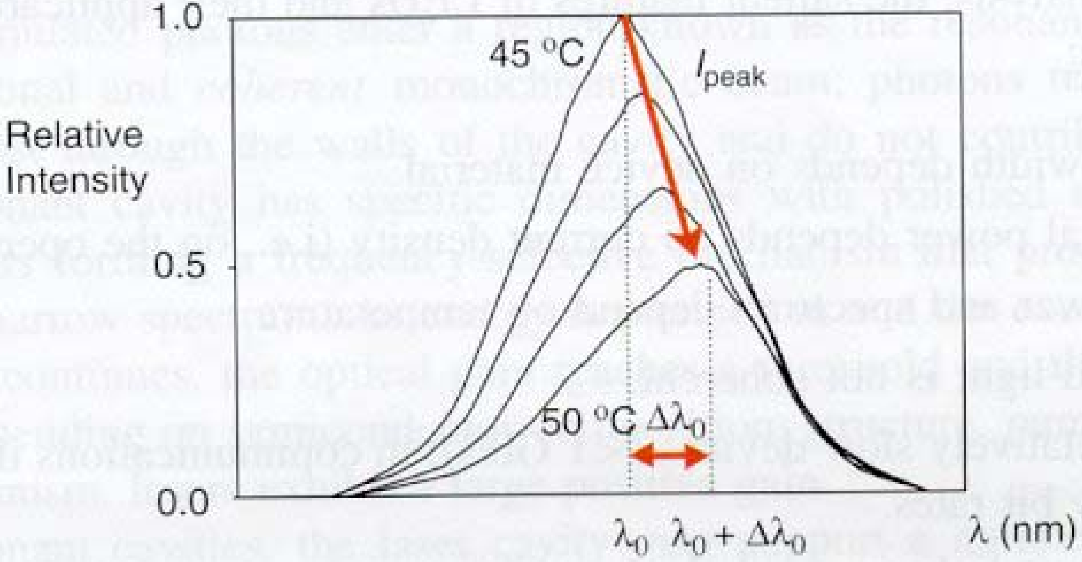


Figure 2.49 Effect of temperature on wavelength and optical intensity of solid state light sources.

LED: Temperature-dependent Wavelength Drift

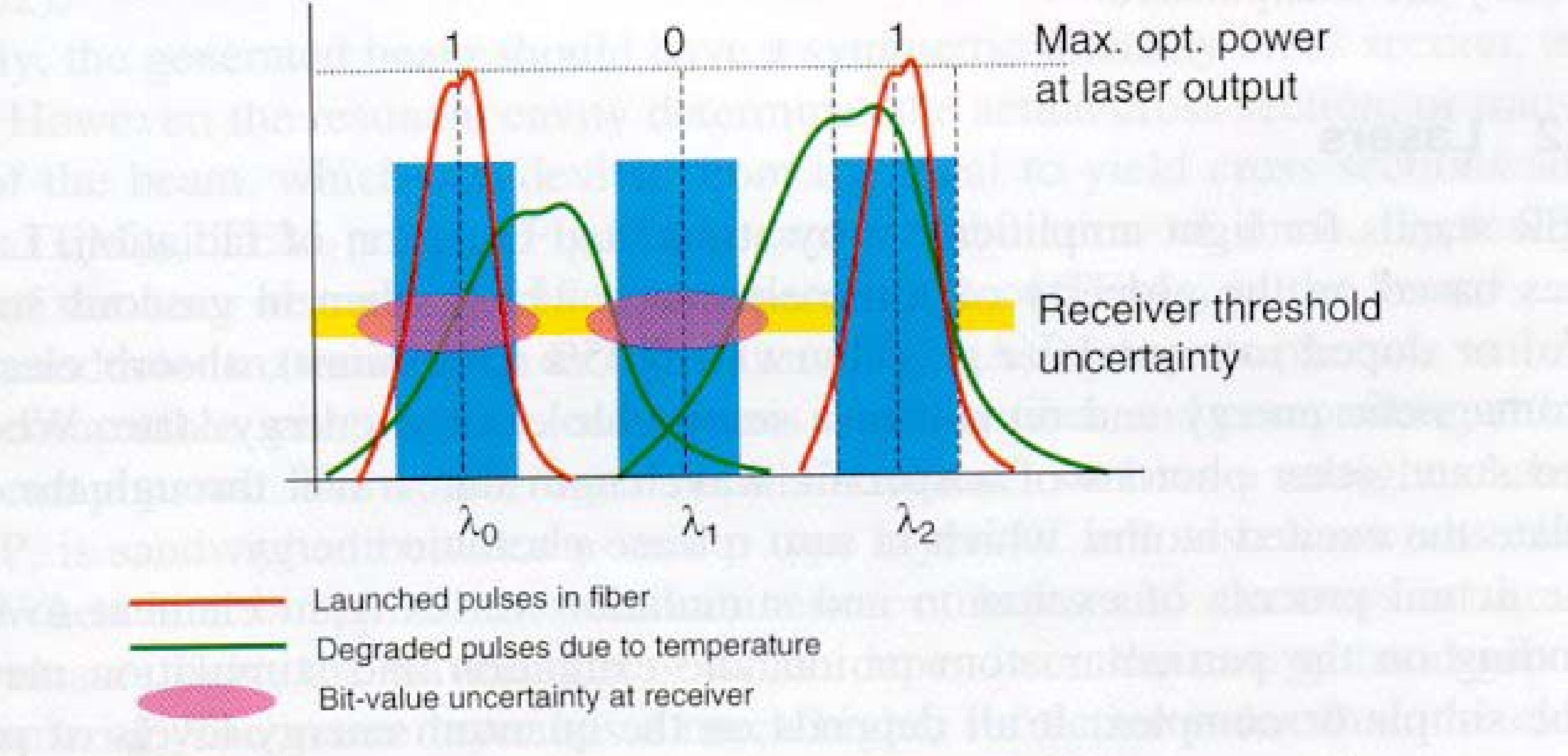


Figure 2.50 Effect of wavelength drift on cross talk due to temperature increase.

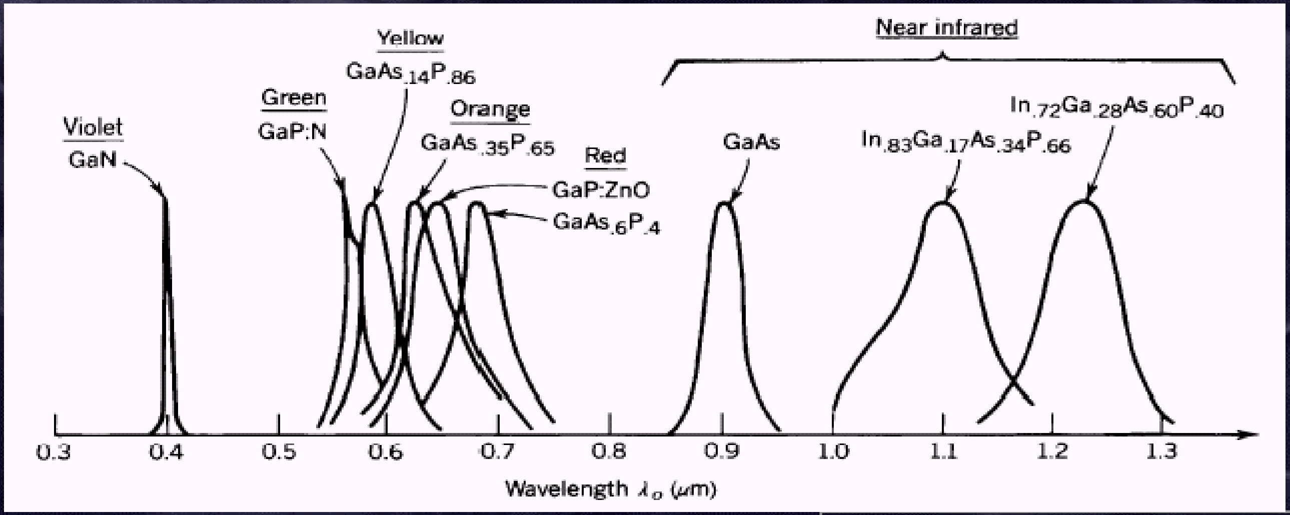
LEDs: Useful in Free-space-Optical Communication

- Output Optical Power

$$P = \frac{1.24}{\lambda} I$$

- P — Output Optical Power
- λ — wavelength
- I — Input Electrical Current

- Output Optical Spectral Width



Lasers vs Optical Amplifiers

- As reflectivity of the cavity boundaries (aka facets) ↑, the gain is high only for the resonant λs of the cavity
  - All resonant λs add in phase
  - Gain in general is a function of the λ and reflectivity
- If reflectivity (R) and gain is sufficiently high, the amplifier will "oscillate" I.e. produce light output ***even in the absence*** of an input signal!!!
  - This **lasing threshold** is where a laser is no longer a mere amplifier, but an oscillator
  - W/o input signal, stray spontaneous emissions are amplified and appear as light output
- Output is "coherent": it is the result of stimulated emission
- LASER = "**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation"

Lasing

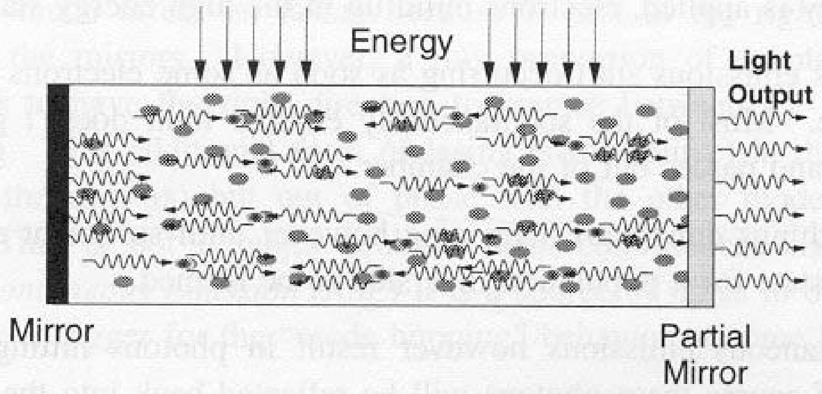


Figure 65. Lasing

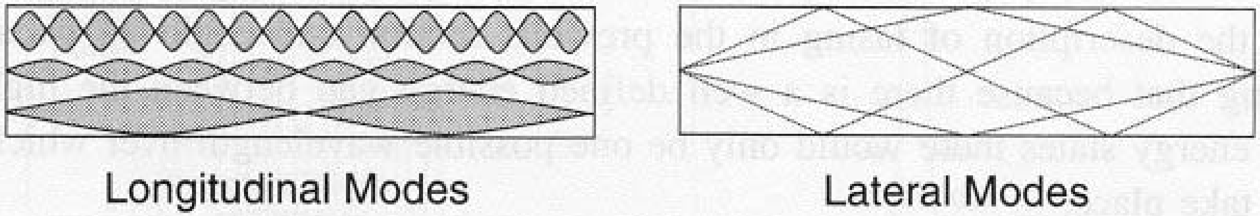


Figure 68. Resonance Modes in the Cavity of a Fabry-Perot Laser

Modes, Spectral Width and Linewidth

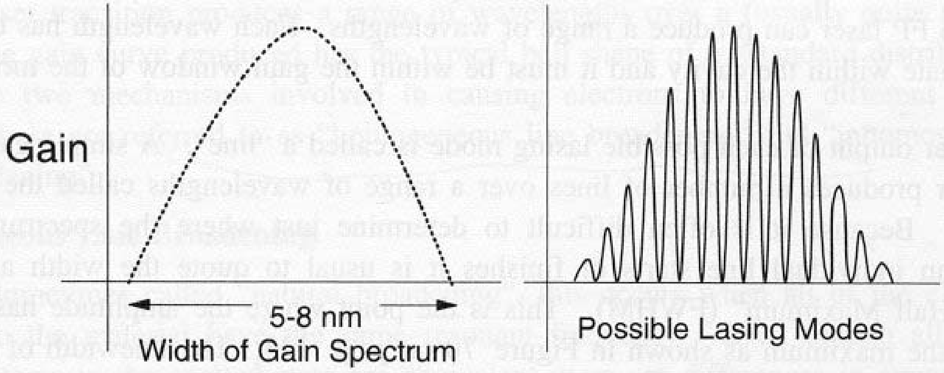


Figure 69. Modes Produced in a Typical Fabry-Perot Laser

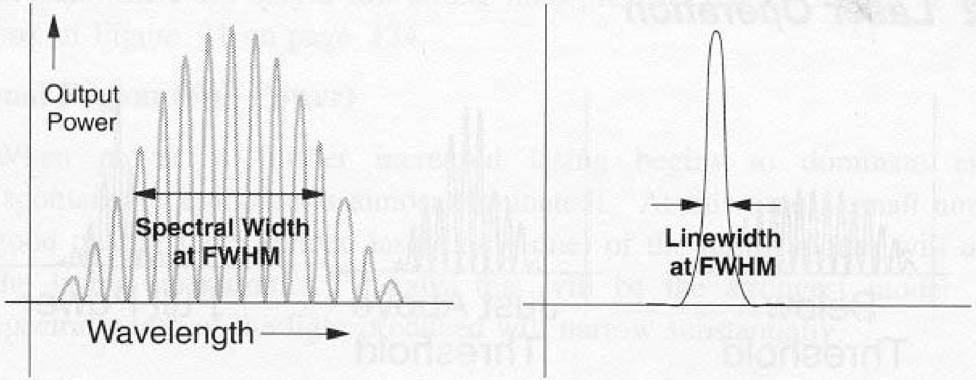


Figure 70. Spectral Width and Linewidth. These are usually measured as the width at half the maximum signal amplitude. That is at FWHM (Full Width Half Maximum).

Fabry-Perot Laser Sources

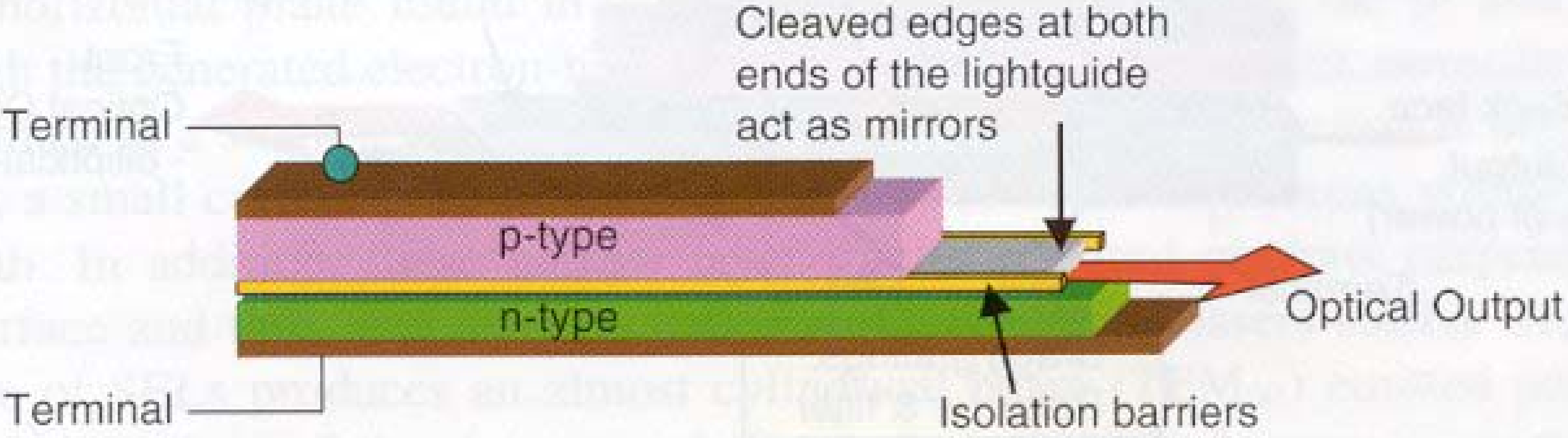


Figure 2.54 Fundamentals of a Fabry–Perot laser source.

Laser: Output Behavior vs Applied Power

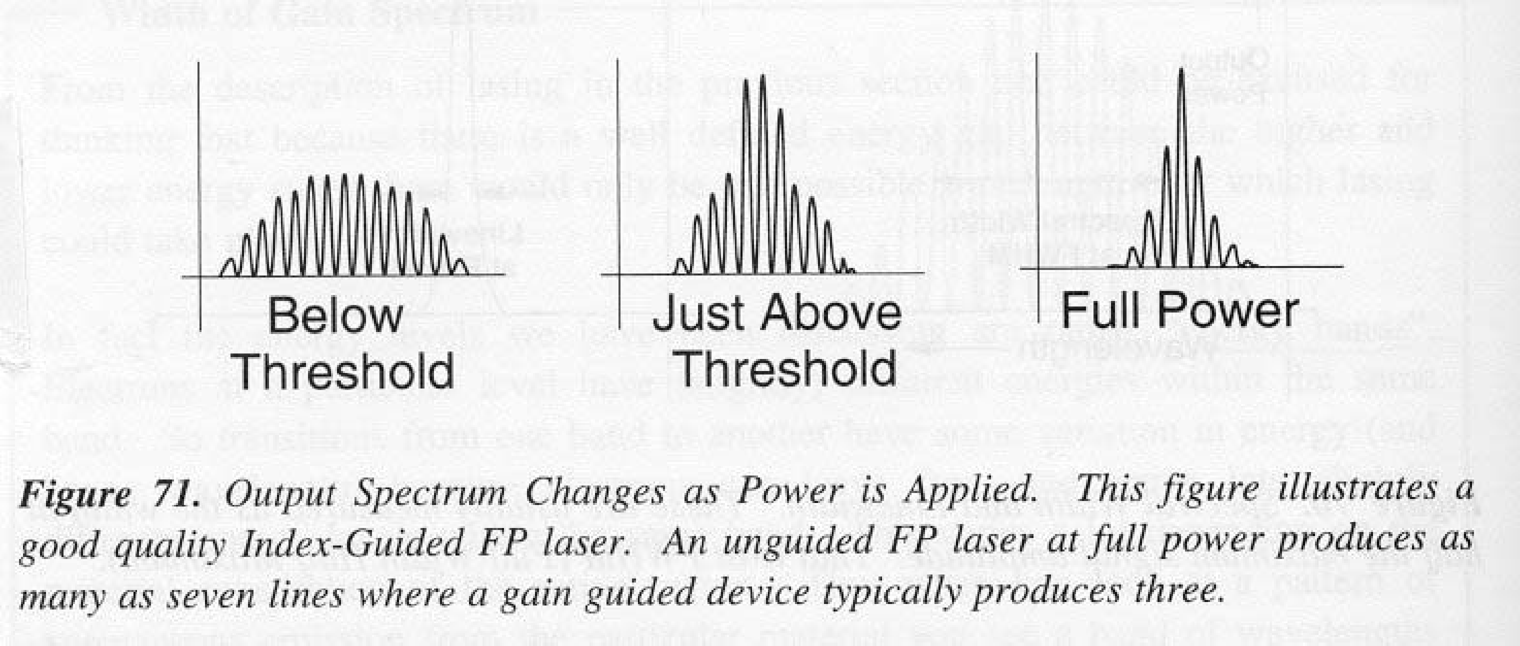


Figure 71. Output Spectrum Changes as Power is Applied. This figure illustrates a good quality Index-Guided FP laser. An unguided FP laser at full power produces as many as seven lines where a gain guided device typically produces three.

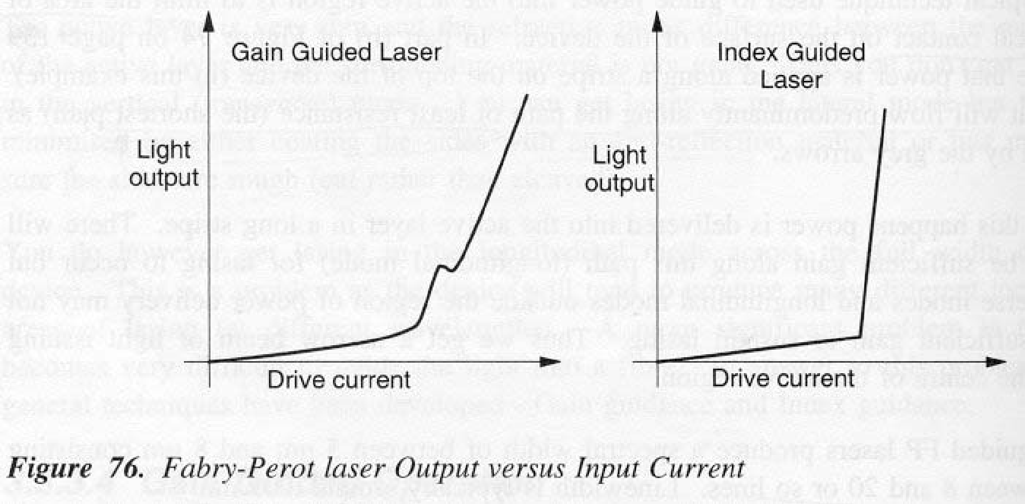


Figure 76. Fabry-Perot laser Output versus Input Current

Directing the Light in a Fabry-Perot Laser

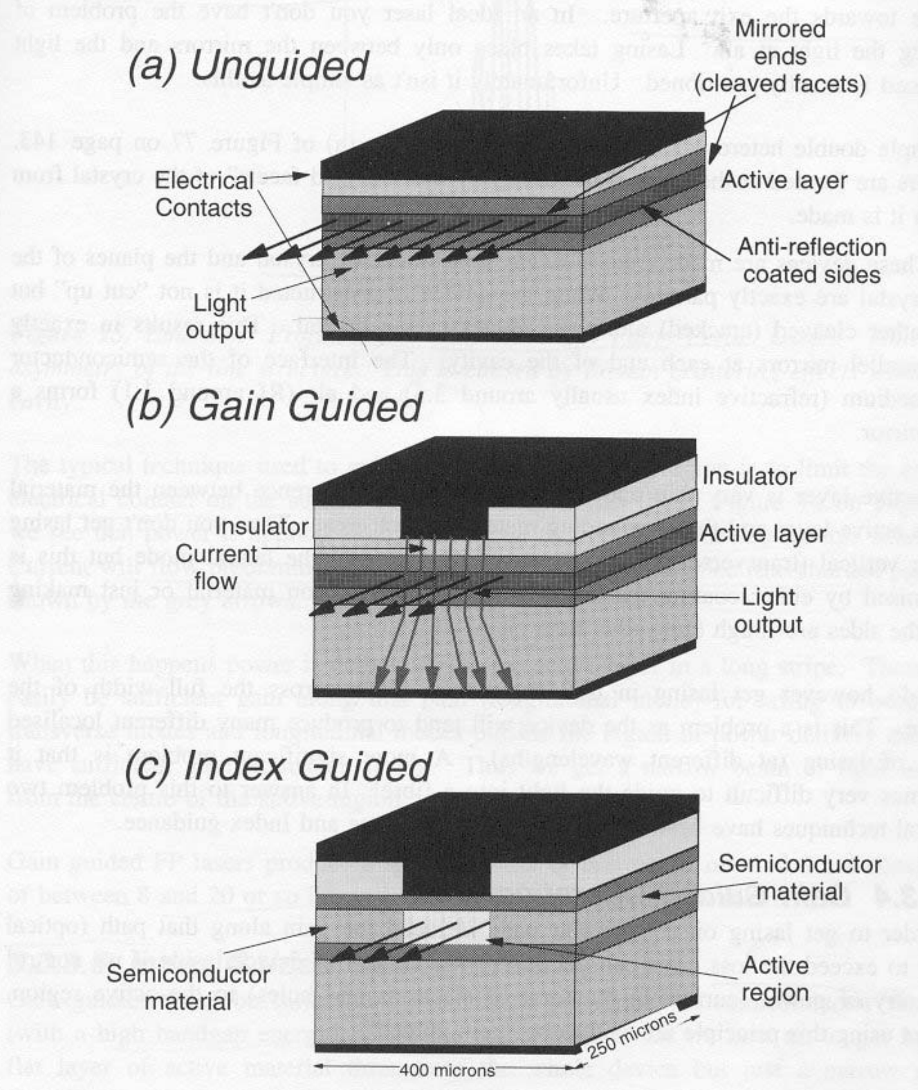
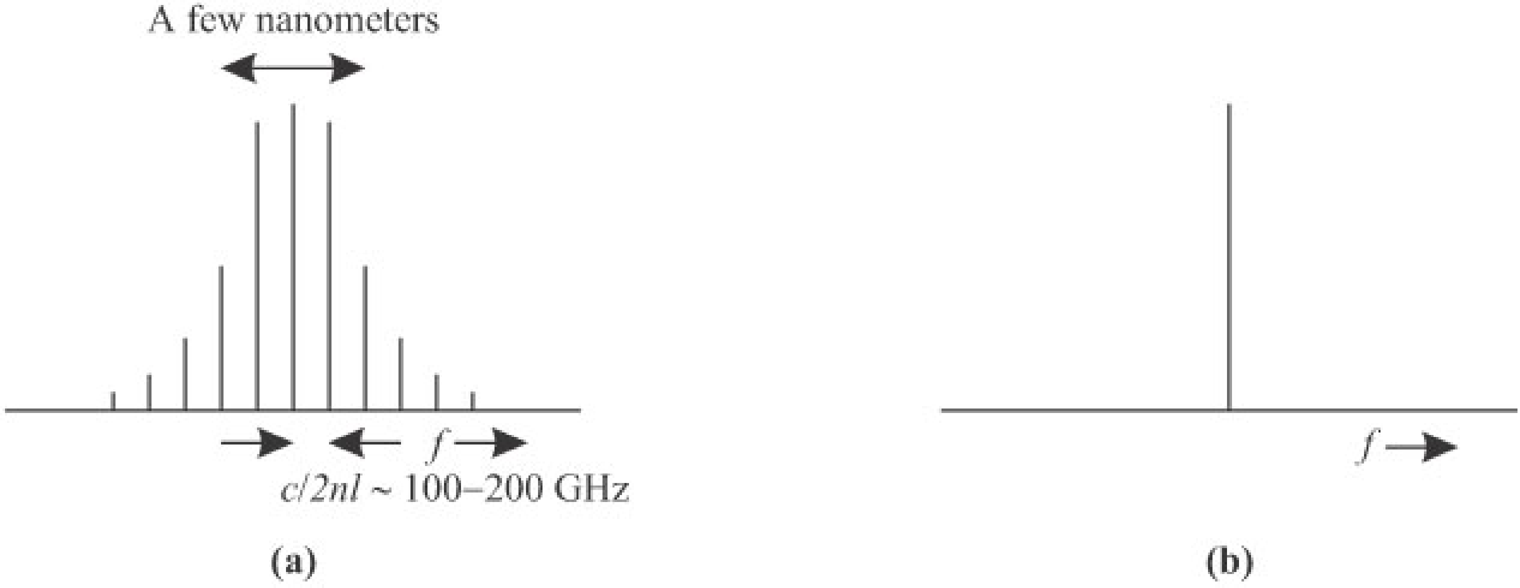


Figure 74. Directing the Light in a Fabry-Perot Laser

Longitudinal Modes: SLM and MLM

- λ: within the b/w of the gain medium inside the cavity
- Cavity length should be integral multiple of λ/2
  - Such λs are called "longitudinal modes"
  - FP laser is a multiple-longitudinal mode (MLM) laser (Large spectral width (10 nm or ~1.3 Thz!)
- Desired: single-longitudinal mode (SLM):
  - Add a filter to suppress other λs by 30dB+



Multi-mode output of Laser Cavity

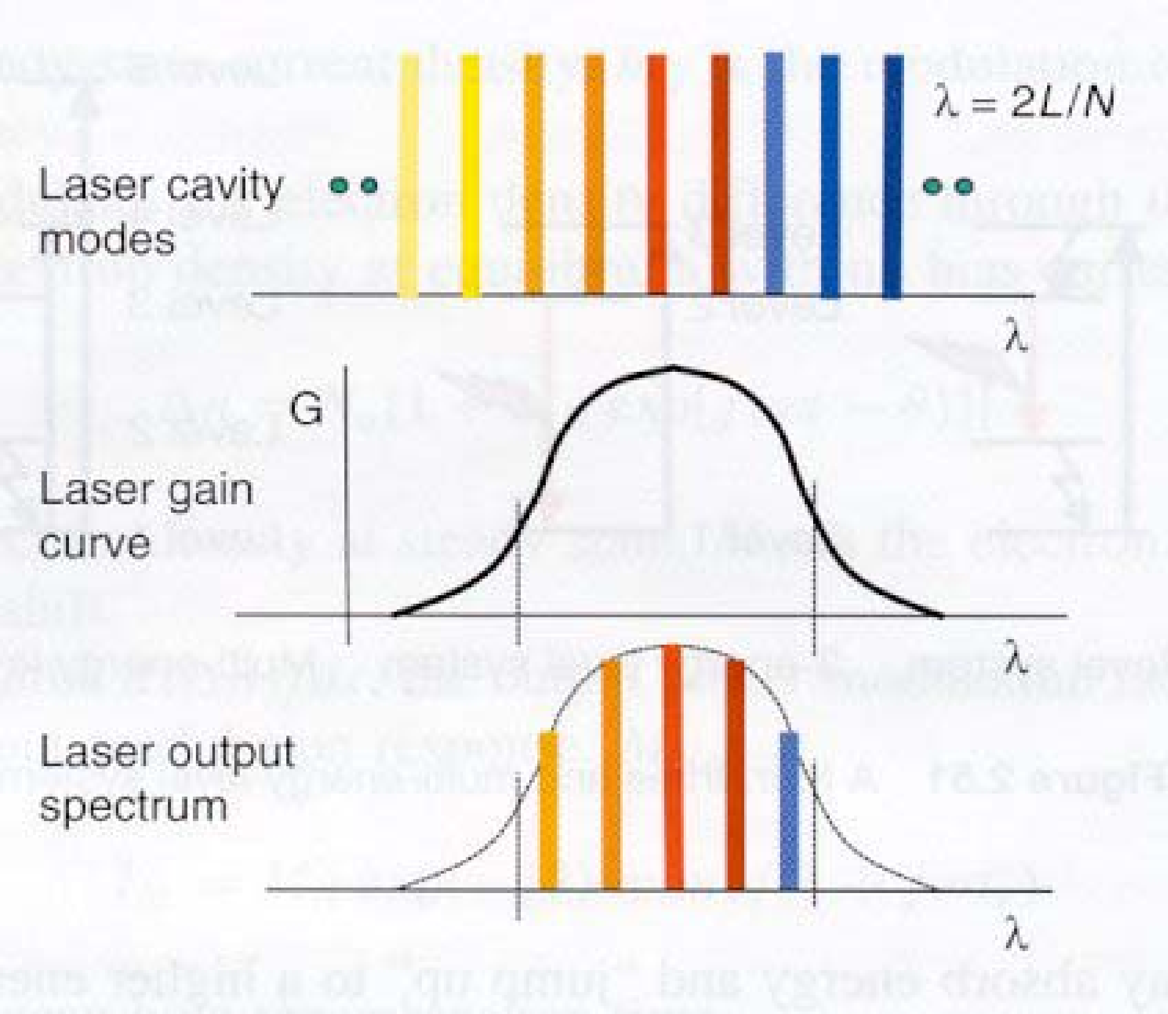
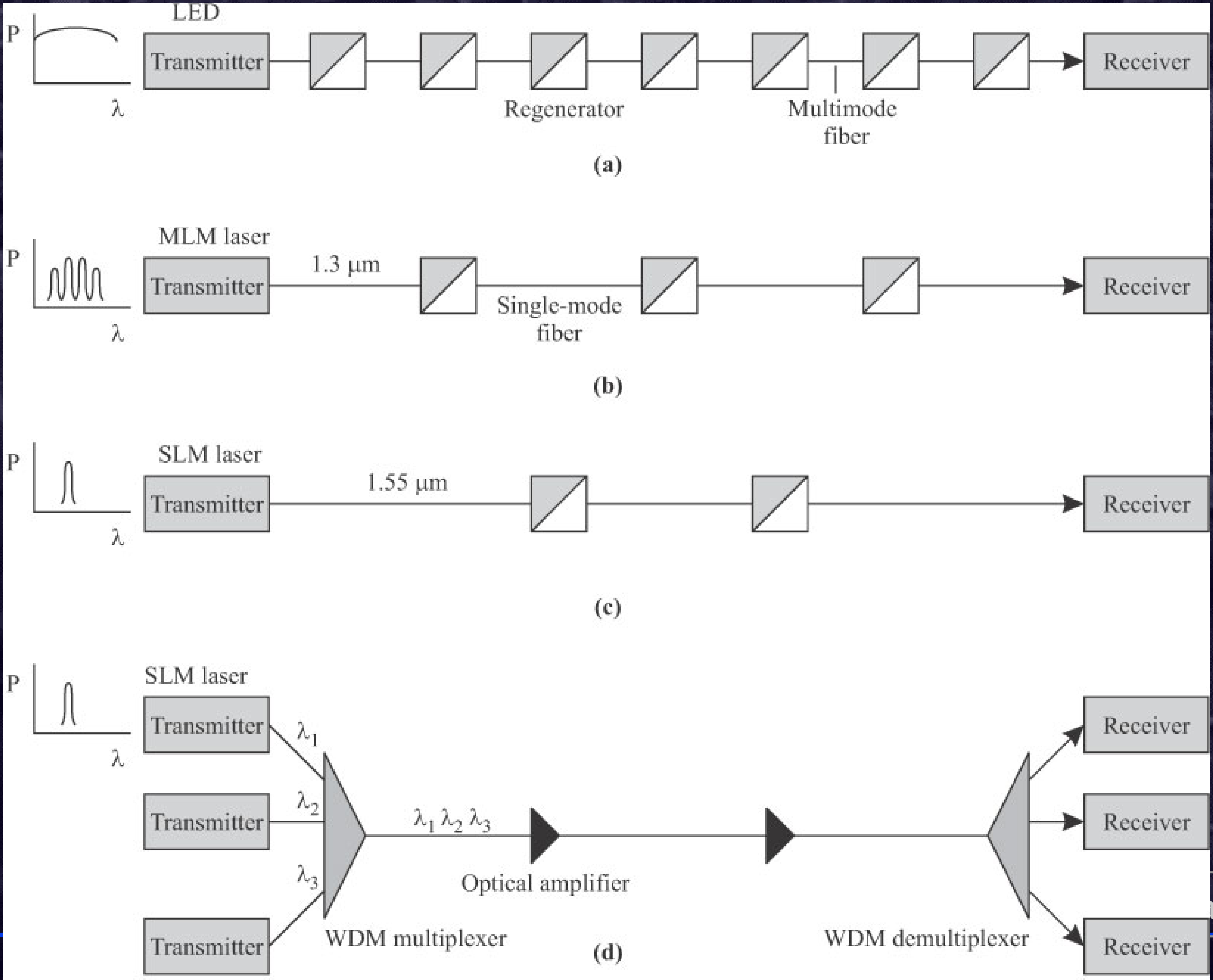


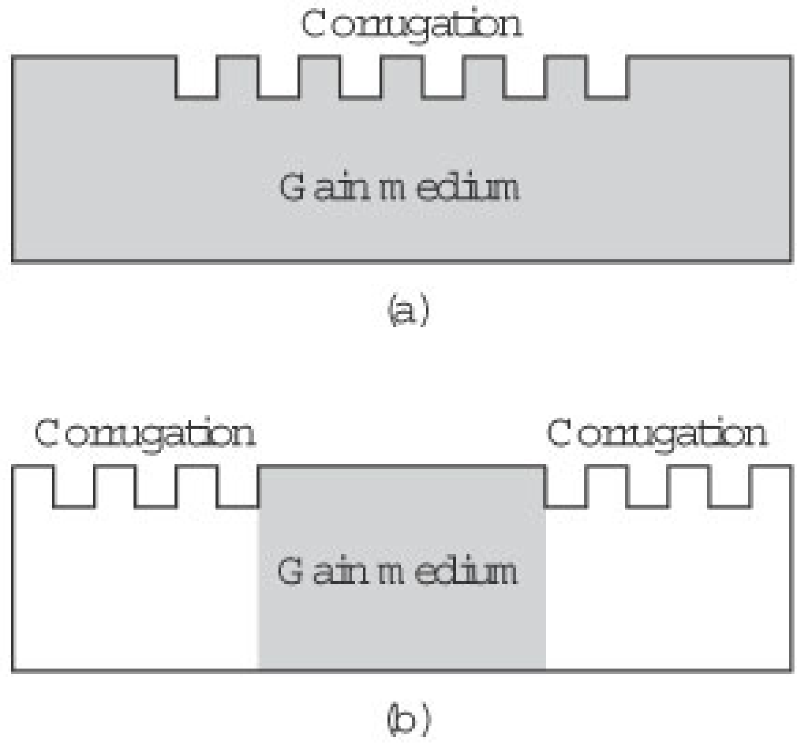
Figure 2.52 Multimode output of a laser cavity.

Recall: History of SLM/MLM Usage



Distributed Feedback (DFB) Lasers

- Idea: Provide a *distributed set of reflections* (feedback) by a series of closely-spaced reflectors
  - Done using a periodic variation in width of cavity
  - Bragg condition satisfied for many λs; only the λ s.t. the corrugation period is $\lambda/2$ is preferentially amplified
- Corrugation inside gain region: called DFB laser
- Corrugation outside gain region: called DBR (distributed Bragg reflector) laser



Bragg Laser

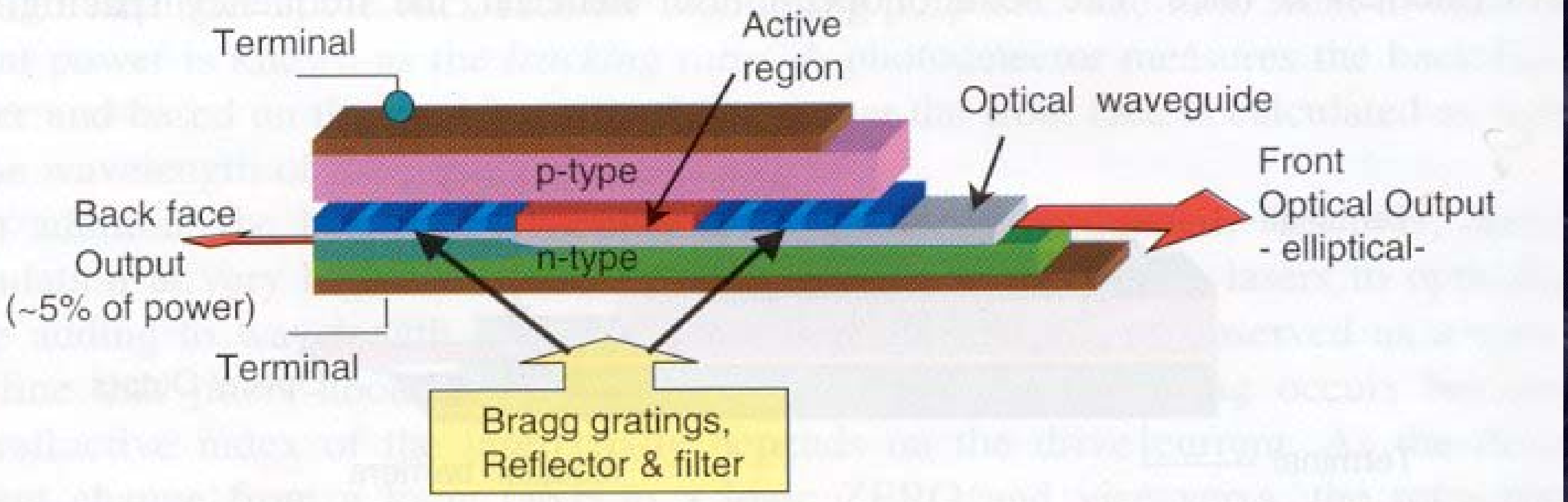


Figure 2.55 Fundamentals of a Bragg laser (notice the ~5% laser light from the back face).

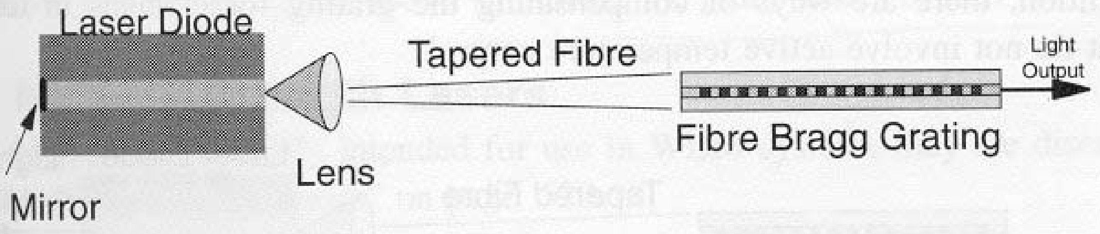


Figure 90. Stabilisation of Fabry-Perot Laser with a Fibre Bragg Grating

In-Fibre Laser using FBGs

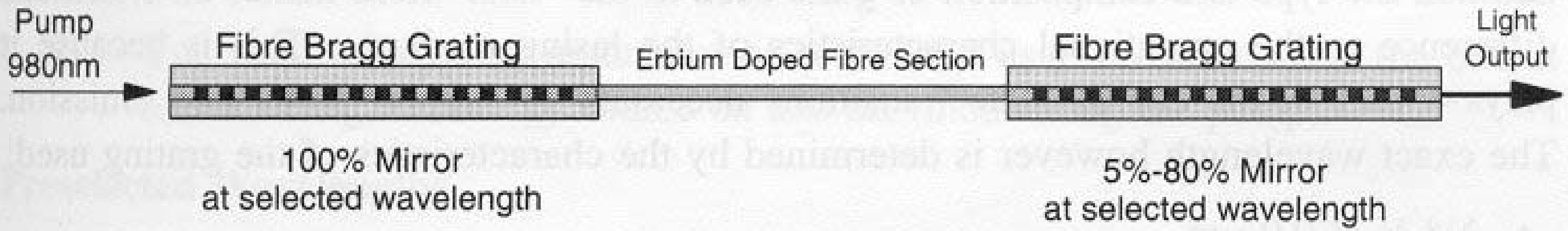
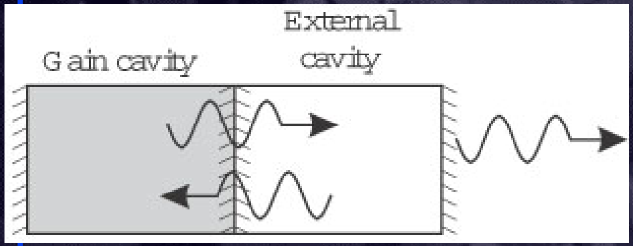
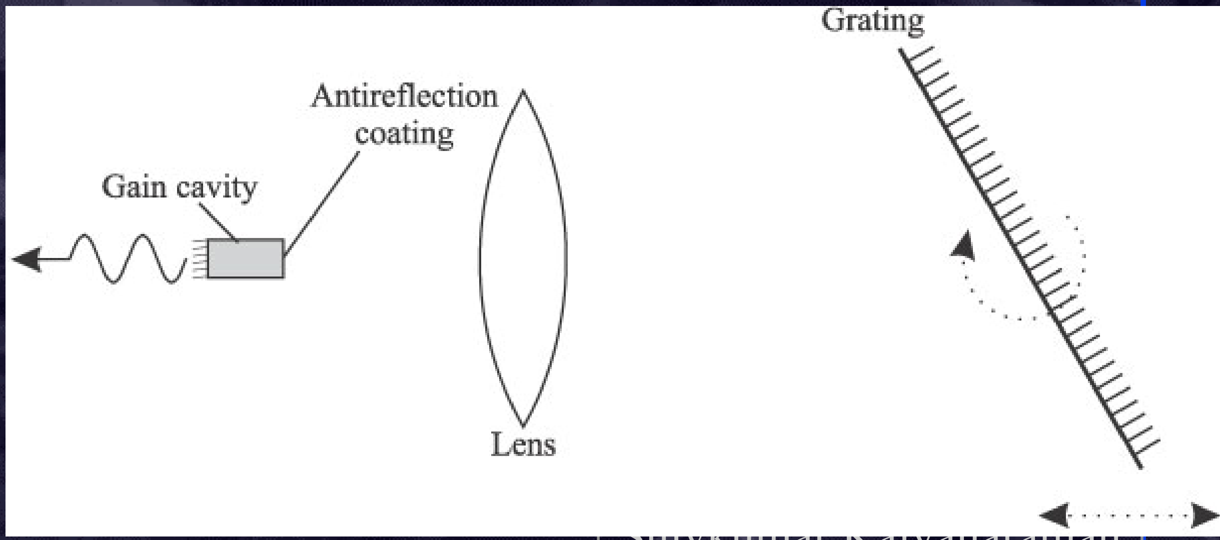


***Figure 93.** In-Fibre Laser Using FBGs. Depending on the detailed design the exit mirror might have any reflectivity (at the specified wavelength) between about 5% and 80%.*

External Cavity Lasers

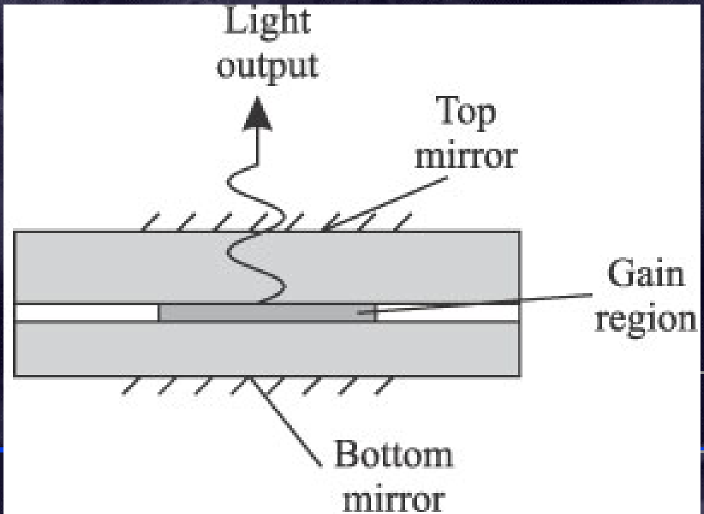
- Only those λs which are resonant for both primary and external cavities are transmitted
- Diffraction grating can be used in external cavity with λ-selective reflection at grating and anti-reflection coating outside of the primary cavity facet
- Used in test equipment: cannot modulate at high speed





VCSELs: Vertical Cavity Surface-Emitting Lasers

- Frequency (longitudinal mode) spacing = c/2nl
- *If l is made small*, mode spacing increases beyond cutoff of gain region bandwidth => SLM!
- Thin active layer: deposited on a semiconductor substrate => "vertical cavity" & "surface emitting"
- For high mirror reflectivity, a stack of alternating low- and high-index dielectrics (I.e. dielectric mirrors) are used
- Issues: Large ohmic resistance: heat dissipation problem
  - Room-temperature 1.3um VCSELs recently shown



VCSELs

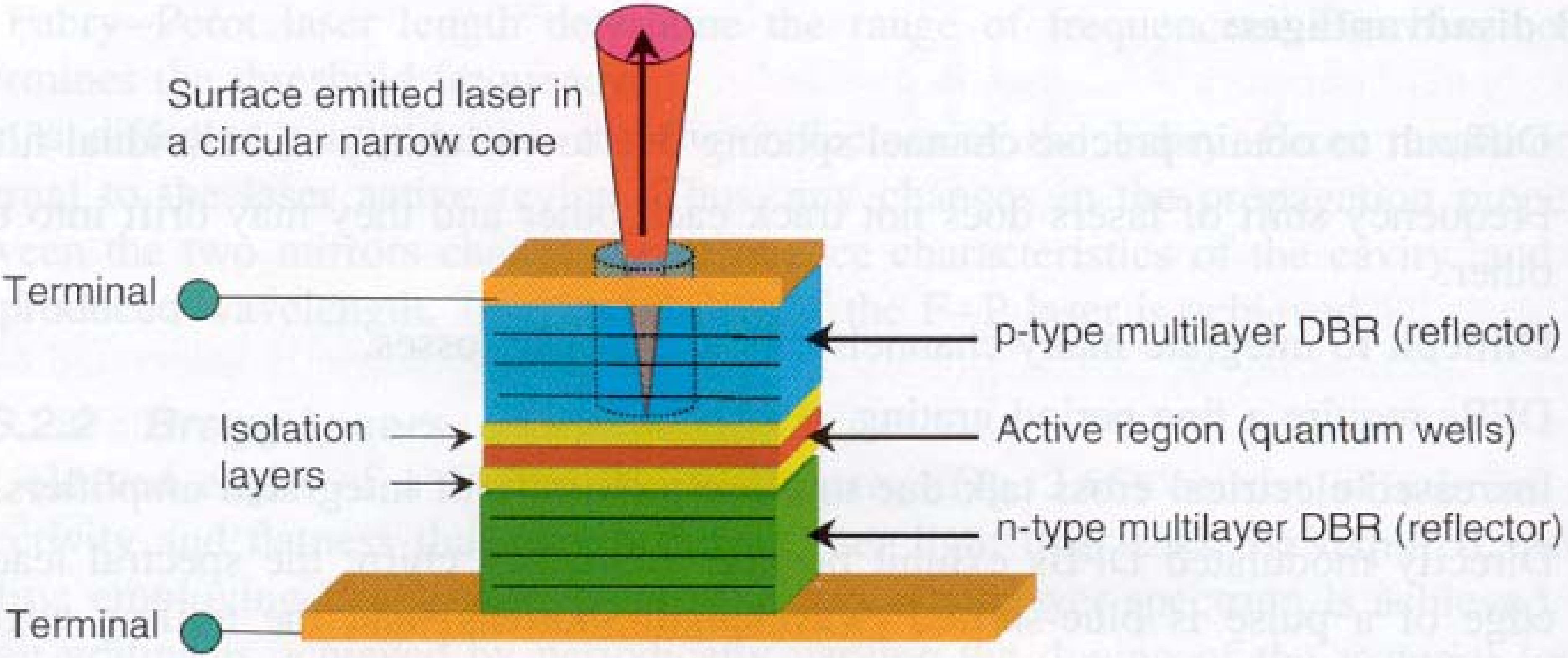


Figure 2.56 Fundamentals of a vertical-cavity surface-emitting lasers.

VCSEL Structure

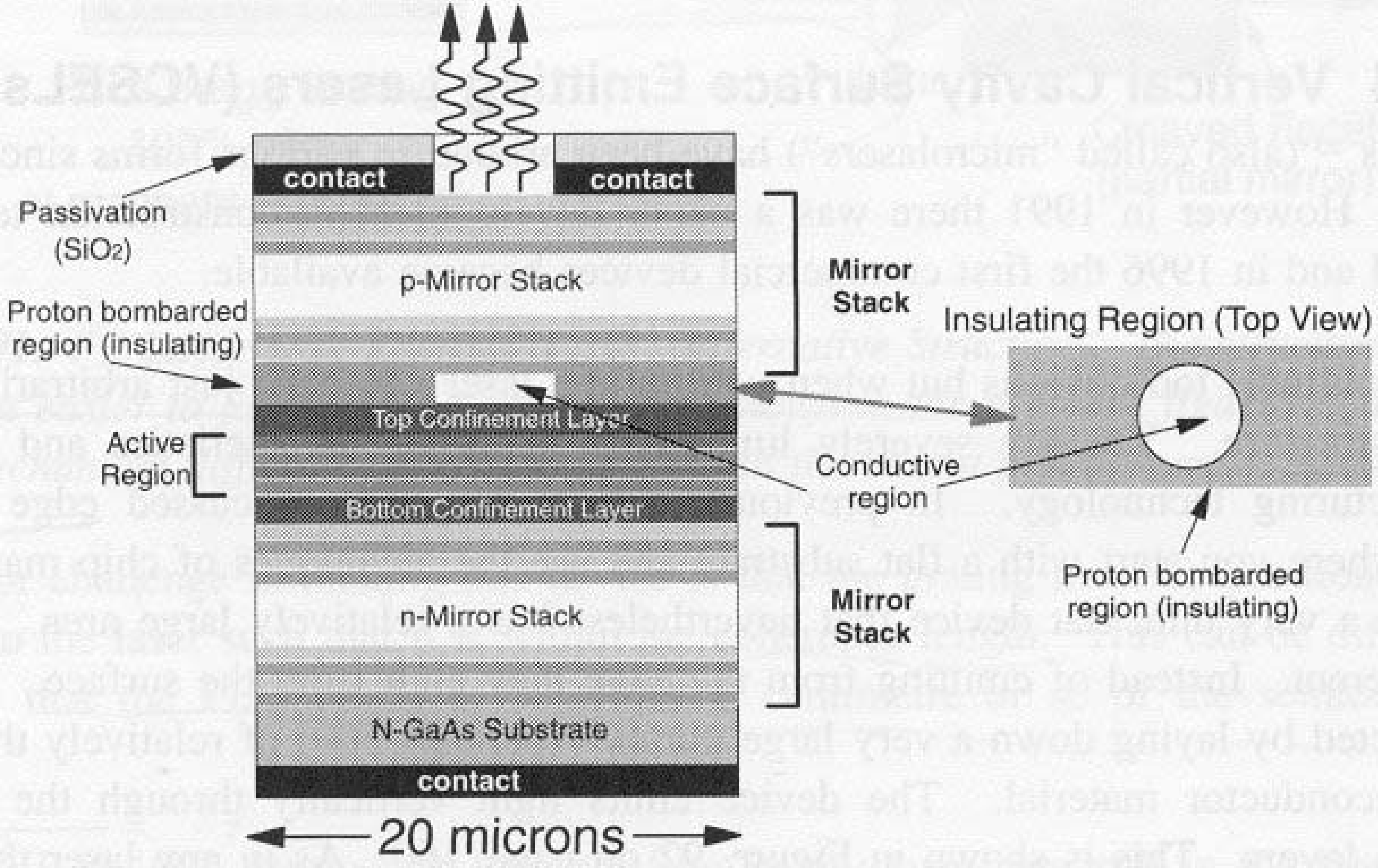
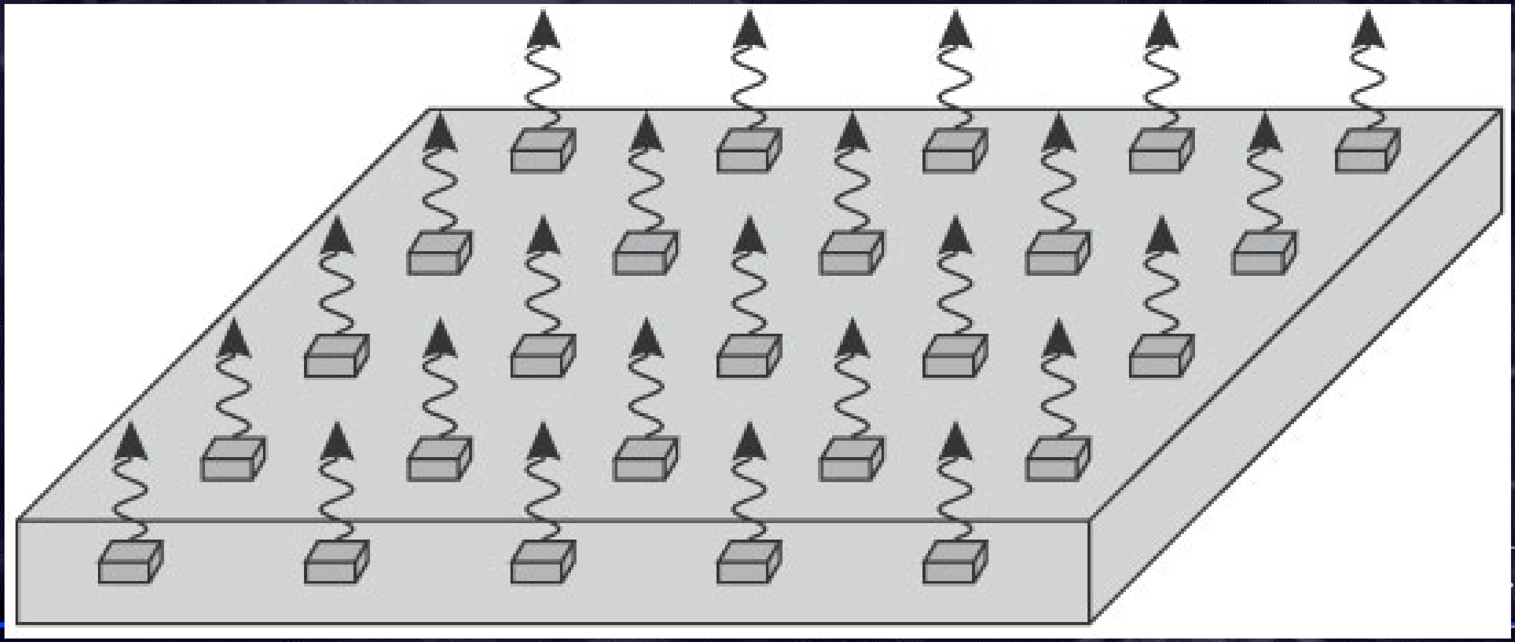


Figure 92. VCSEL Structure

Wavelength-Selective VCSEL Array

- High array packing densities possible with VCSELs compared to edge-emitting lasers (silicon fabrication)
- Used a tunable laser by turning on required laser
- Harder to couple light into fiber
- Yield problems: if one laser does not meet spec, the whole array is wasted



Combining VCSELs

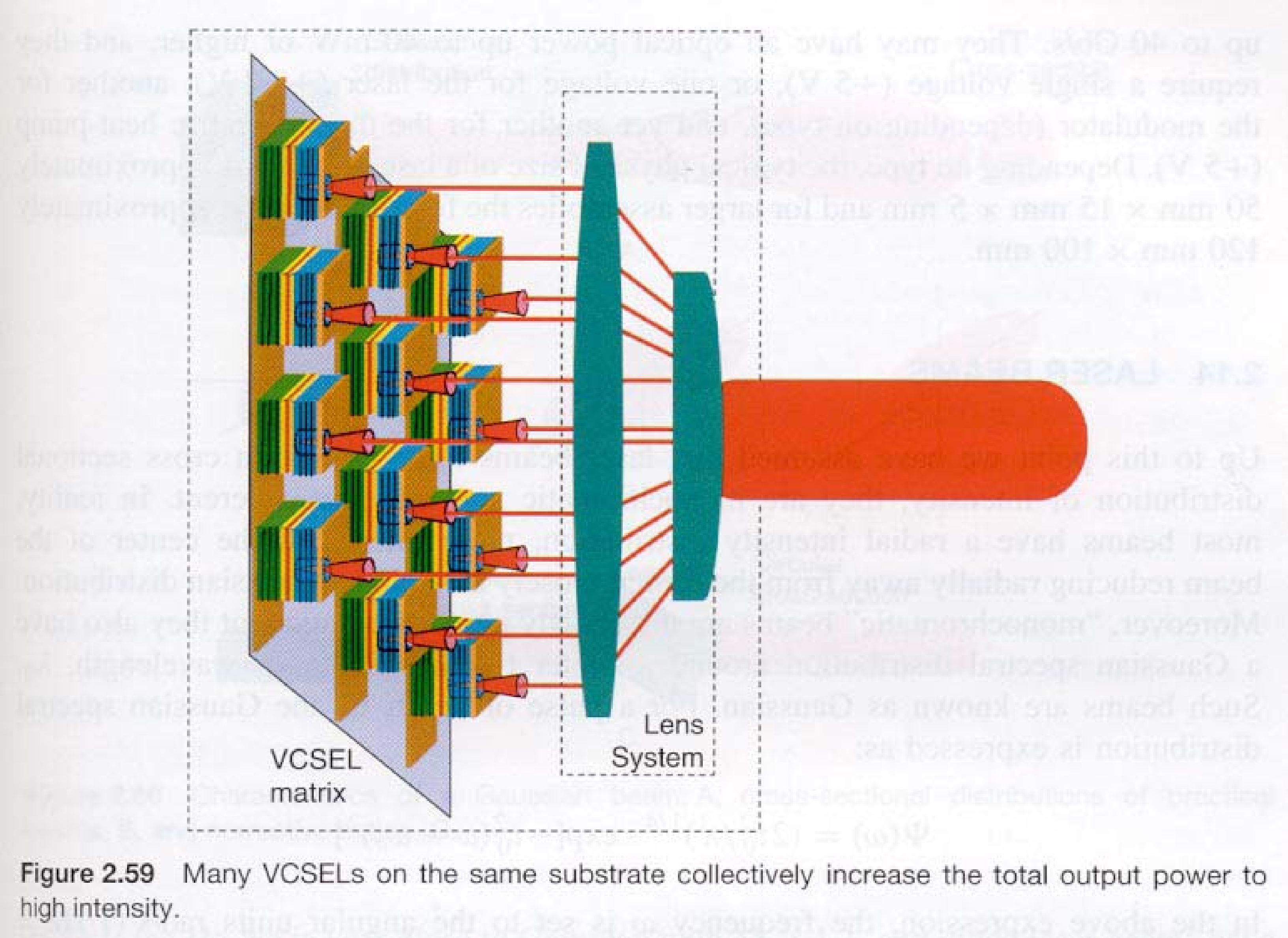
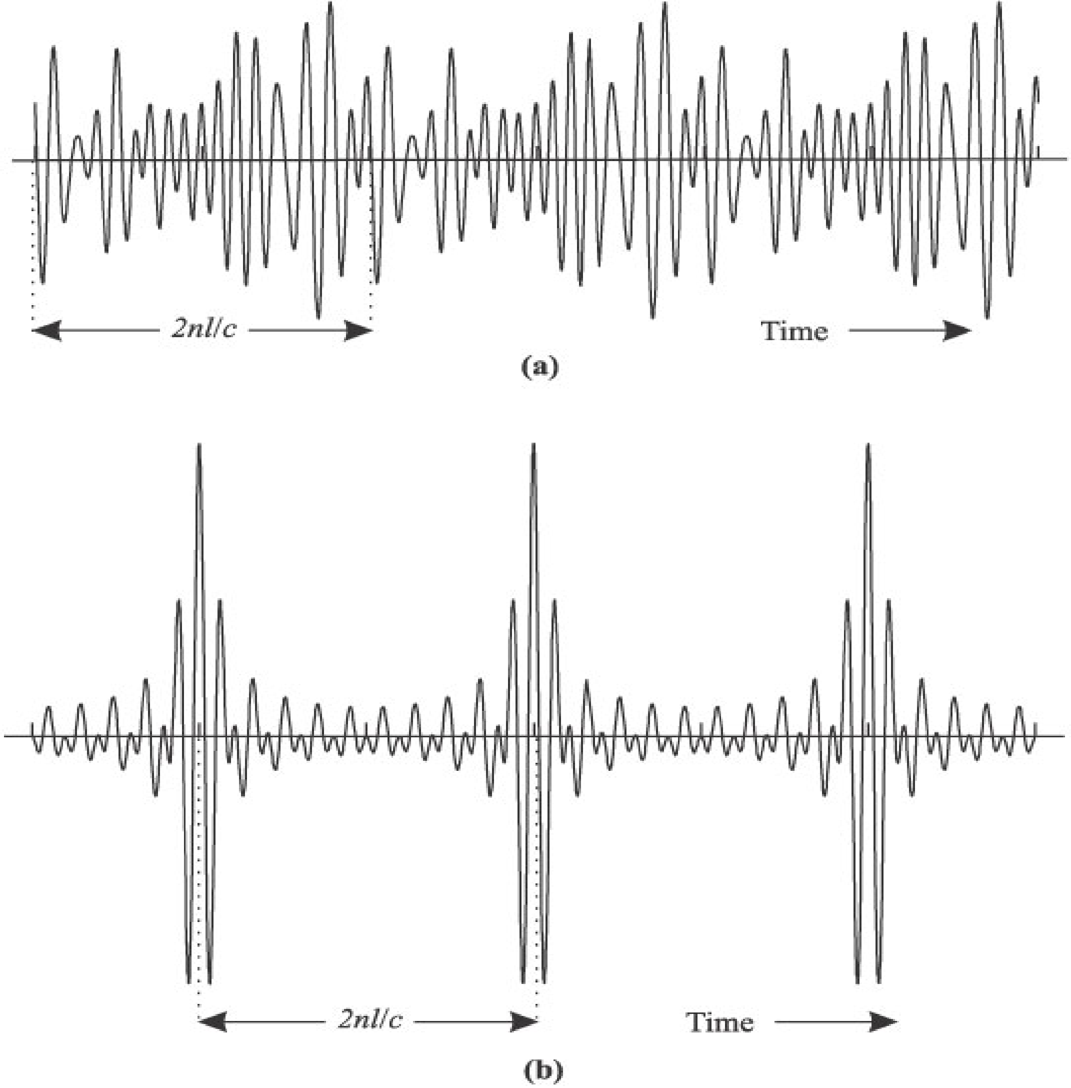


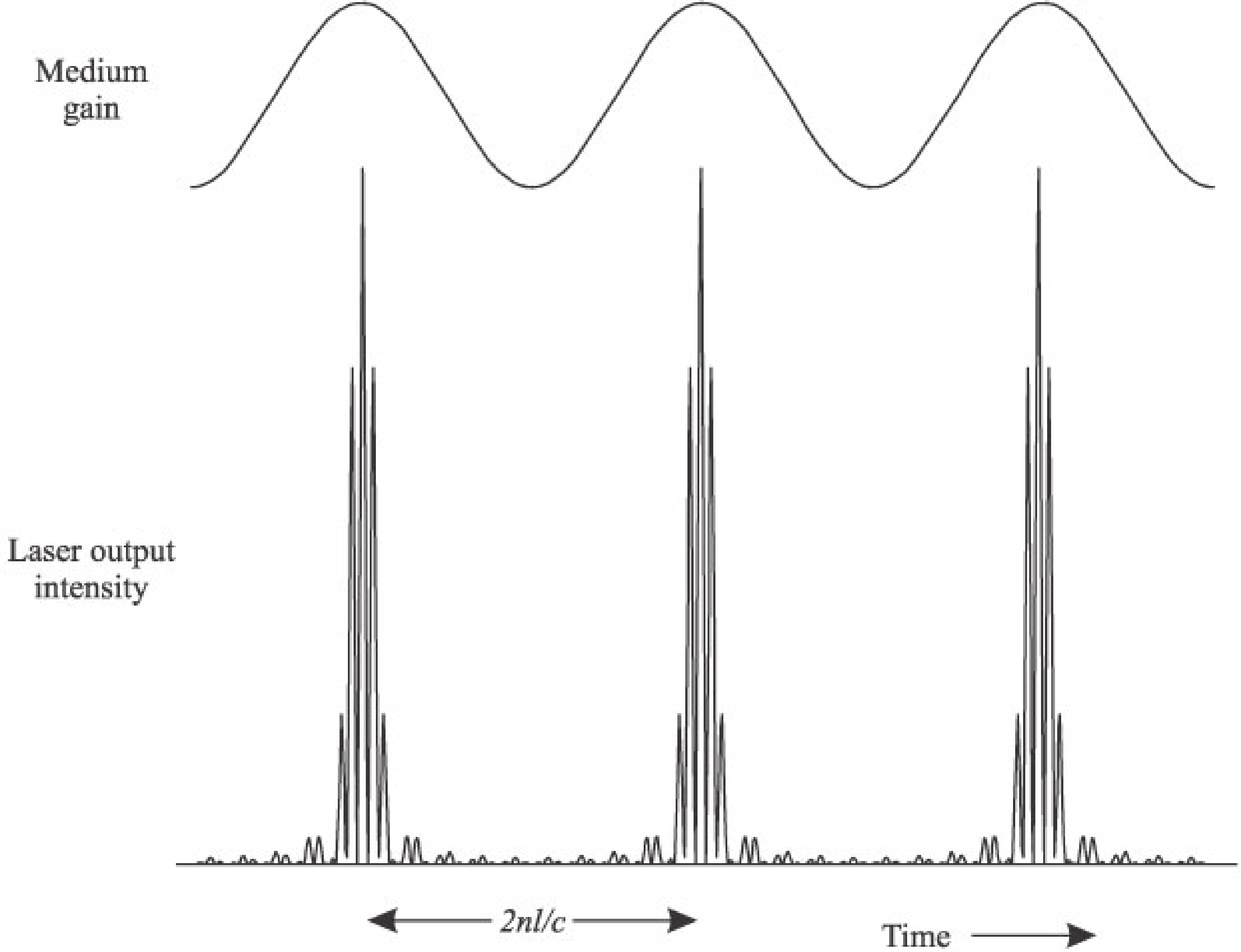
Figure 2.59 Many VCSELs on the same substrate collectively increase the total output power to high intensity.

Mode-locked Lasers

- Match the phase of the longitudinal modes => regular pulsing in time-domain (aka "mode locking")
- Used in O-TDM
- Achieved by using <u>longer cavities</u> (eg: fiber laser) or <u>modulating the gain of cavity</u>



Mode Locking by Amplitude Modulation of Cavity Gain



Gaussian Beams

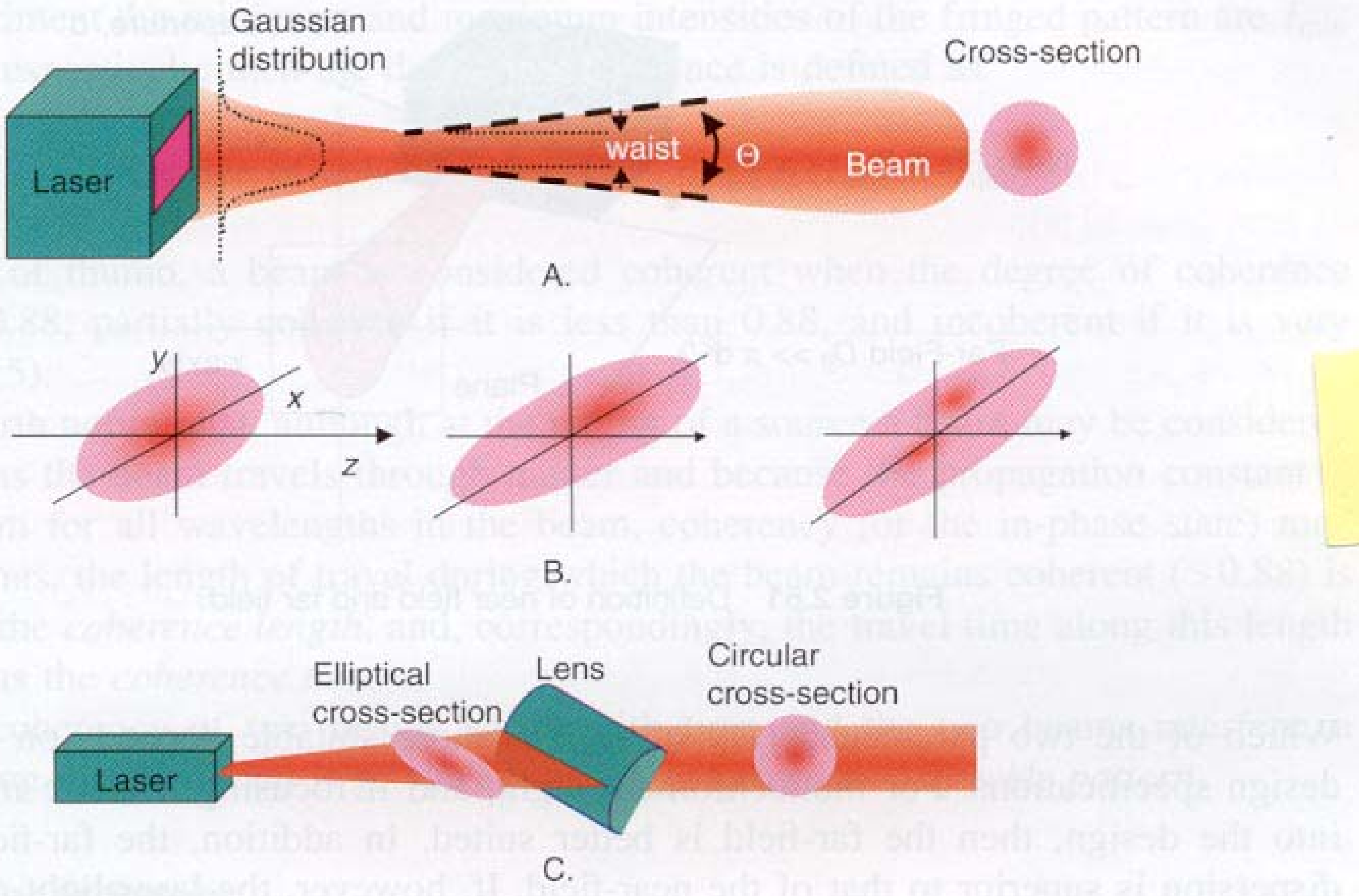
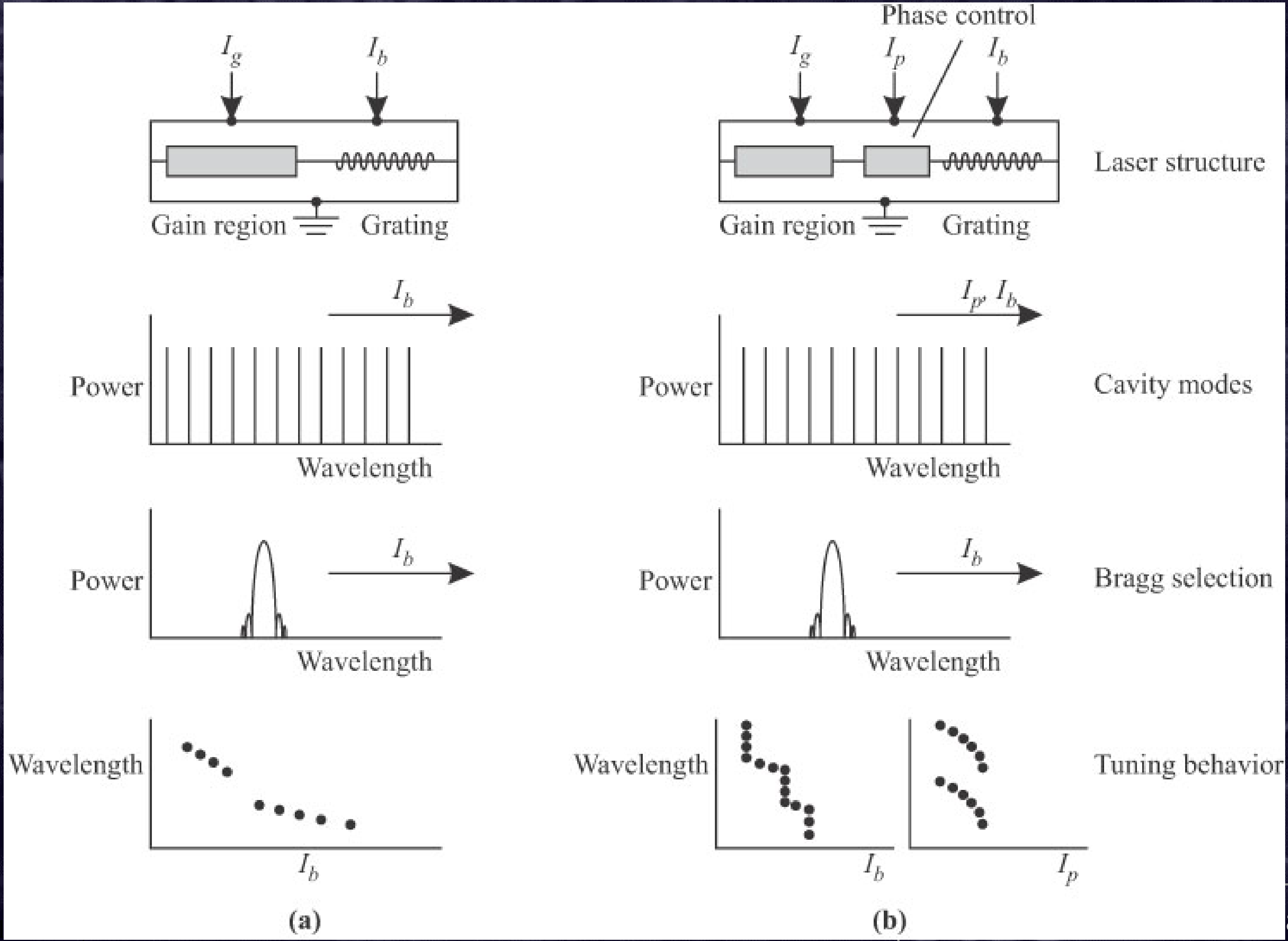


Figure 2.60 Characteristics of a Gaussian beam, A, cross-sectional distributions of practical beams, B, and corrective action, C.

Tunable Lasers

- Tunable lasers: key enabler of *re-configurable* optical networks
- Tunability characteristics:
  - Rapid (< ms ranges)
  - Wide and continuous range of over 100 nm
  - Long lifetime and stable over lifetime
  - Easily controllable and manufacturable
- Methods:
  - Electro-optical: changing RI by injecting current or applying an E-field (approx 10-15 nm)
  - Temperature tuning: (1 nm range) may degrade lifetime of laser
  - Mechanical tuning: using MEMS => compact

Tunable Two- & Three-section DBR Lasers



Tunable DBR Lasers (Contd)

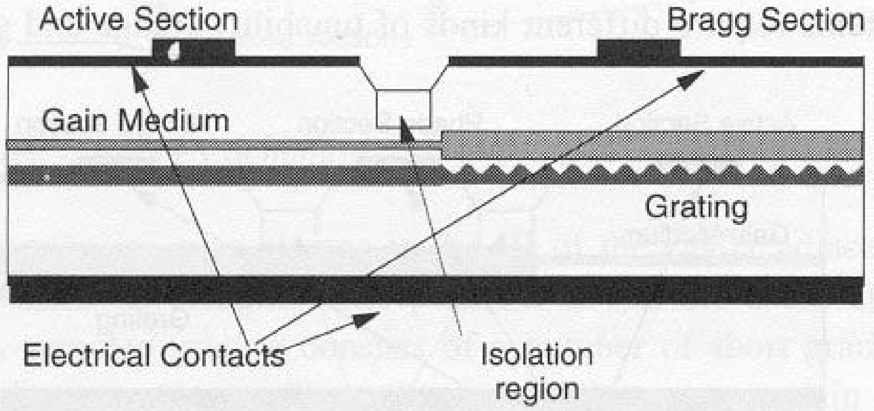


Figure 84. Tunable 2-Section DBR Laser

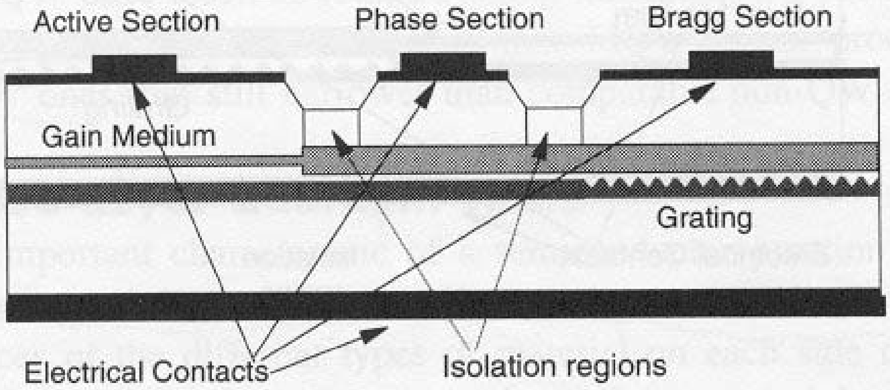
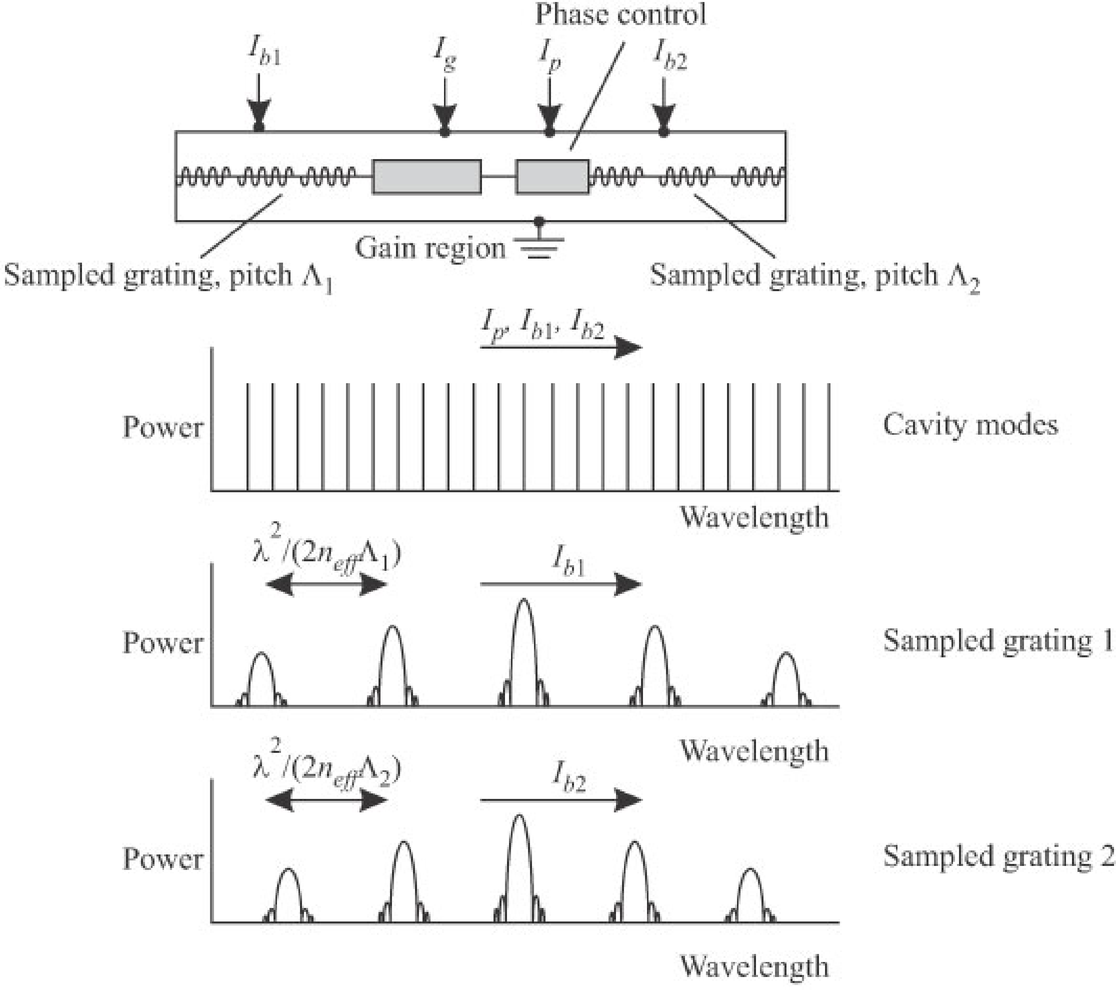


Figure 85. Tunable 3-Section DBR Laser

Sampled Grating DBR

- Goal: larger tuning range by combining tuning ranges at different peaks (aka “combs”)



Sampled Grating DBR (contd)

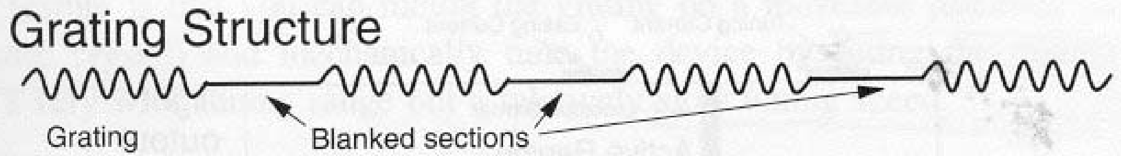


Figure 86. Sampled Grating - Schematic

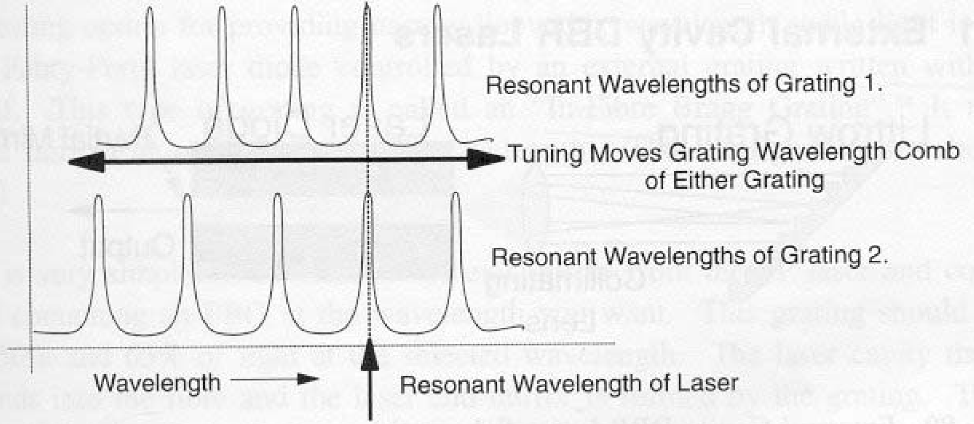
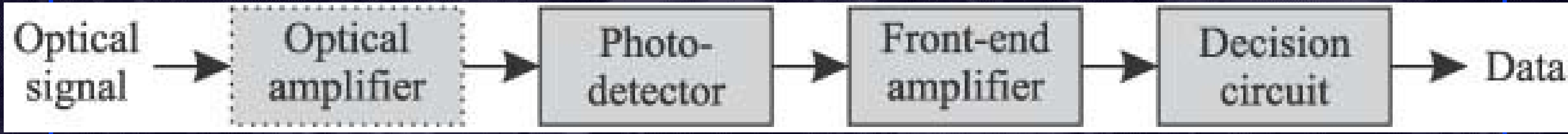
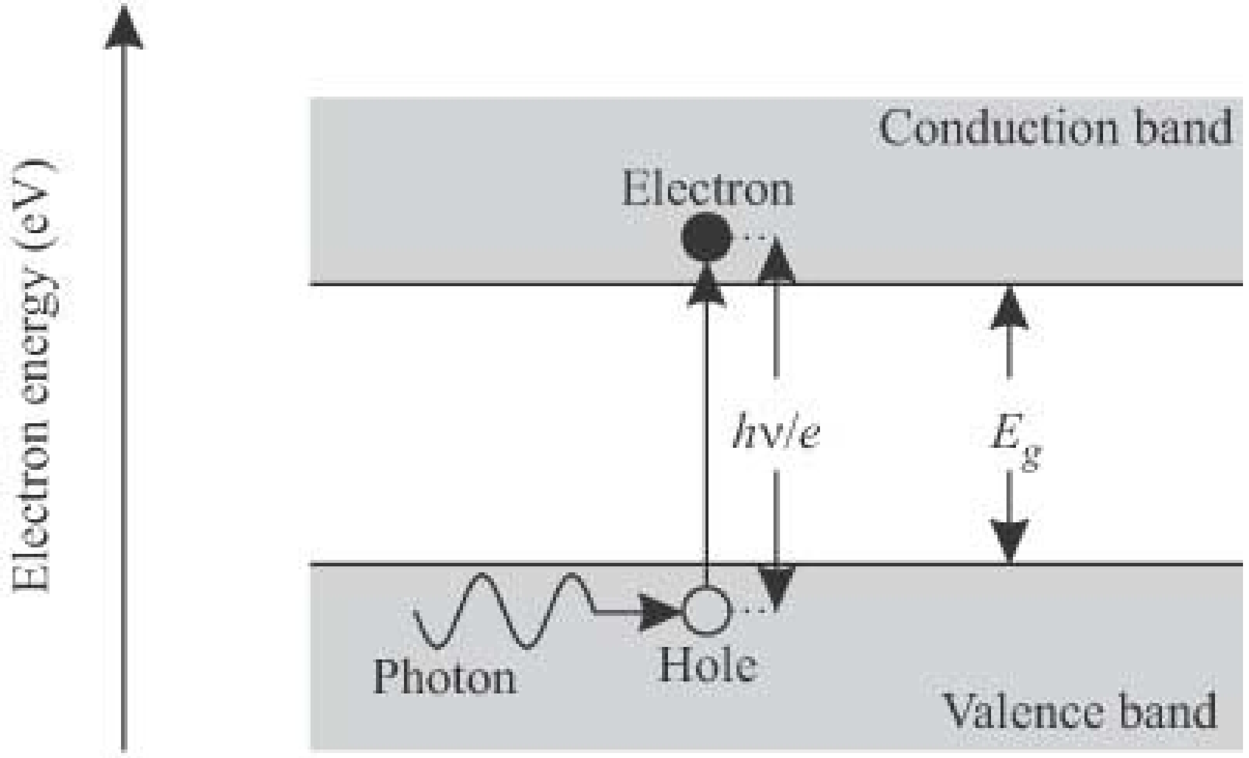


Figure 87. Principle of Operation. Each grating has a different set of possible resonances. One section is tuned until one of its resonances is the same as one of the possibilities of the other grating. This then becomes the lasing wavelength.

Photodetectors

Optical Receivers: Basic Ideas





Photoconductive Detector

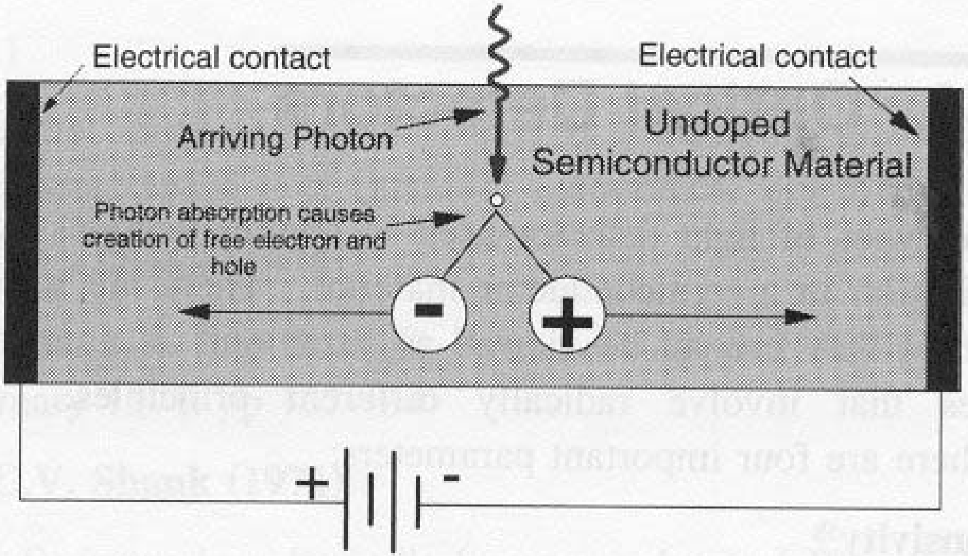


Figure 97. Photoconductive Detector - Principle

* Application of external bias => absorbed photons lead to electron/hole pairs and a current (aka "*photo-current*")

- Energy of incident photon *at least* the bandgap energy => largest λ = cutoff λ
- Si, GaAs <u>cannot</u> be used; InGaAs, InGaAsP used

Practical Photoconductors

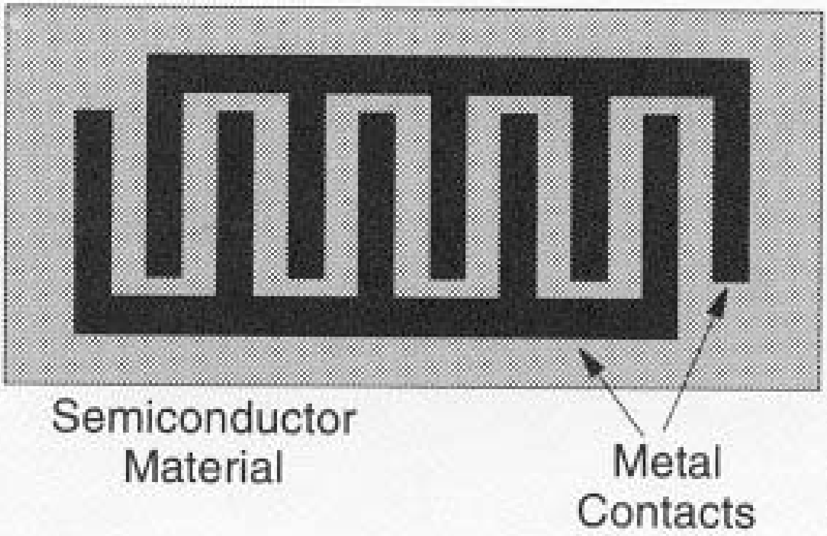
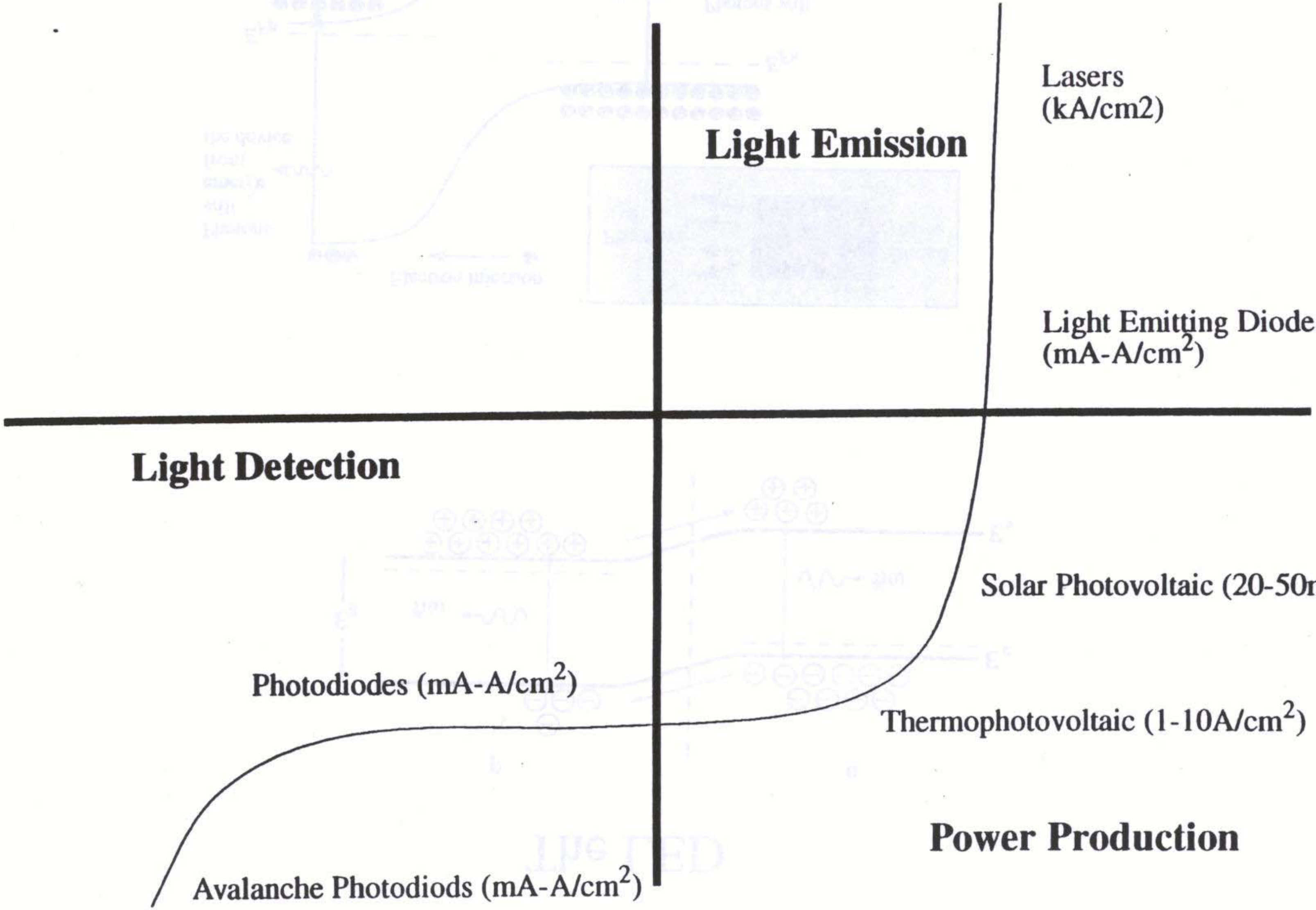


Figure 98. Practical Photoconductive Detector - Schematic

The Many Uses of a PN Junction Diode



Lasers
(kA/cm2)

Light Emission

Light Emitting Diodes
(mA-A/cm^2)

Light Detection

Solar Photovoltaic (20-50mA/cm^2)

Photodiodes (mA-A/cm^2)

Thermophotovoltaic (1-10A/cm^2)

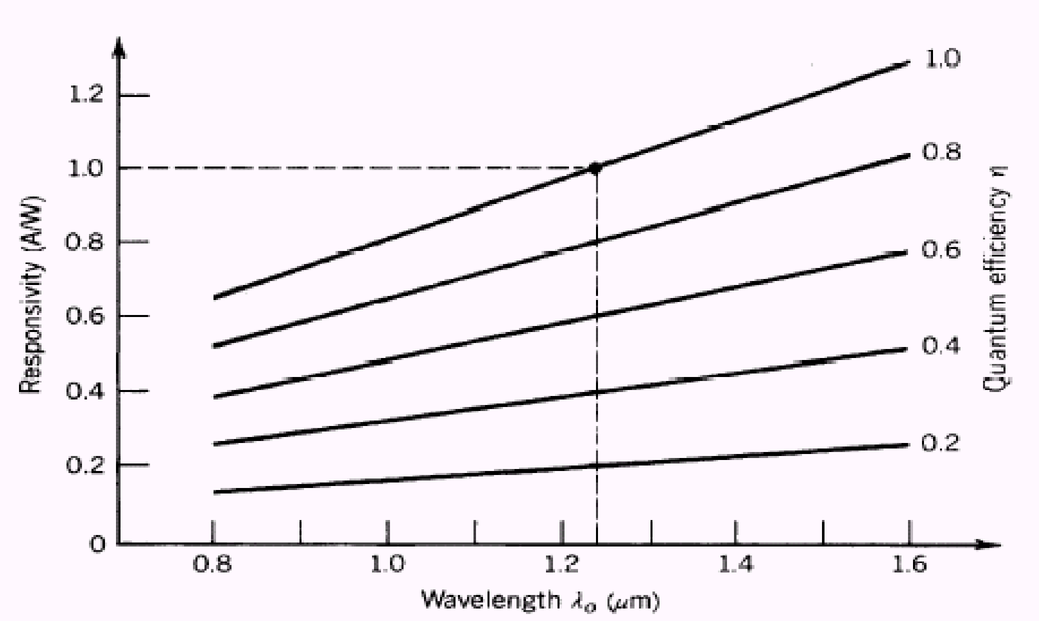
Power Production

Avalanche Photodiods (mA-A/cm^2)

Responsivity

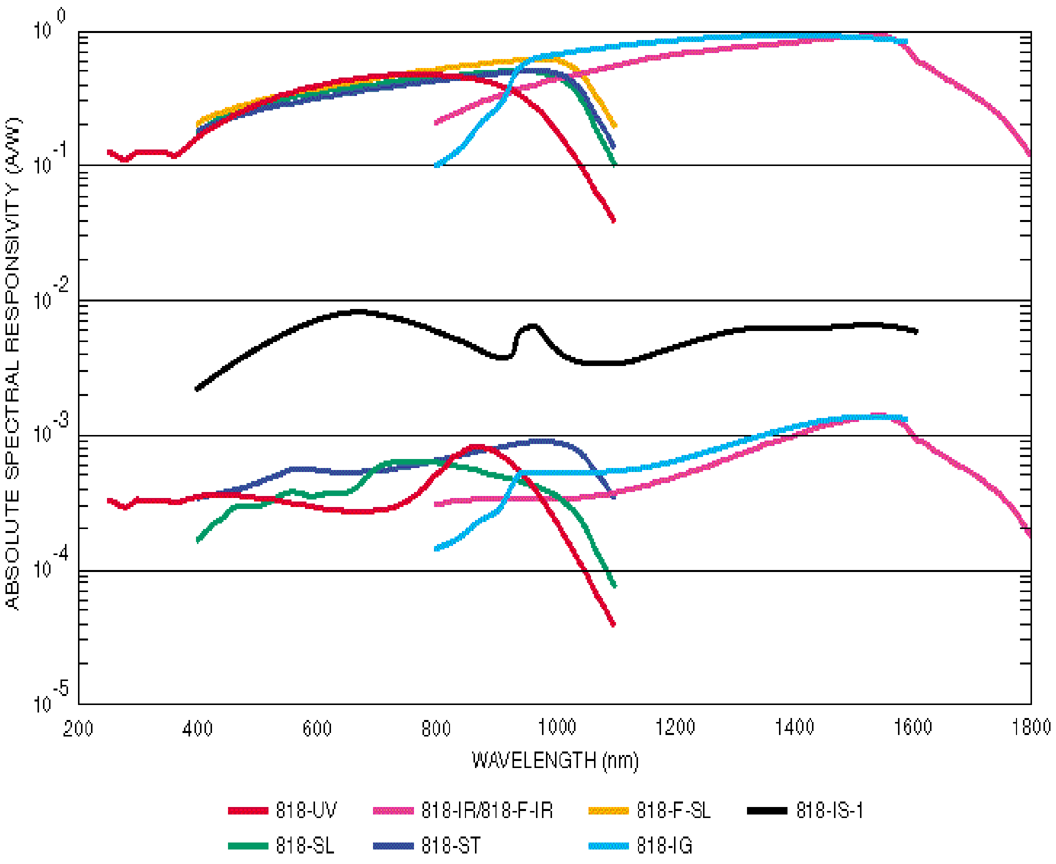
Ratio of electric current flowing in the device to the incident optical power

$$\Re = \frac{\eta e}{h\nu} = \eta \frac{\lambda_o}{1.24}$$



Photoelectric detectors responds to photon flux rather than optical power (unlike thermal detectors)

Responsivity vs λ

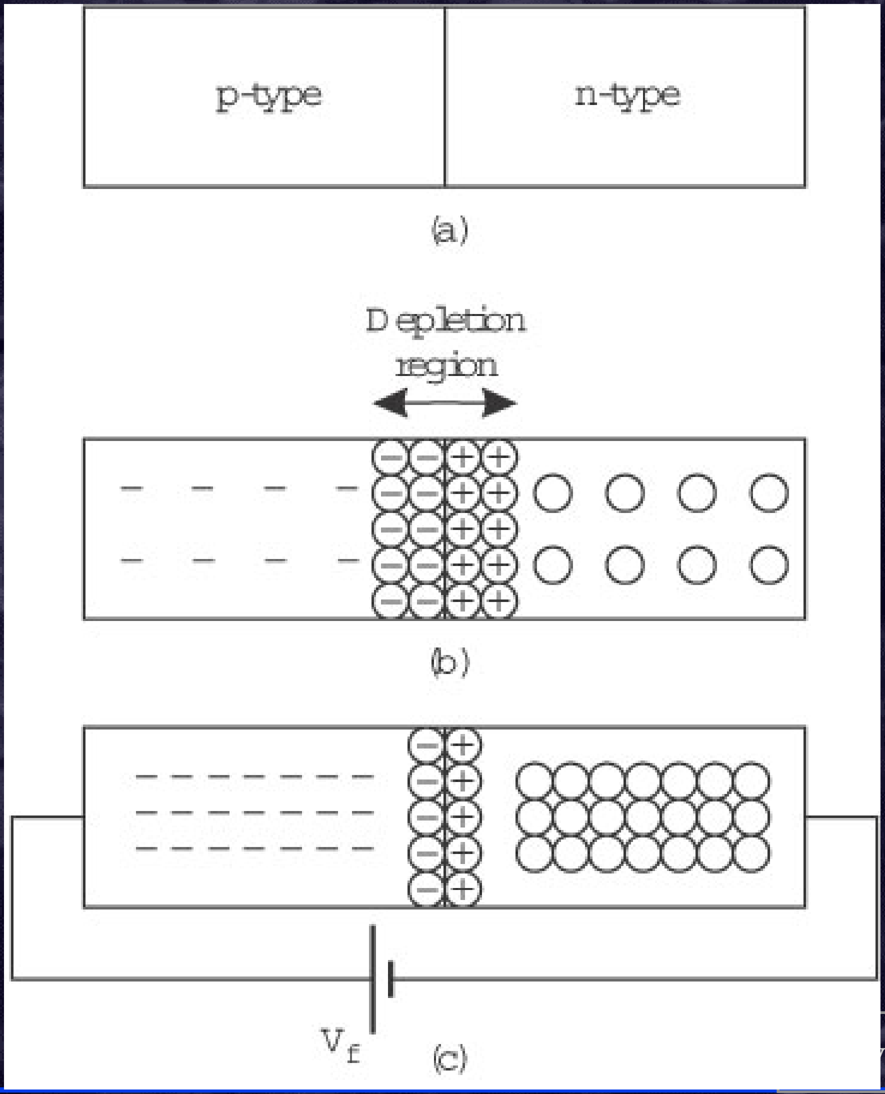


Responsivity is dependent upon the choice of wavelength

Photoconductor vs Photodiode

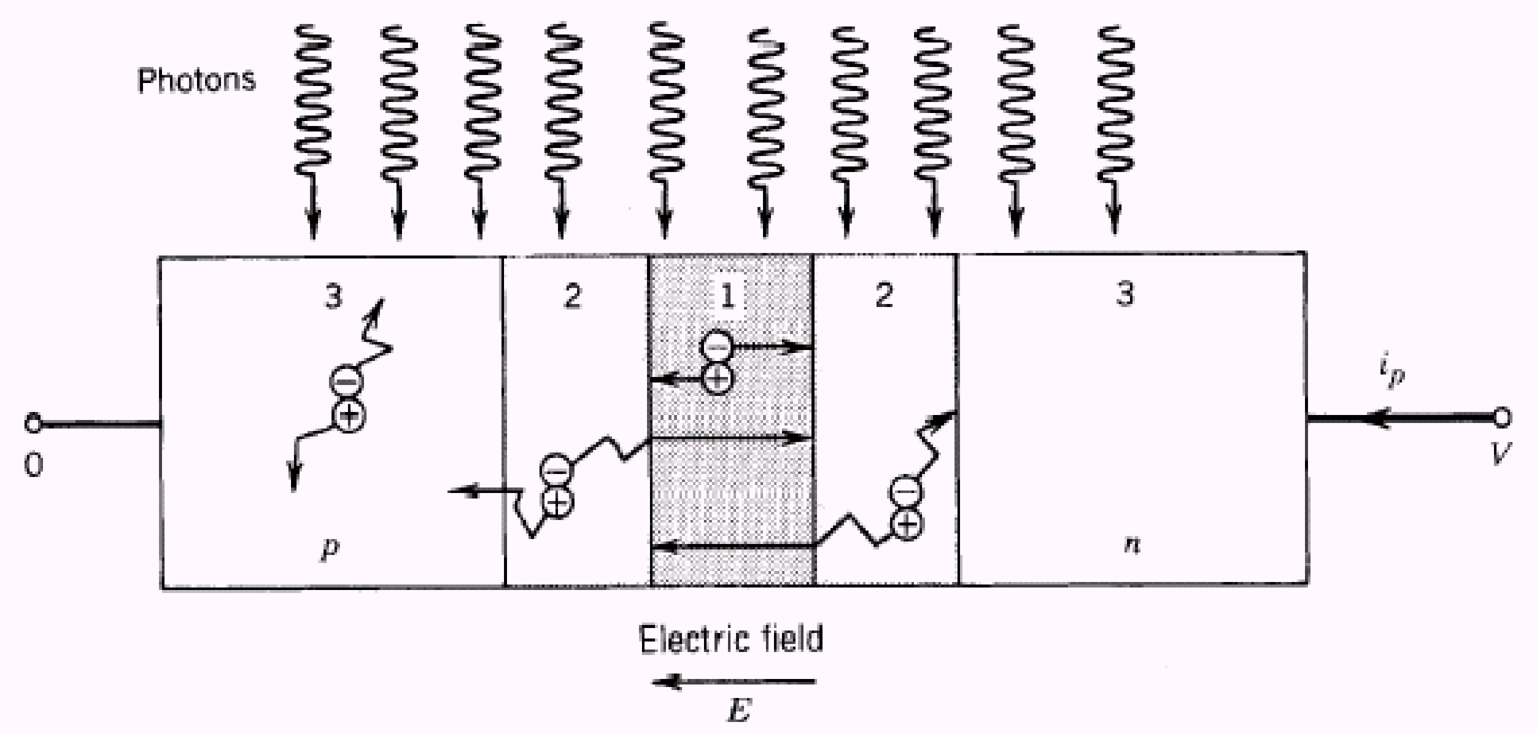
- Photoconductor (I.e. a single semiconductor slab) is not very efficient:
  - Many generated electrons recombine with holes before reaching the external circuit!
- Need to “sweep” the generated conduction-band electrons rapidly OUT of the semiconductor
- Better: use a *pn-junction and reverse-bias* it: positive bias to n-type
  - A.k.a. photo-diode
- Drift current: e-h pairs in the depletion region: rapidly create external current
- Diffusion: e-h pairs created OUTSIDE the depletion region move more slowly and may recombine, reducing efficiency

Reversed-biased PN photodiode



Photodiodes

Reverse biased p-n or p-i-n junctions



Photodiodes are faster than photoconductors

P-I-N Photodiode

- To improve efficiency, use a lightly doped *intrinsic* semiconductor between the p- and n-type semiconductors
- Much of light absorption takes place in the I-region: increases efficiency and responsivity
- Better: make the p- and n-type transparent (I.e. above cuttoff λ) to desired λ: double heterojunction
    - Eg: cuttoff for InP is 0.92 um (transparent in 1.3-1.6 um range), and cuttoff for InGaAs is 1.65um

Avalanche Photodiode

- Photo-generated electron subjected to high electric field (I.e. multiplication region) may knock off more electrons (I.e. force ionization)
- Process = "avalanche multiplication"
- Too large a gain G can lead to adverse noise effects

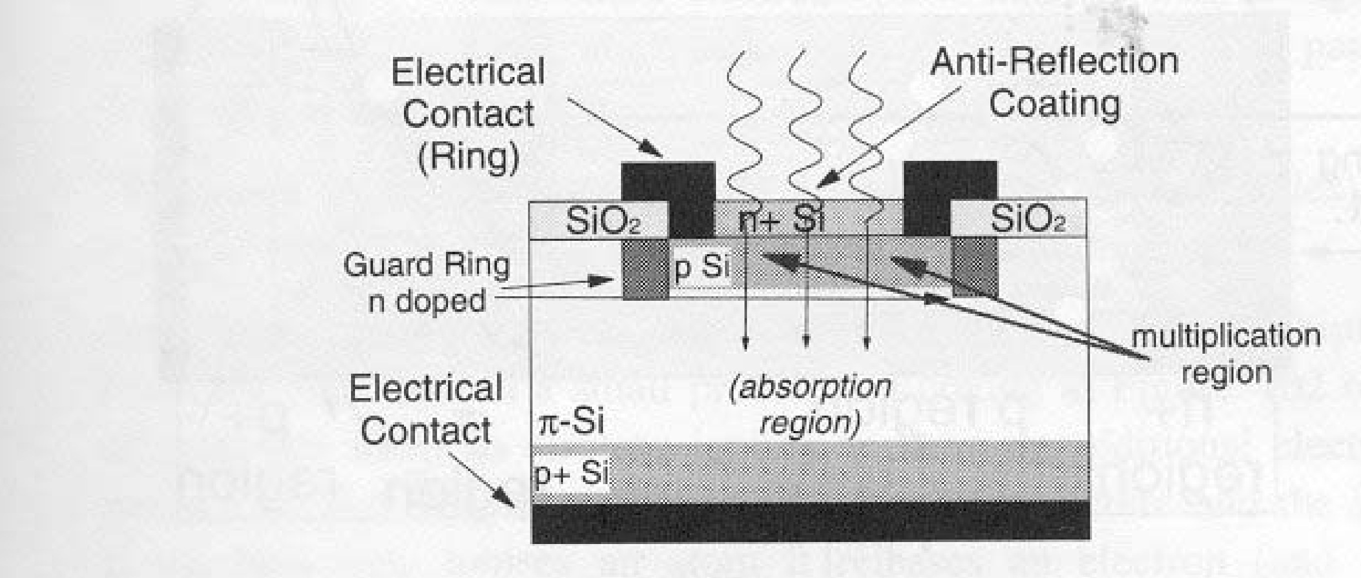


Figure 101. Avalanche Photodiode (APD)

Avalanche Process

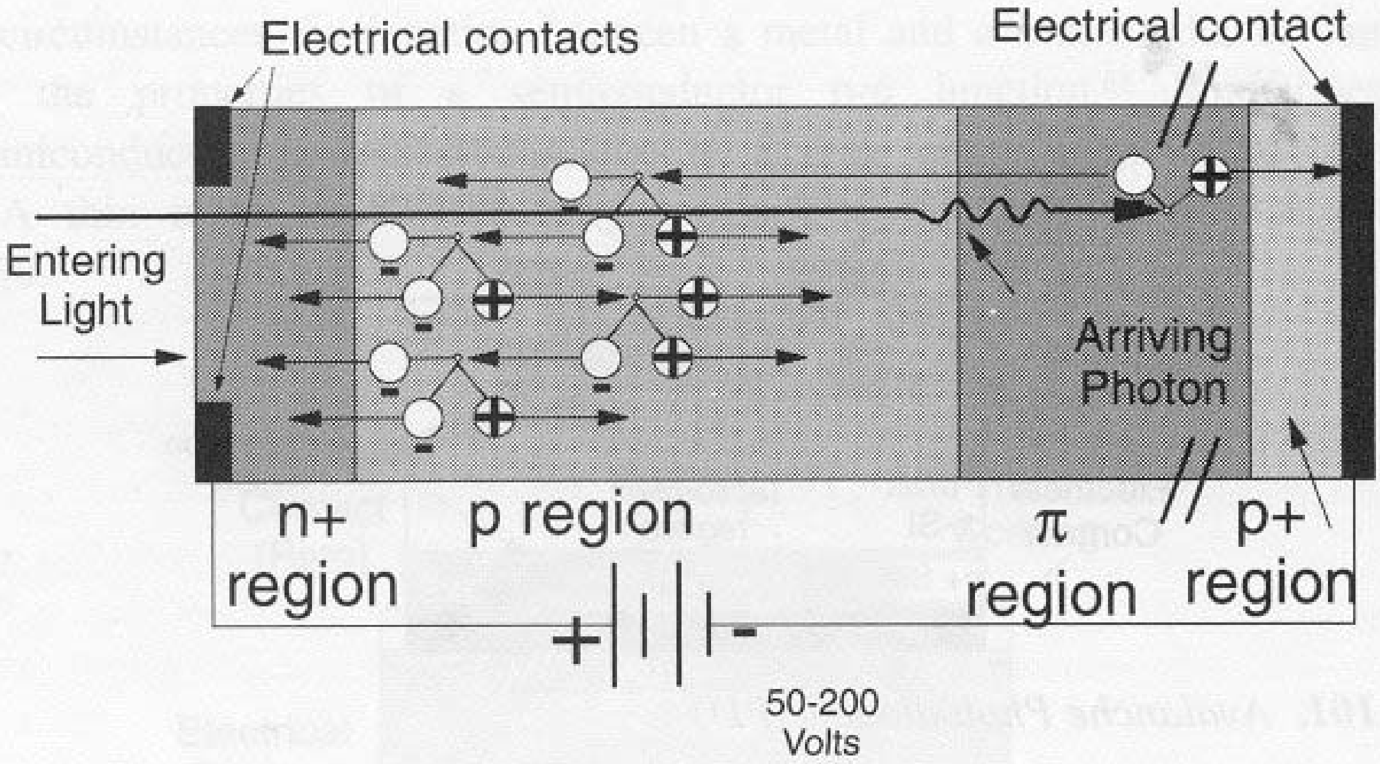


Figure 102. Avalanche (Amplification) Process. The p-region has been enlarged to show avalanche process.

Electric Field Strengths in APD

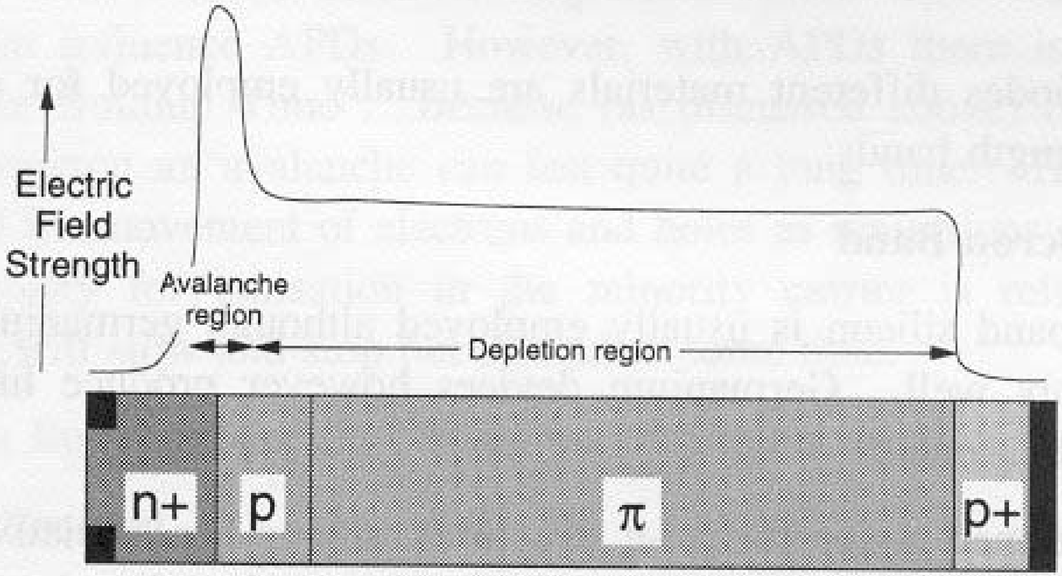
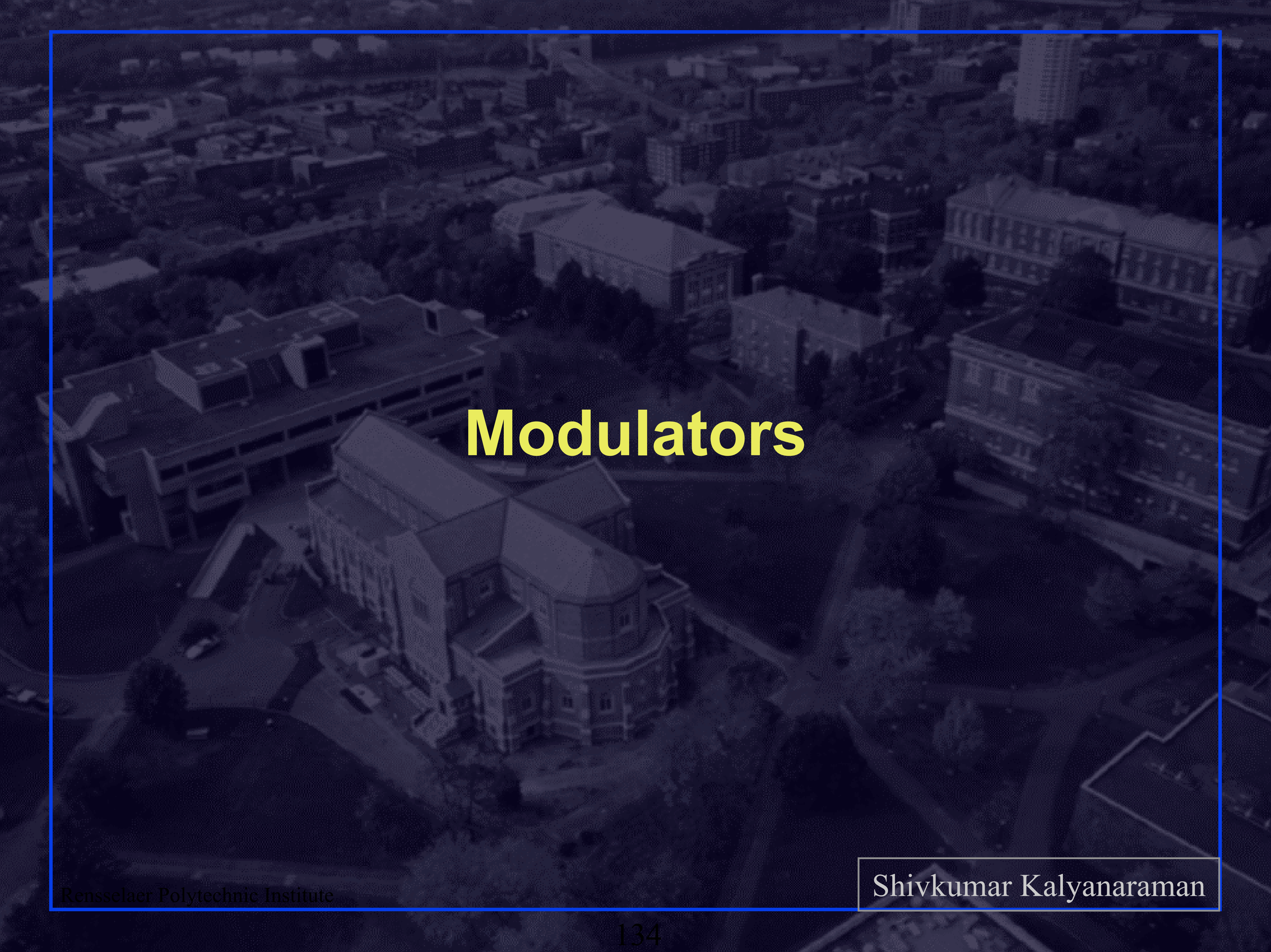
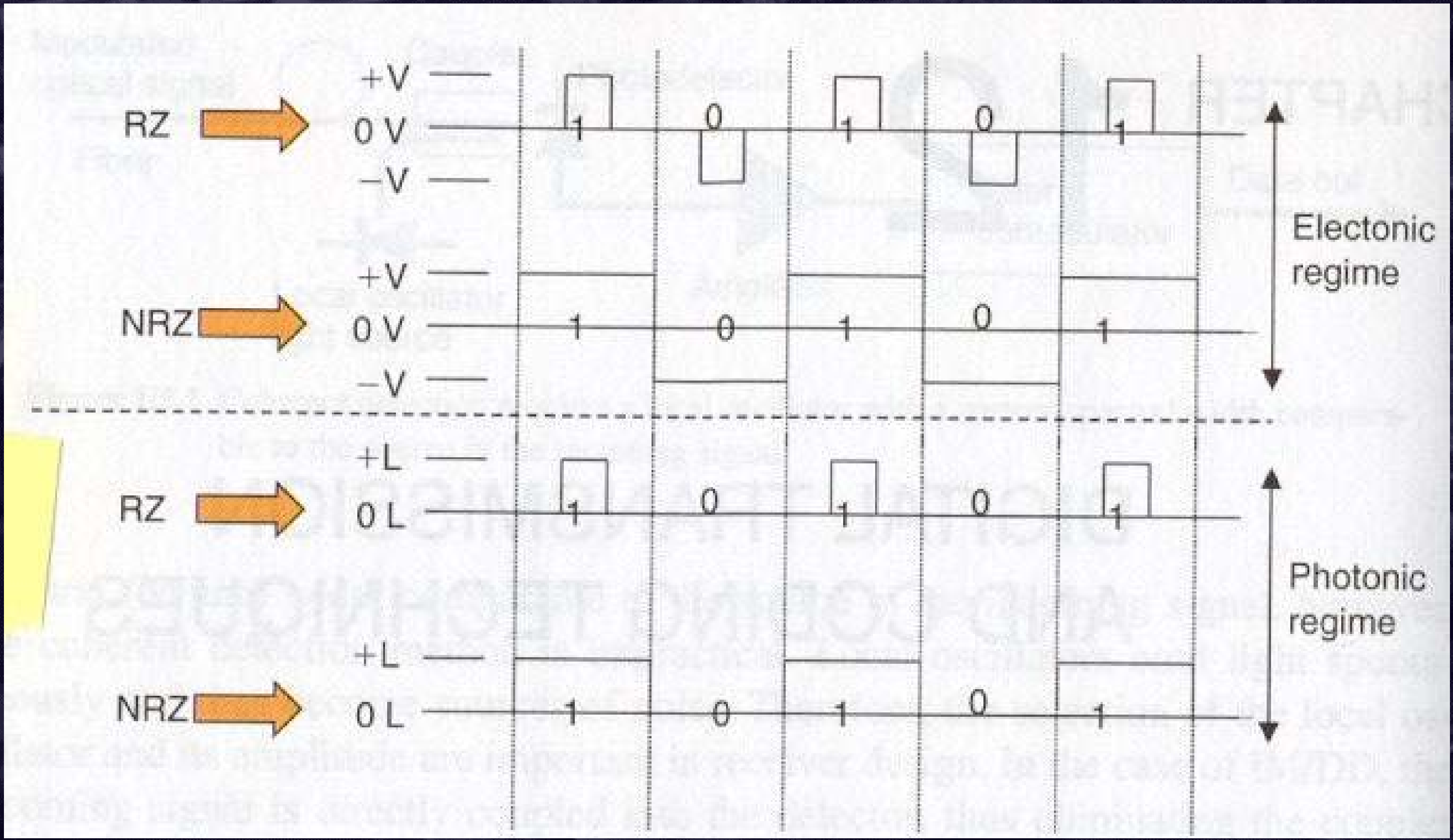


Figure 103. Electric Field Strengths in an APD. Note the very small avalanche region.



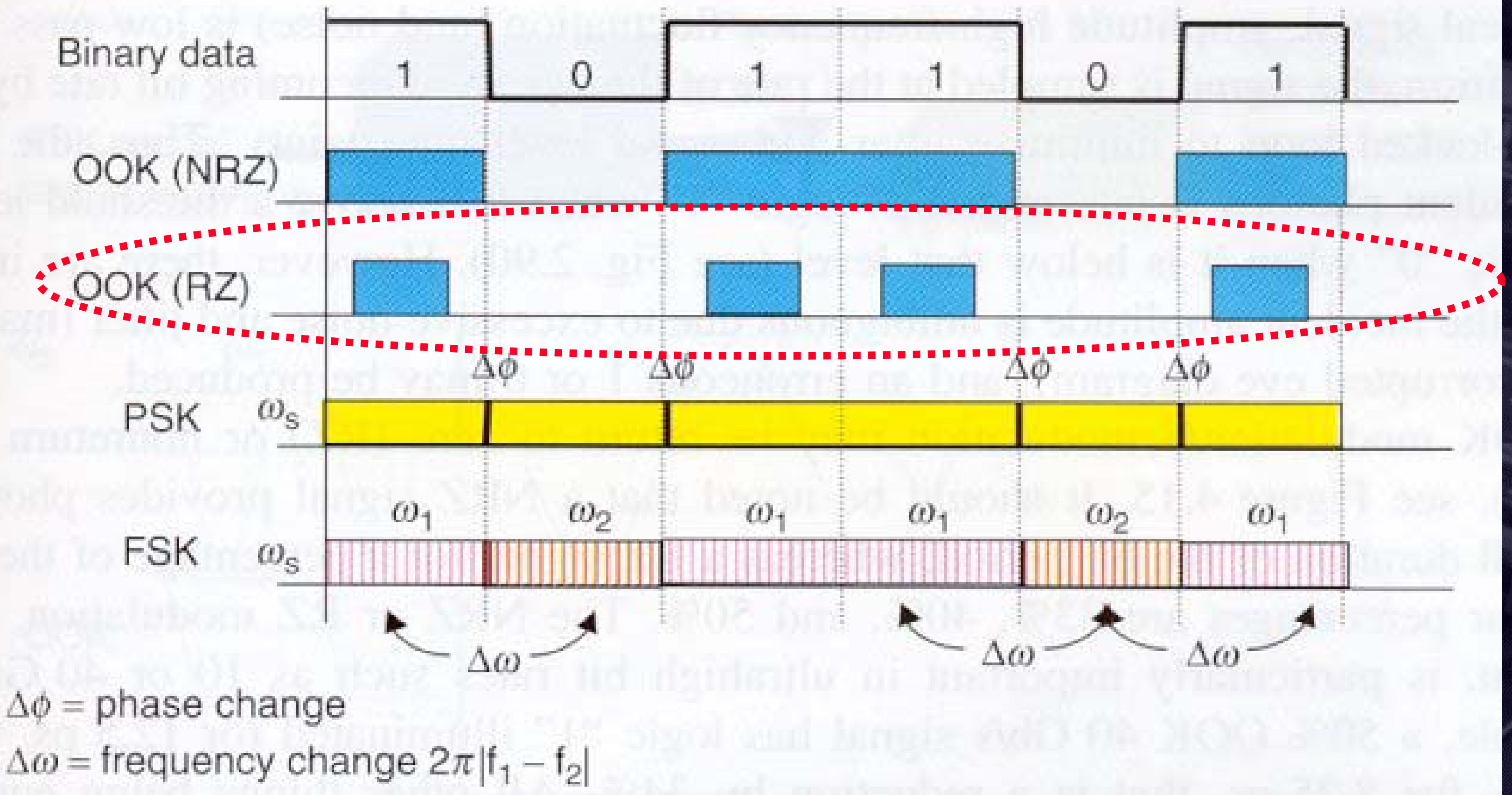
Modulators

Electronic vs Photonic Regime



Cannot go negative in the photonic regime

Optical Modulation Methods



Δφ = phase change

Δω = frequency change $2\pi|f_1 - f_2|$

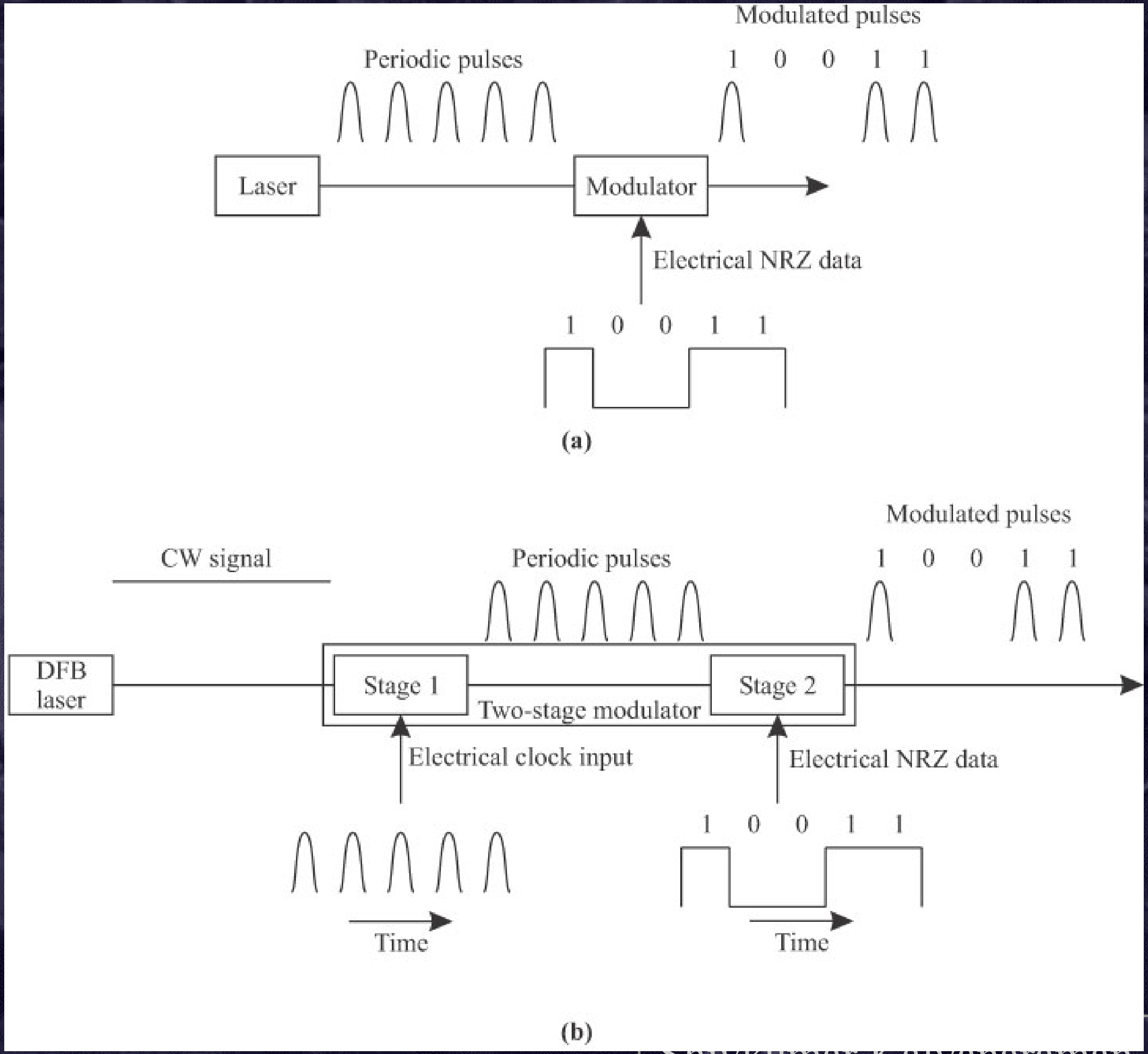
Figure 4.11 Optical modulation methods.

Issues in Optical Modulation

- On-Off keying (OOK) is the simplest
- Direct modulation vs External modulation
  - Extinction ratio: ratio of output power for bit=1 to output power for bit=0
  - Some lasers cannot be directly modulated
  - Direct modulation adds "*chirp*," I.e., time variation of frequency within the pulse!
    - Chirped pulses are more susceptible to chromatic dispersion
    - Combat chirp by increasing the power of bit=0, so that lasing threshold is not lost
    - Reduction of extinction ratio (down to 7dB)
- Solution: external modulation for higher speeds, longer distance/dispersion-limited regimes

External Modulation

- External modulation can be:
- one-stage designs (if mode-locked lasers used) or
- two stage designs



External Modulation (contd)

- Light source is continuously operated (I.e. not modulated)
- External modulation turns light signal ON or OFF
- They can be integrated in same package as laser (eg: electro-absorption or EA modulators)
- EA: applying E-field shrinks bandgap => photons absorbed (Stark effect)

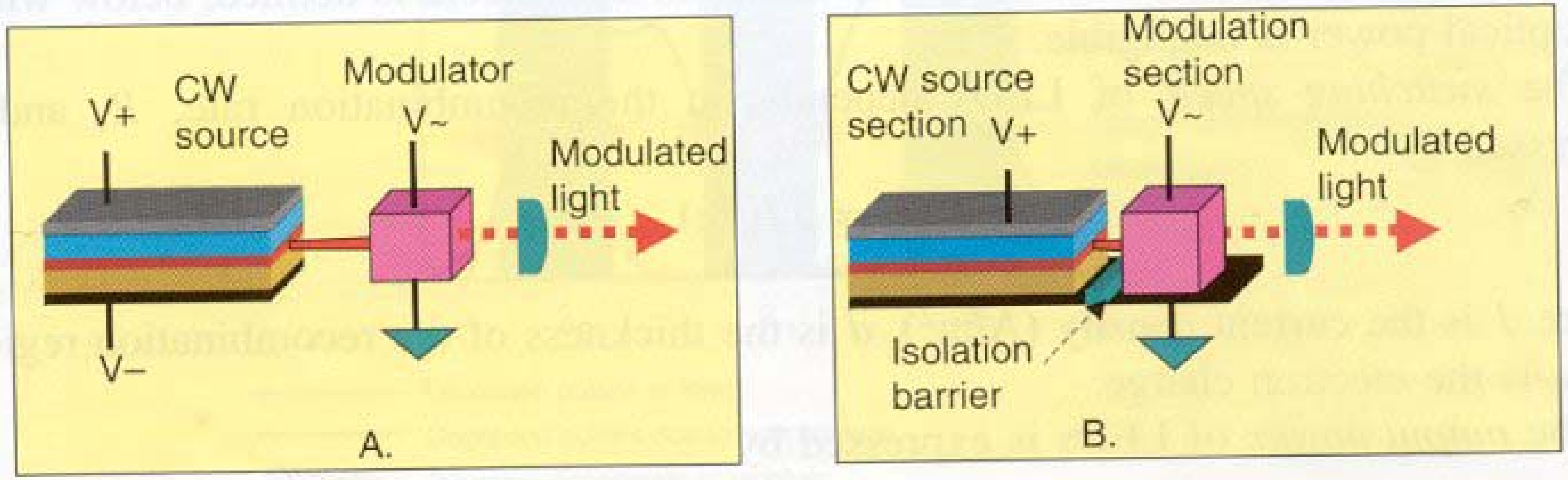
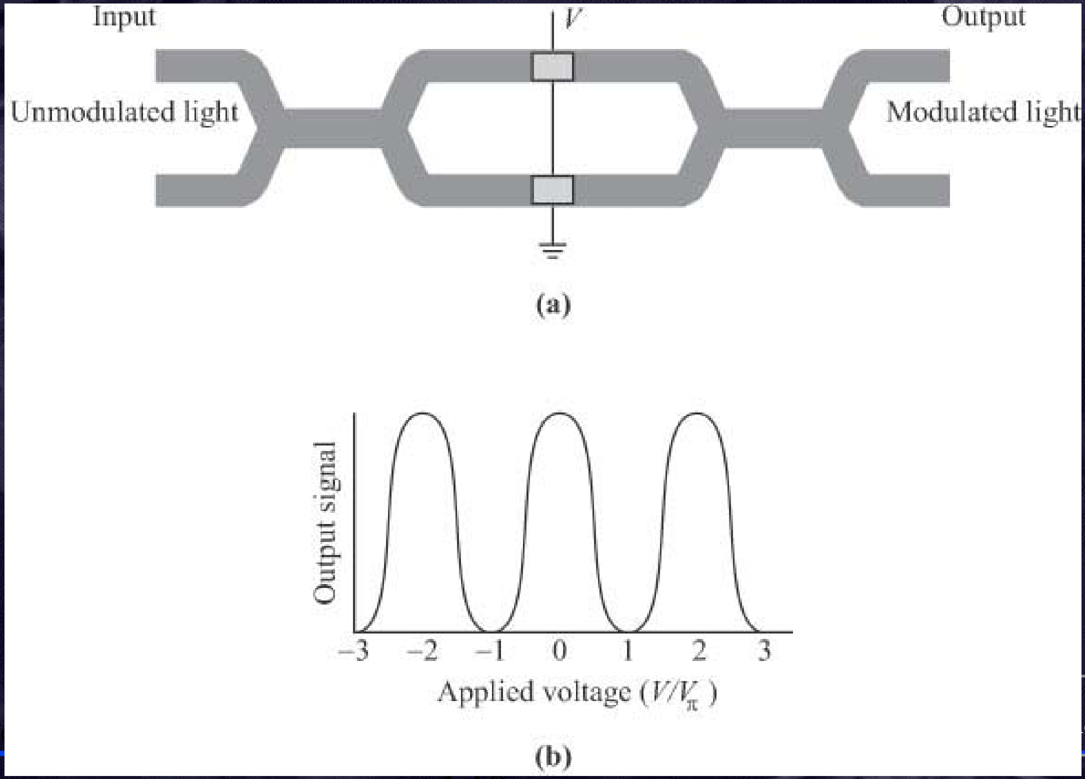


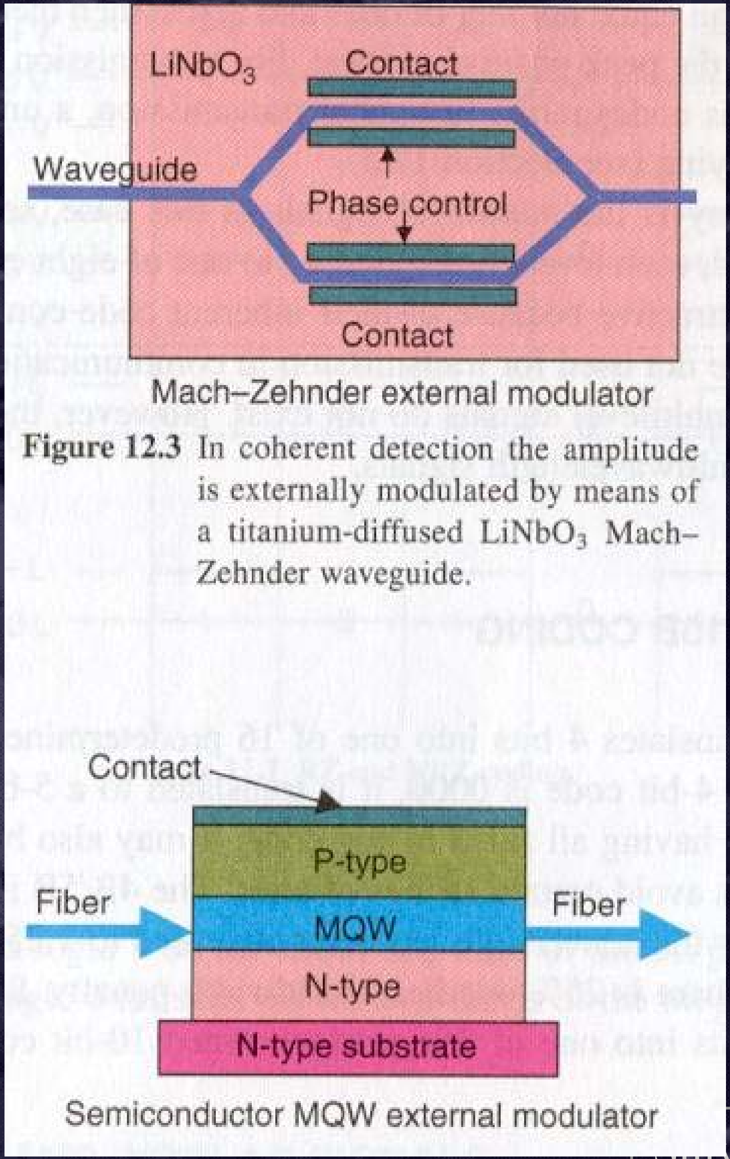
Figure 2.48 A. A continuous wave light source is externally modulated, and B. A monolithically integrated source and modulator.

Lithium Niobate External Modulators

- MZI or directional coupler configuration
- Voltage applied => change RI and determine coupling (or invert phase in MZI)
- MZI design gives good extinction ratio (15-20dB) and precise control of chirp, but is polarization dependent



External Modulators (contd)



Mach–Zehnder external modulator

Figure 12.3 In coherent detection the amplitude is externally modulated by means of a titanium-diffused LiNbO$_3$ Mach–Zehnder waveguide.

Semiconductor MQW external modulator

Optical Modulators

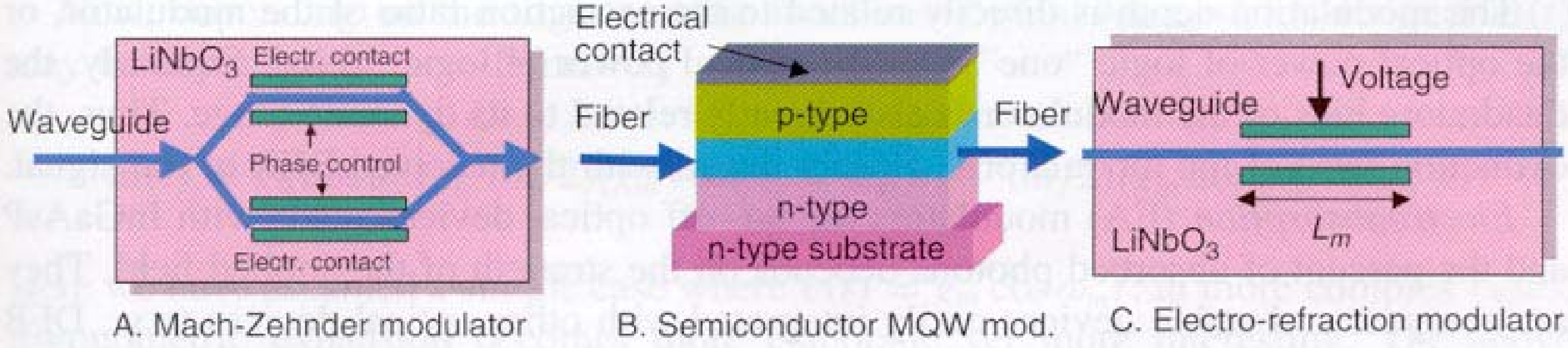


Figure 2.63 Shown are three types of optical modulators, a Mach–Zehnder, a multi-quantum well (MQW), and an electro-refraction modulator.

Cross-Gain & Cross-Phase Modulation

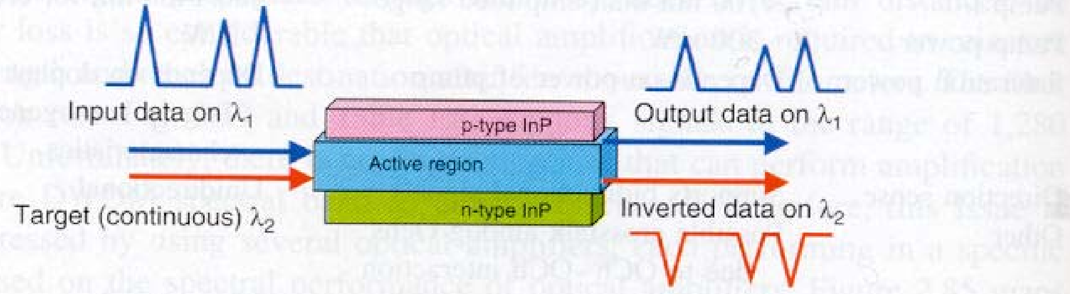


Figure 2.87 Cross-gain modulation transfers inverted data from one wavelength channel to another.

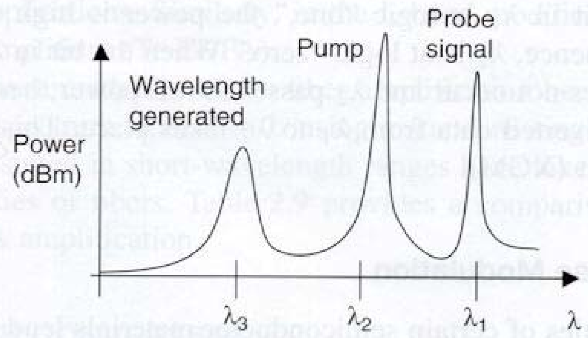


Figure 2.89 When two high power wavelengths are in close proximity and in dispersion-shifted doped fiber, a third wavelength is produced.

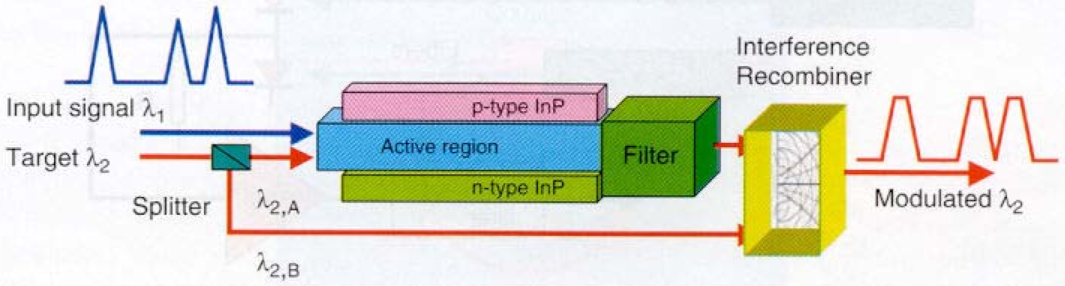


Figure 2.88 Principles of a cross-phase modulating devices.

Eye Diagrams

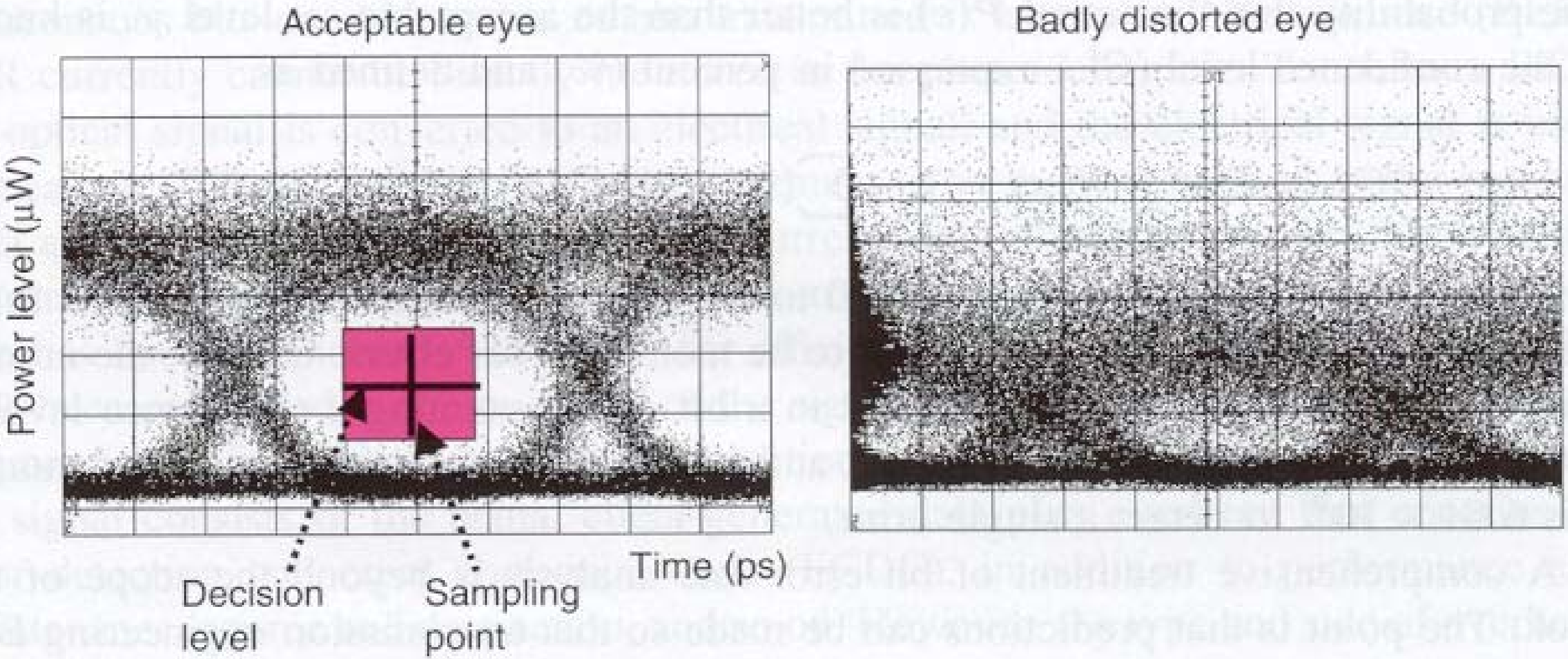


Figure 2.93 Eye diagrams provide a quick and qualitative measure of the quality and integrity of the signal at the receiver (optical has already been converted to electrical).

Eye Diagrams (contd)

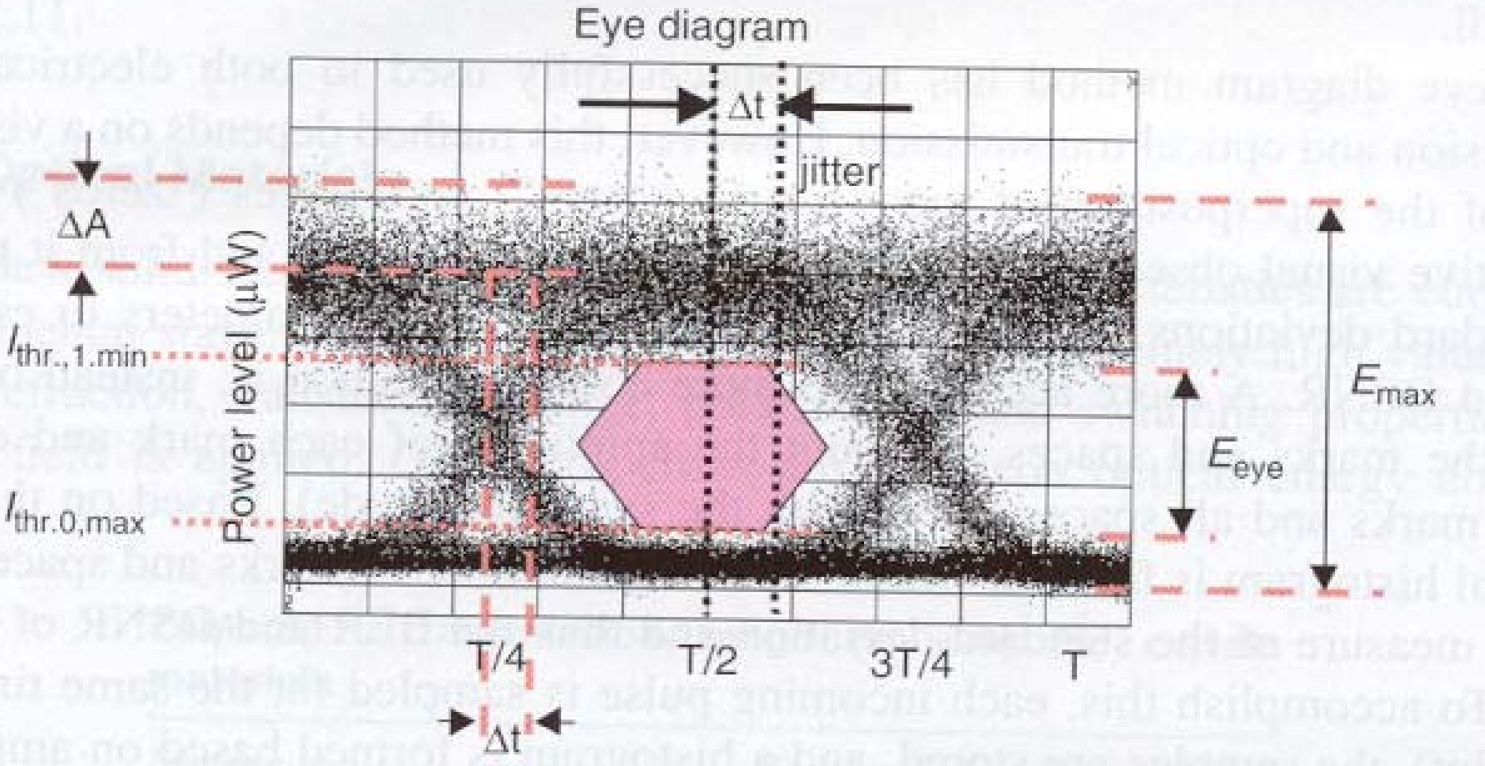
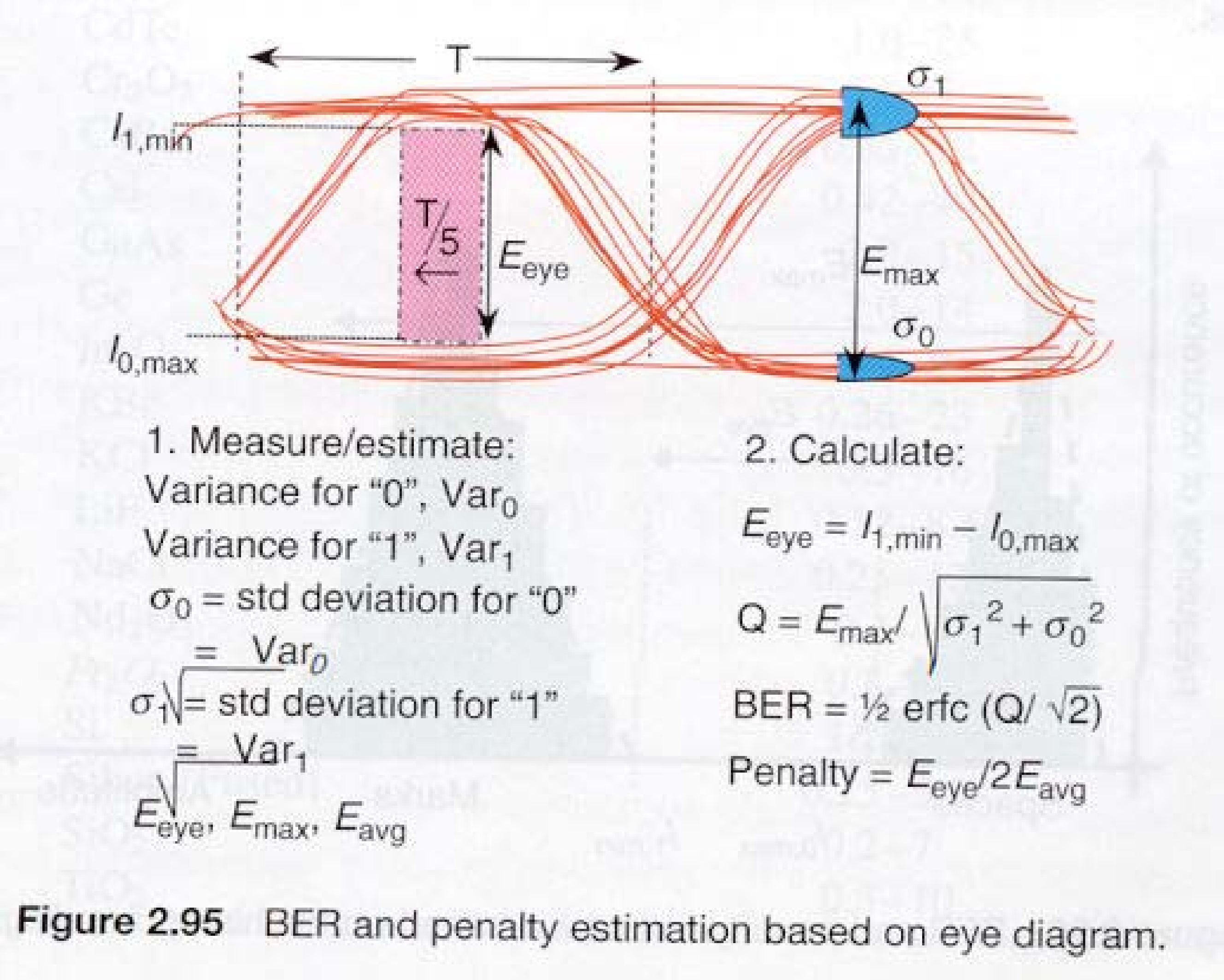


Figure 2.94 Threshold levels (power and jitter) mapped on eye diagram.

BER Estimation w/ Eye Diagrams



1. Measure/estimate:

Variance for "0", Var_0

Variance for "1", Var_1

σ_0 = std deviation for "0" $= \sqrt{\text{Var}_0}$

σ_1 = std deviation for "1" $= \sqrt{\text{Var}_1}$

E_{eye}, $E_{\max}$, E_{avg}

2. Calculate:

$E_{eye} = I_{1,\min} - I_{0,\max}$

$Q = E_{\max} / \sqrt{\sigma_1^2 + \sigma_0^2}$

$\text{BER} = \frac{1}{2} \operatorname{erfc}(Q/\sqrt{2})$

$\text{Penalty} = E_{eye} / 2E_{avg}$

Figure 2.95 BER and penalty estimation based on eye diagram.

BER Estimation (contd)

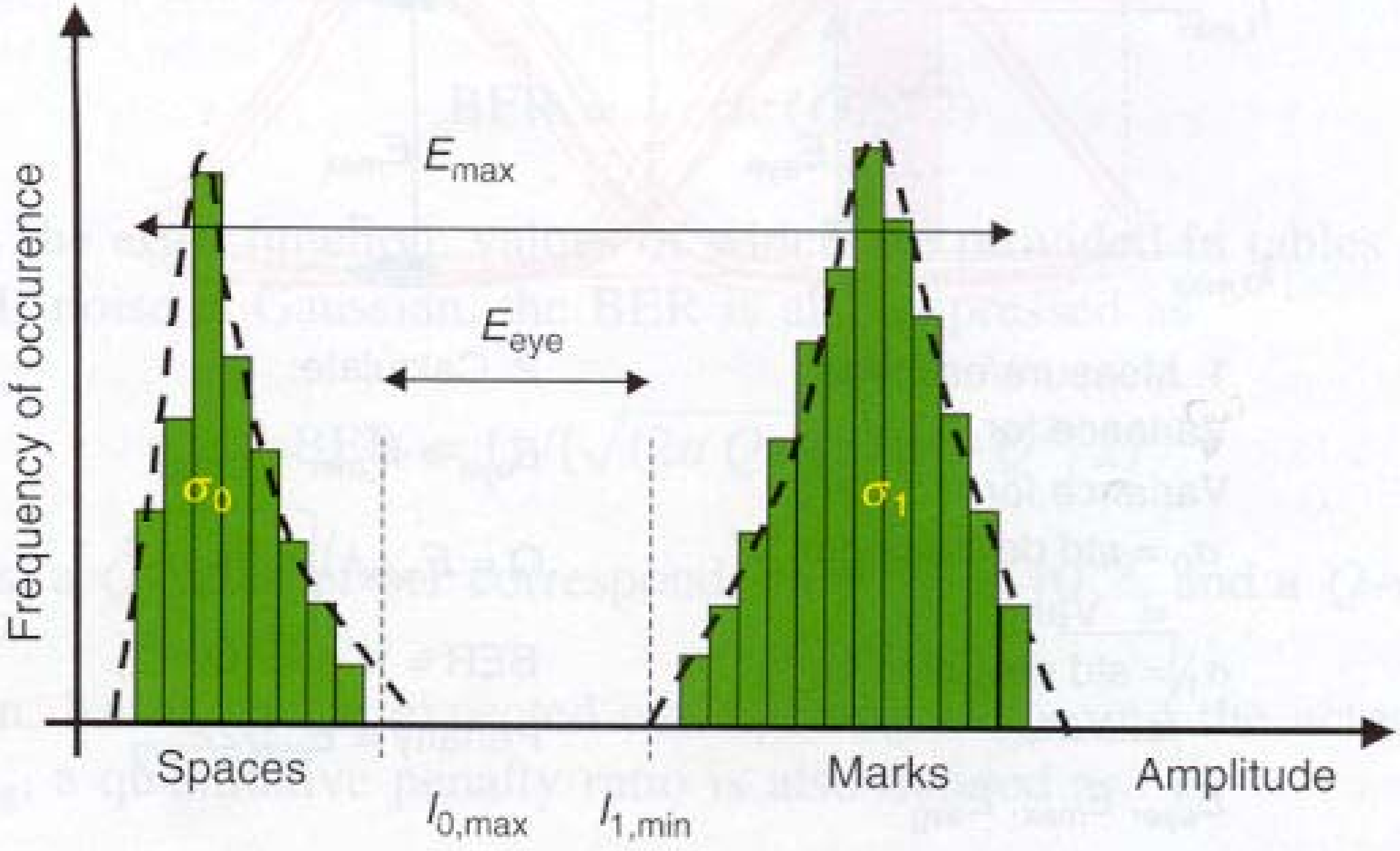
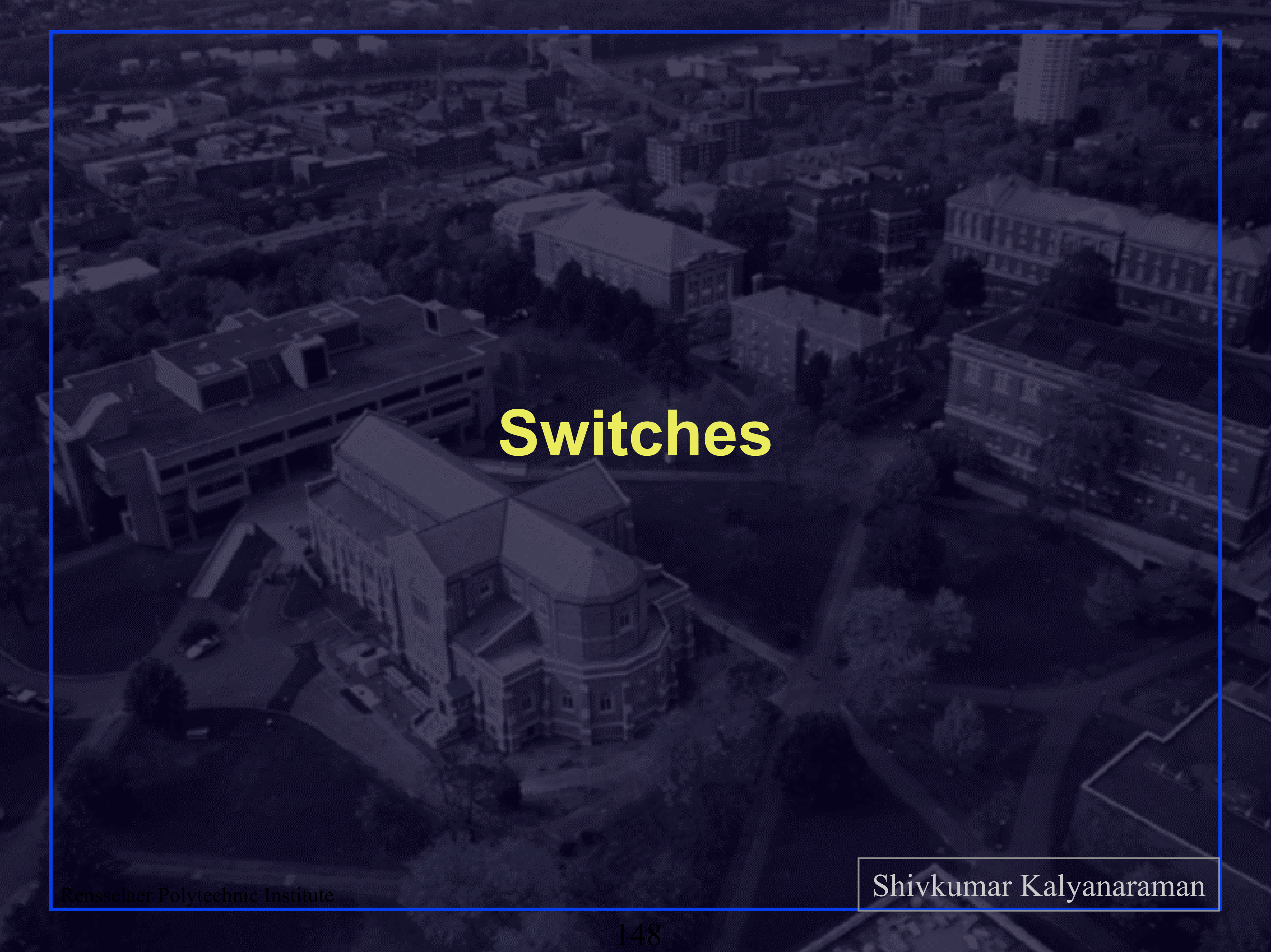


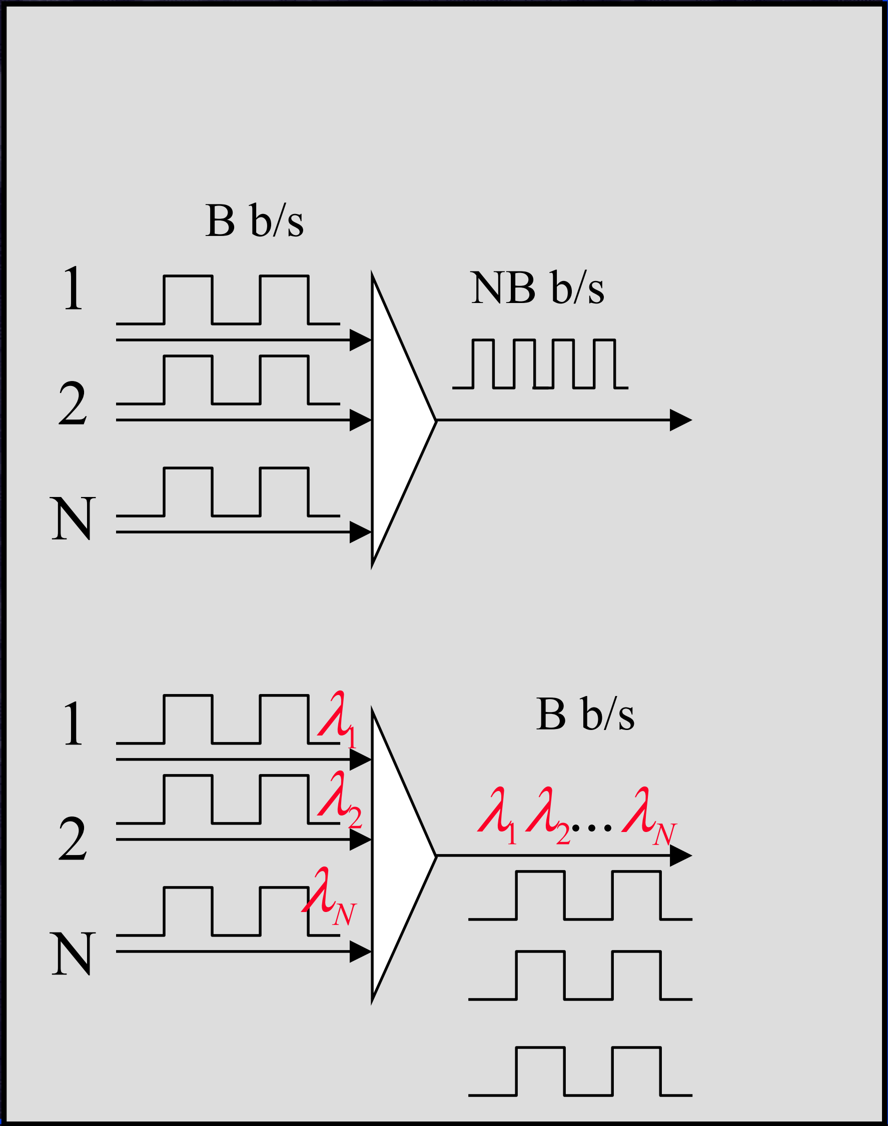
Figure 2.96 BER and penalty estimation based on the histogram diagram.



Switches

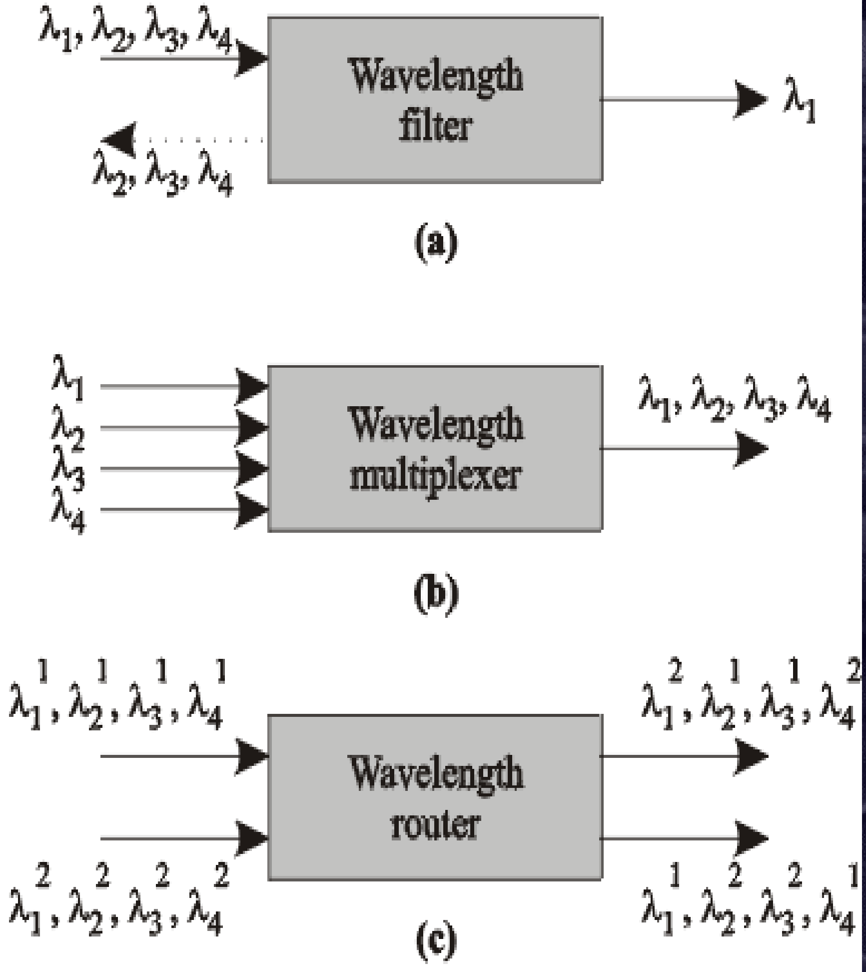
Multiplexing: WDM

- TDM: Time Division Multiplexing
  - 10Gb/s upper limit
- WDM: Wavelength Division Multiplexing
  - Use multiple carrier frequencies to transmit data simultaneously



Multiplexers, Filters, Routers

- Filter selects one wavelength and rejects all others
- Multiplexor combines different wavelengths
- Router exchanges wavelengths from one input to a different output



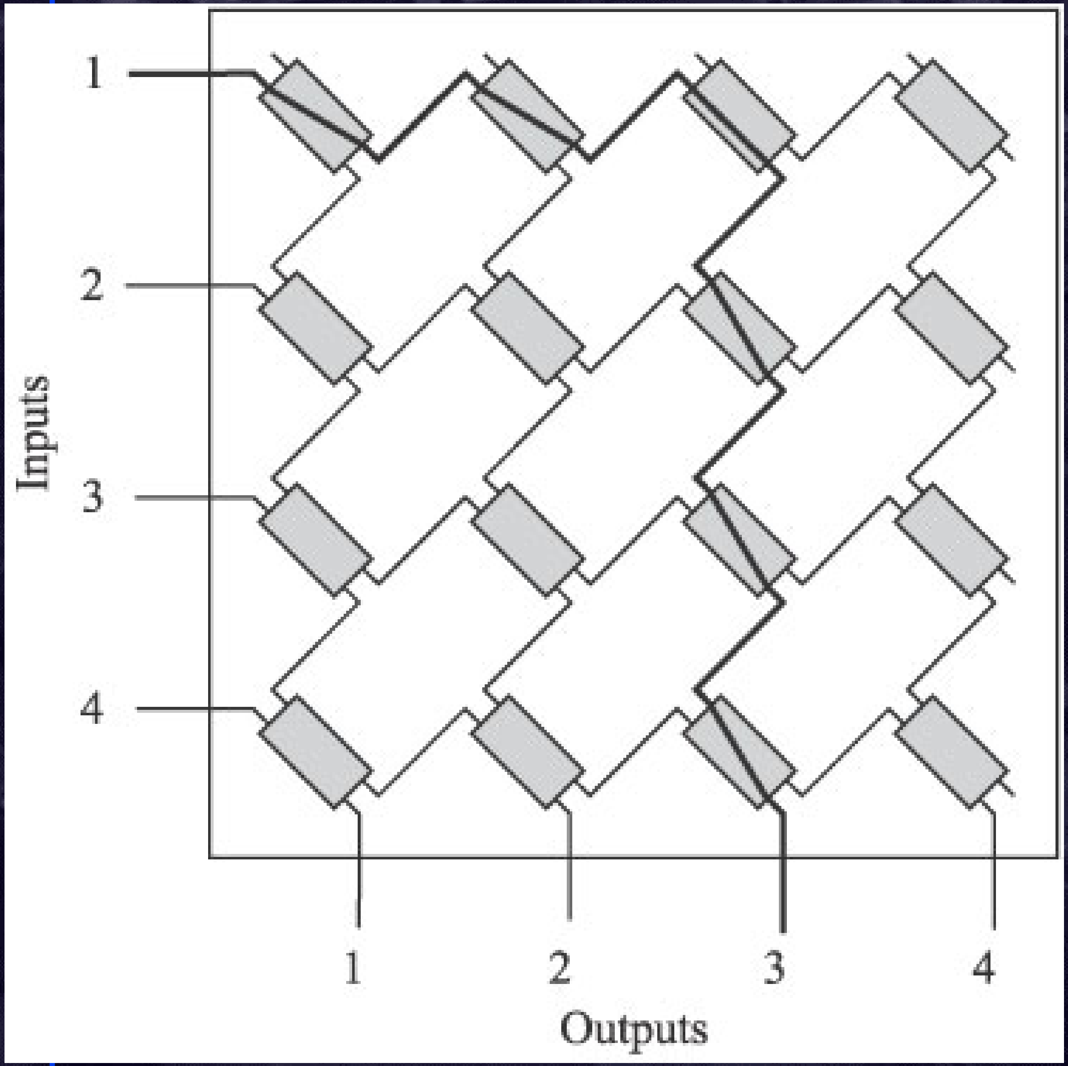
Switch Parameters

- Extinction Ratio: ratio of output power in ON state to the power in the OFF state
  - 10-25 dB in external modulators
- Insertion loss: fraction of power lost
  - Different losses to different outputs => larger dynamic range => may need to equalize (esp. for large switches)
- Crosstalk: ratio of power at desired vs undesired output
- Low polarization dependent loss (PDL)
- Latching: maintain switch state even if power turned off
- Readout capability: to monitor current state
- Reliability: measured by cycling the switch through its states a few million times

Switch Considerations

- Number of switch elements: complexity of switch
- Loss uniformity:different losses to different outputs (esp for large switches)
- Number of crossovers: waveguide crossovers introduce power loss and crosstalk (not a problem for free-space-switches)
- Blocking Characteristics: Any unused input port can be connected to any unused output port?
  - *Wide-sense non-blocking:* without requiring any existing connection to be re-routed => make sure future connections will not block
  - *Strict-sense non-blocking*: regardless of previous connections
  - *Re-arrangeably non-blocking:* connections may be re-routed to make them non-blocking

Crossbar Switch

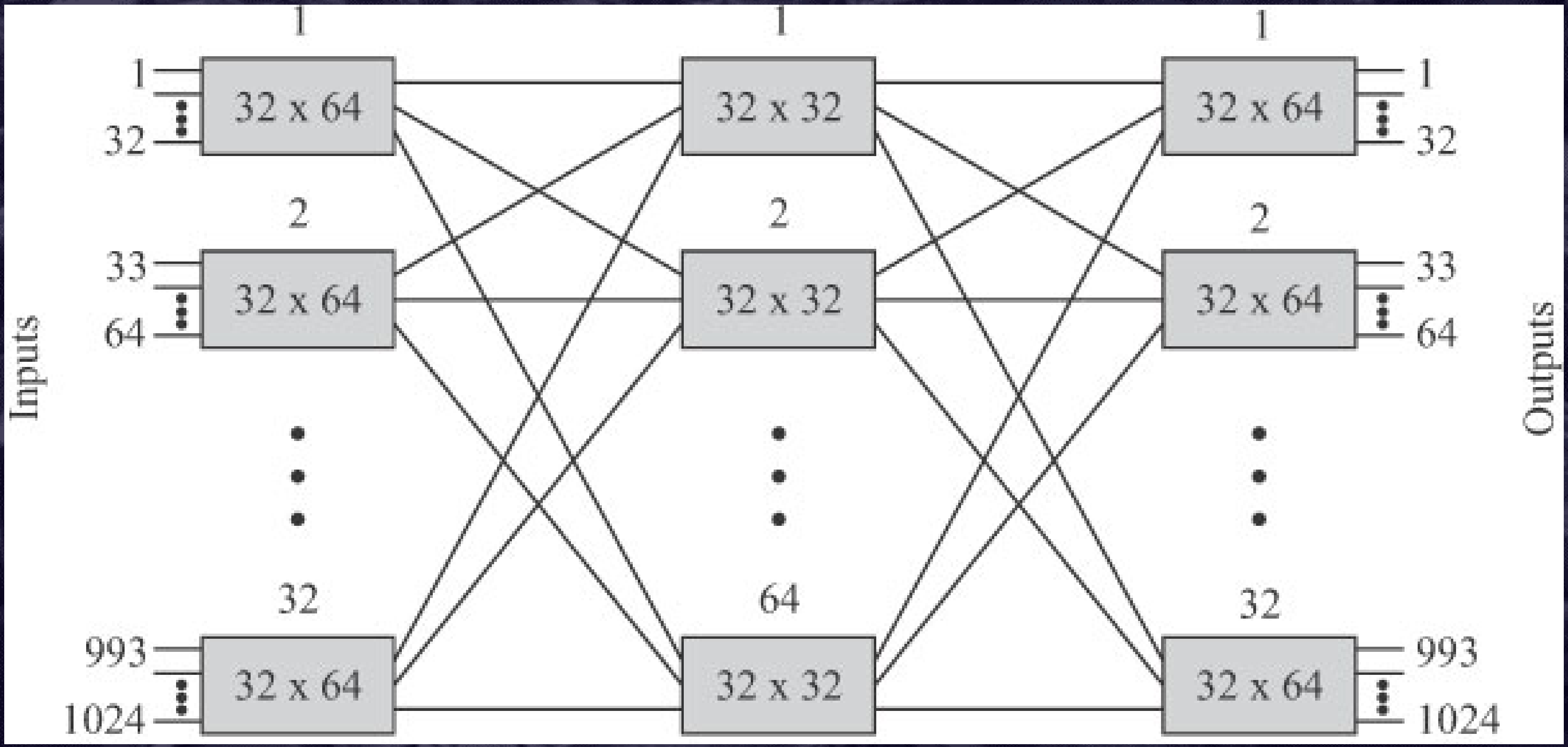


Wide-sense non-blocking

Shortest path length = 1 vs longest = 2n-1

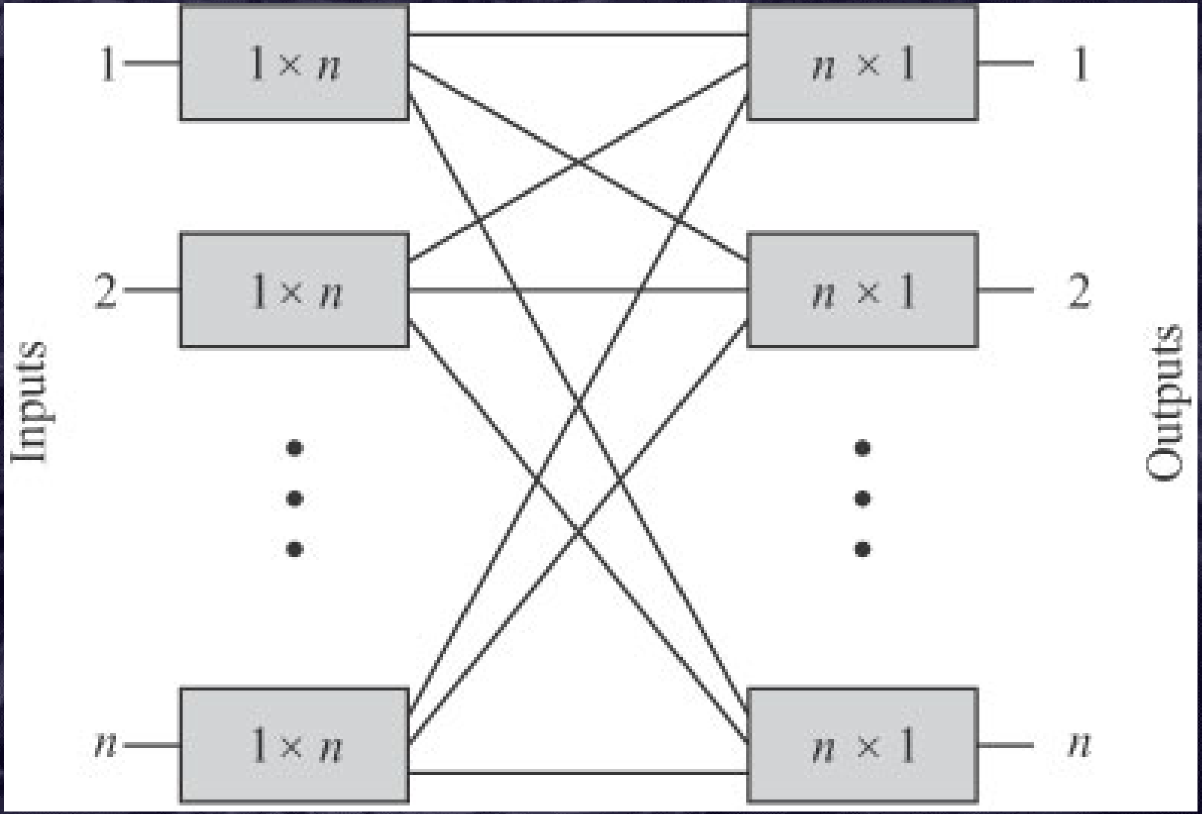
Fabricated w/o any crossovers

Clos Architecture



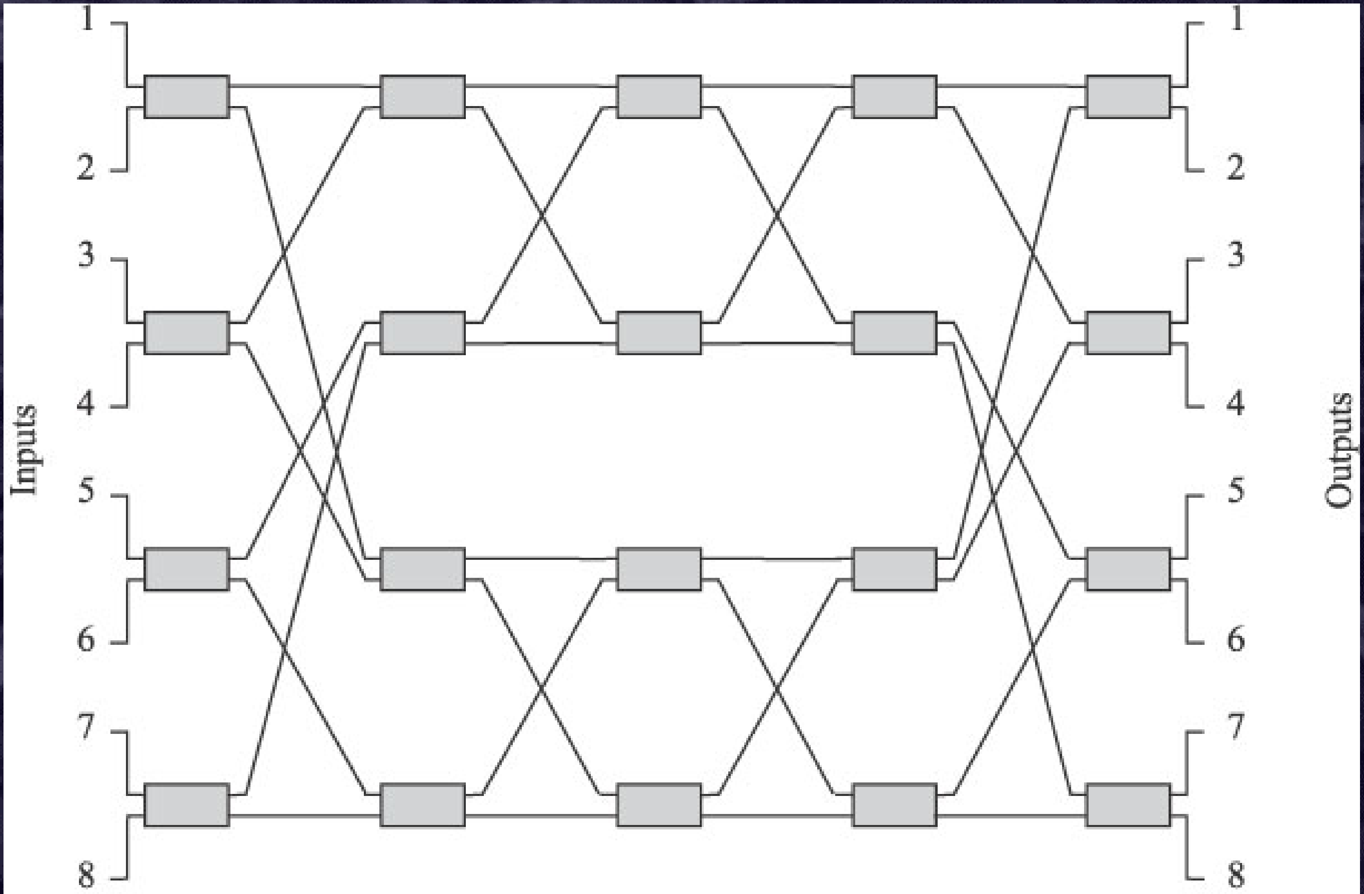
* Strict-sense non-blocking; used in large port-count s/ws
* N = mk; k (m x p) switches in first/last stages; p (k x k) switches in middle stage; * Non-blocking if p >= 2m - 1
* Lower number of crosspoints than crossbar ($n^{2/3}$)

Spanke Architecture



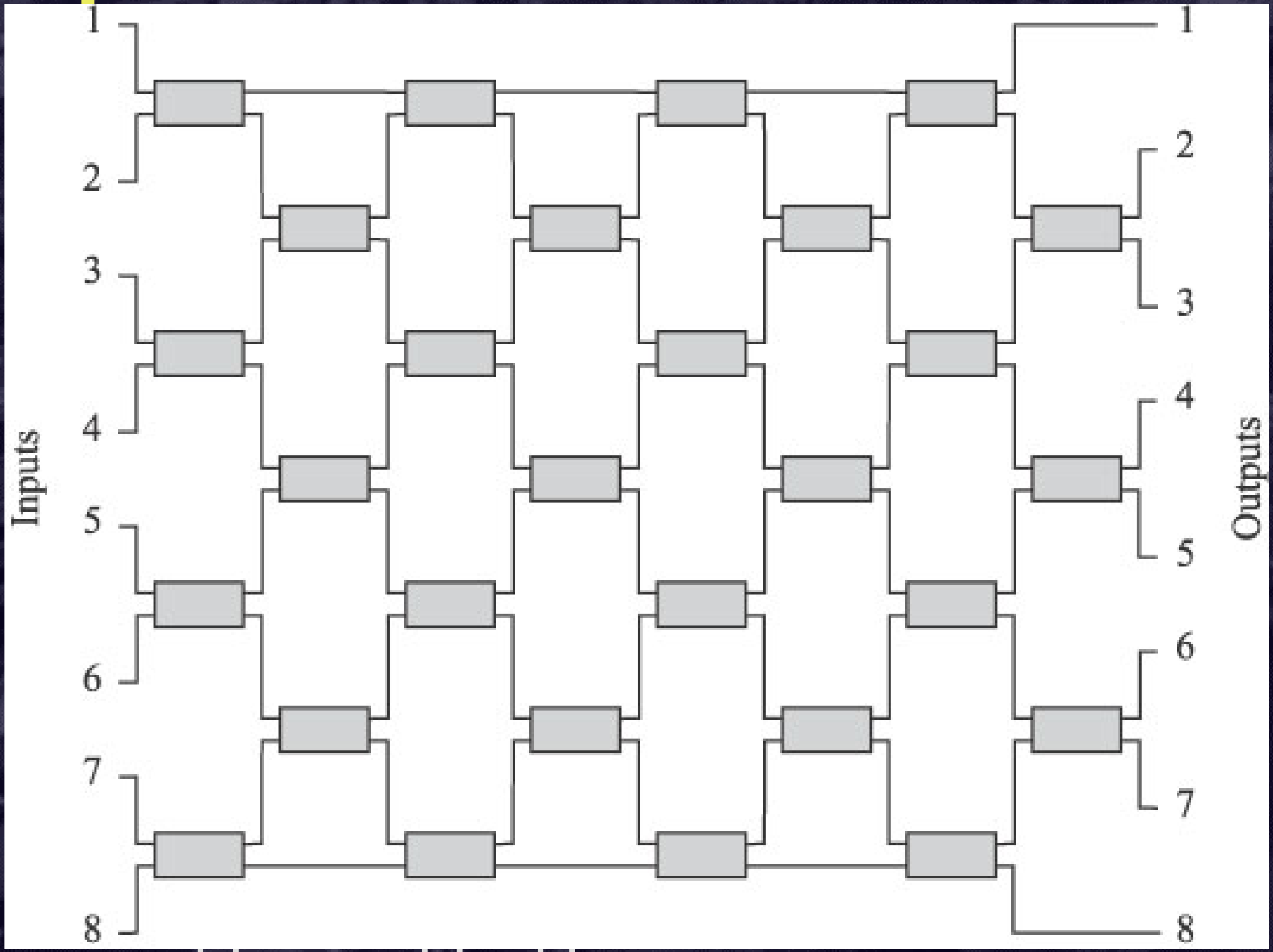
- Strict-sense non-blocking
- Only 2 stages: 1xn and nx1 switches used instead of 2x2
- Switch cost scales linearly with n
- Lower insertion loss and equal optical path lengths

Benes Architecture



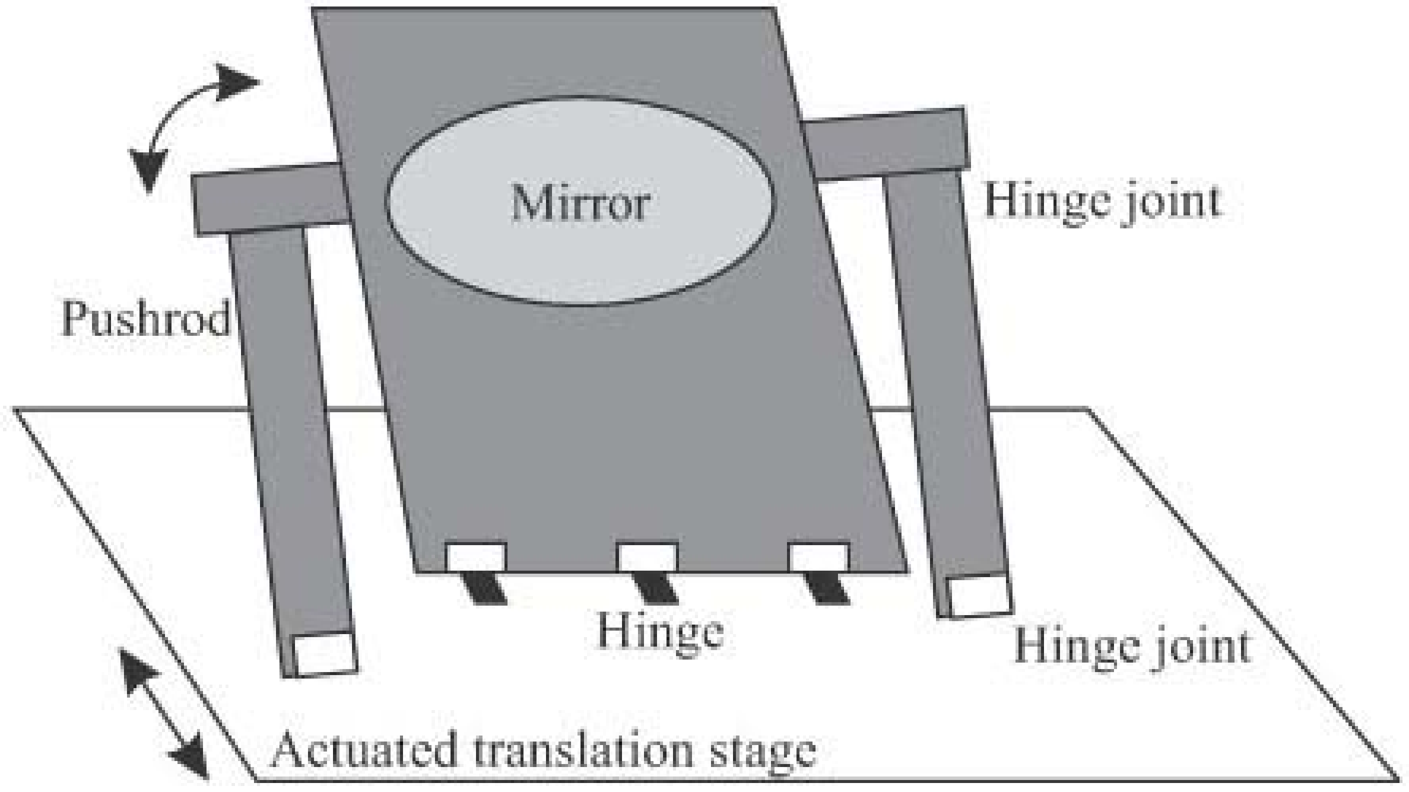
- Rearrangeably non-blocking
- Efficient in number of 2x2 components
- -ves: not WS-non-blocking and requires waveguide crossovers

Spanke-Benes Architecture

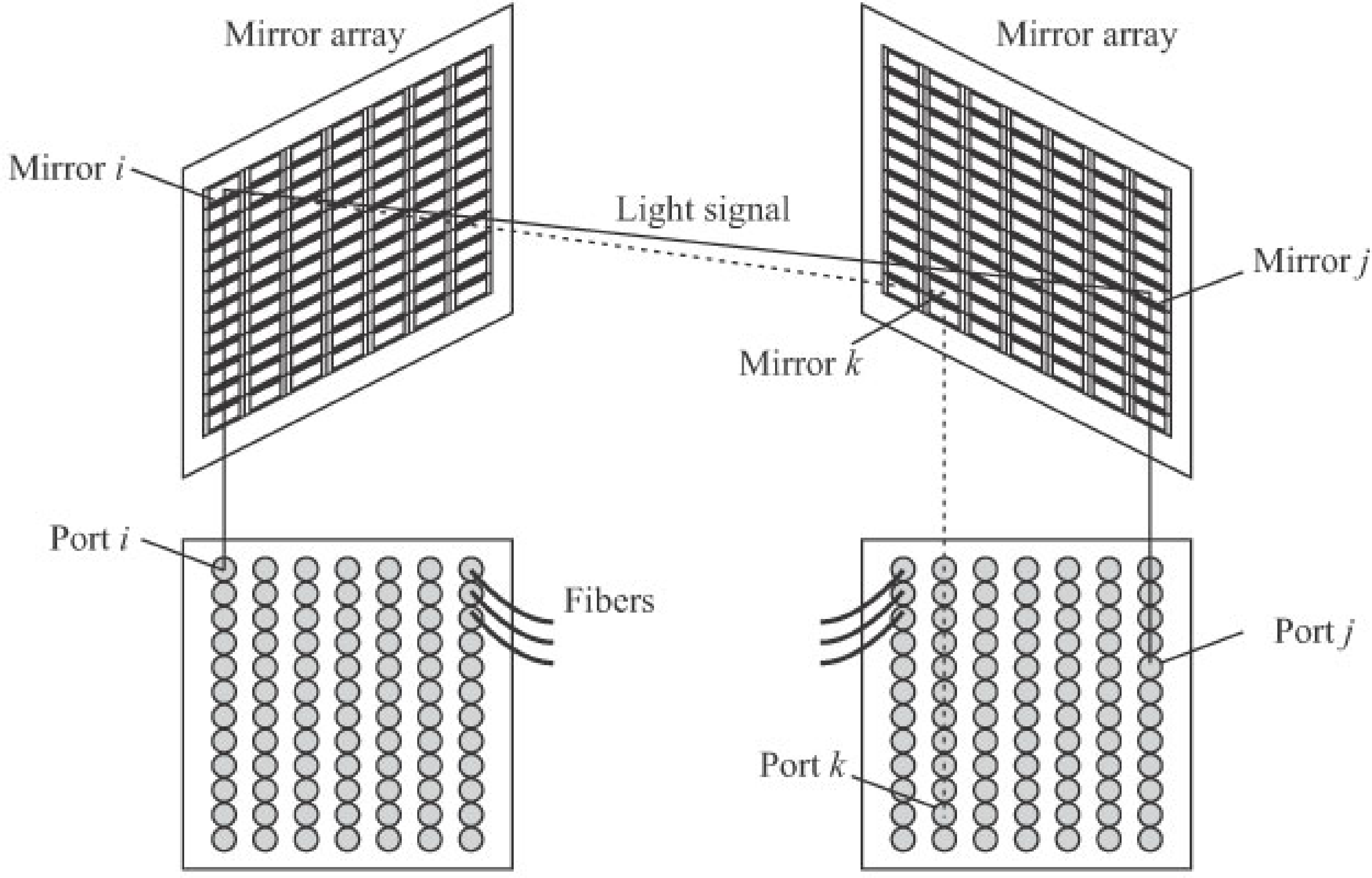


- Rearrangeably non-blocking
- Efficient in number of 2x2 components
- Eliminates waveguide crossovers: n-stage planar…

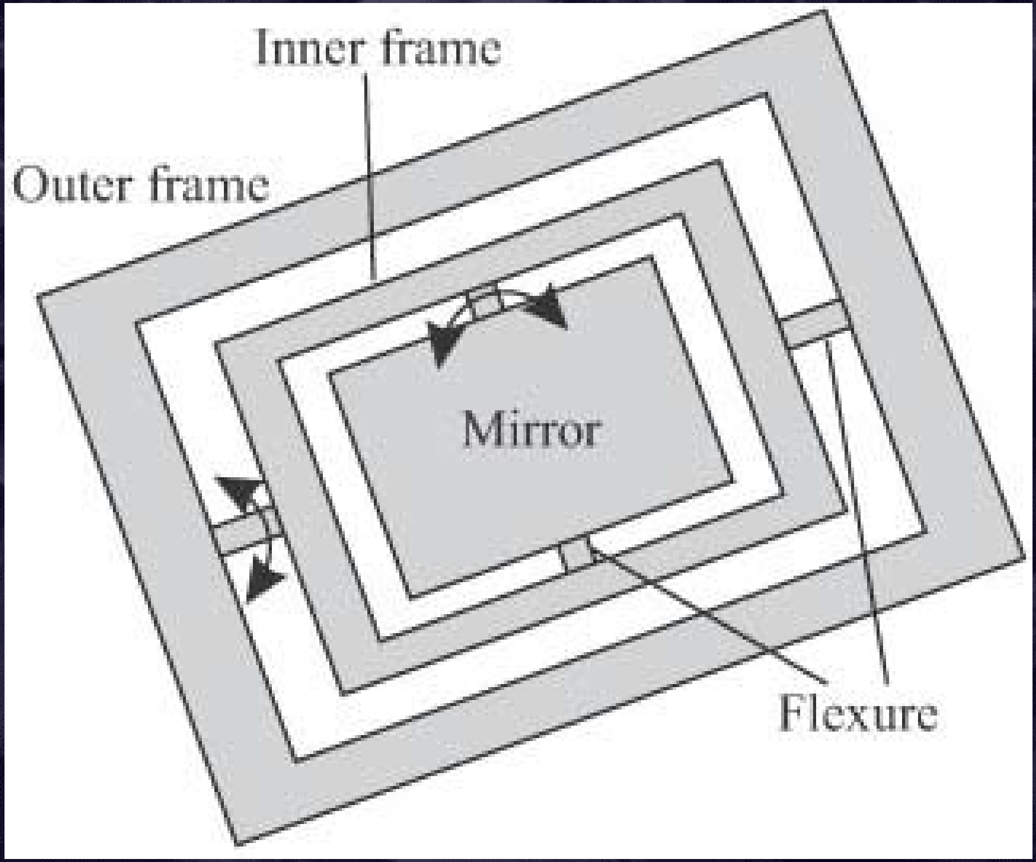
MEMS Mirror Switching Component



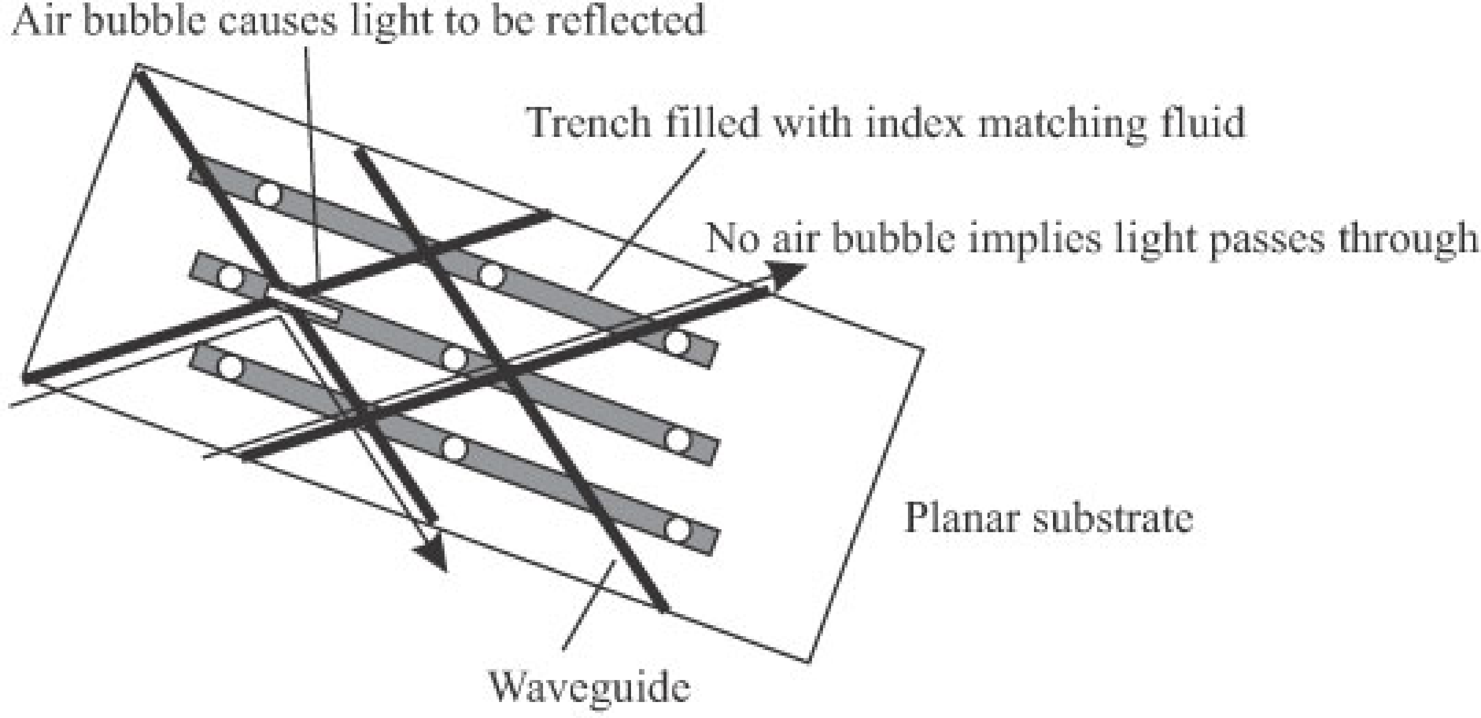
NxN Switching with MEMS Mirror Arrays



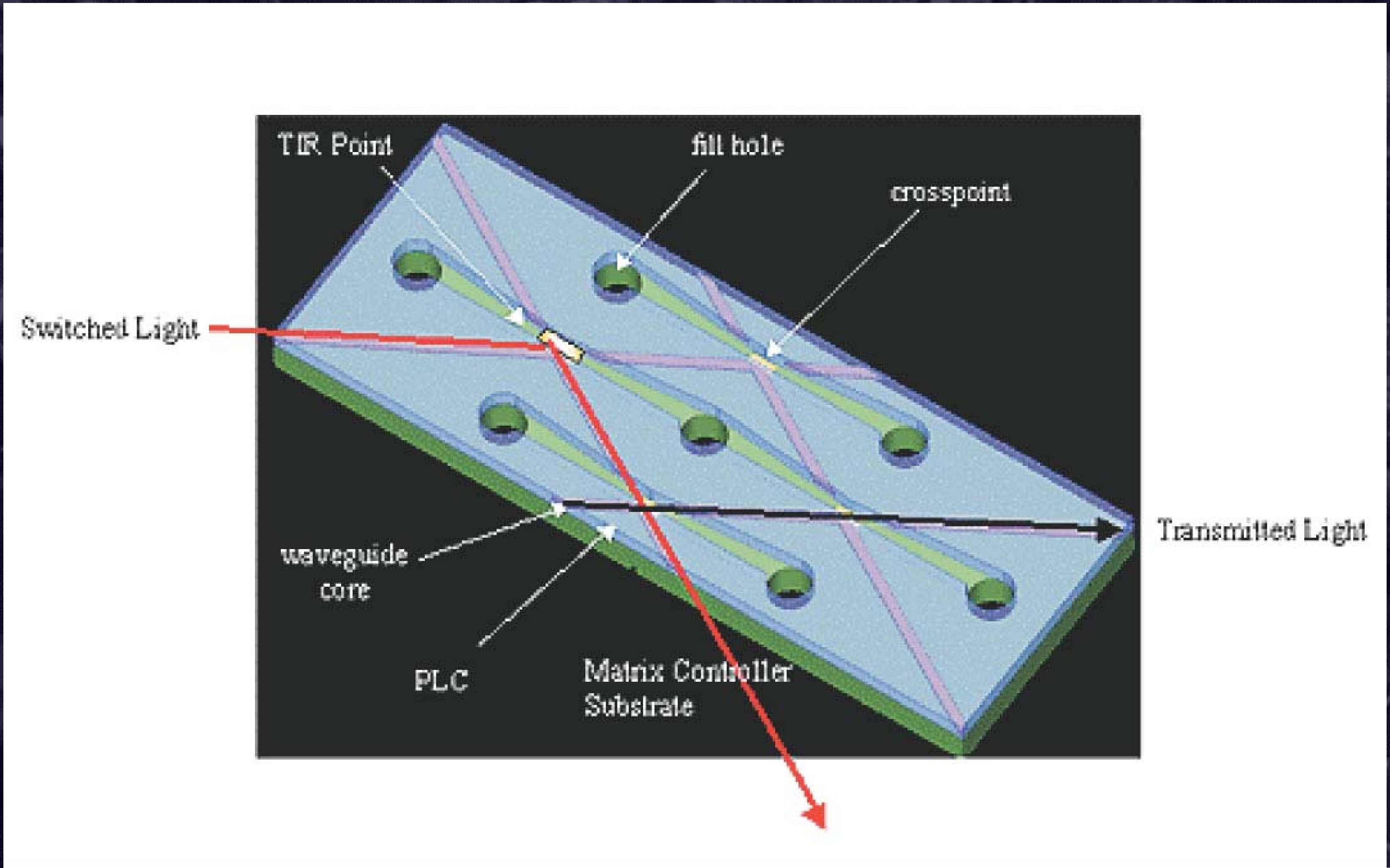
Analog Beam Steering Mirror



Planar Waveguide Switch



Planar Waveguide Switch



1x2 Liquid Crystal Switch