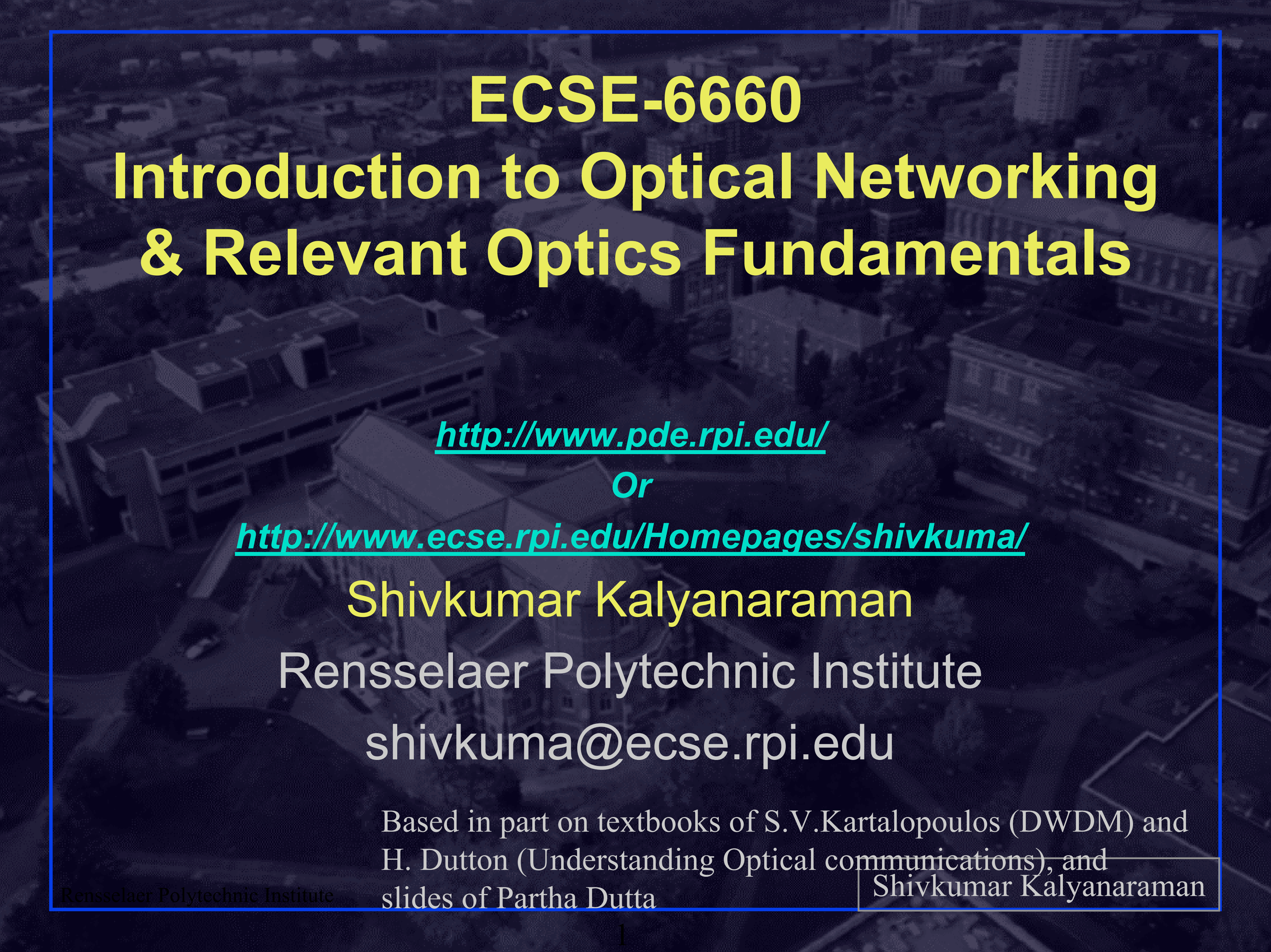

ECSE-6660
Introduction to Optical Networking & Relevant Optics Fundamentals

http://www.pde.rpi.edu/

Or

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

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

Overview

- Quick History
- Relevant Properties of Light
- Components of Fiber Optic Transmission and Switching Systems
- Chapter 2 of Ramaswami/Sivarajan

Quick History of Optical Networking

- **1958:** Laser discovered
- **Mid-60s:** Guided wave optics demonstrated
- **1970:** Production of low-loss fibers
  - Made long-distance optical transmission possible!
- **1970:** invention of semiconductor laser diode
  - Made optical transceivers highly refined!
- **70s-80s:** Use of fiber in telephony: SONET
- **Mid-80s:** LANs/MANs: broadcast-and-select architectures
- **1988:** First trans-atlantic optical fiber laid
- **Late-80s:** EDFA (*optical* amplifier) developed
  - Greatly alleviated distance limitations!
- **Mid/late-90s:** DWDM systems explode
- Late-90s: *Intelligent* Optical networks

Big Picture: Optical Transmission System Pieces

1.1.1 Optical Transmission System Concepts

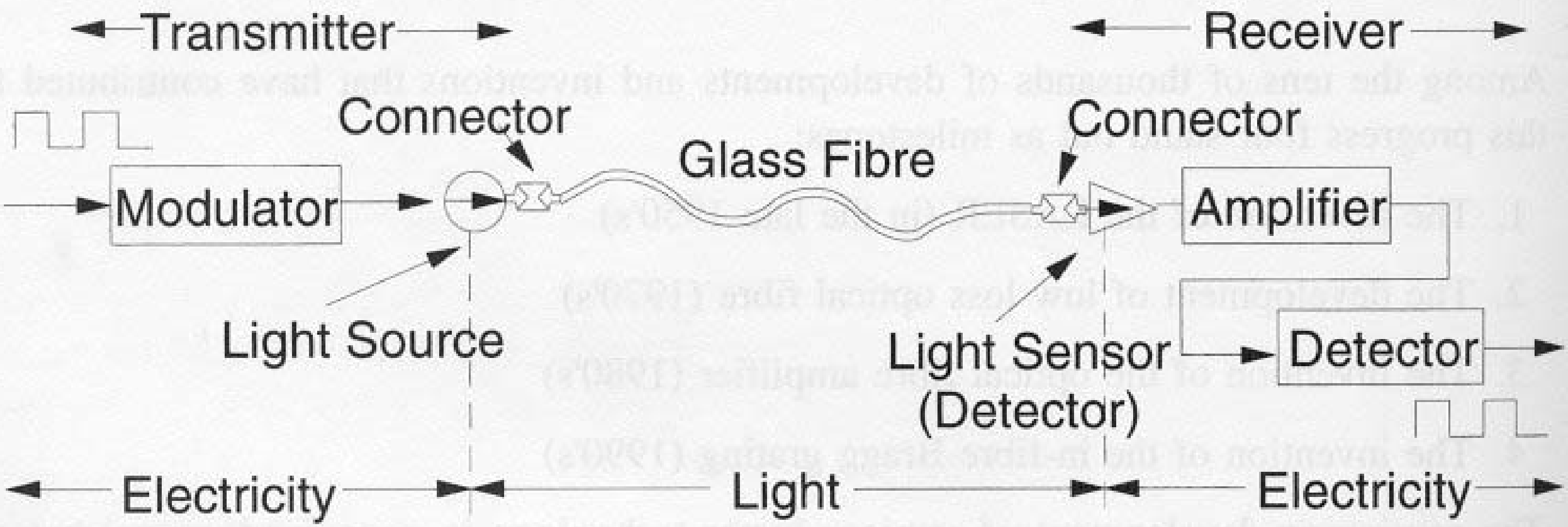
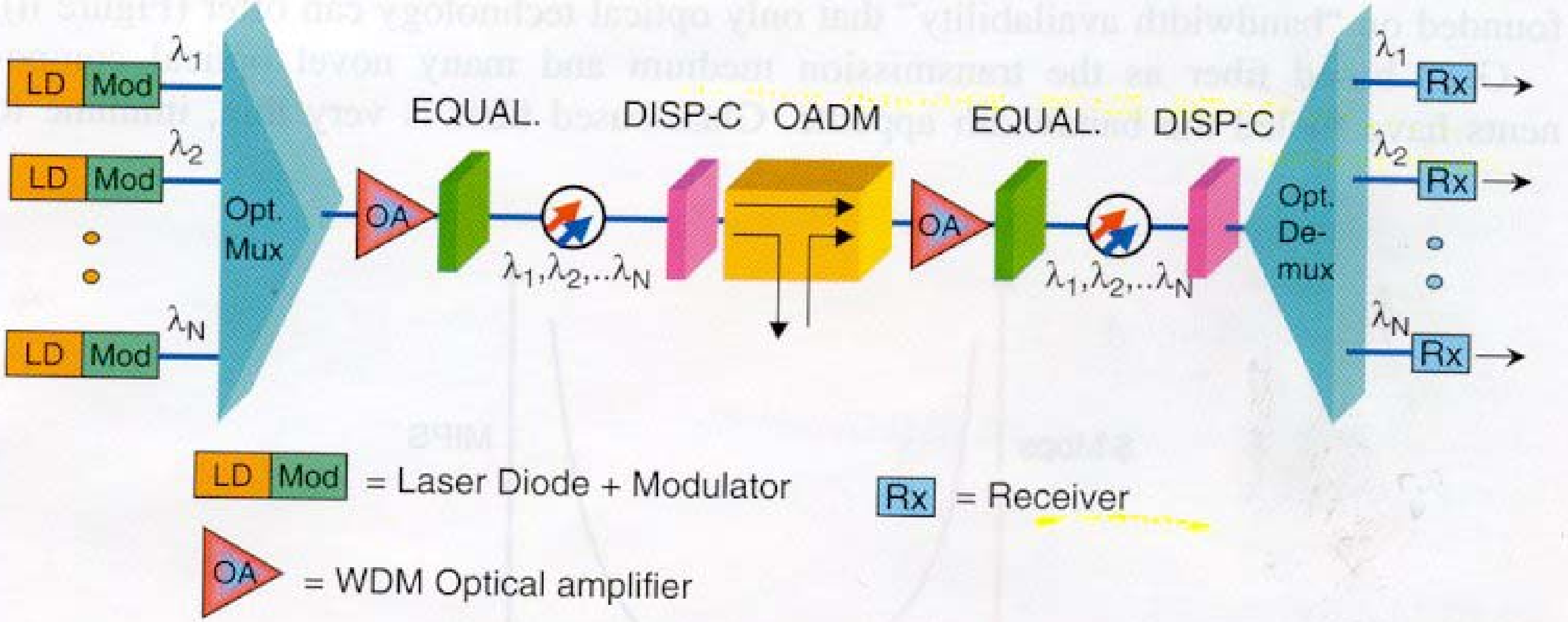


Figure 1. Optical Transmission - Schematic

Big Picture: DWDM Optical components



LD Mod = Laser Diode + Modulator

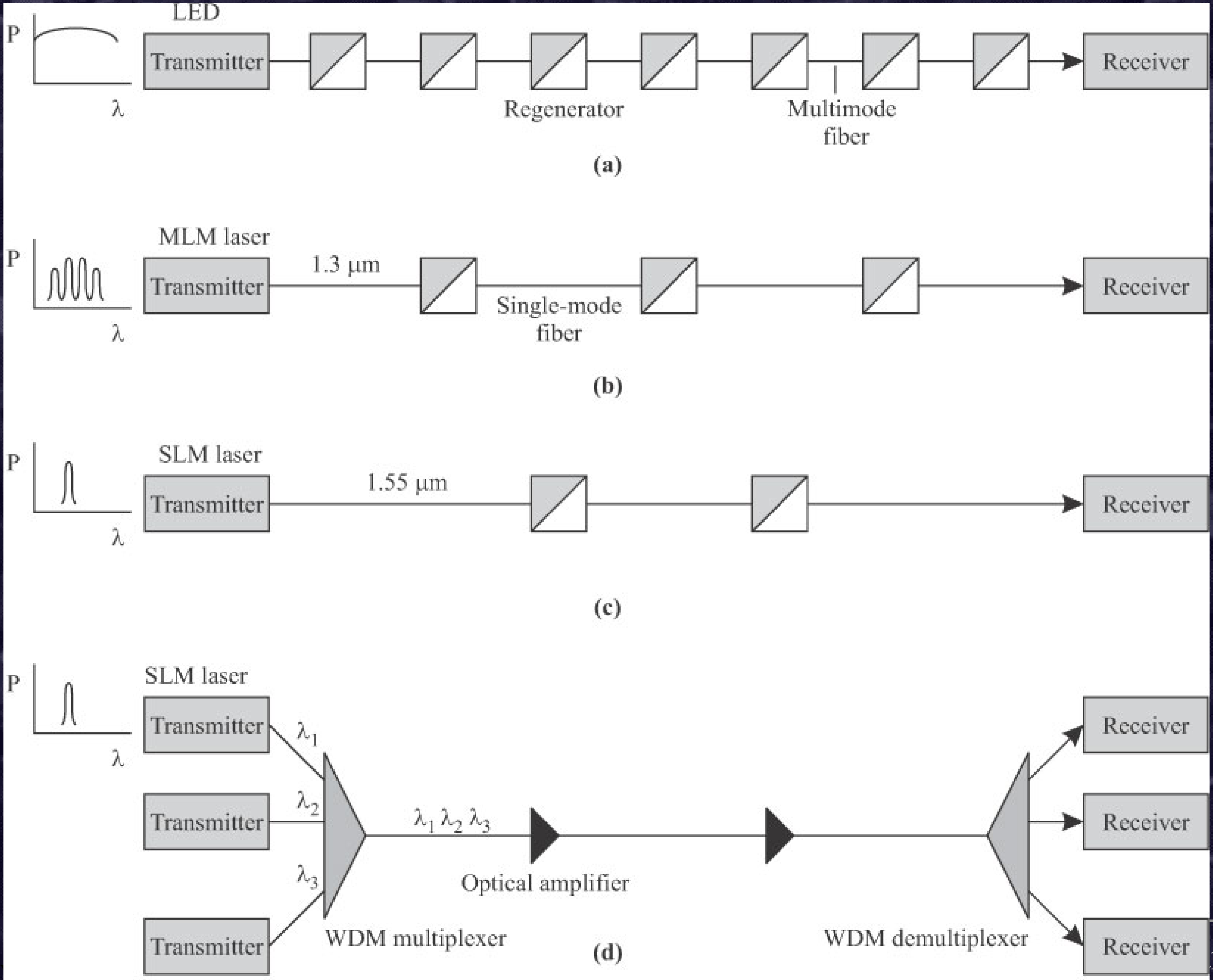
Rx = Receiver

OA = WDM Optical amplifier

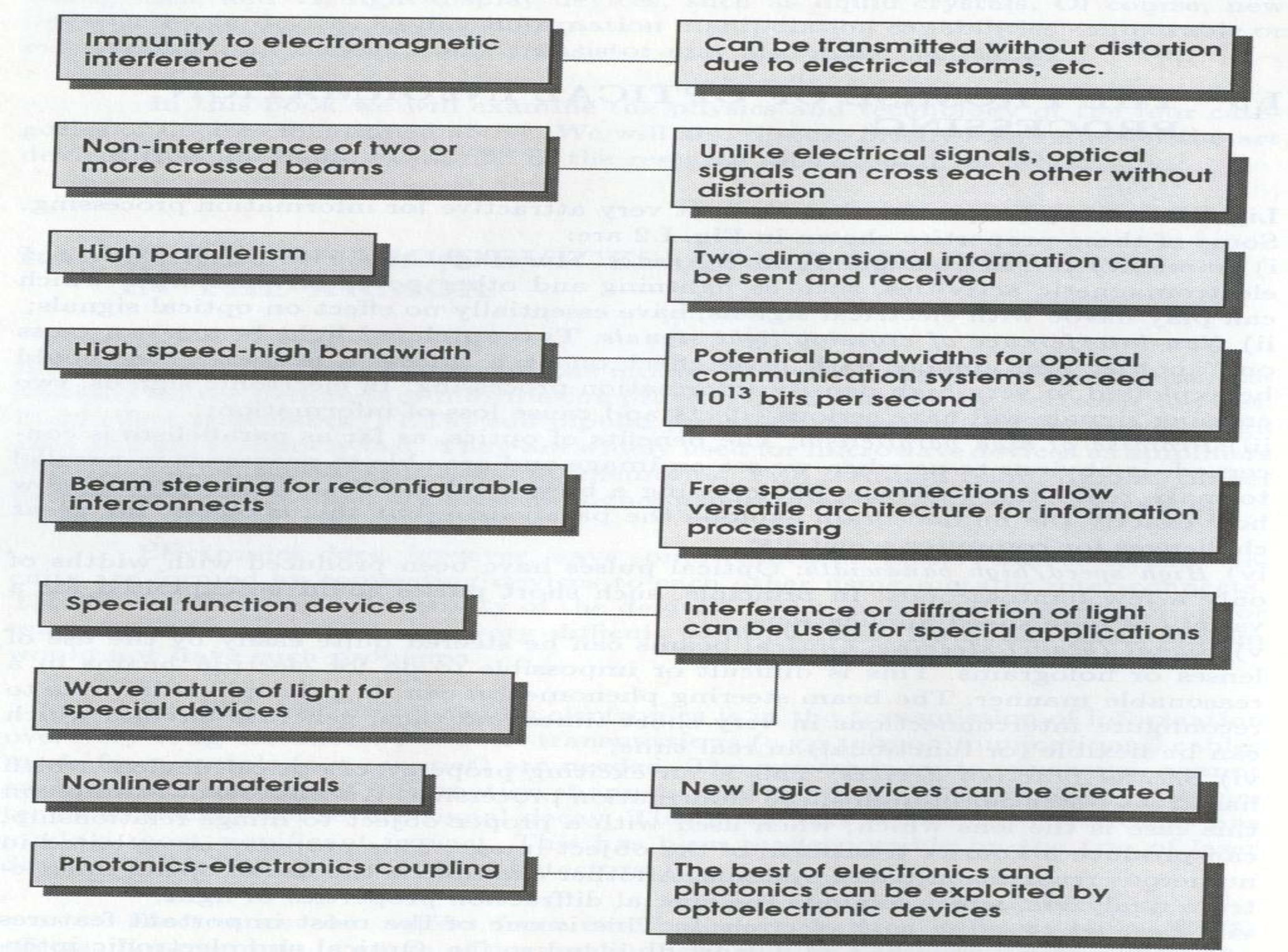
DISP-C = WDM Dispersion compensation
EQUAL. = WDM Equalization
OADM = Optical Add-Drop Multiplexer

Figure iii A broad range of optical components has made it possible for WDM networks to transport several Terabits per second.

Evolution of Fiber Transmission Systems



Bigger Picture: Key Features of Photonics



Immunity to electromagnetic interference	Can be transmitted without distortion due to electrical storms, etc.
Non-interference of two or more crossed beams	Unlike electrical signals, optical signals can cross each other without distortion
High parallelism	Two-dimensional information can be sent and received
High speed-high bandwidth	Potential bandwidths for optical communication systems exceed 10^{13} bits per second
Beam steering for reconfigurable interconnects	Free space connections allow versatile architecture for information processing
Special function devices	Interference or diffraction of light can be used for special applications
Wave nature of light for special devices	
Nonlinear materials	New logic devices can be created
Photonics-electronics coupling	The best of electronics and photonics can be exploited by optoelectronic devices

Electromagnetic Spectrum

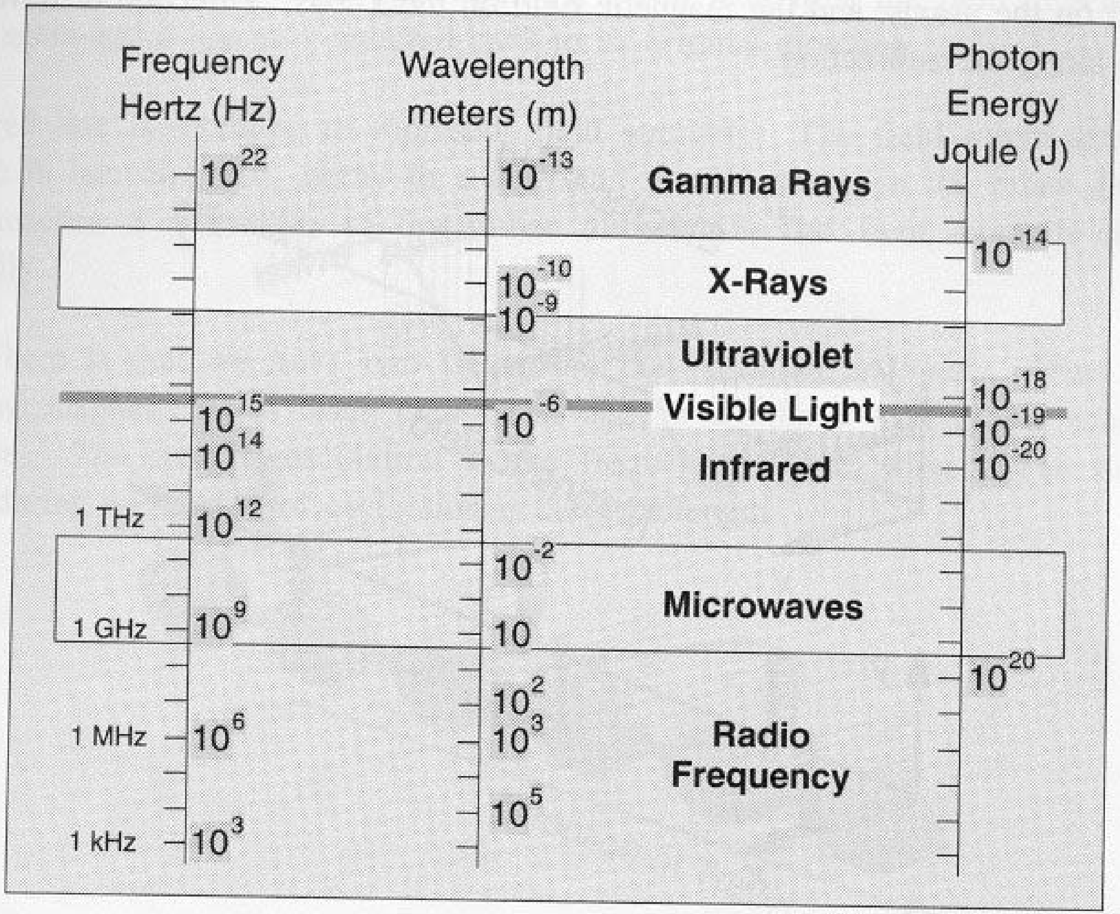
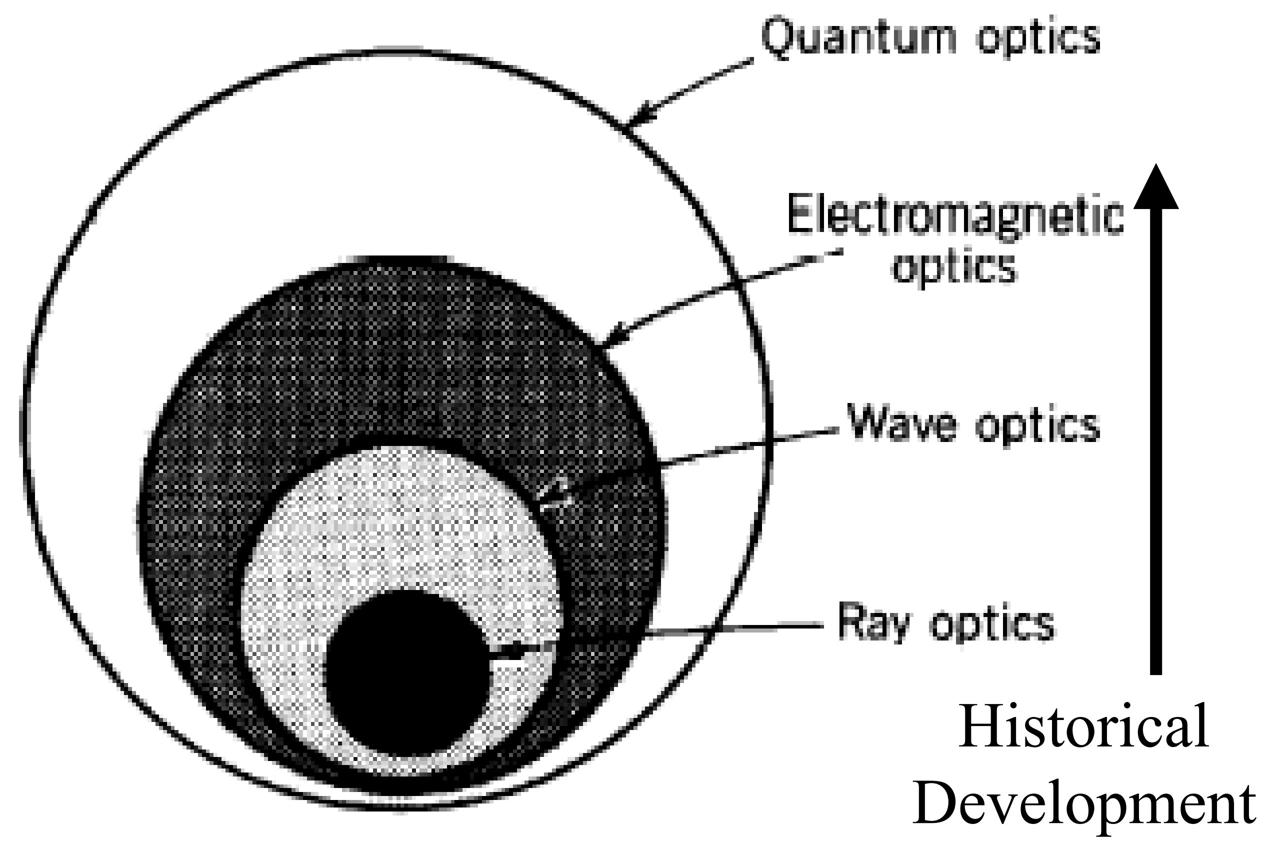


Figure 2. The Electromagnetic Spectrum

What is Light? Theories of Light



What is Light?

- Wave nature:
  - Reflection, refraction, diffraction, interference, polarization, fading, loss …
- Transverse EM (TEM) wave:
  - Interacts with any charges in nearby space…
  - Characterized by frequency, wavelength, phase and propagation speed
  - Simplified Maxwell's equations-analysis for monochromatic, planar waves
  - Photometric terms: luminous flux, candle intensity, illuminance, Luminance…
- Particle nature:
  - Number of photons, min energy: E = hu
  - "Free" space => no matter OR EM fields
  - Trajectory affected by strong EM fields

Light Attributes of Interest

- Dual Nature: EM wave and particle
- Many λs: wide & continuous spectrum
- Polarization: circular, elliptic, linear: affected by *fields and matter*
- Optical Power: wide range; affected by matter
- Propagation:
  - Straight path in free space
  - In matter it is affected variously (absorbed, scattered, through);
  - In waveguides, it follows bends
- Propagation speed: diff λs travel at diff speeds in matter
- Phase: affected by variations in fields and matter

Interaction of Light with Matter

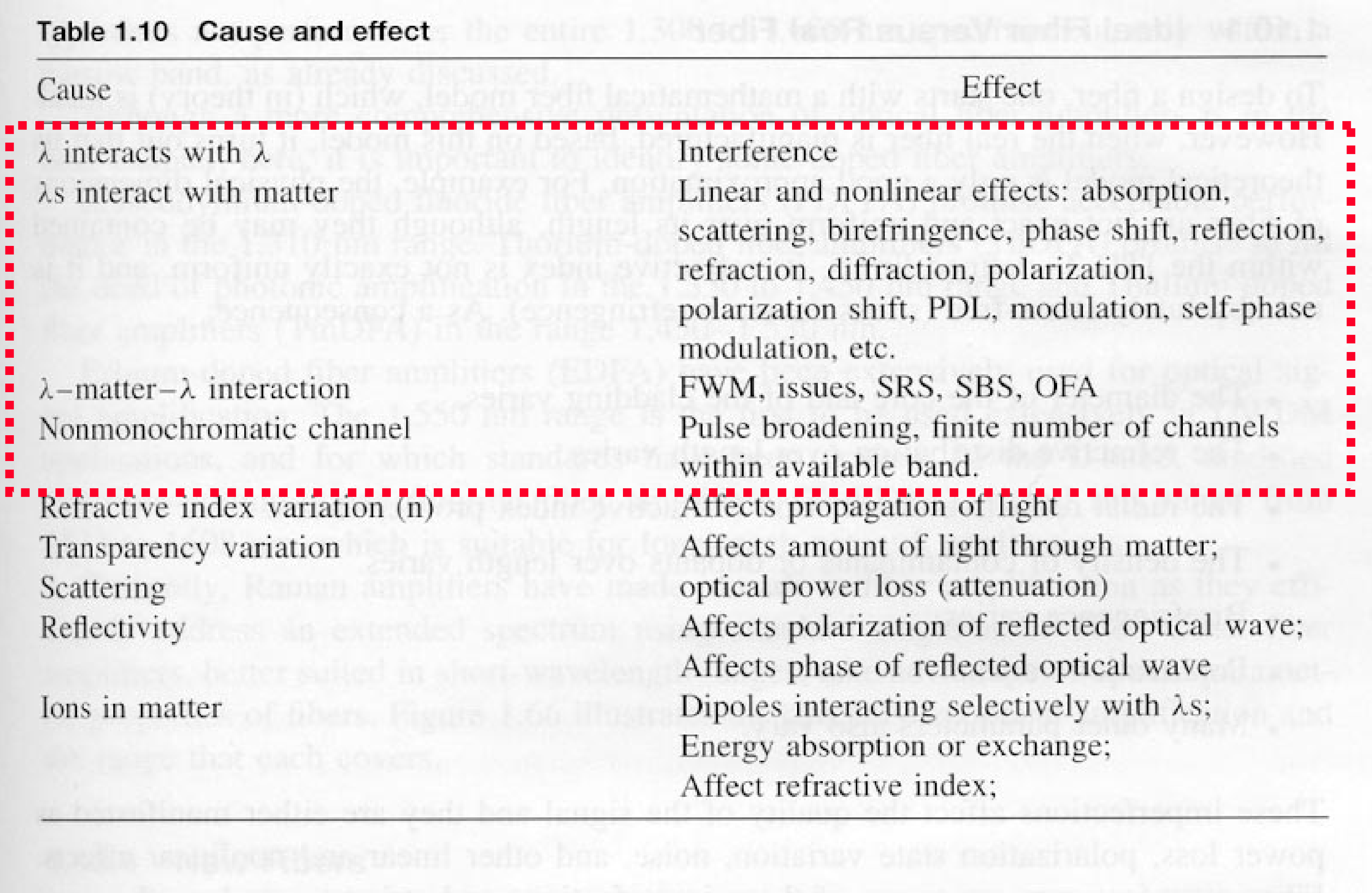


Table 1.10 Cause and effect

Cause	Effect
λ interacts with λ	Interference
λs interact with matter	Linear and nonlinear effects: absorption, scattering, birefringence, phase shift, reflection, refraction, diffraction, polarization, polarization shift, PDL, modulation, self-phase modulation, etc.
λ−matter−λ interaction	FWM, issues, SRS, SBS, OFA
Nonmonochromatic channel	Pulse broadening, finite number of channels within available band.
Refractive index variation (n)	Affects propagation of light
Transparency variation	Affects amount of light through matter;
Scattering	optical power loss (attenuation)
Reflectivity	Affects polarization of reflected optical wave; Affects phase of reflected optical wave
Ions in matter	Dipoles interacting selectively with λs; Energy absorption or exchange; Affect refractive index;

Goal: Light Transmission on Optical Fiber

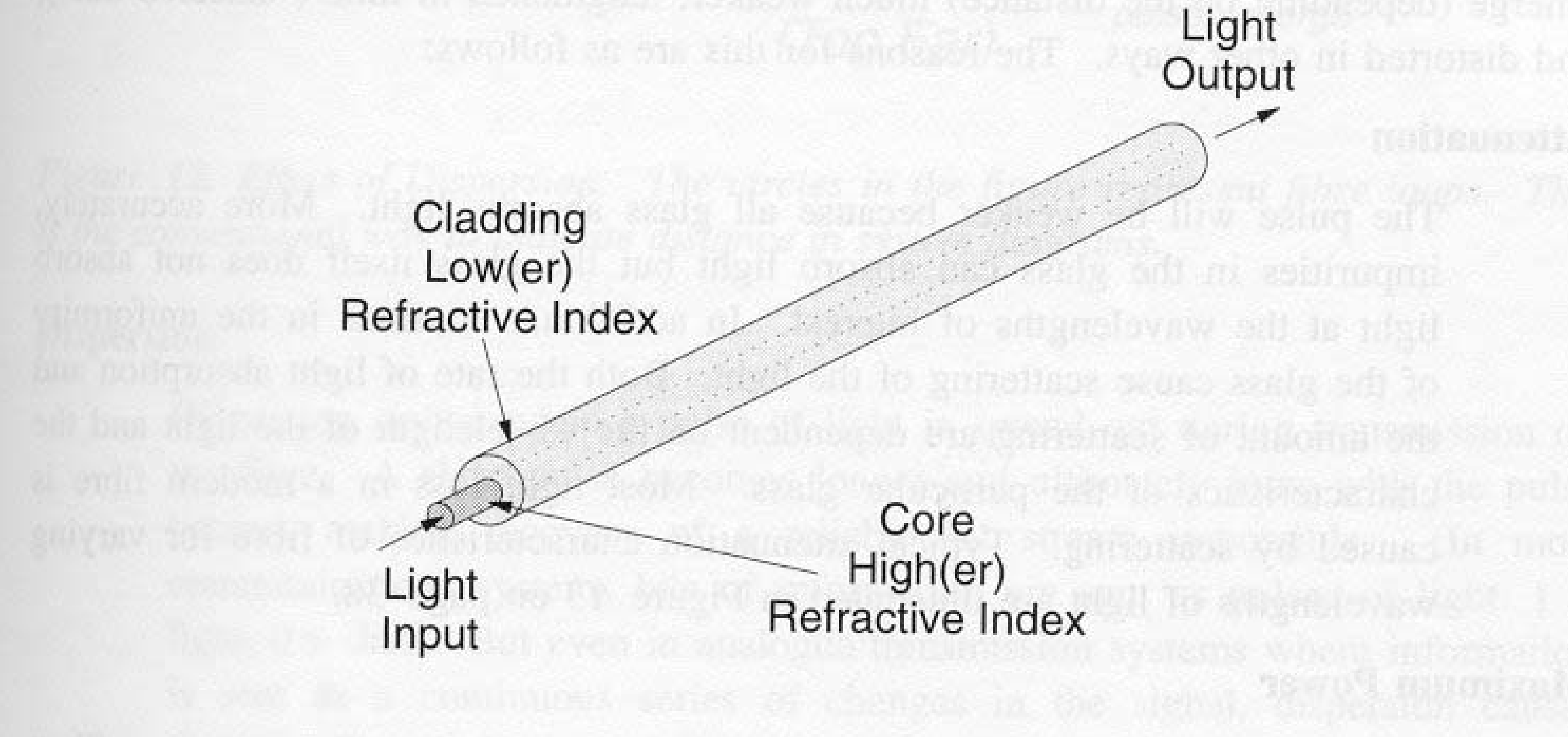
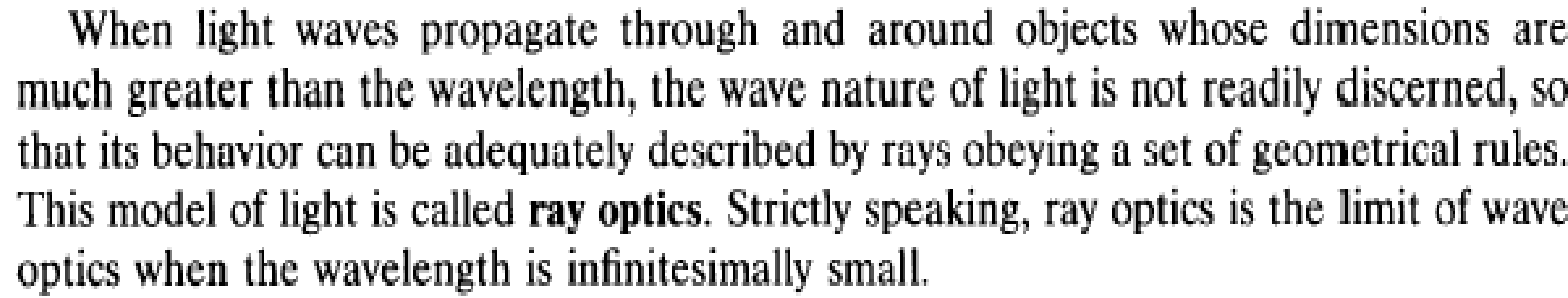


Figure 11. Basic Principle of Light Transmission on Optical Fibre

Need to understand basic ideas of λ interacts with λs and with matter

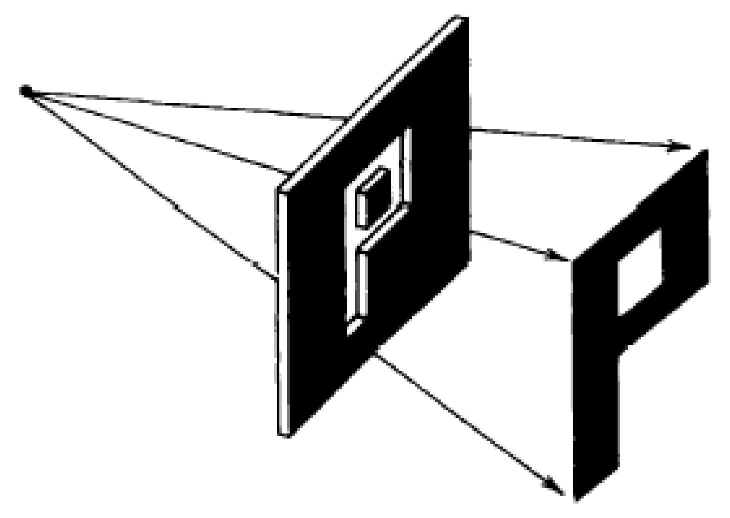
Light interaction with other λs and interaction with matter

Interaction with Matter: Ray Optics

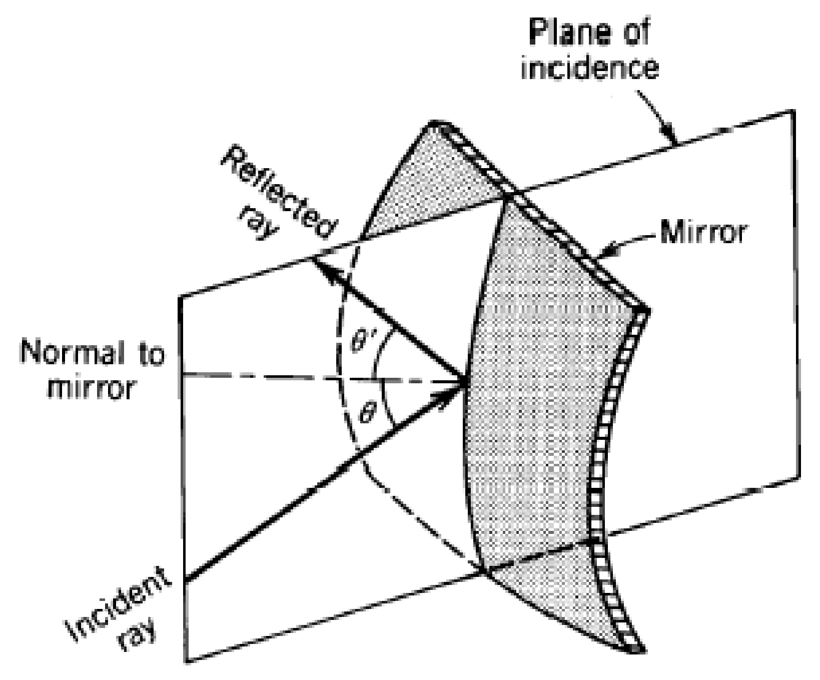


When light waves propagate through and around objects whose dimensions are much greater than the wavelength, the wave nature of light is not readily discerned, so that its behavior can be adequately described by rays obeying a set of geometrical rules. This model of light is called **ray optics**. Strictly speaking, ray optics is the limit of wave optics when the wavelength is infinitesimally small.

- Light rays travel in straight lines

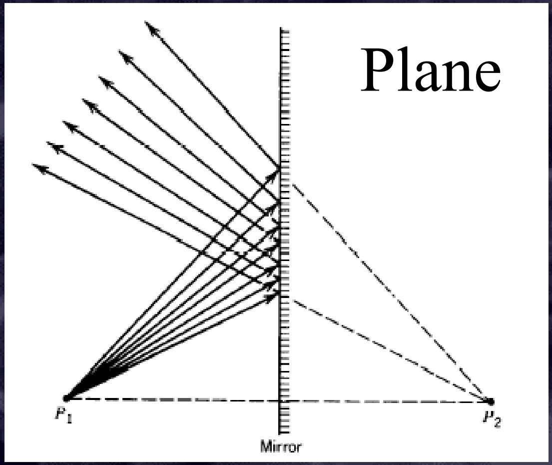


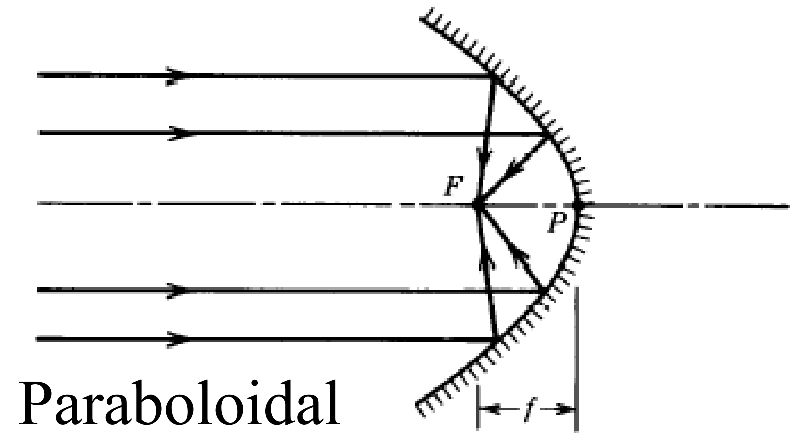
Reflection of Light

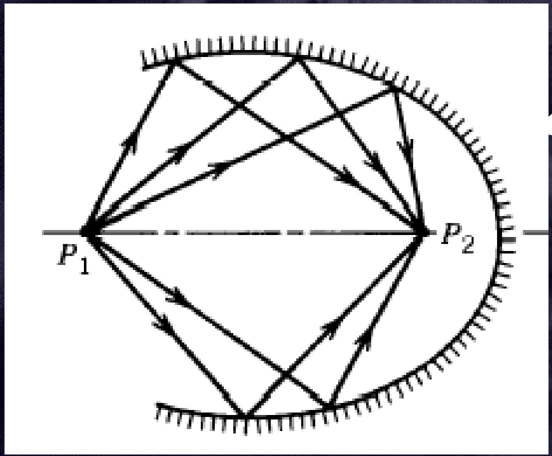


The reflected ray lies in the plane of incidence; the angle of reflection equals the angle of incidence.

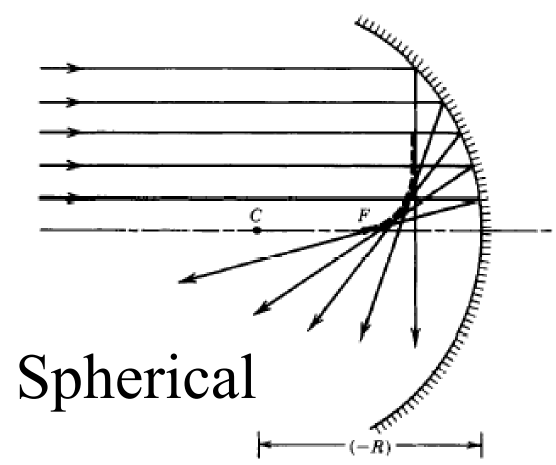
Reflection Applications: Mirrors & MEMS



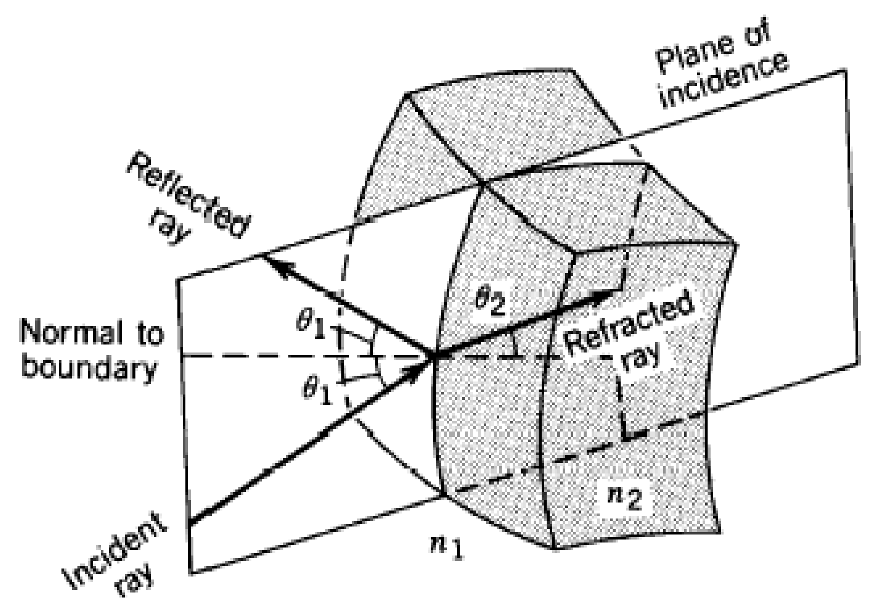




Elliptical



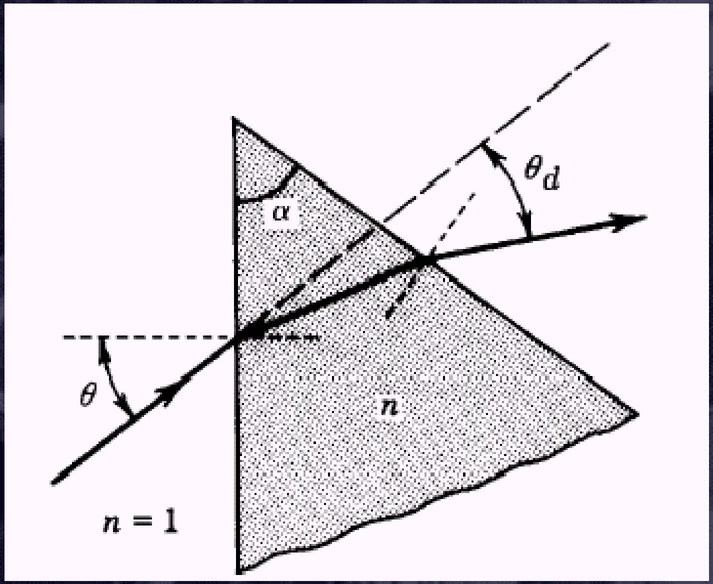
Refraction of Light

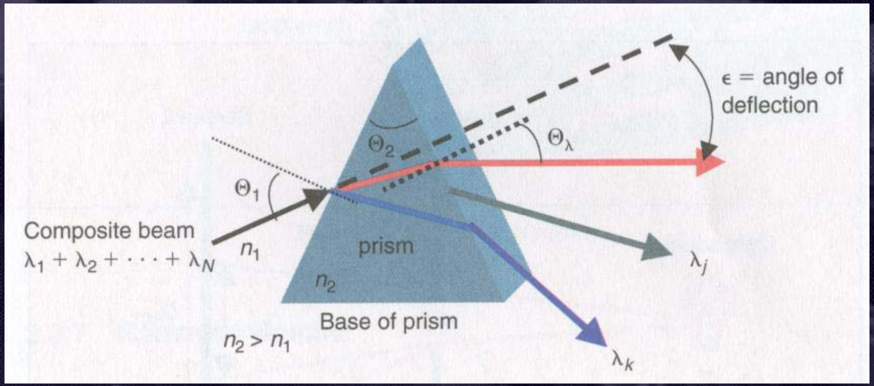


The refracted ray lies in the plane of incidence; the angle of refraction θ_2 *is related to the angle of incidence* θ_1 *by Snell's law,*

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 .$$

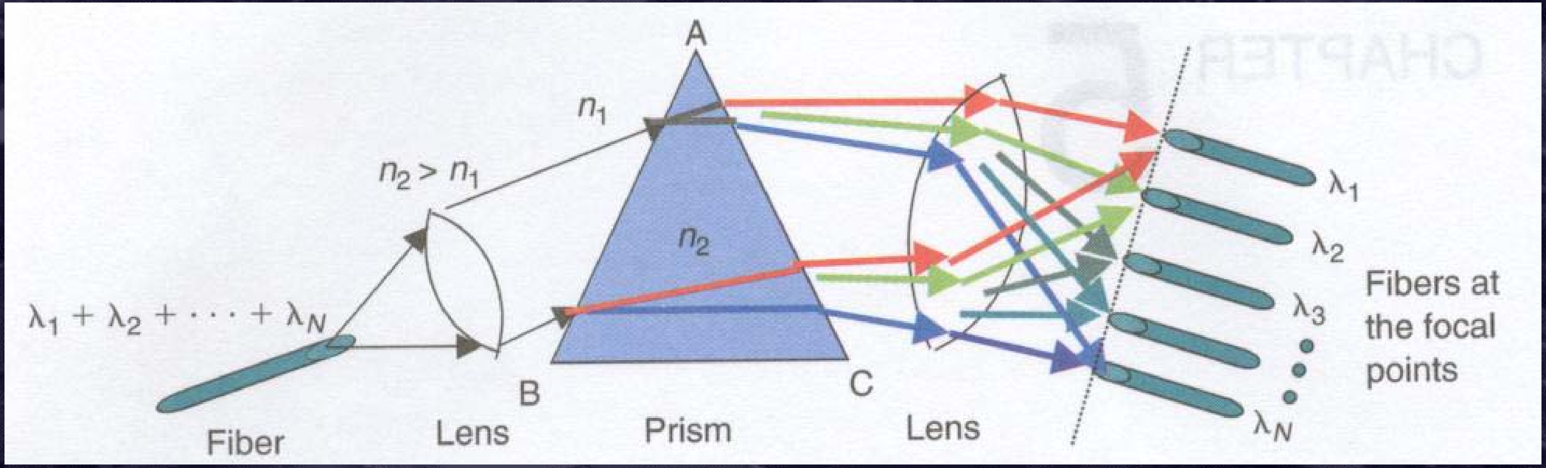
Ray Deflection by Prism

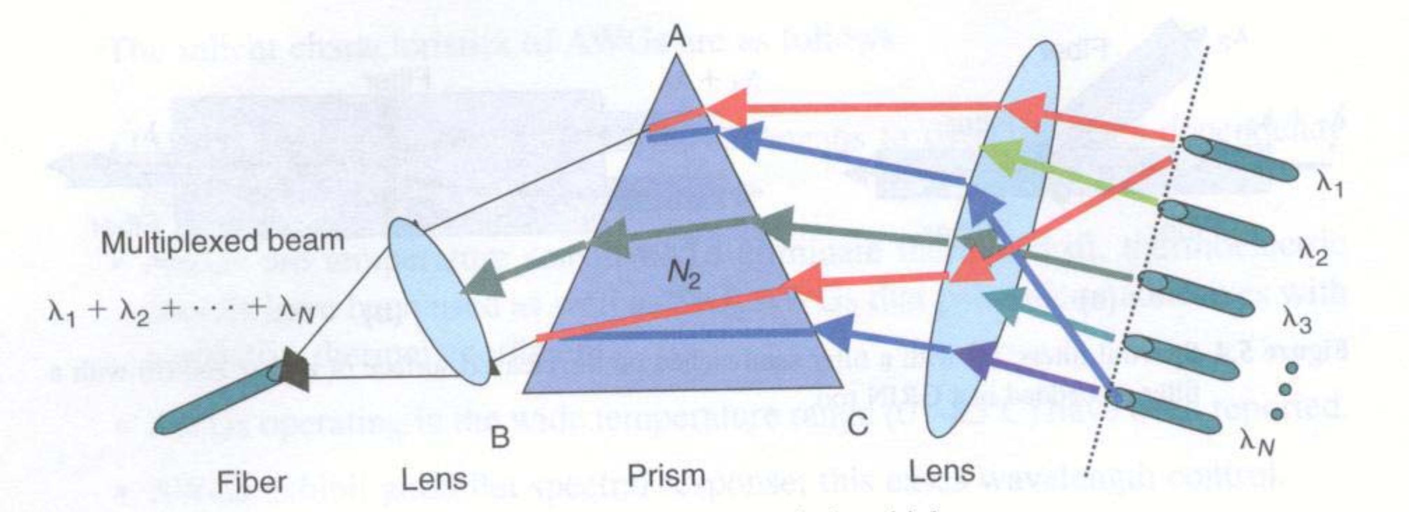




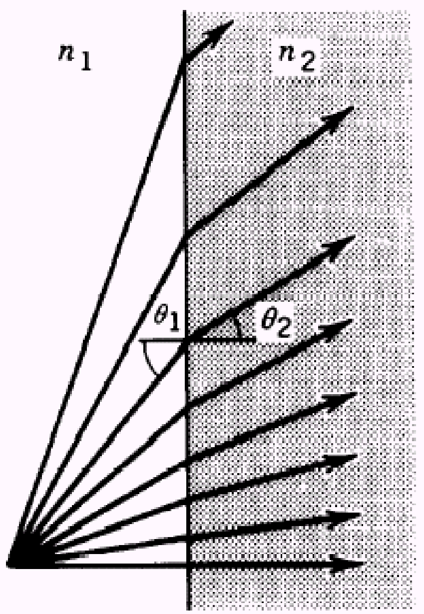
- Newton’s Rainbow: Deflection angle dependent on the wavelength;
- Used in optical multiplexers and de-multiplexers !

Optical Multiplexer & DeMultiplexer

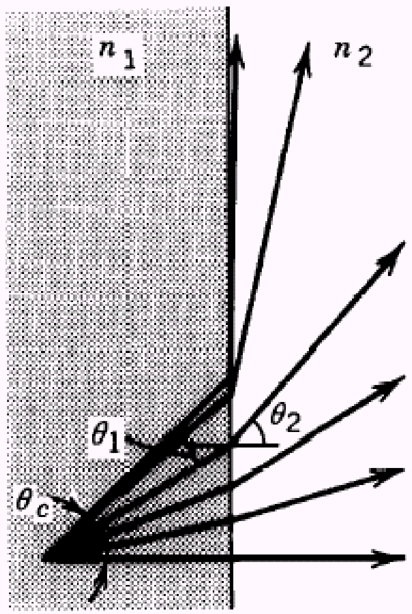




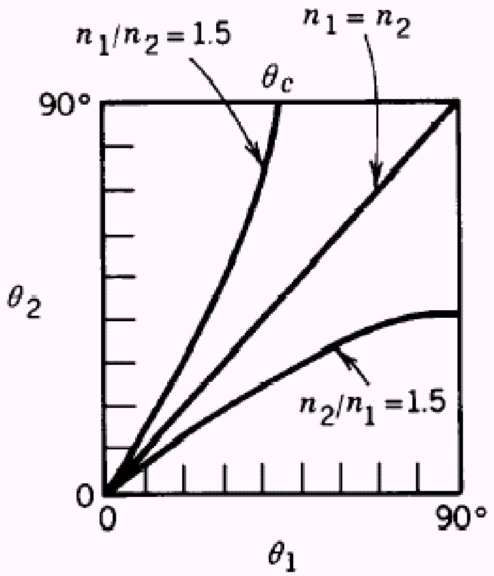
Internal & External Reflections



External refraction



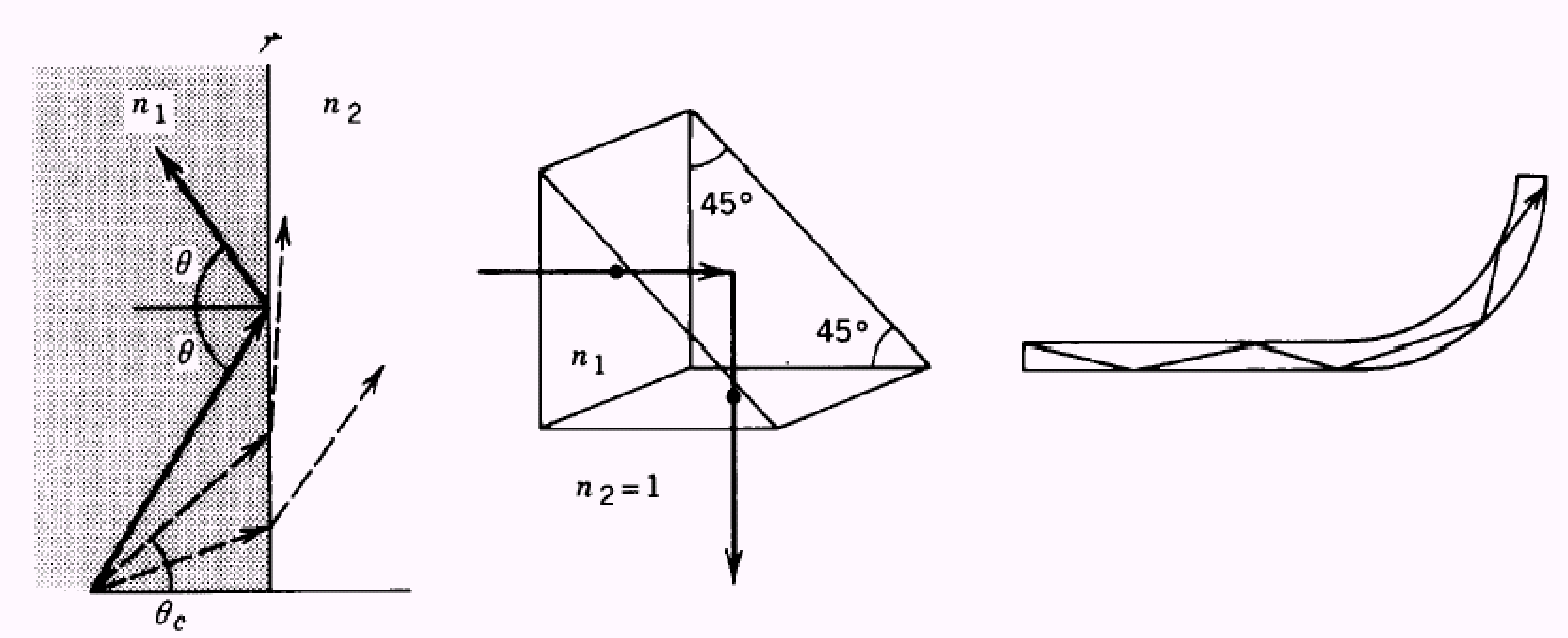
Internal refraction



- Critical Angle for Total Internal Reflection:

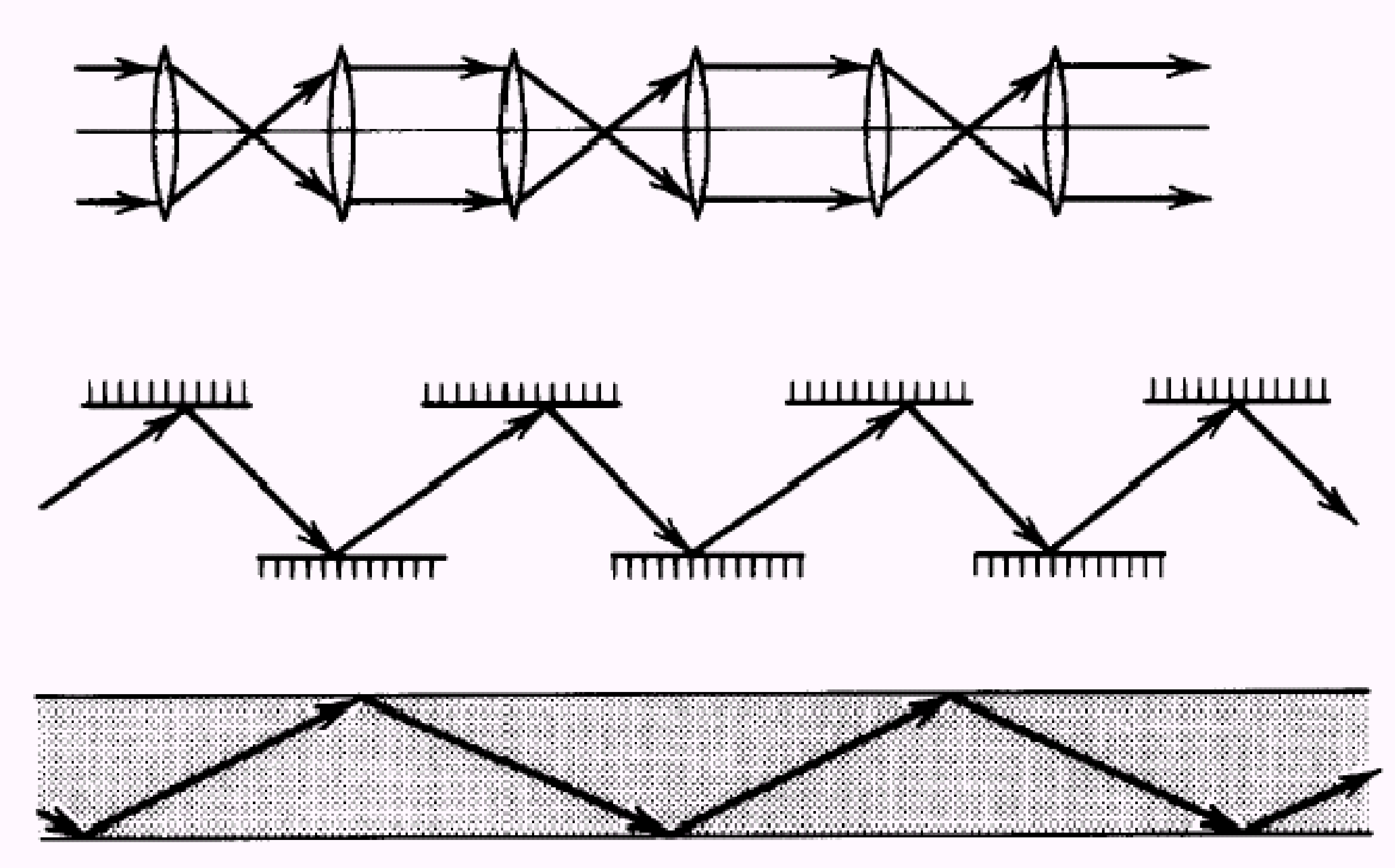
$$\theta_c = \sin^{-1}\frac{n_2}{n_1}.$$

Total Internal Reflection

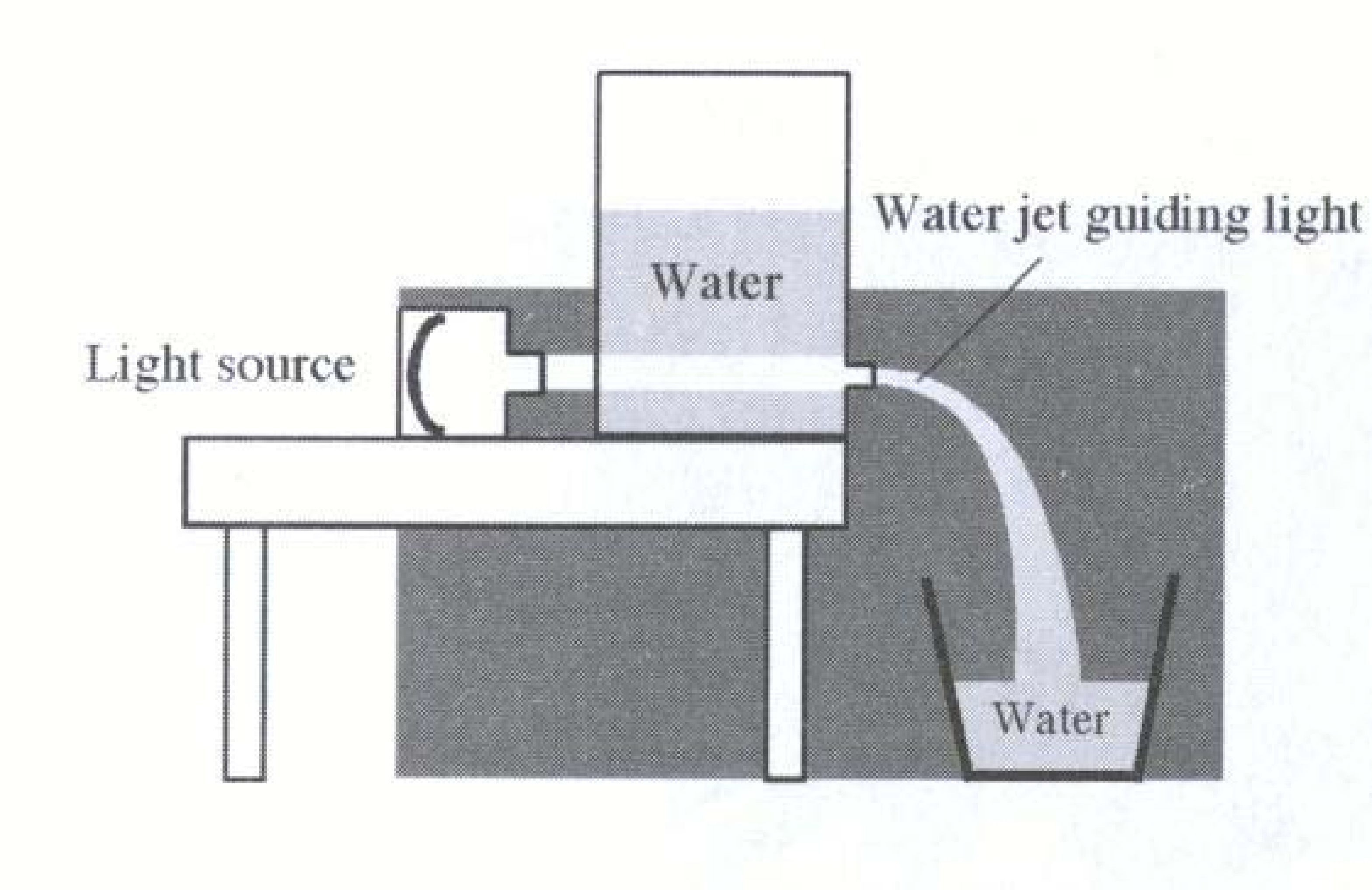


- Total internal reflection forms the back-bone for fiber optical communication

Light (Wave) Guides: Reflection vs Total Internal Reflection

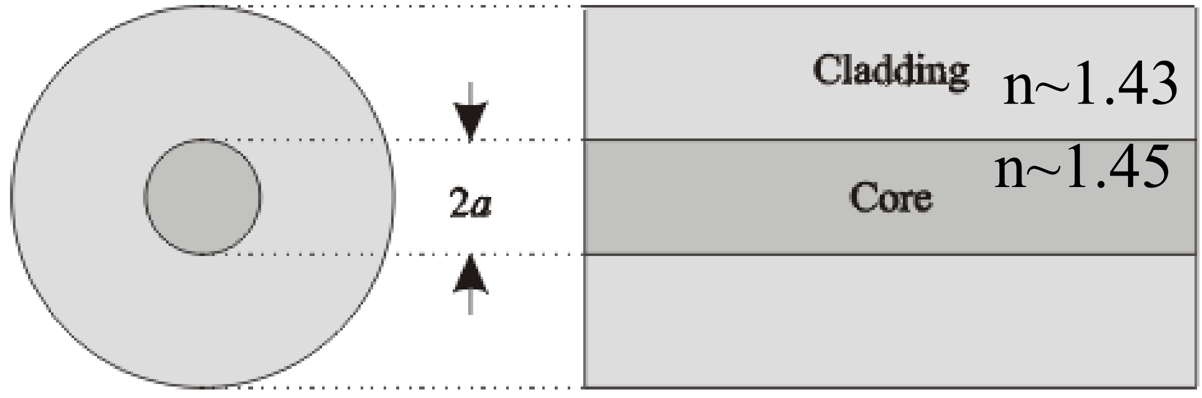


Light Guiding: Concept of Optical Fiber



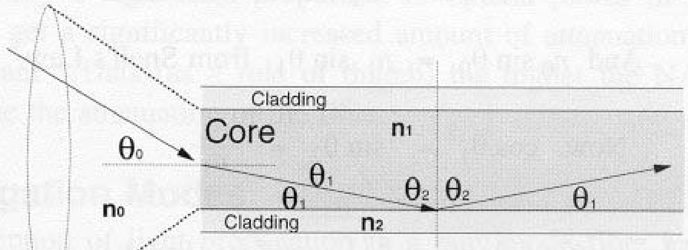
Geometrical Optics: Fiber Structure

- Fiber Made of Silica: SiO_2 (primarily)
- Refractive Index, $n = c_{vacuum}/c_{material}$
- $n_{core} > n_{cladding}$



- Numerical Aperture:

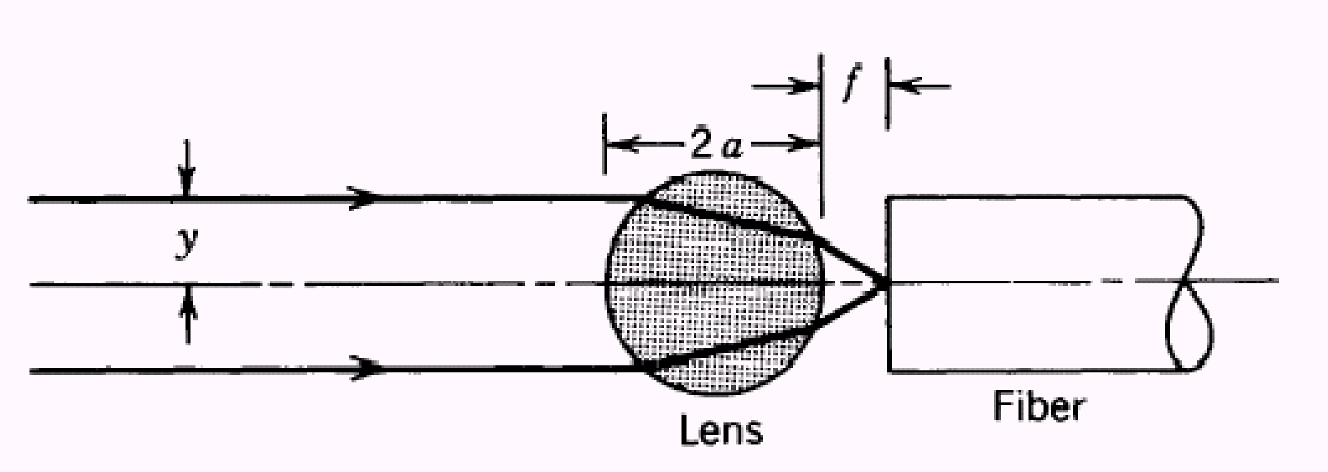
Measures light-gathering capability



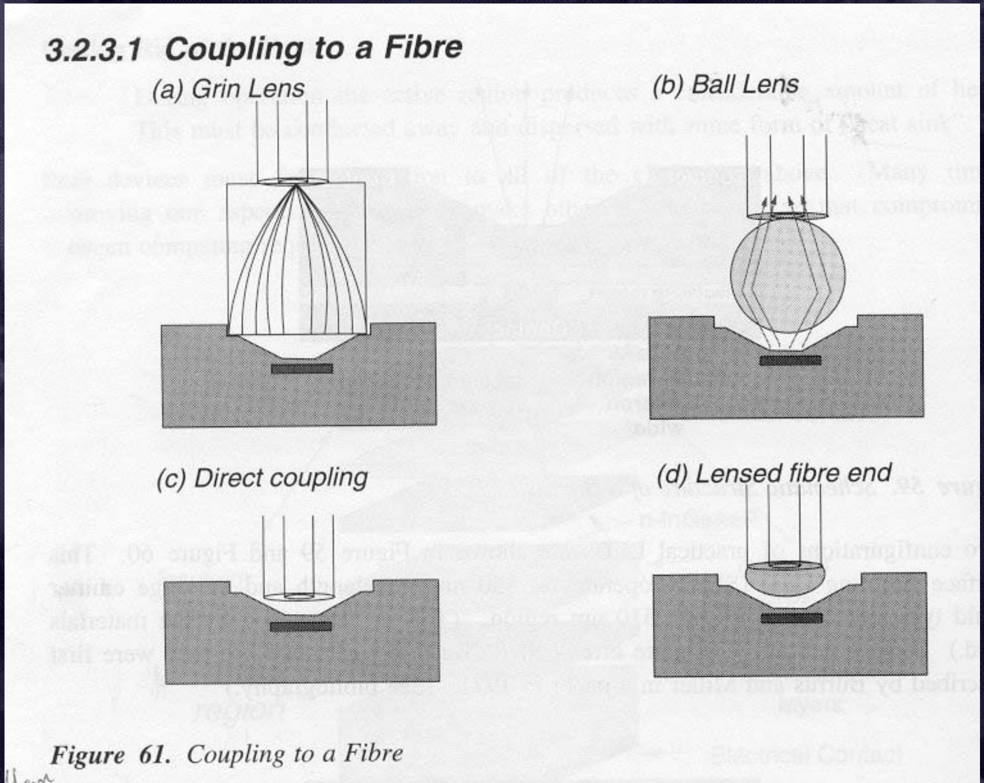
n_0 = refractive index of air (= 1)
n_1 = refractive index of core
n_2 = refractive index of cladding

Figure 26. Calculating the Numerical Aperture

Light Coupling into a fiber



Effect of numerical aperture…



3.2.3.1 Coupling to a Fibre

(a) Grin Lens

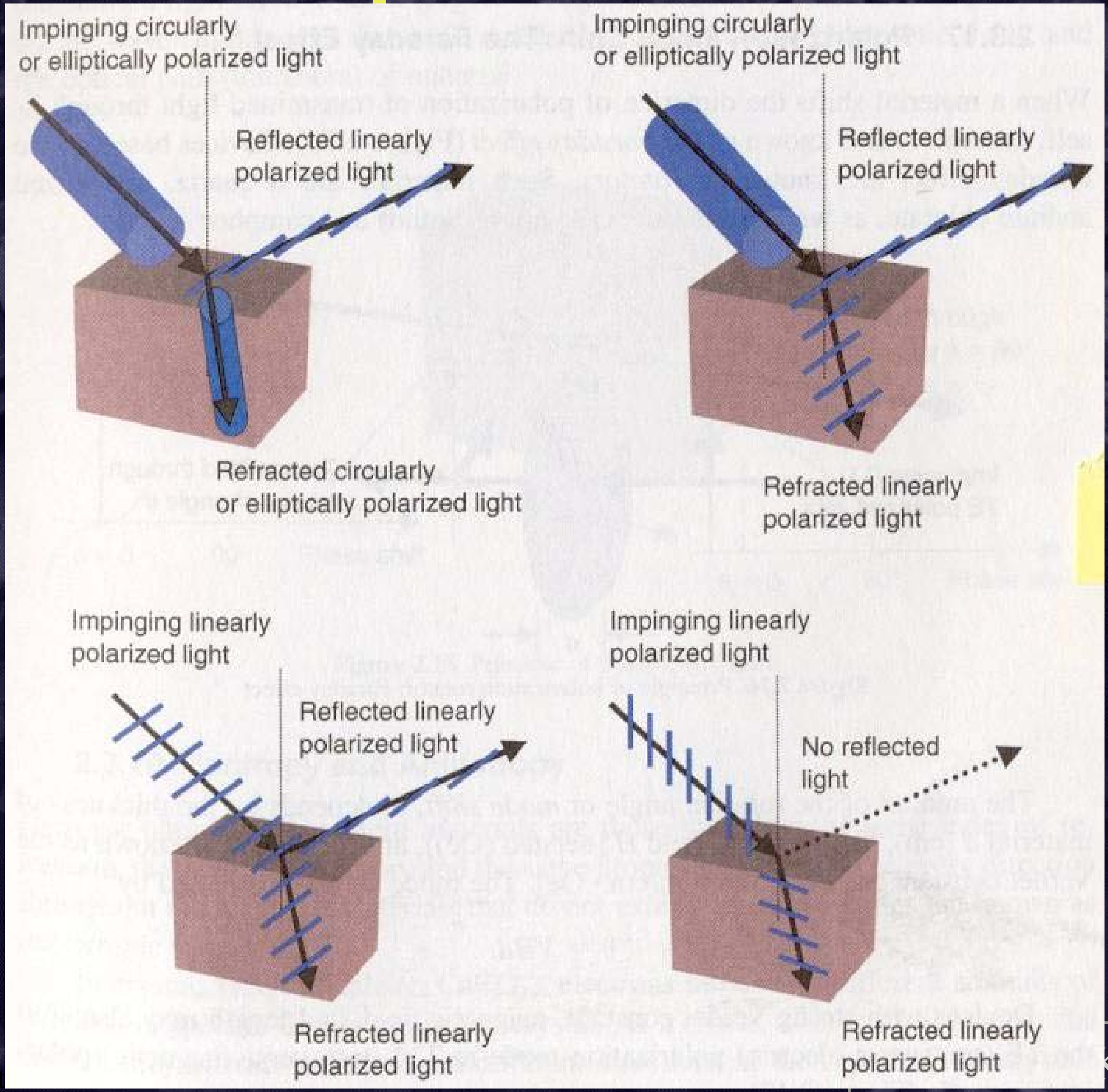
(b) Ball Lens

(c) Direct coupling

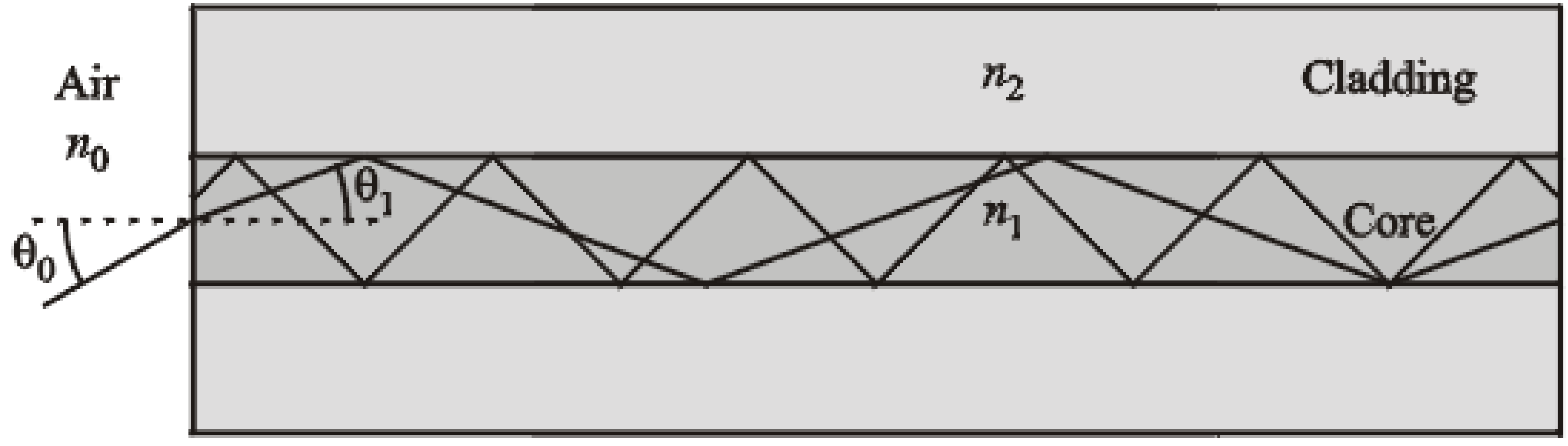
(d) Lensed fibre end

Figure 61. Coupling to a Fibre

Light Coupling is Polarization Dependent



Geometrical Optics Applied to Fiber



- Light propagates by total internal reflection
- Modal Dispersion: Different path lengths cause energy in narrow pulse to spread out
- δT = time difference between fastest and slowest ray

Total Internal Reflection & Modes

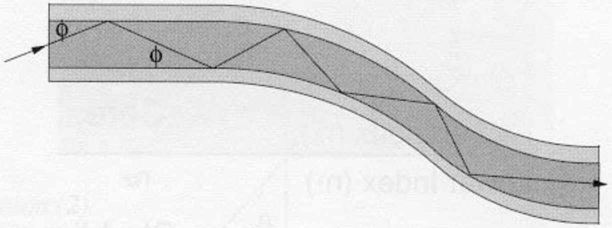


Figure 20. Light Propagation in Multimode Fibre. Light is bound within the fibre due to the phenomena of "total internal reflection" which takes place at the interface between the core of the fibre and the cladding.

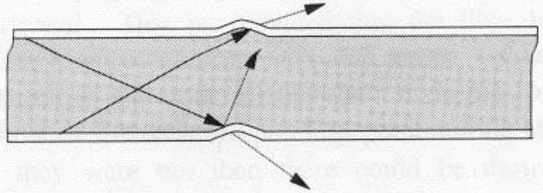


***Figure 30.** Effect of a Micro-Bend*

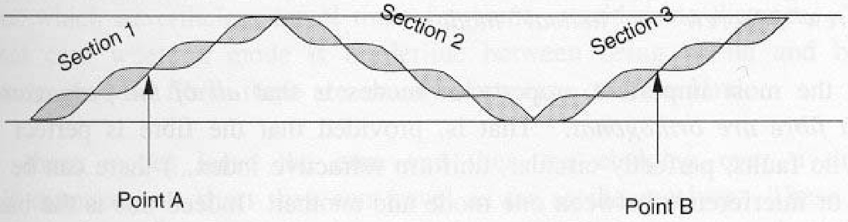


Figure 27. Multimode Propagation. At corresponding points in its path, each mode must be in phase with itself. That is, the signal at Point A must be in phase with the signal at Point B.

- Impacts how much a fiber can be bent!
- Micro-bends can eat up energy, kill some modes!
- Modes are standing wave patterns in wave- or EM-optics!

EM Optics: Optical Electromagnetic Wave

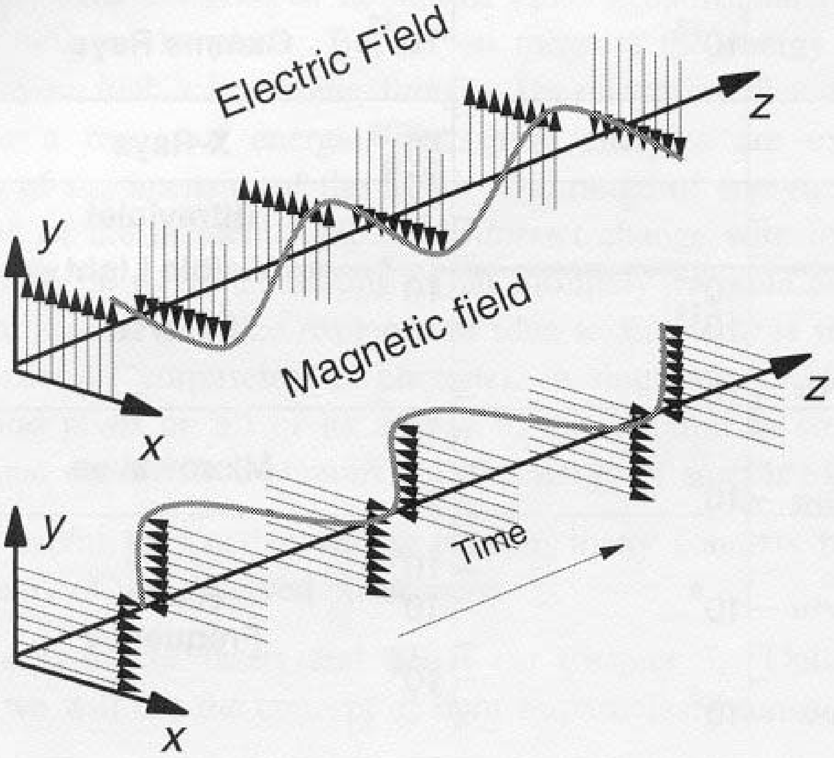


Figure 3. *The Structure of an Electromagnetic Wave. Electric and magnetic fields are actually superimposed over the top of one another but are illustrated separately for clarity in illustration. The z-direction can be considered to be either a representation in space or the passing of time at a single point.*

Linear polarization assumed …

Amplitude Fluctuations of TEM Waves

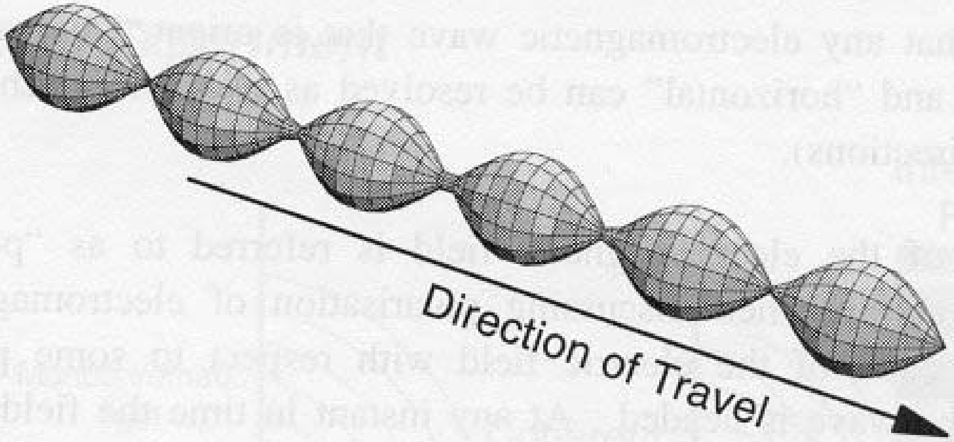
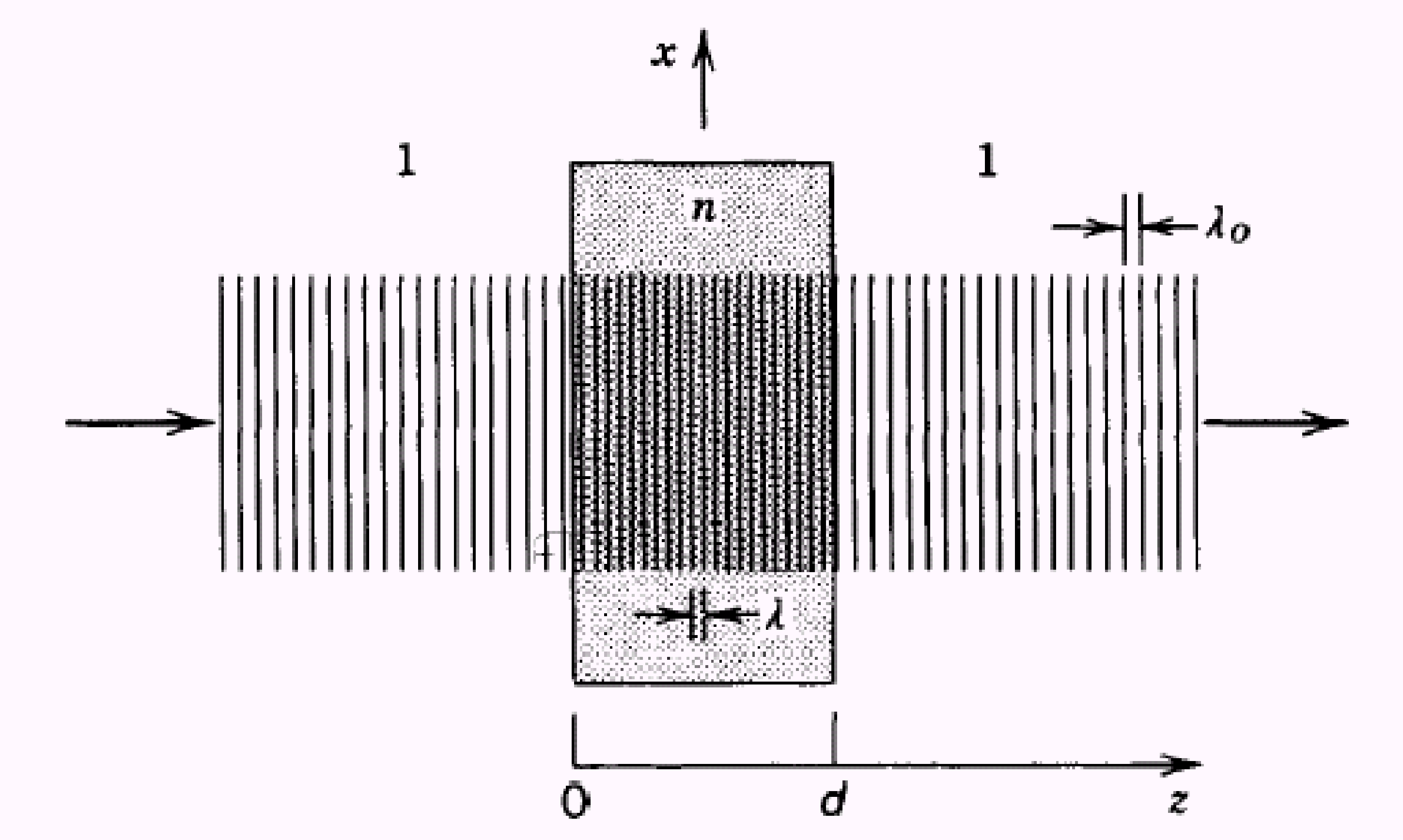


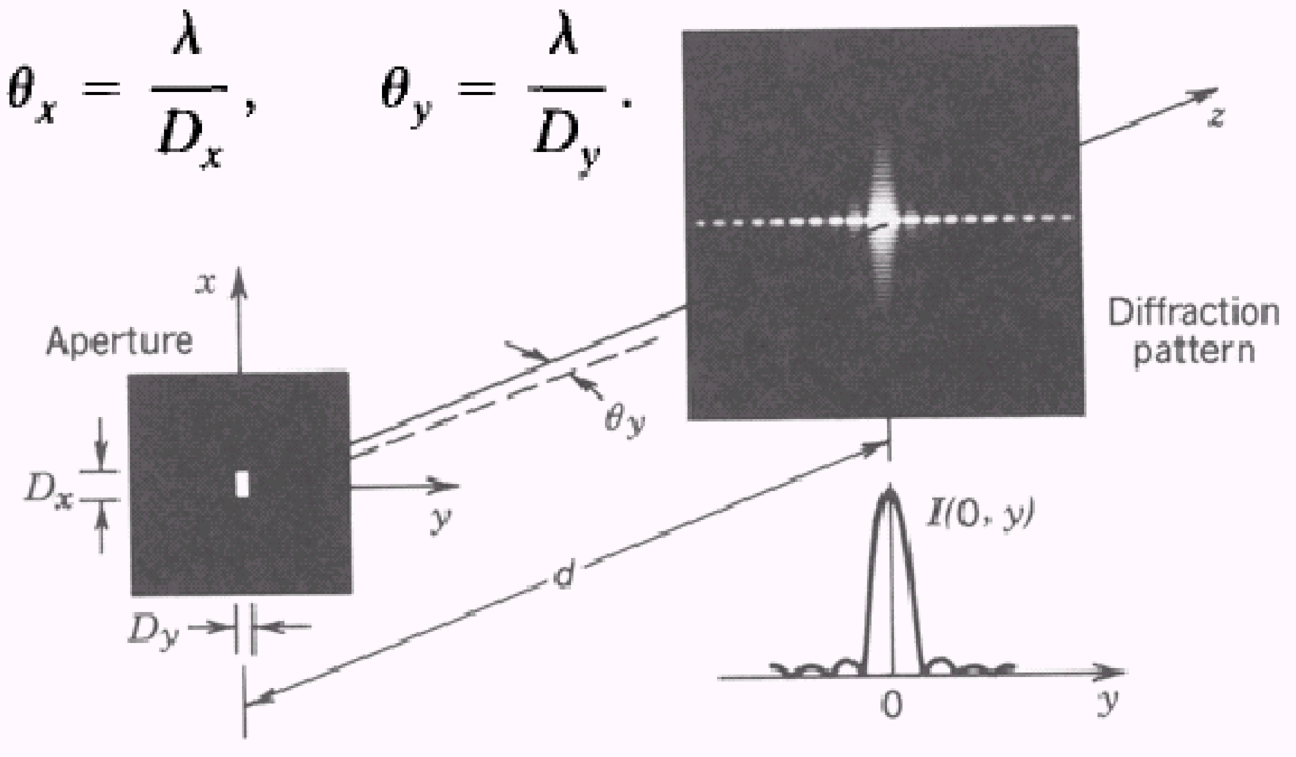
Figure 4. *Amplitude Fluctuation in an Electromagnetic Wave. Here both the electric field and the magnetic field are shown as a single field oscillating about a locus of points which forms the line of travel.*

Speed of Light in a Medium

As a monochromatic wave propagates through media of different refractive indices, its frequency remains same, but its velocity, wavelength and wavenumber are altered.



Diffraction or Fresnel Phenomenon



$$\theta_x = \frac{\lambda}{D_x}, \qquad \theta_y = \frac{\lambda}{D_y}.$$

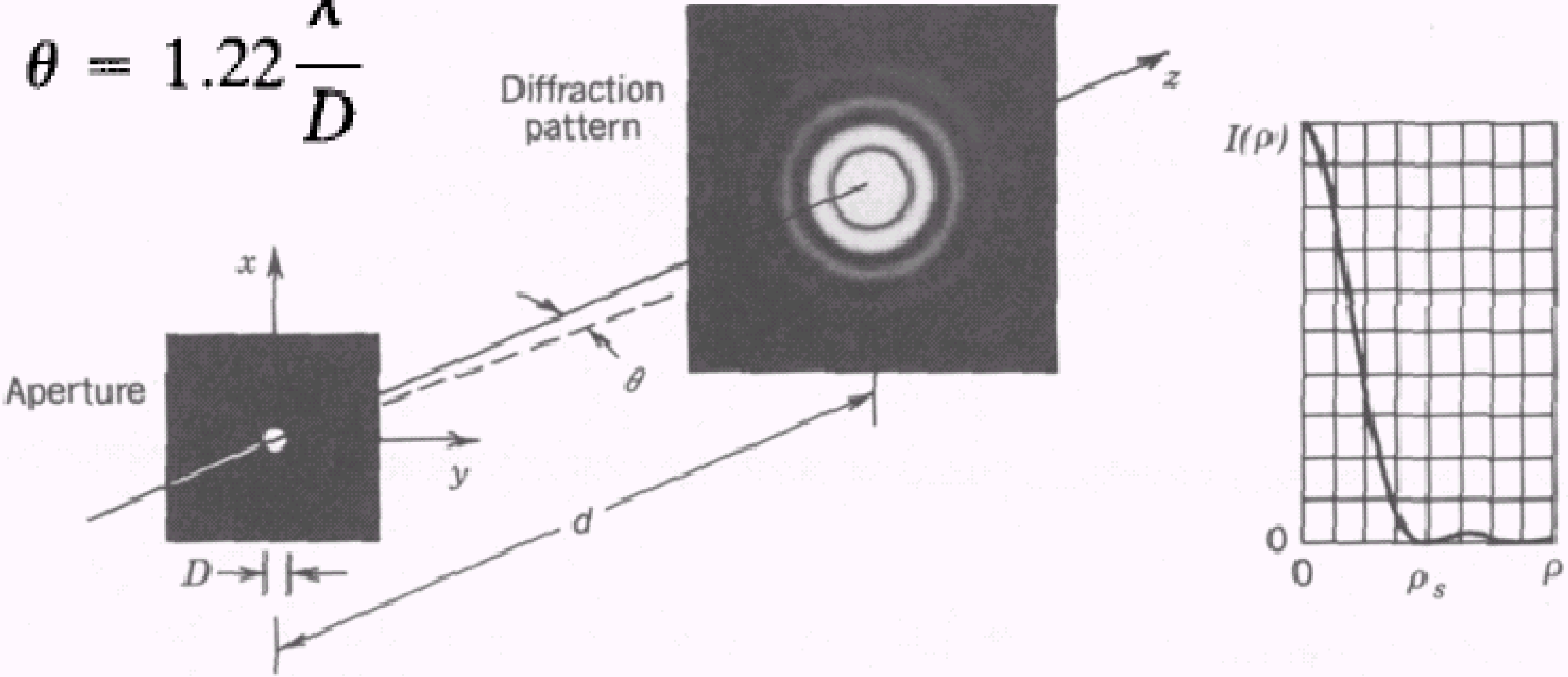
$$D_y < D_x$$

diffraction pattern is wider in the y direction

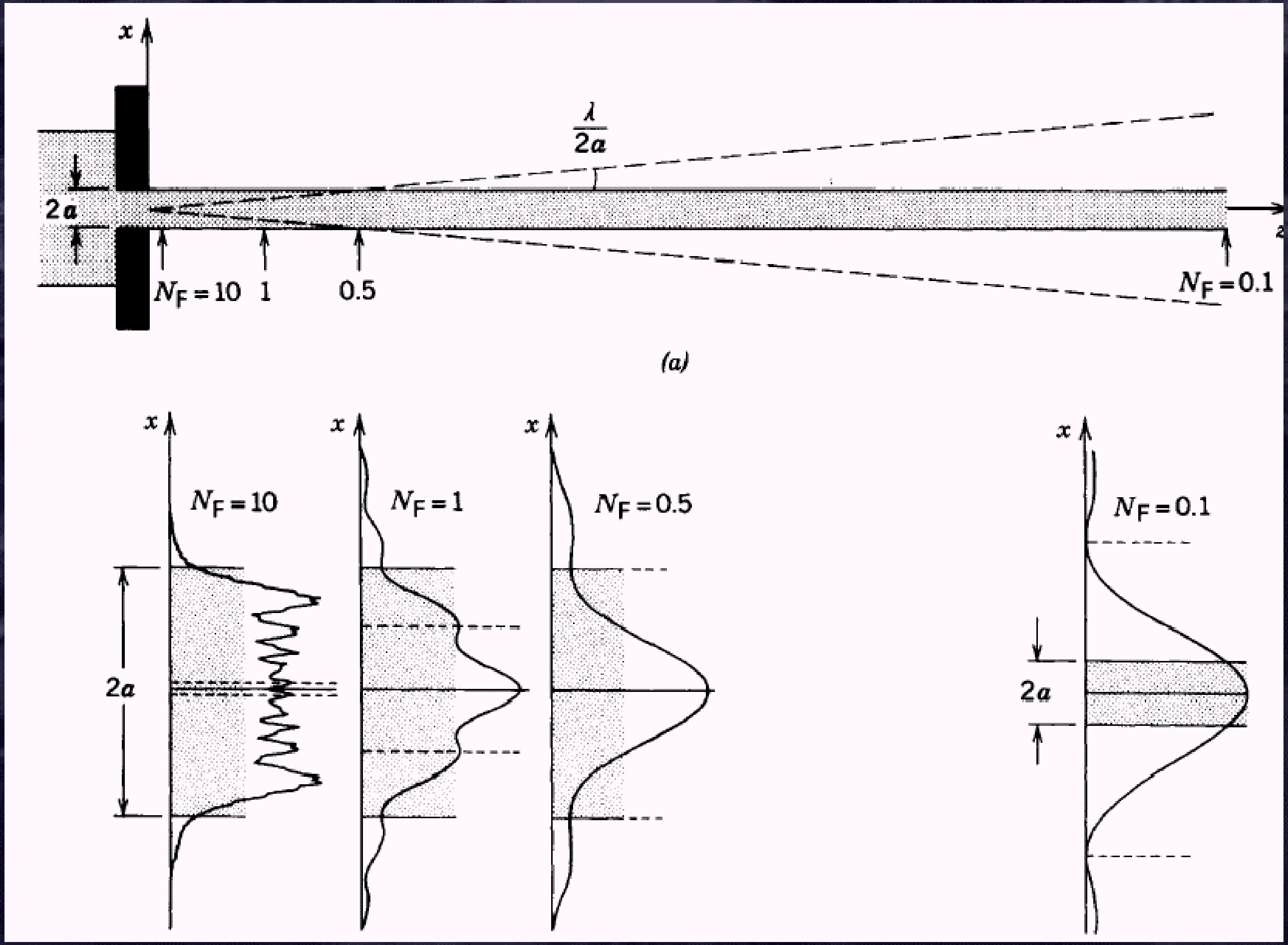
Cannot be explained by ray optics!

Diffraction Pattern from a Circular Aperture

$$\theta = 1.22\frac{\lambda}{D}$$

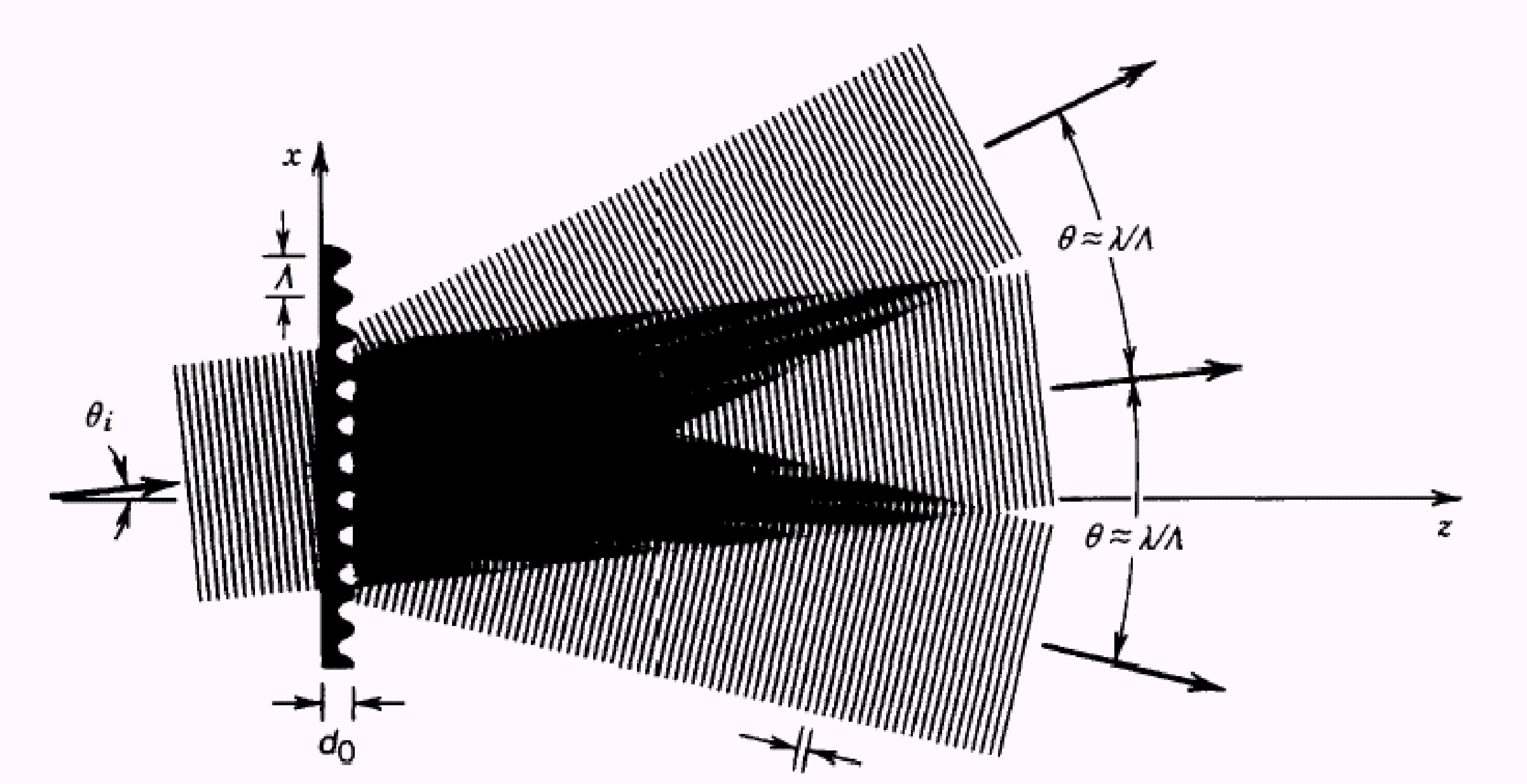


Diffraction Patterns at Different Axial Positions



Diffraction Grating

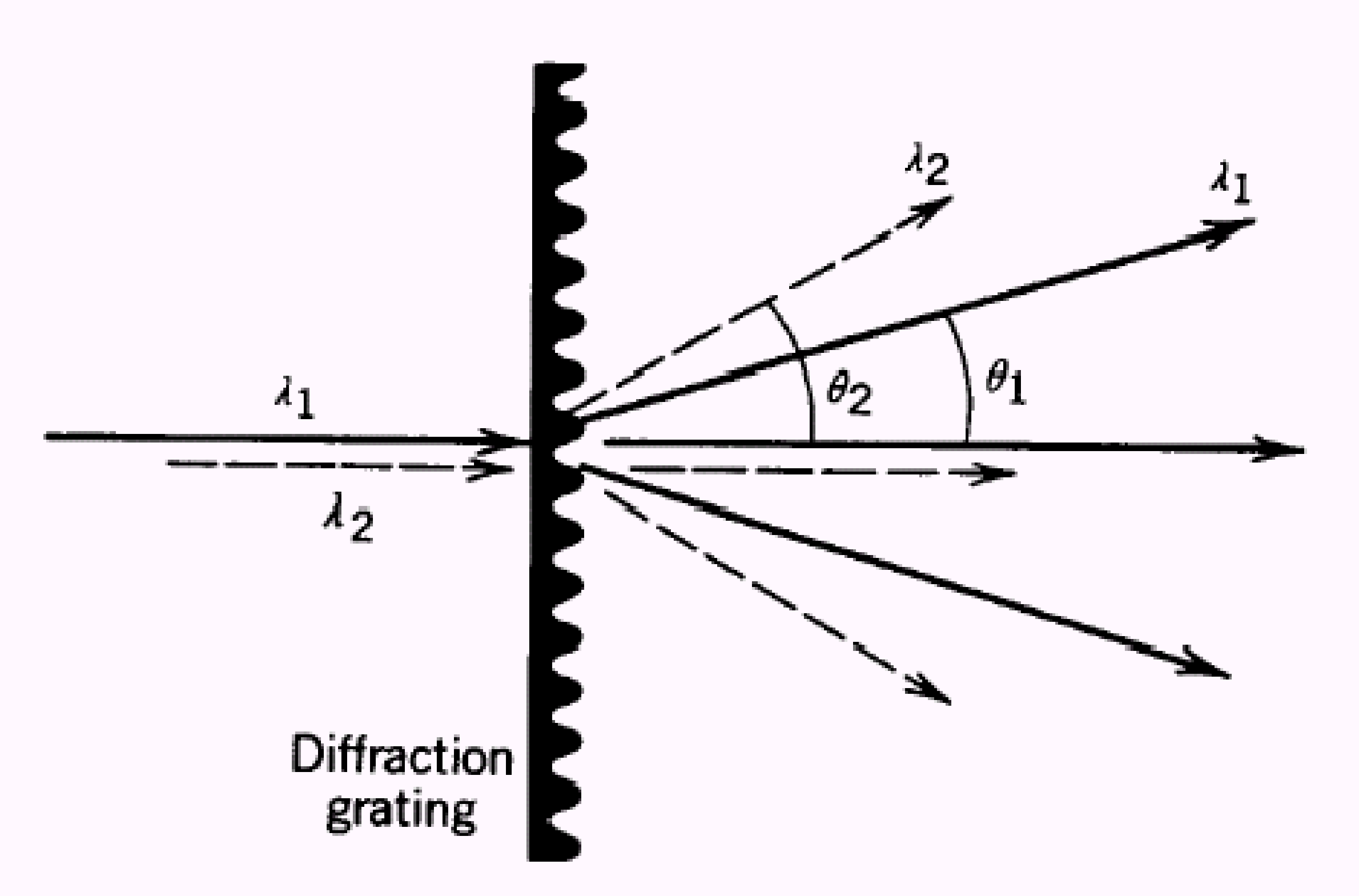
- Periodic thickness or refractive index variation (“grooves”)



* Diffraction also occurs w/ pin hole of size of ~λ

* In polychromatic light, different wavelengths diffracted differently

Diffraction Grating as a Spectrum Analyzer



Interference: Young's Experiment

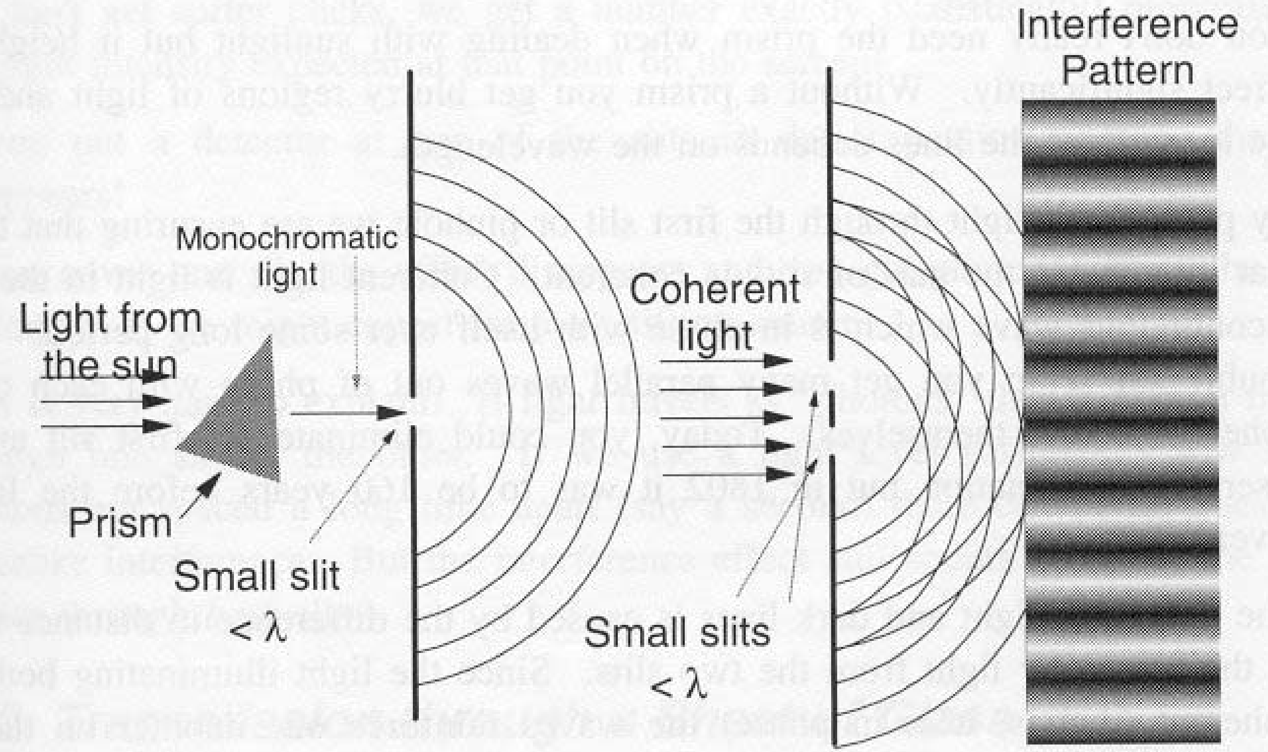
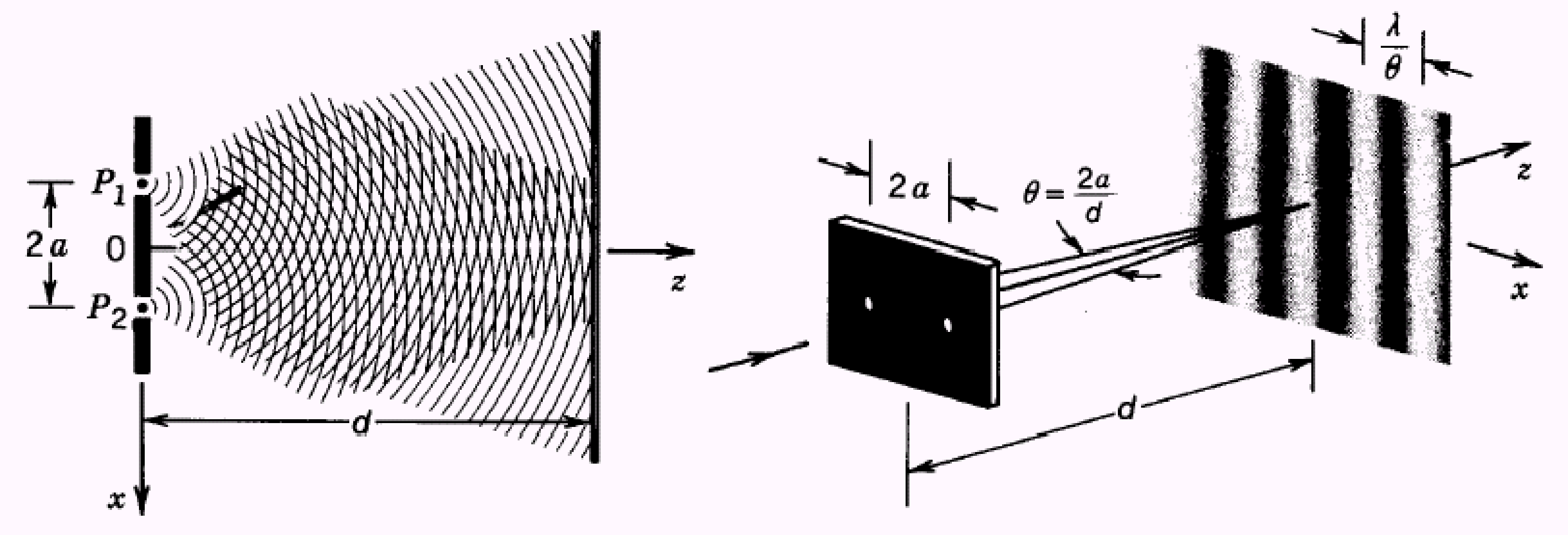


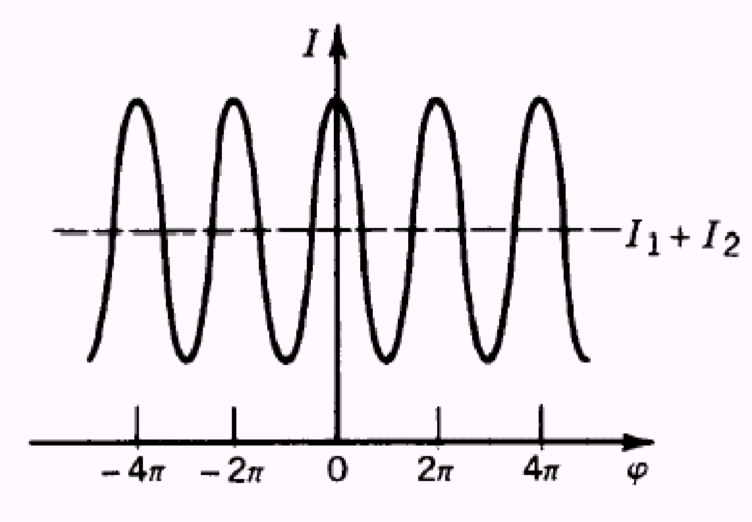
Figure 6. Young's Experiment

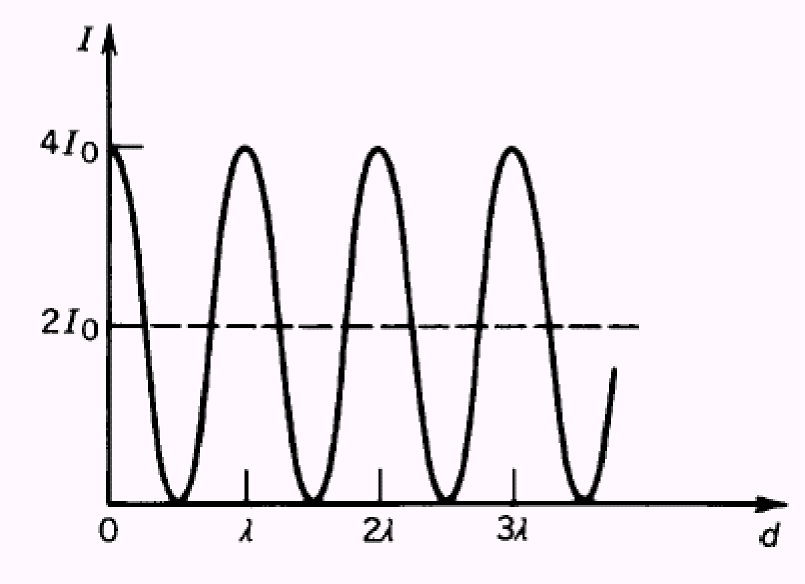
Interference is simple superposition, and a wave-phenomenon

Interference of Two Spherical Waves



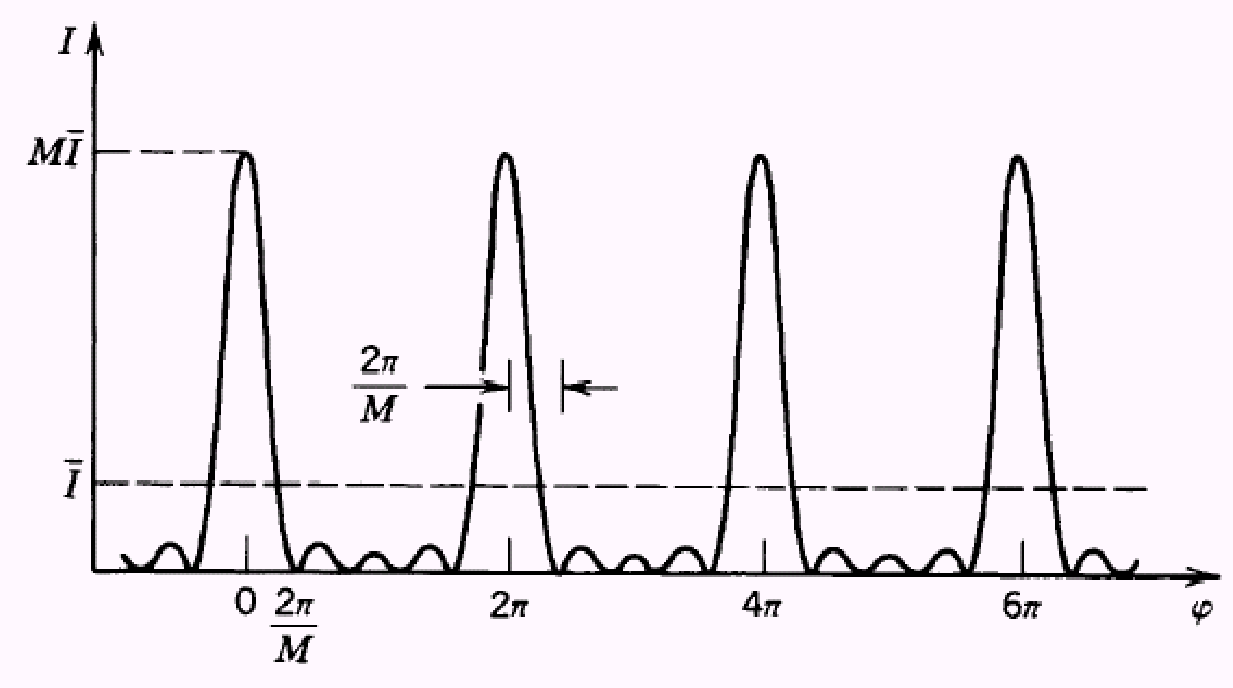
Interference of Two Waves





$$\boxed{I = I_1 + I_2 + 2(I_1 I_2)^{1/2} \cos \varphi,}$$

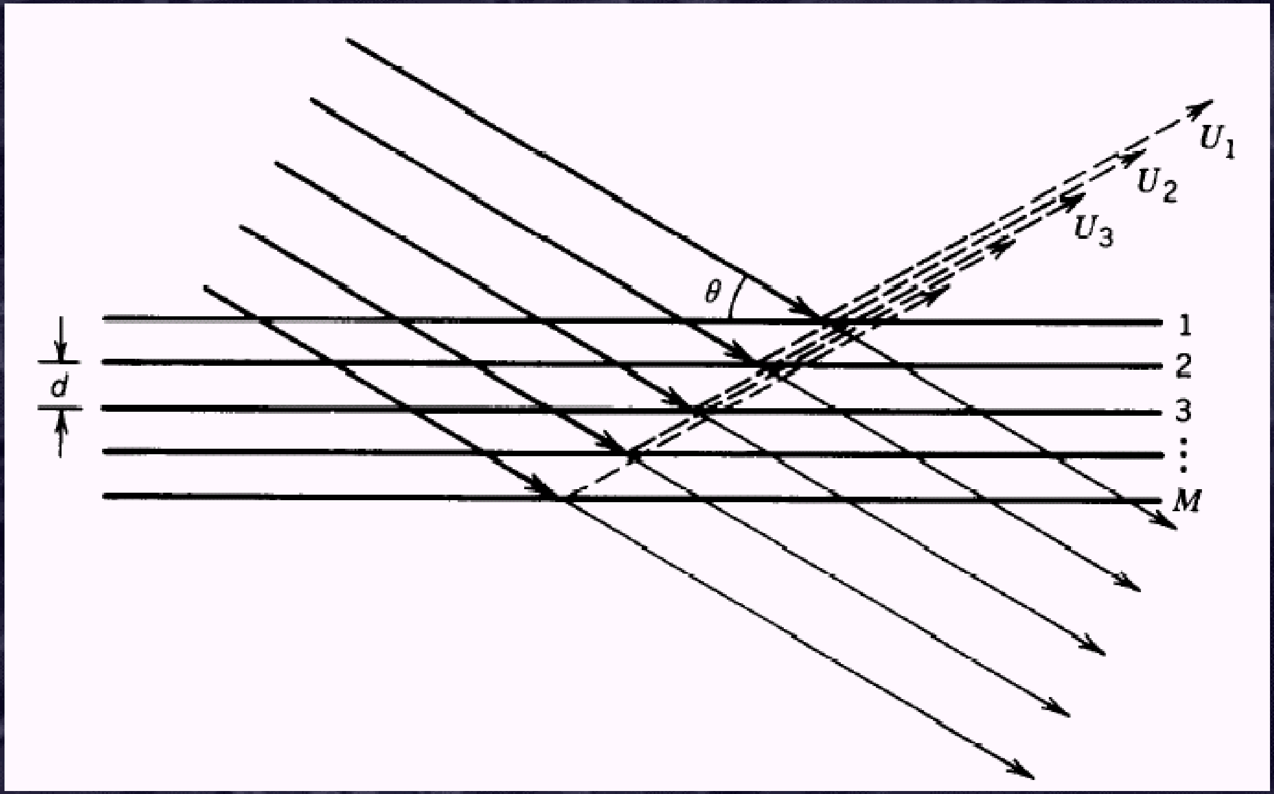
Multiple Waves Interference (Equal Amplitude, Equal Phase Differences)



Sinc-squared function

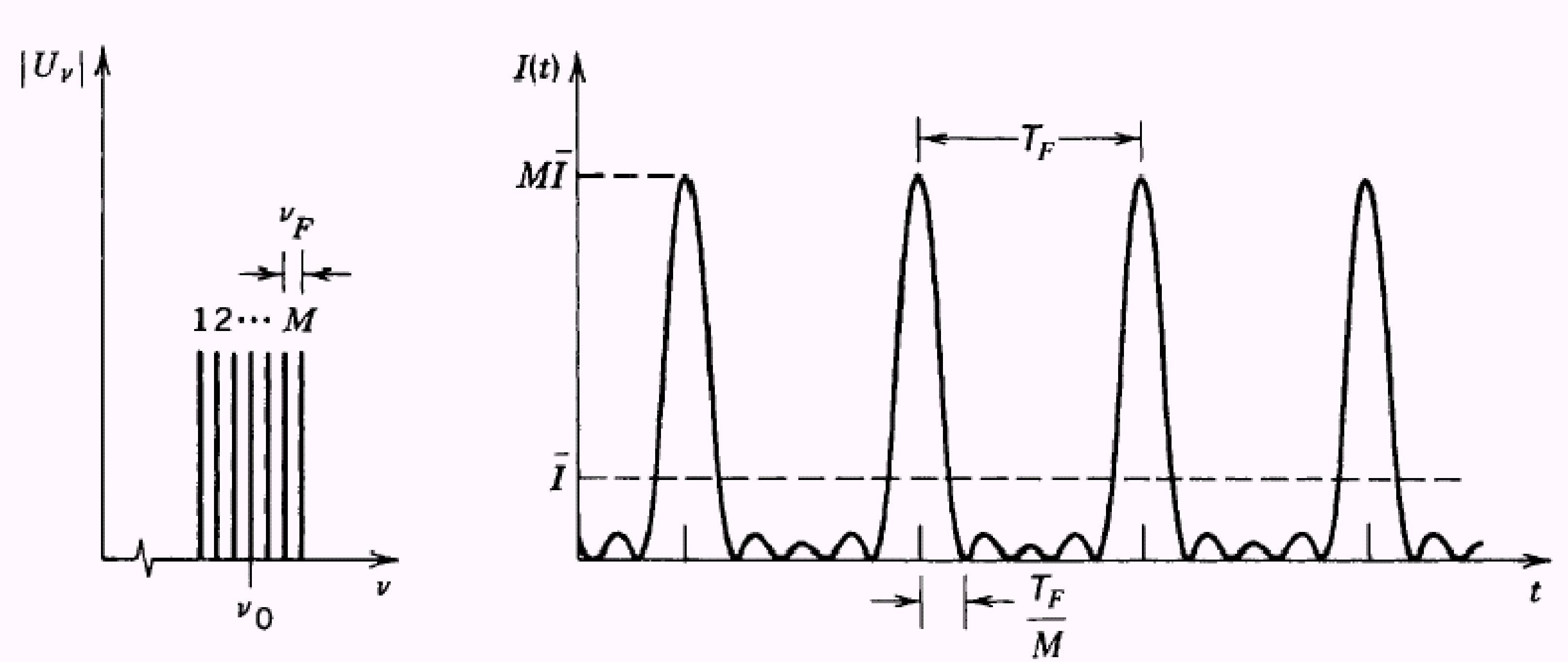
$$I = I_0 \frac{\sin^2(M\varphi/2)}{\sin^2(\varphi/2)}.$$

Application: Bragg Reflection & Interference



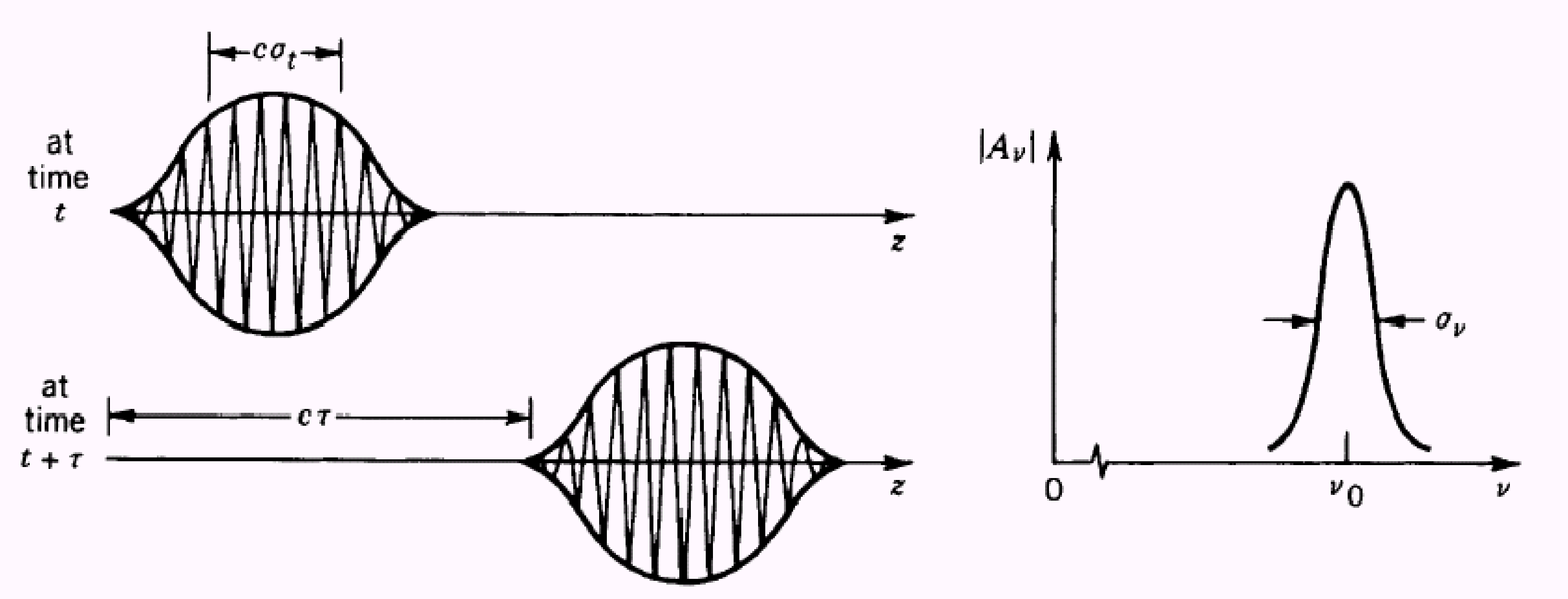
$$\boxed{\sin\theta = \frac{\lambda}{2d}.}$$

High Intensity, Narrow Pulses from Interference between M Monochromatic Waves



- Used in Phase locked lasers

Propagation of a Polychromatic Wave



Optical Splicing Issues: Speckle Patterns

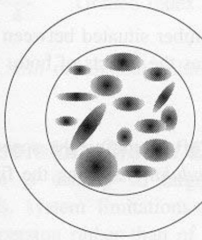


Figure 31. Typical Speckle Pattern. The speckle pattern is the pattern of energy as it appears at the end of a fibre.

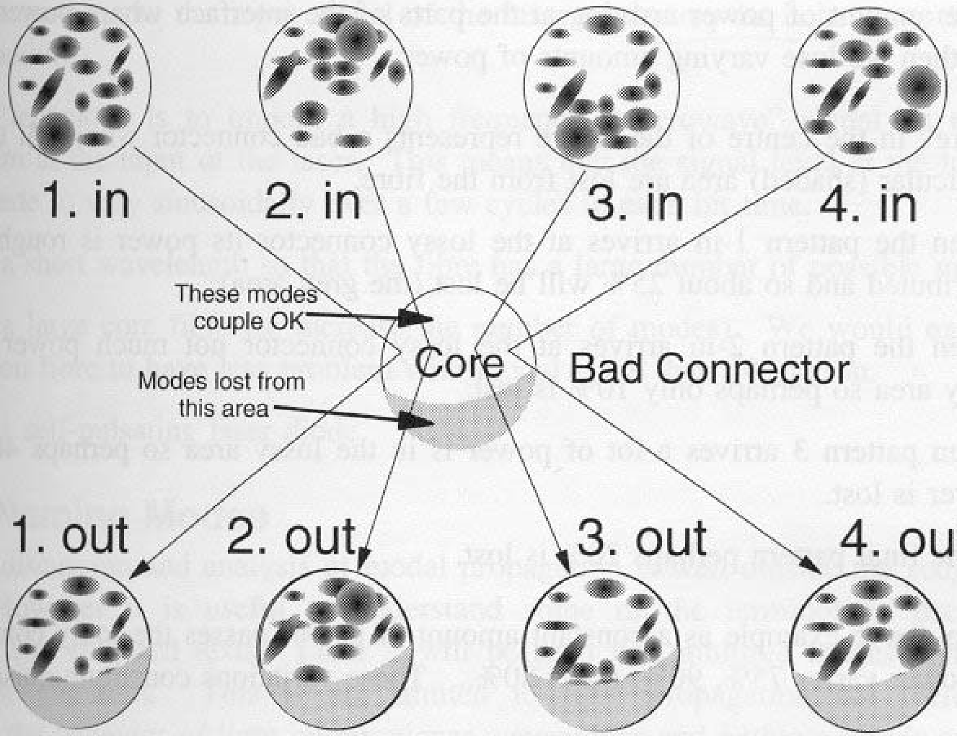


Figure 33. Origin of Modal Noise. The speckle pattern changes rapidly over time, however, energy is conserved and all the power is conserved. When the signal meets a lossy connector, power is lost from some modes and other modes may be unaffected. Since the amount of power in the lost modes changes randomly, the amount of power passing the connector varies randomly.

Speckle patterns are time-varying and arise from solution of Maxwell's equations (> geometric optics)

Recall: Interaction of Light with Matter

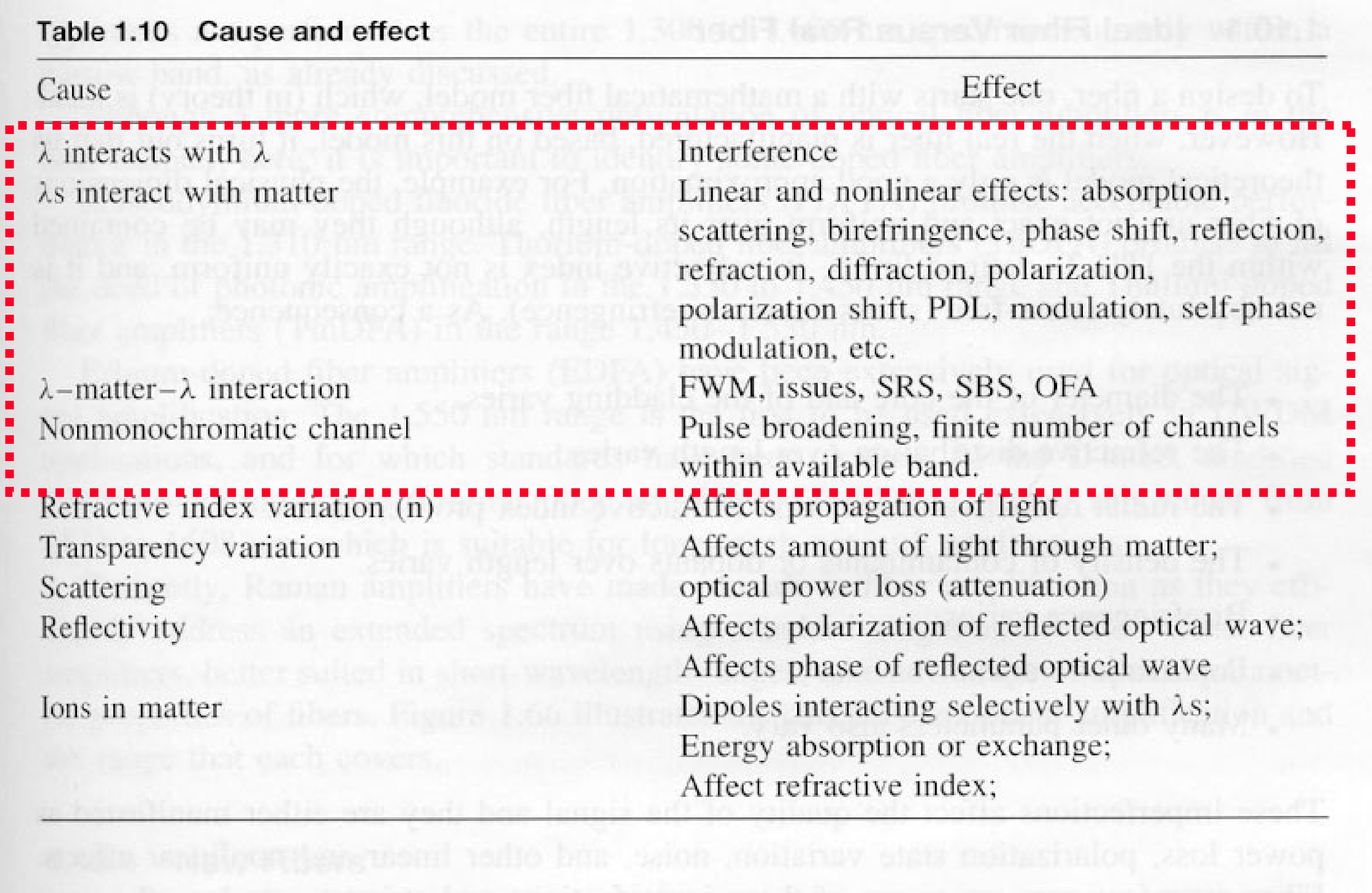
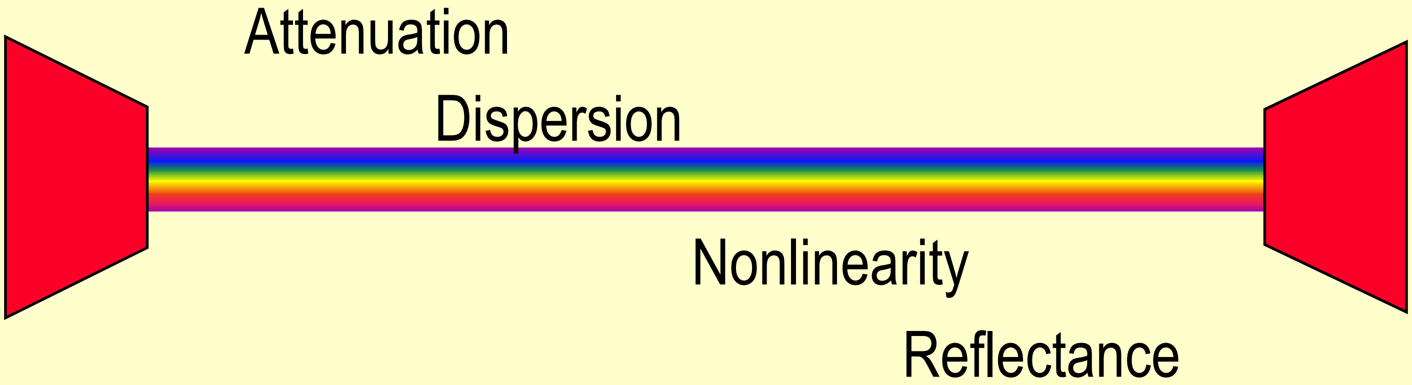


Table 1.10 Cause and effect

Cause	Effect
λ interacts with λ	Interference
λs interact with matter	Linear and nonlinear effects: absorption, scattering, birefringence, phase shift, reflection, refraction, diffraction, polarization, polarization shift, PDL, modulation, self-phase modulation, etc.
λ–matter–λ interaction	FWM, issues, SRS, SBS, OFA
Nonmonochromatic channel	Pulse broadening, finite number of channels within available band.
Refractive index variation (n)	Affects propagation of light
Transparency variation	Affects amount of light through matter;
Scattering	optical power loss (attenuation)
Reflectivity	Affects polarization of reflected optical wave; Affects phase of reflected optical wave
Ions in matter	Dipoles interacting selectively with λs; Energy absorption or exchange; Affect refractive index;

Optical Transmission: More Light-Matter Interaction Effects



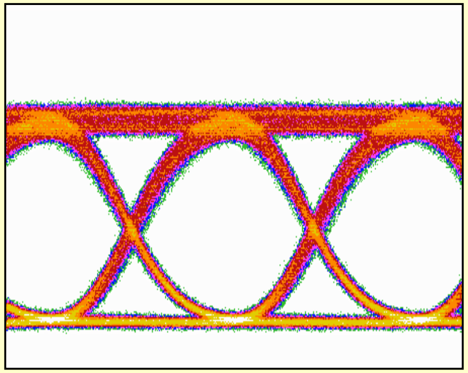
Attenuation

Dispersion

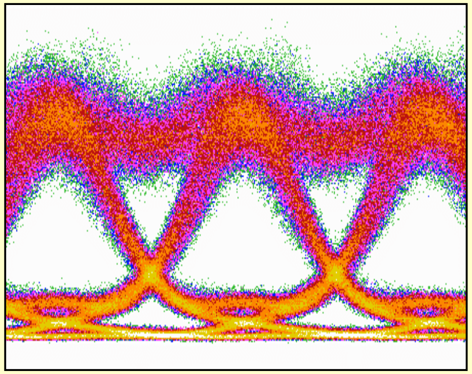
Nonlinearity

Reflectance

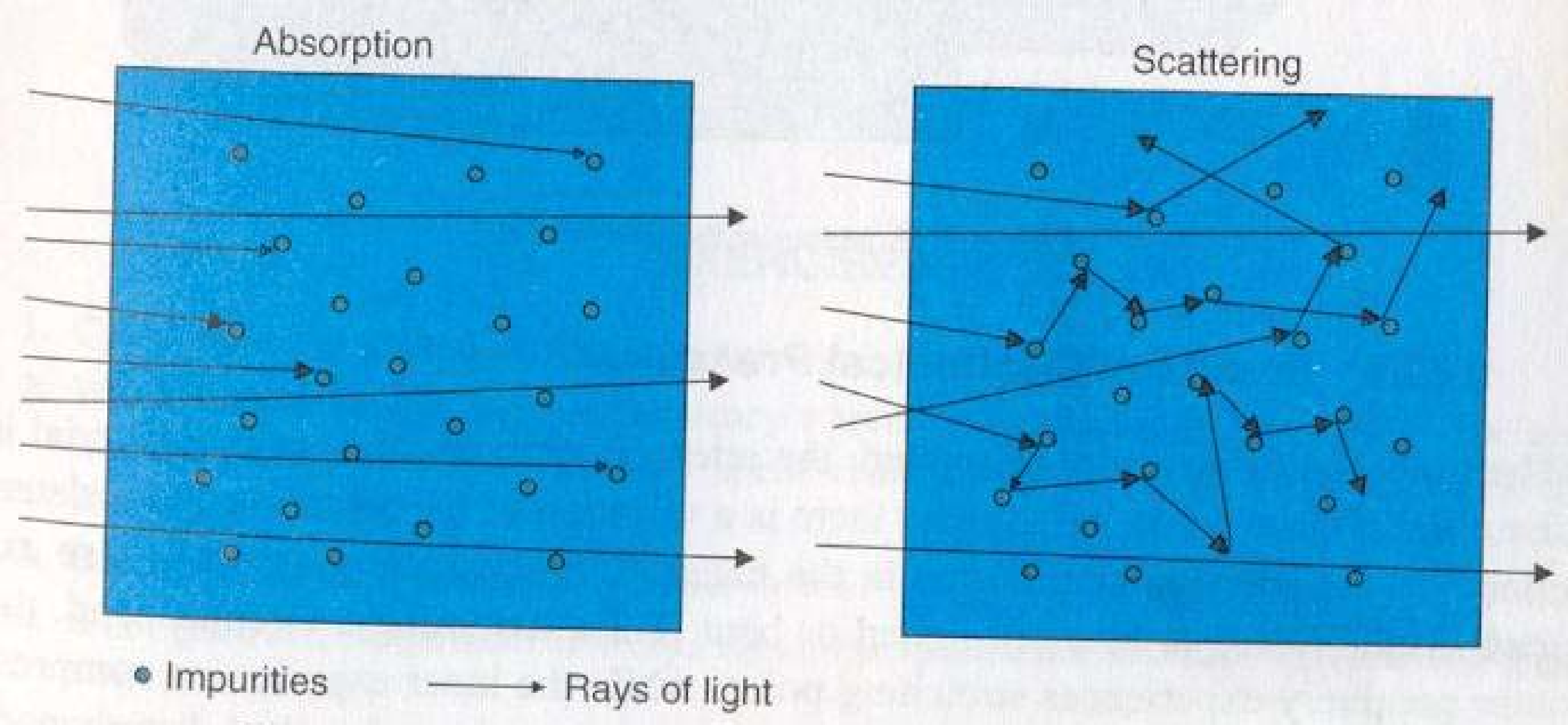
Transmitted data waveform



Waveform after 1000 km

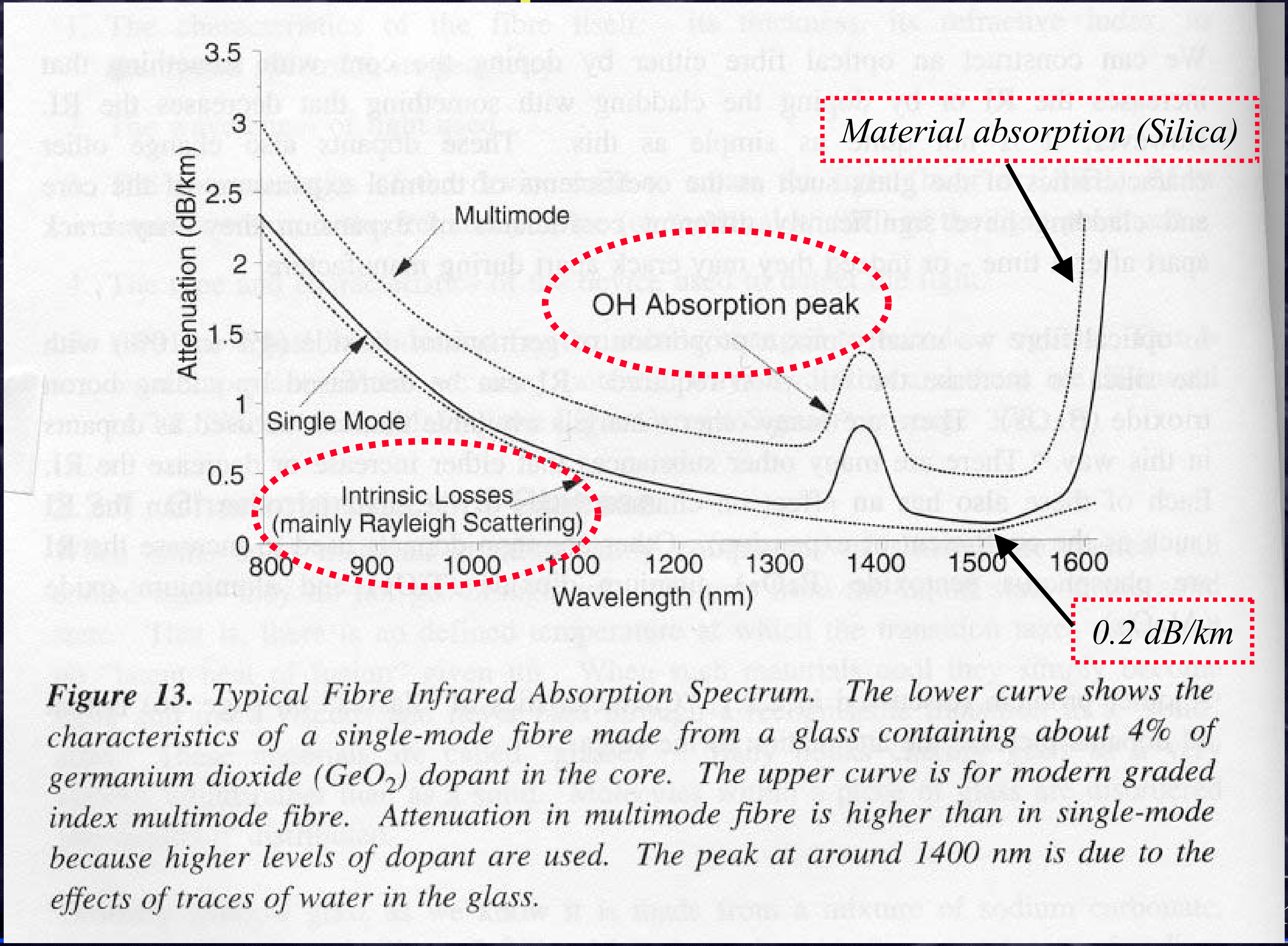


Absorption vs Scattering



Both are linear effects that lead to "attenuation". Rayleigh scattering effects dominate much more than absorption (in lower Wavelengths, but decreases with wavelength)

Absorption and Attenuation: Absorption Spectrum



Material absorption (Silica)

OH Absorption peak

0.2 dB/km

Figure 13. *Typical Fibre Infrared Absorption Spectrum. The lower curve shows the characteristics of a single-mode fibre made from a glass containing about 4% of germanium dioxide (GeO_2) dopant in the core. The upper curve is for modern graded index multimode fibre. Attenuation in multimode fibre is higher than in single-mode because higher levels of dopant are used. The peak at around 1400 nm is due to the effects of traces of water in the glass.*

Fiber:Transmission Windows

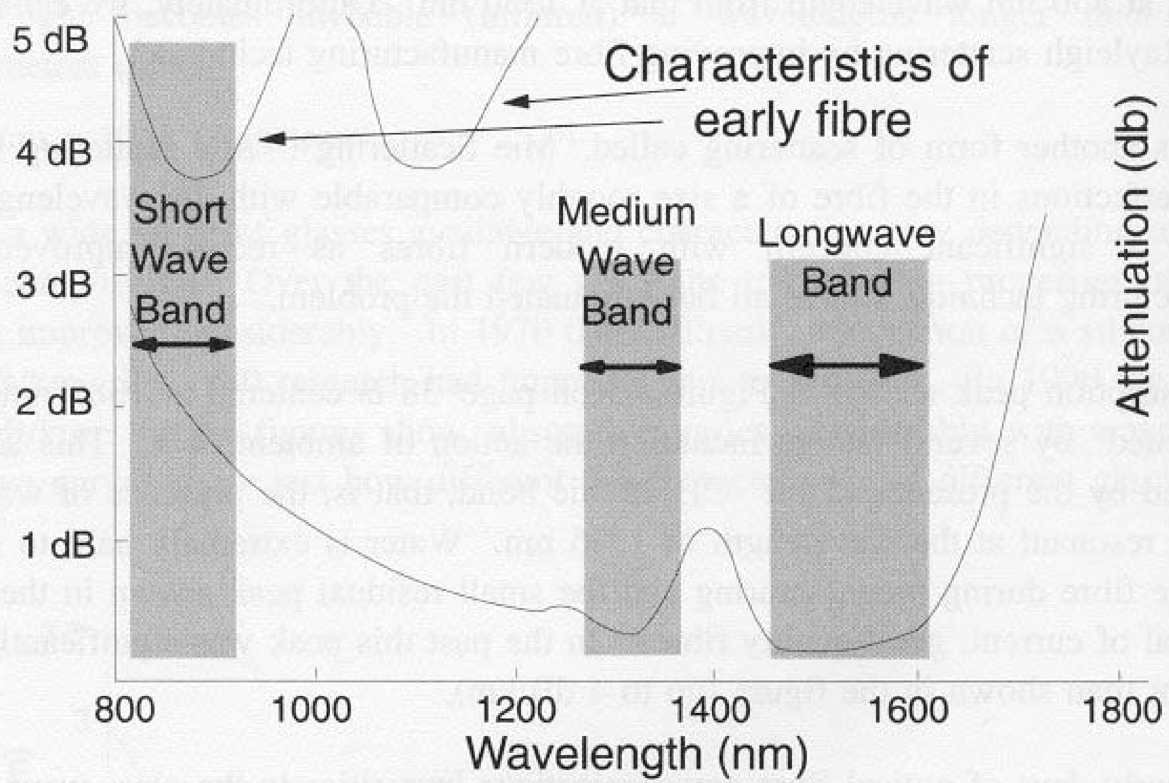
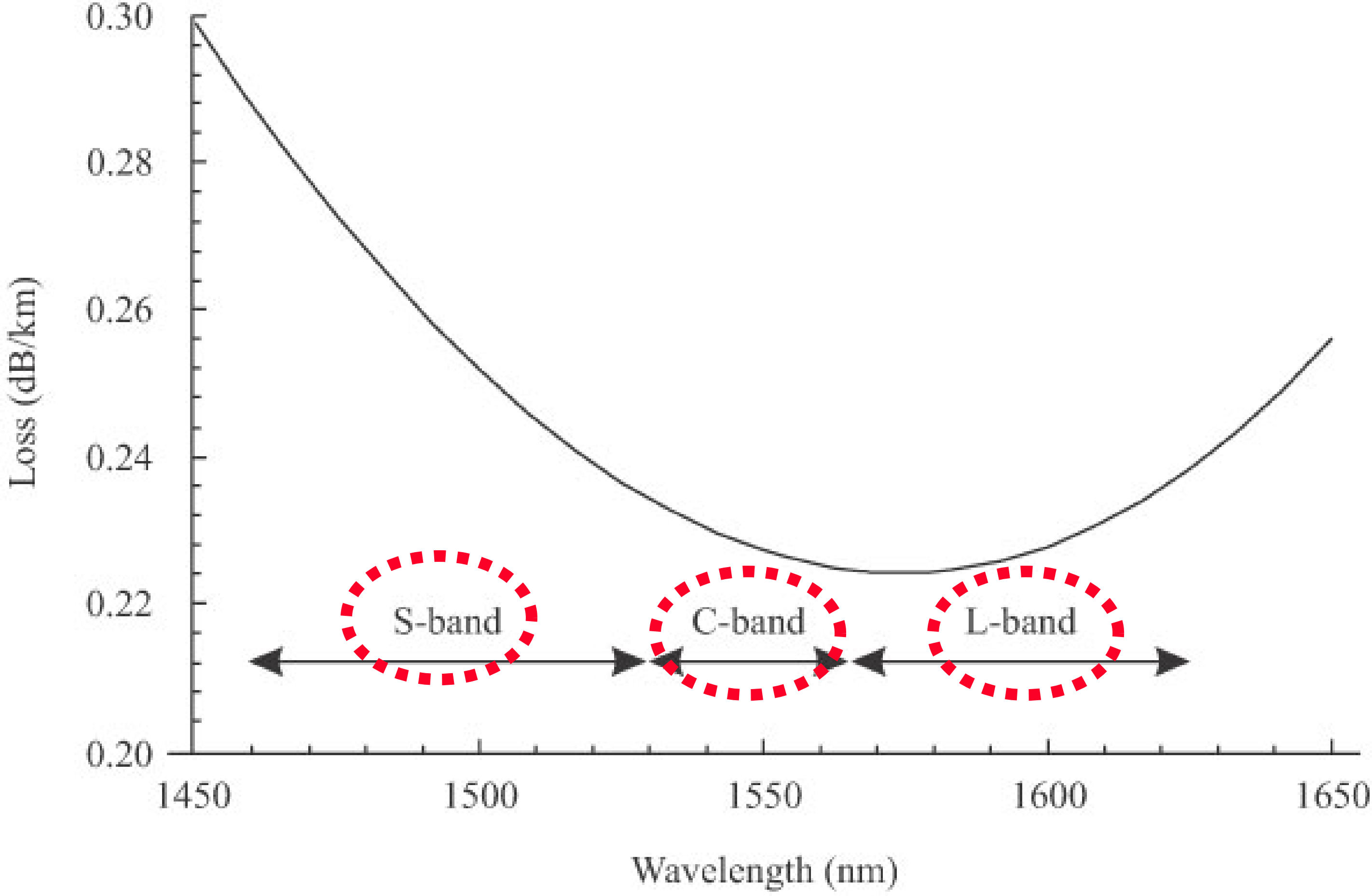


Figure 14. *Transmission Windows. The upper curve shows the absorption characteristics of fibre in the 1970s. The lower one is for modern fibre.*

Lucent's new AllWave Fiber (1998) eliminates absorption peaks due to watervapor in the 1400nm area!

Transmission Bands



Bandwidth: over 35000 Ghz, but limited by bandwidth of EDFAs (optical amplifiers): studied later…

Optical Amplifier: Limitations on Practical Bandwidths

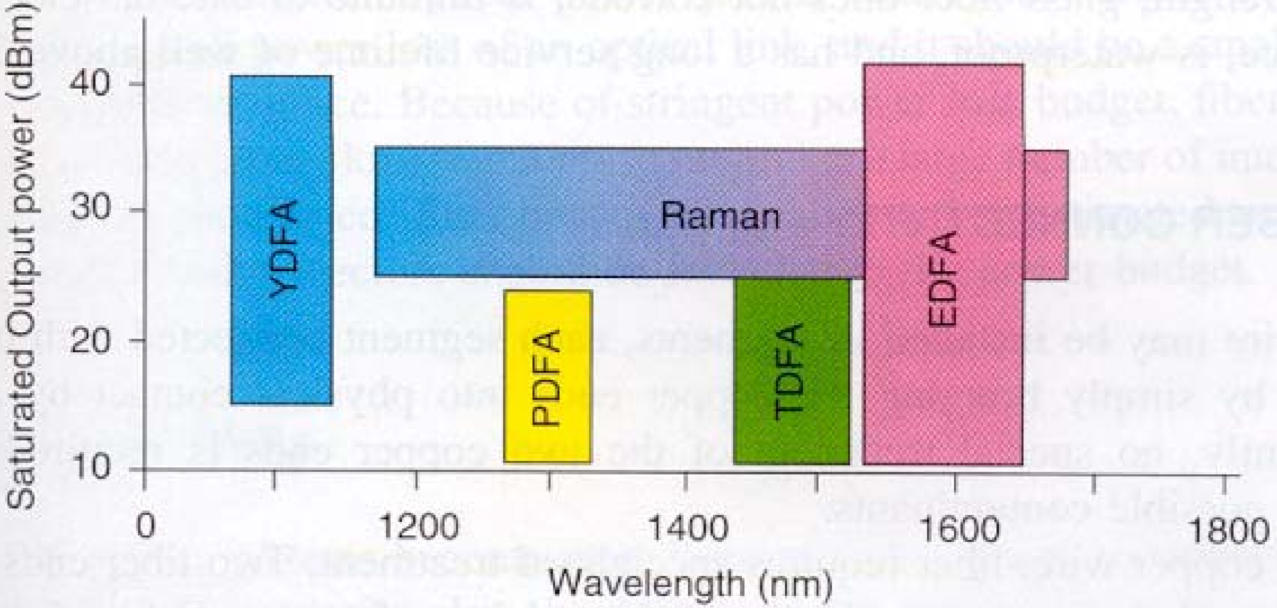
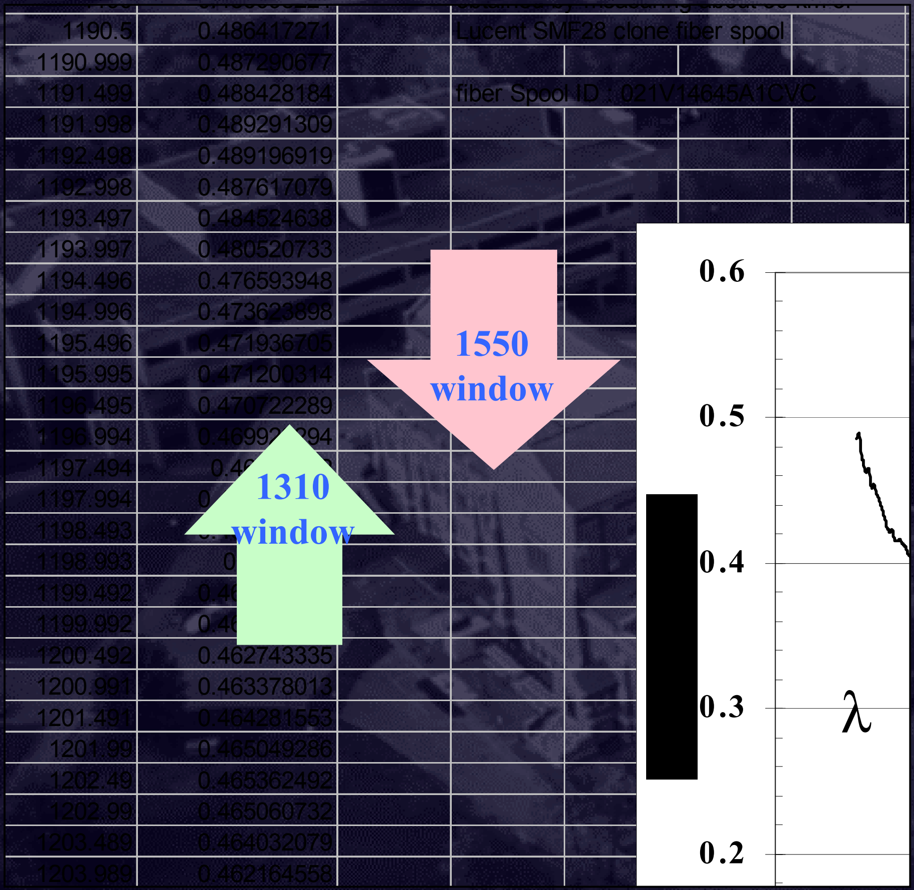


Figure 1.66 Optical amplifiers are many, each suitable for a different spectral range.

EDFAs popular in C-band
Raman: proposed for S-band
Gain-shifted EFDA for L-band

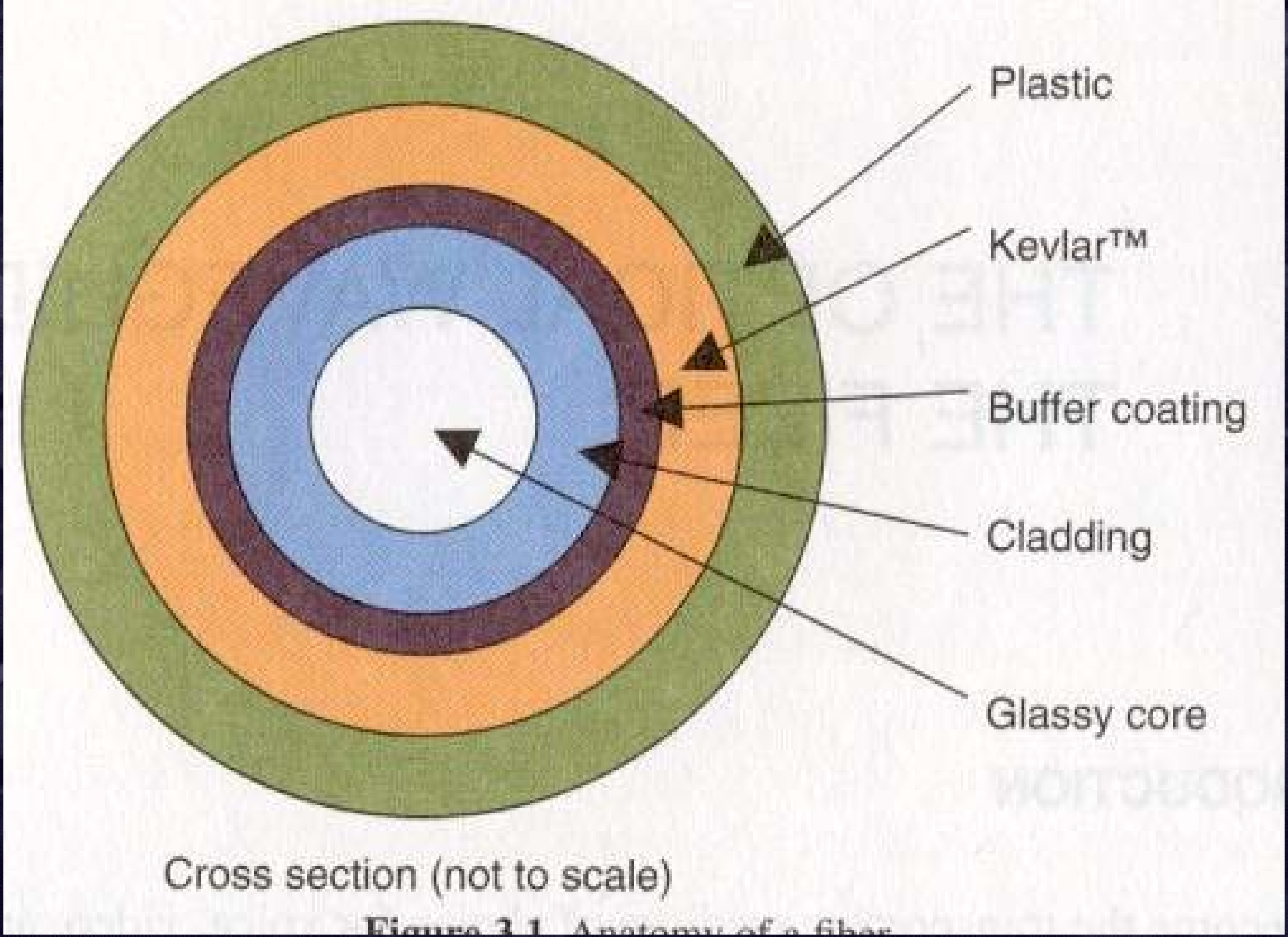
Fiber Attenuation



1190.5	0.486417271	Lucent SMF28 clone fiber spool
1190.999	0.487290677	
1191.499	0.488428184	fiber Spool ID : 021V14645A1CVC
1191.998	0.489291309	
1192.498	0.489196919	
1192.998	0.487617079	
1193.497	0.484524638	
1193.997	0.480520733	
1194.496	0.476593948	
1194.996	0.473623898	
1195.496	0.471936705	
1195.995	0.471200314	
1196.495	0.470722289	
1196.994	[illegible]	
1197.494	[illegible]	
1197.994	[illegible]	
1198.493	[illegible]	
1198.993	[illegible]	
1199.492	[illegible]	
1199.992	[illegible]	
1200.492	0.462743335	
1200.991	0.463378013	
1201.491	0.464281553	
1201.99	0.465049286	
1202.49	0.465362492	
1202.99	0.465060732	
1203.489	0.464032079	
1203.989	0.462164558	

- Two windows:
  - **1310 & 1550 nm**
- 1550 window is preferred for **long-haul** applications
  - Less attenuation
  - Wider window
  - Optical amplifiers

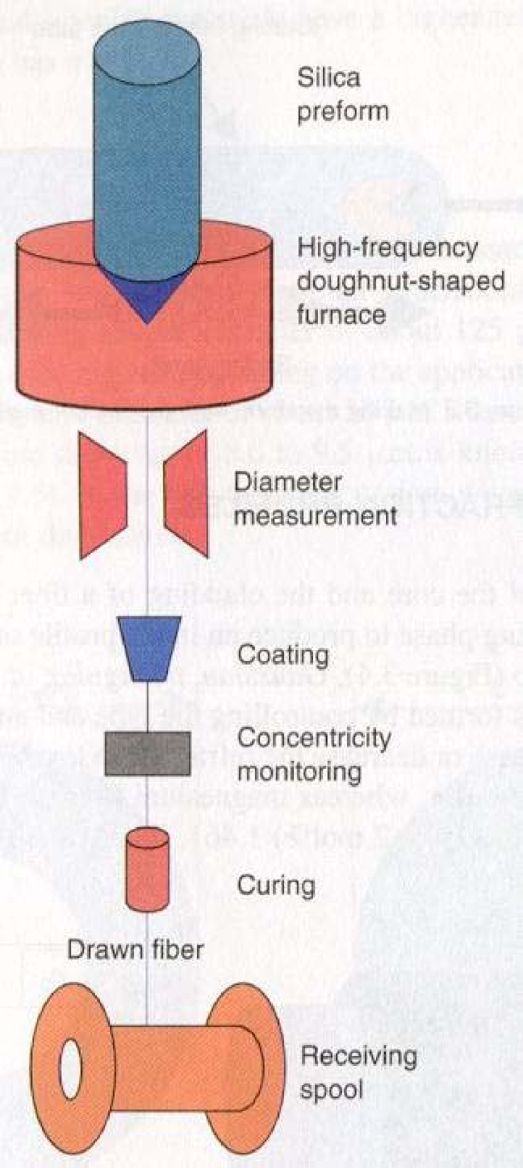
Fiber Anatomy



Cross section (not to scale)

Figure 3.1 Anatomy of a fiber

Fiber Manufacturing

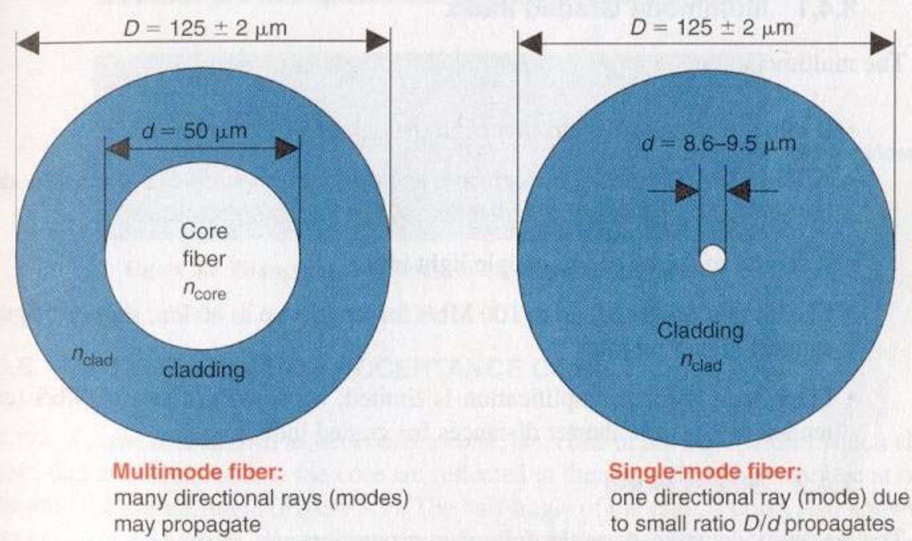


- Dopants are added to control RI profile of the fiber (discussed later)
- Fiber: stronger than glass

- A fiber route may have several cables
- Each cable may have upto 1000 fibers
- Each fiber may have upto 160 wavelengths
- Each wavelength may operate at 2.5Gbps or 10 Gbps

Single vs. Multimode Fiber

- Silica-Based Fiber Supports 3 Low-Loss “Windows”: 0.8, 1.3 , 1.55 μm wavelength
- Multimode Fibers Propagate Multiple Modes of Light
  - core diameters from 50 to 85 μm
  - modal dispersion limitations
- Single-mode Fibers Propagate One Mode Only
  - core diameters from 8 to 10 μm
  - chromatic dispersion limitations



Multimode fiber: many directional rays (modes) may propagate

Single-mode fiber: one directional ray (mode) due to small ratio D/d propagates

Summary: Single-mode vs Multi-mode

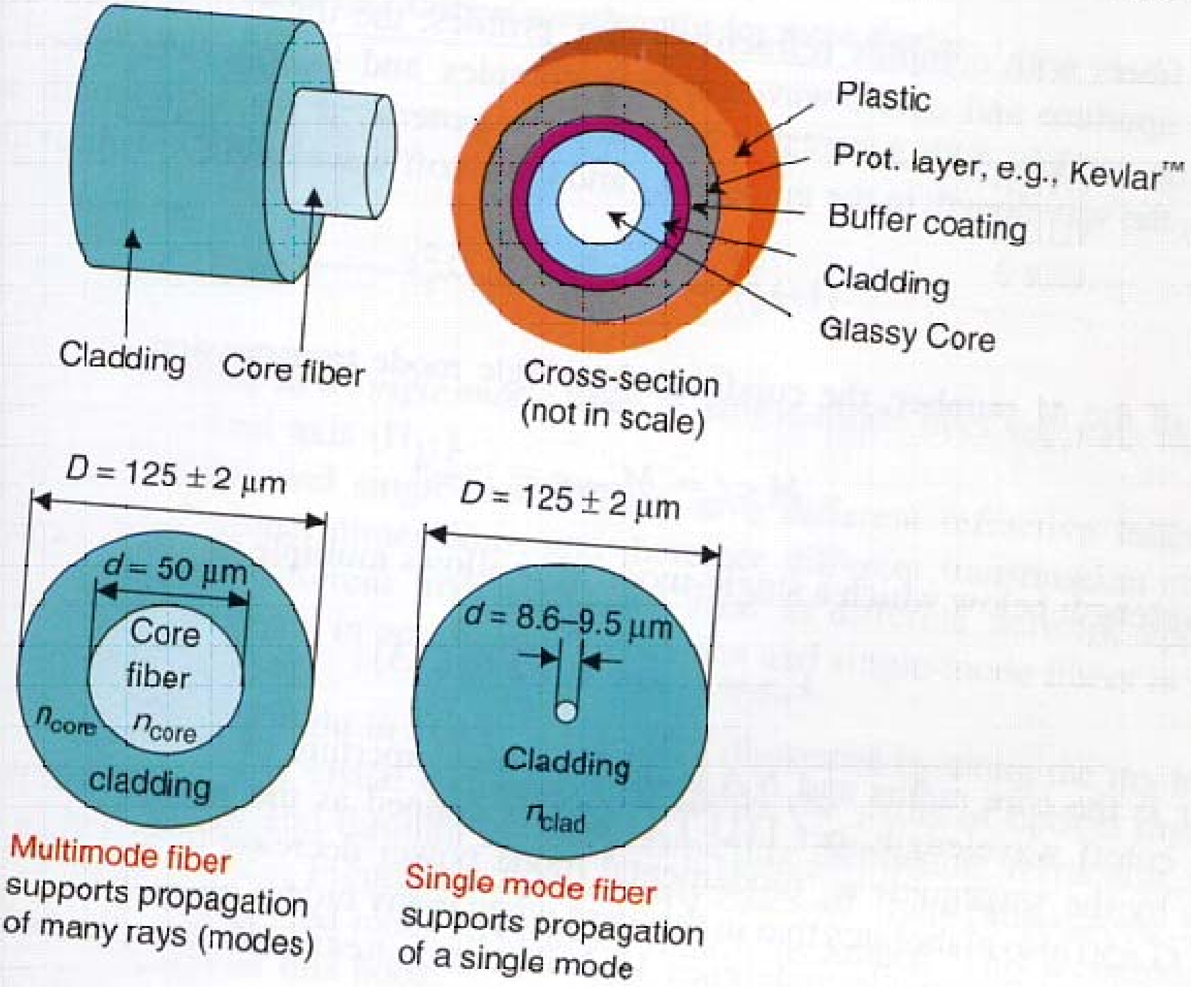


Figure 1.36 Anatomy of a multi-mode and single-mode fiber.

Multimode vs Single mode: Energy distributions

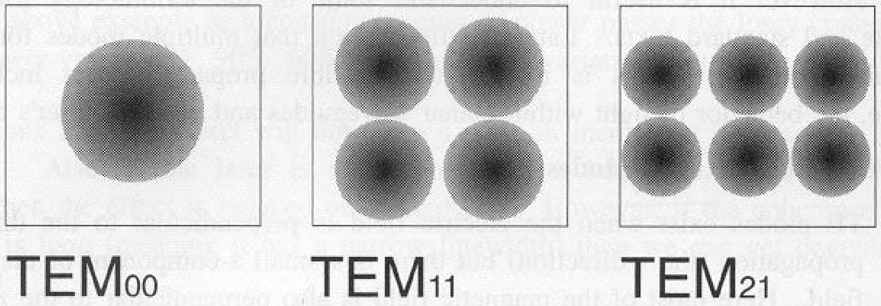


Figure 34. Energy Distribution of Some TEM Modes. The numbering system used here applies to TE, TM and TEM modes.

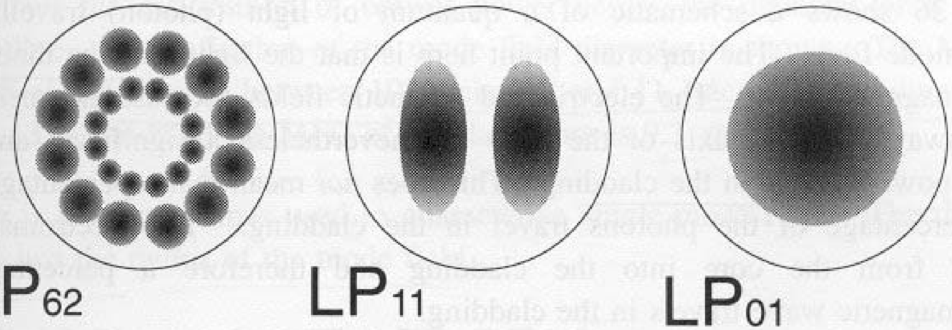


Figure 35. Energy Distribution of Some LP Modes in Fibre

Single Mode Characteristics (contd)

- It (almost) eliminates delay spread
- More difficult to splice than multimode due to critical core requirements
- More difficult to couple all photonic energy from a source into it; light propagates both in core and cladding!
- Difficult to study propagation w/ ray theory; requires Maxwell’s equations
- Suitable for transmitting modulated signals at 40 Gb/s and upto 200 km w/o amplification
- Long lengths and bit rates >= 10 Gbps bring forth a number of issues due to residual nonlinearity/birefringence of the fiber
- Fiber temperature for long lengths and bit rates > 10 Gbps becomes significant.

Single Mode Light Propagation

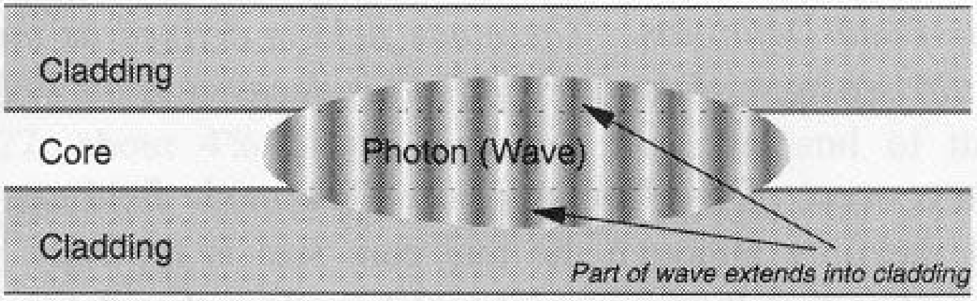


Figure 36. Single-Mode Propagation

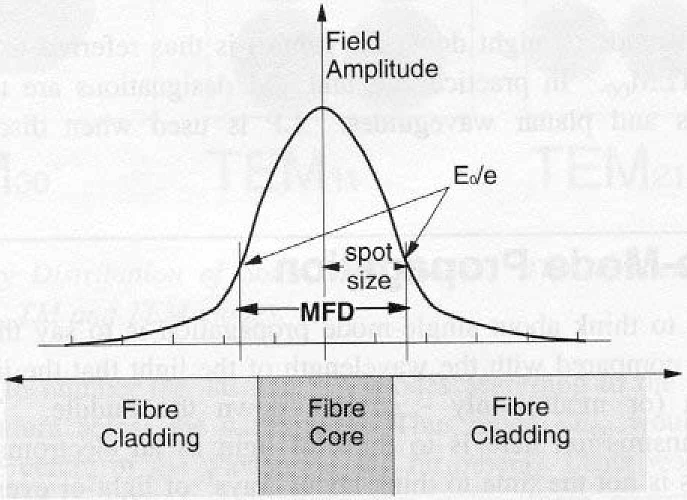
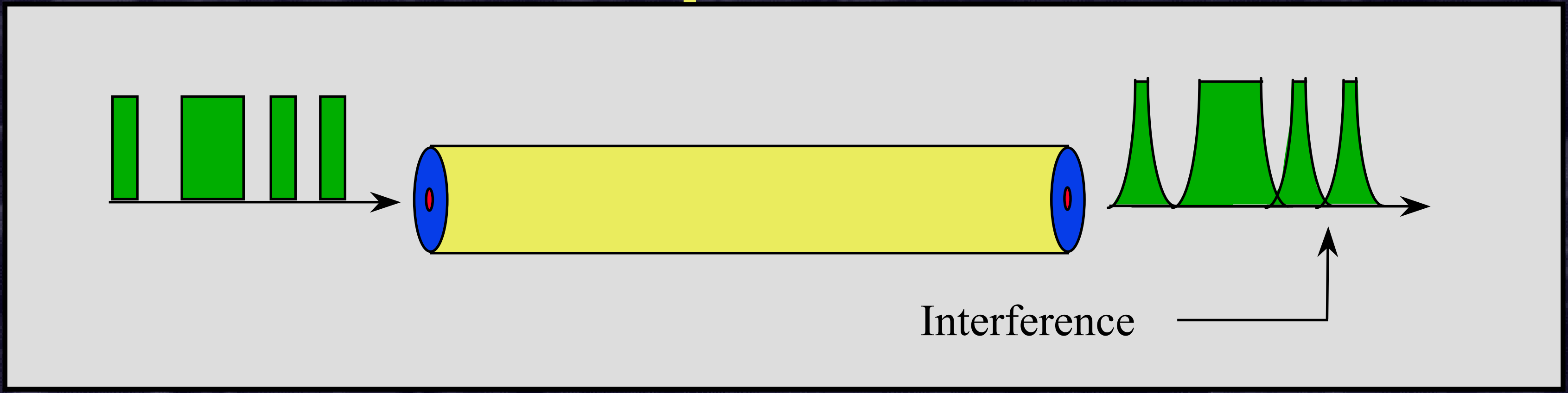


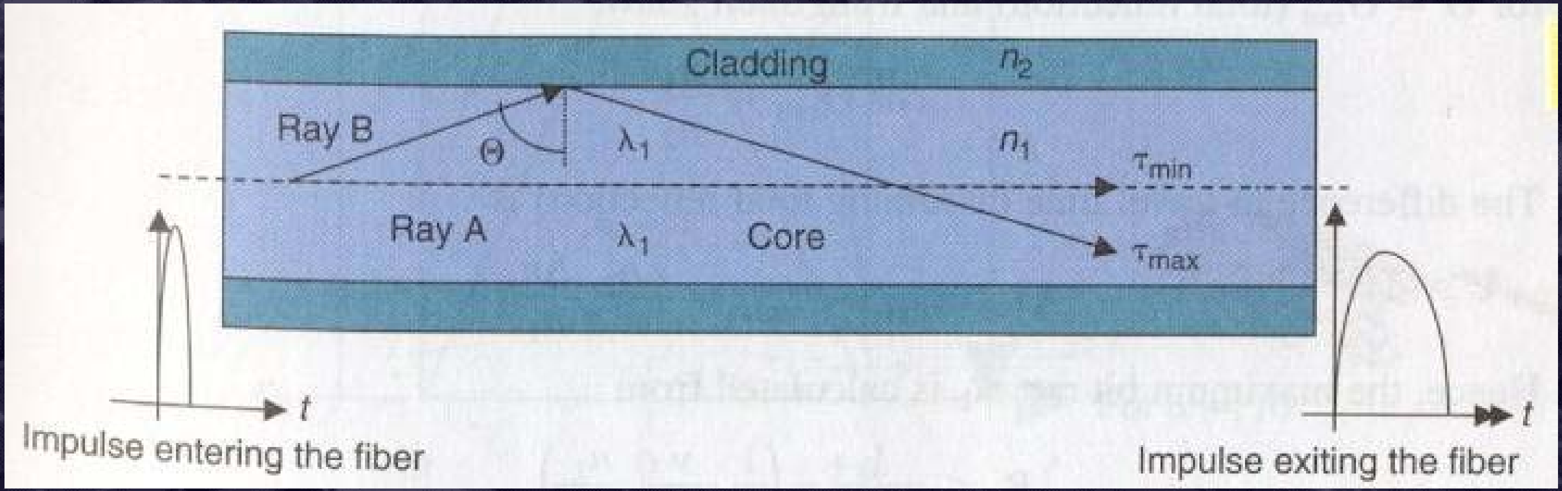
Figure 37. *Mode Field Definition. The mode field is defined as the distance between the points where the strength of the electric field is decayed to 0.37 (1/e) of the peak.*

Dispersion



- Dispersion **causes the pulse to spread** as it travels along the fiber
- **Chromatic dispersion** important for single mode fiber
  - Depends on fiber type and laser used
  - Degradation scales as (data-rate)^2
- Was not important for < 2.5Gbps, < 500km SMF fibers
- **Modal dispersion** limits use of multimode fiber to short distances

Effects of Dispersion



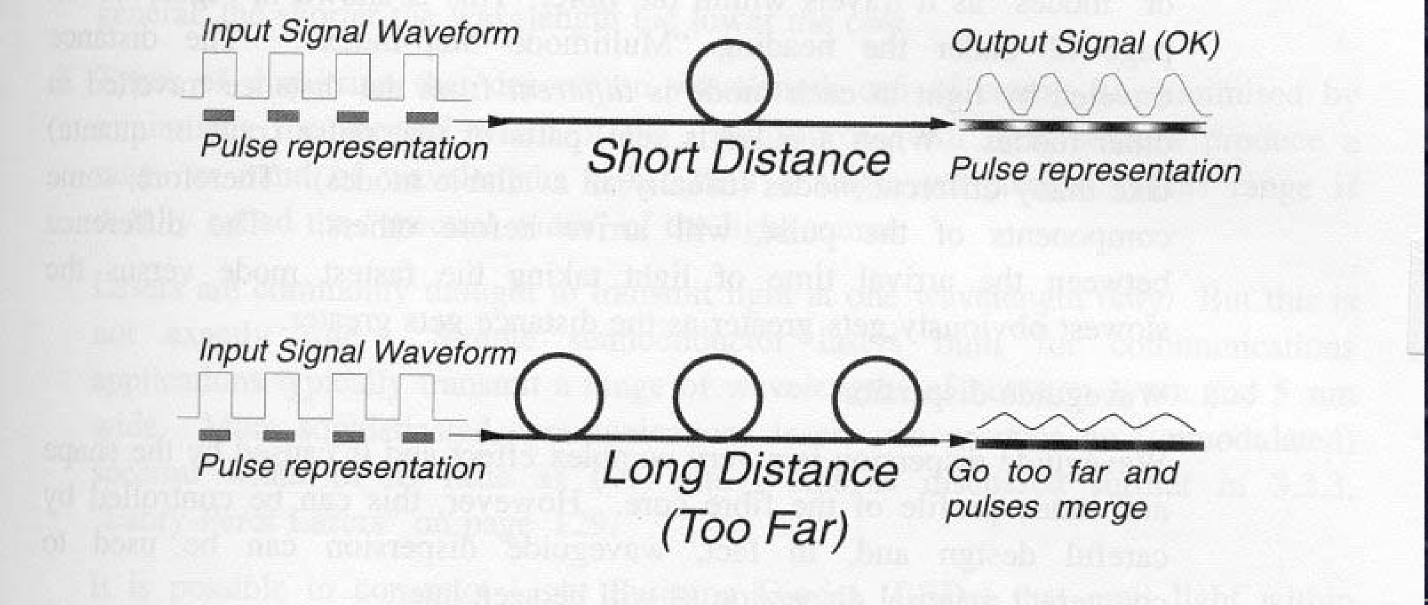
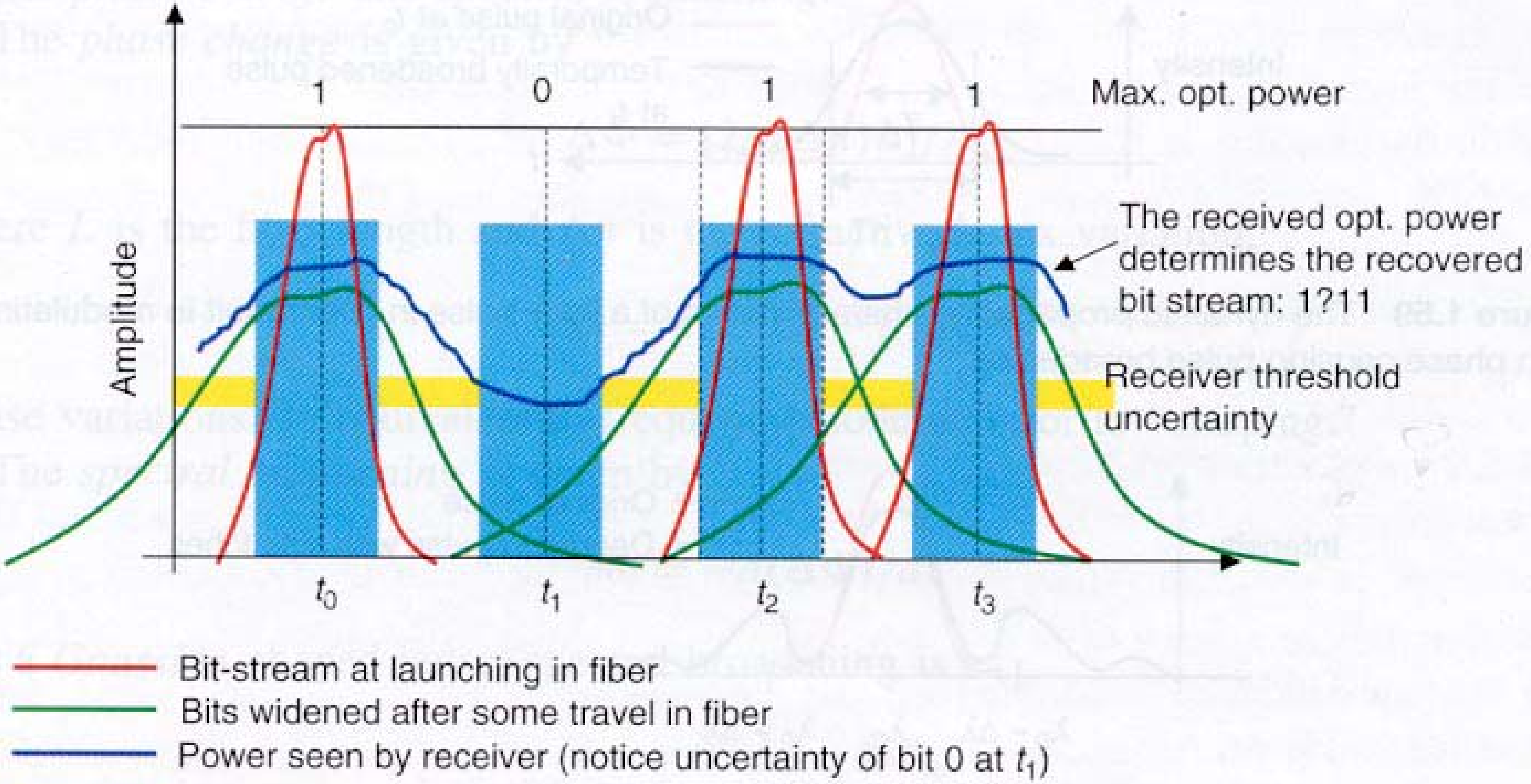


Figure 12. Effect of Dispersion. The circles in the figure represent fibre loops. This is the conventional way to indicate distance in system diagrams.

Pulse-Widening Effect on ISI & BER



The received opt. power determines the recovered bit stream: 1?11

Figure 1.61 Effect of excessive pulse-widening on ISI and BER.

Combating Modal Dispersion in Multimode Fiber: Refractive Index Profiles

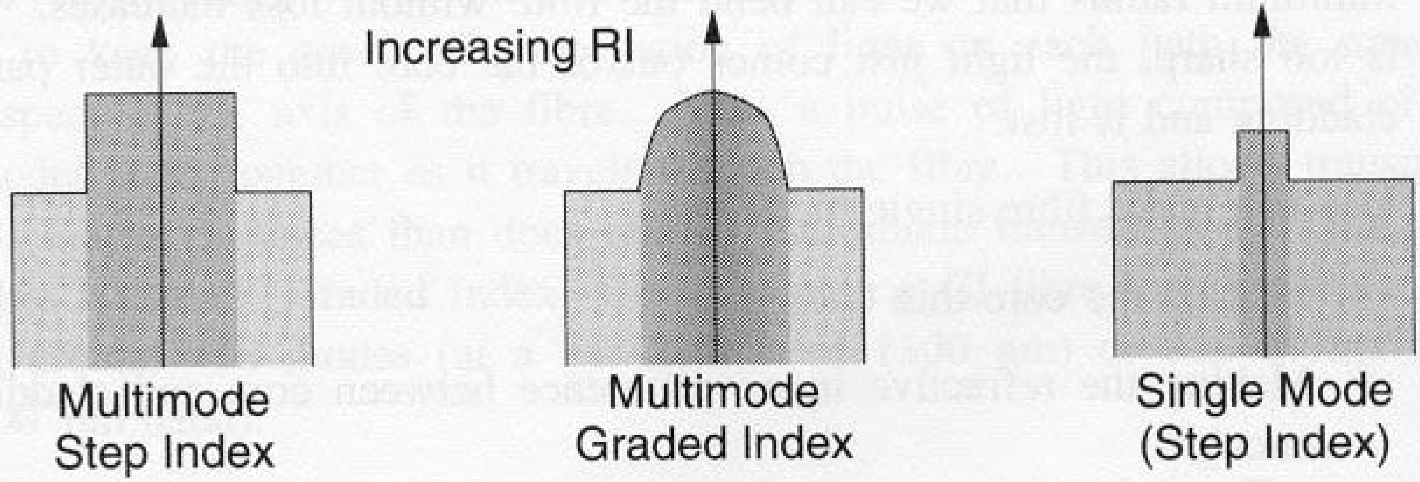
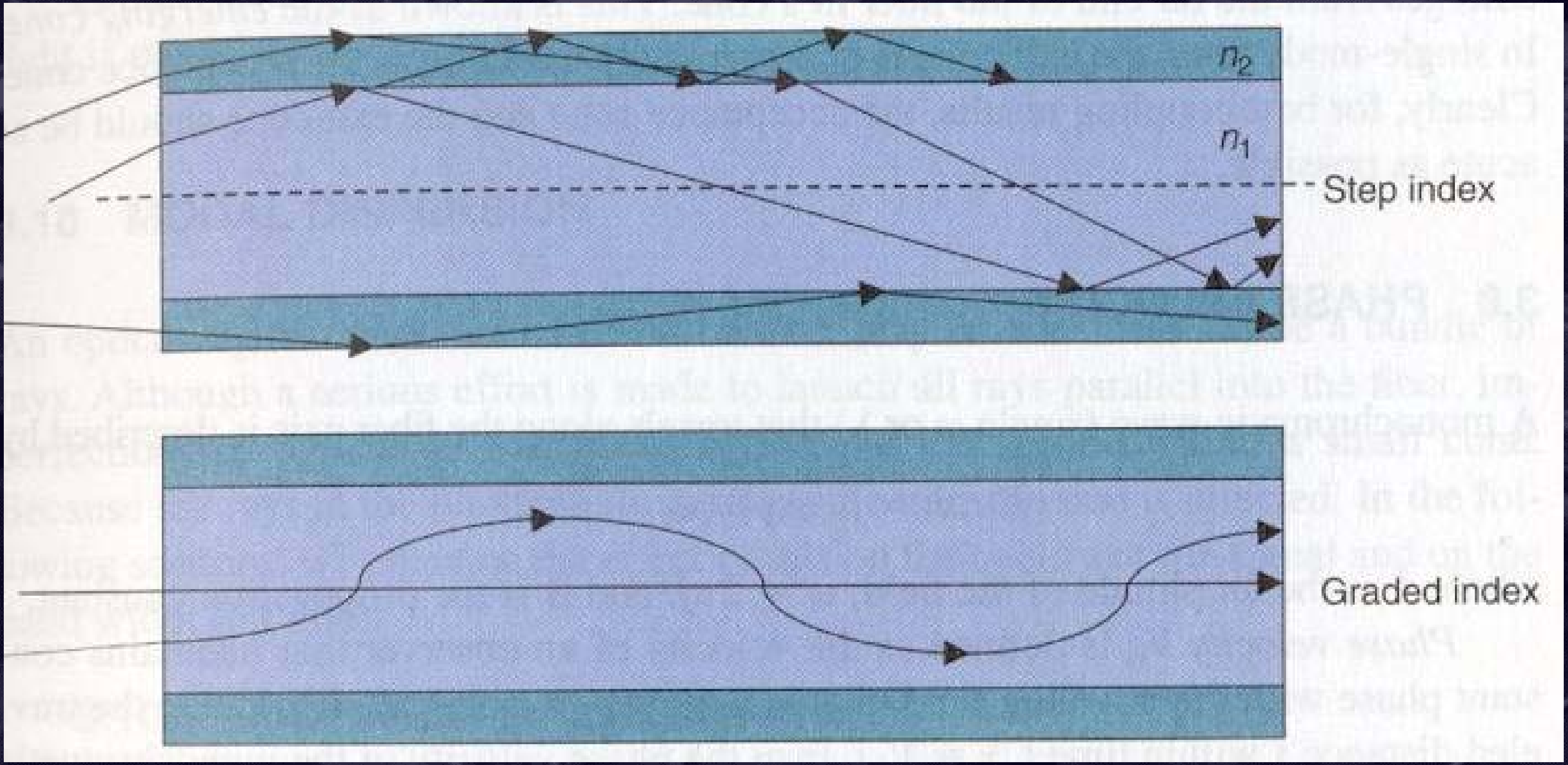


Figure 19. Fibre Refractive Index Profiles

Graded Index (contd)



Graded Index MultiMode Characteristics (contd)

- Minimizes delay spread (modal dispersion), but it is still significant at long lengths
- One percent index difference between core/cladding amounts to 1-5ns/km delay spread
  - Step index has 50 ns/km spread
- Easier to splice and couple light into it
- Bit rate is limited (100 Mbps etc) for 40 km.
- Higher bit rates for shorter distances
- Fiber span w/o amplification is limited
- Dispersion effects for long lengths, high bit rates is a limiting factor

Chromatic Dispersion

- Different spectral components of a pulse travel at different velocities
- Also called *group-velocity-dispersion (GVD),*

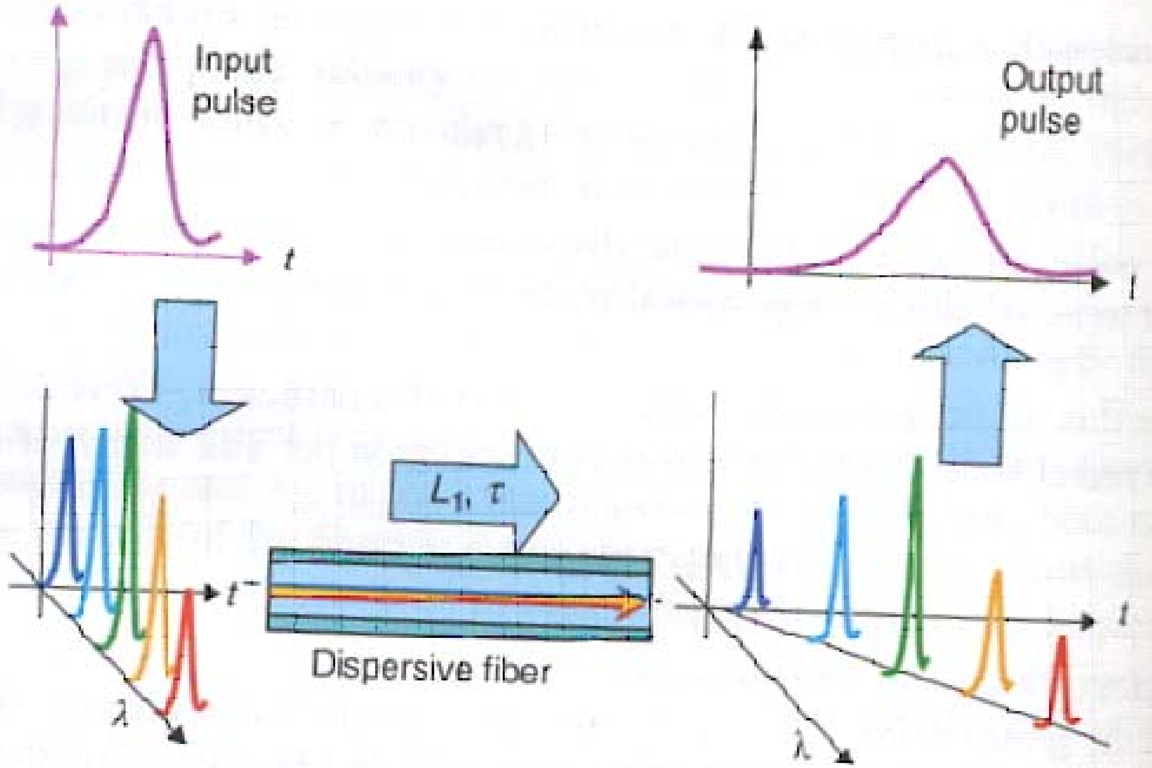


Figure 1.46 Chromatic dispersion: How it works.

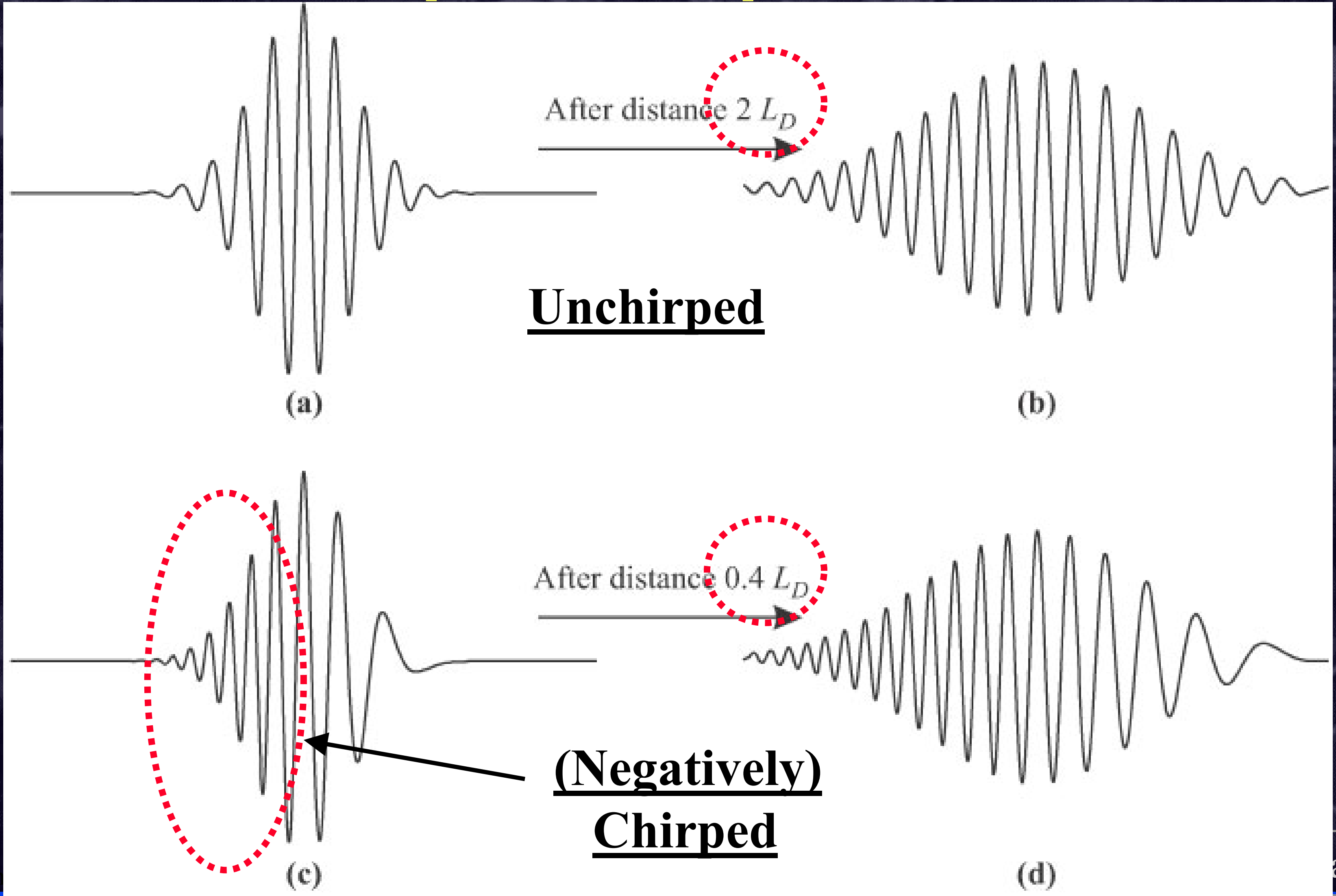
Chromatic Dispersion

- Different spectral components of a pulse travel at different velocities
- Also called *group-velocity-dispersion (GVD),* aka β_2
- Sub-components:
  - **Material dispersion:** frequency-dependent RI
  - **Waveguide dispersion:** light energy propagates partially in core and cladding.
  - Effective RI lies between the two (weighted by the power distribution).
  - Power distribution of a mode between core/cladding a function of wavelength!
- GVD parameter (β_2) > 0 => *normal* dispersion (1.3µm)
- GVD parameter (β_2) < 0 => *anomalous* dispersion (1.55µm)

Pulse Shaping: Chirped Gaussian Pulses

- Since chromatic dispersion affects pulse shape, we study how pulse shaping may affect the outcome
- Gaussian: envelope of pulse
- Chirped: frequency of launched pulse changes with time
- Semiconductor lasers + modulation, or nonlinear effects also lead to chirping
- With anomalous c-dispersion in normal 1.55 um fibers ($\beta_2 < 0$), and negative chirping ($\kappa < 0$, natural for semi-laser outputs), the pulse broadening effects are exacerbated (next slide)
- Key parameter: *dispersion length (L_D)*
  - @1.55um, L_D = 1800 km for OC-48 and L_D = 155 km for OC-192)
  - If d << L_D then chromatic dispersion negligible

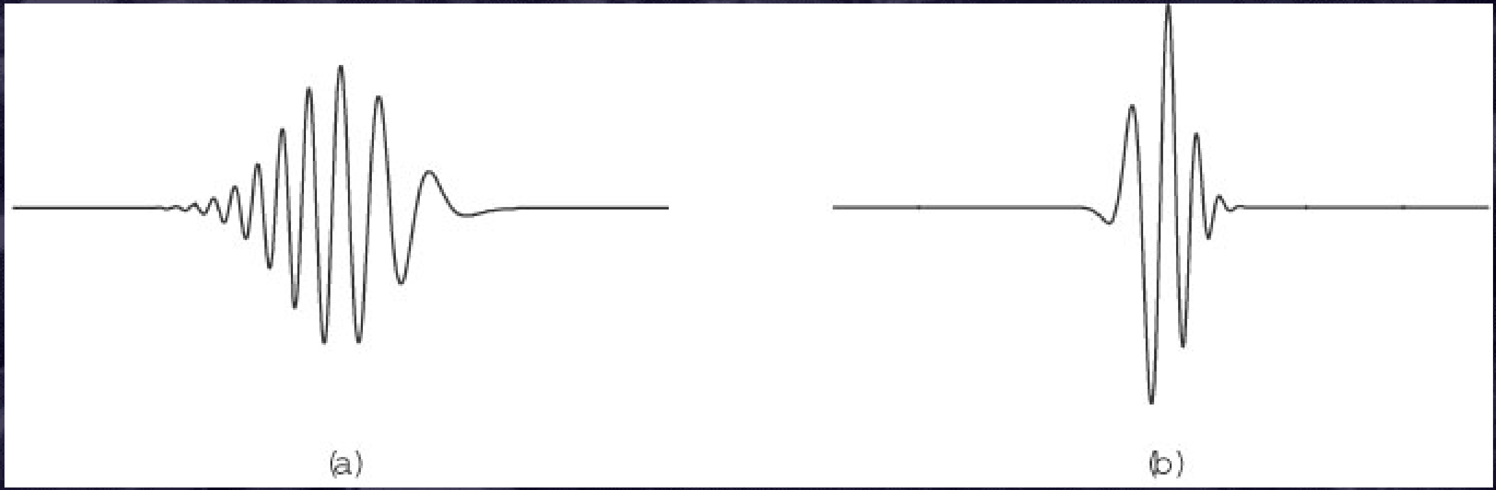
Chromatic Dispersion effect on Unchirped/Chirped Pulses



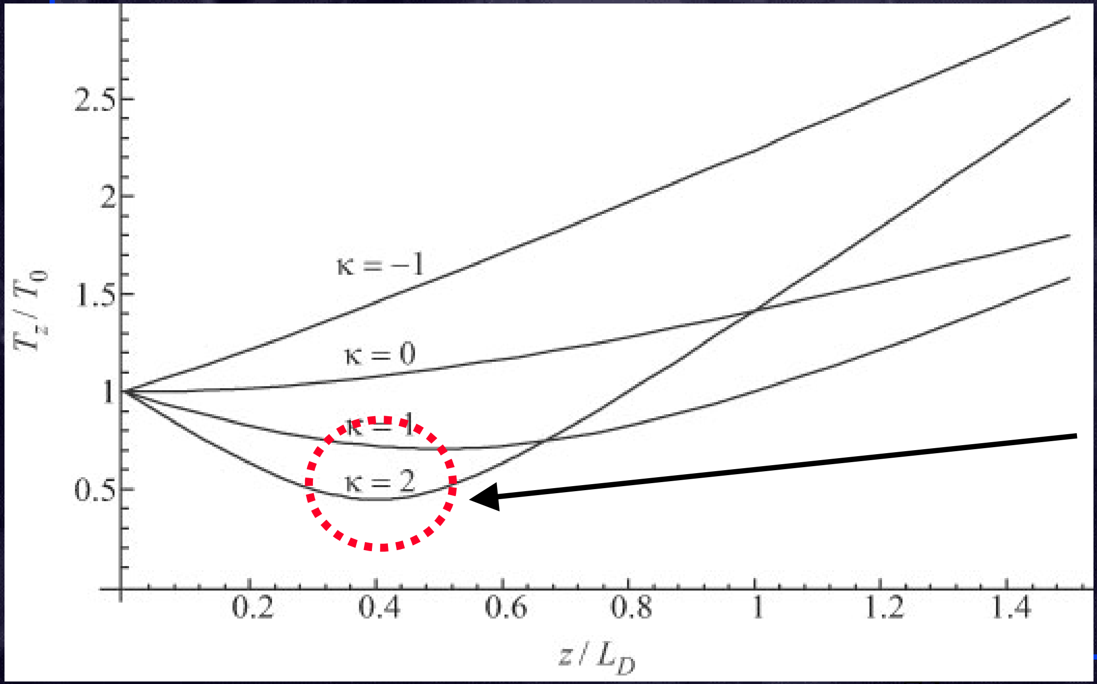
Unchirped

(Negatively) Chirped

Chirped Pulses May Compress (I.e. not broaden)!



(a) (b)



* Depends upon chirping parameter (κ) and GVD Parameter (β_2), I.e $\kappa \beta_2 < 0$

* Pulse may compress upto a particular distance and then expand (disperse)

* Corning's metrocor fiber: positive β_2 in 1.55 um band!

Combating Chromatic Dispersion: Dispersion Shifted Fiber

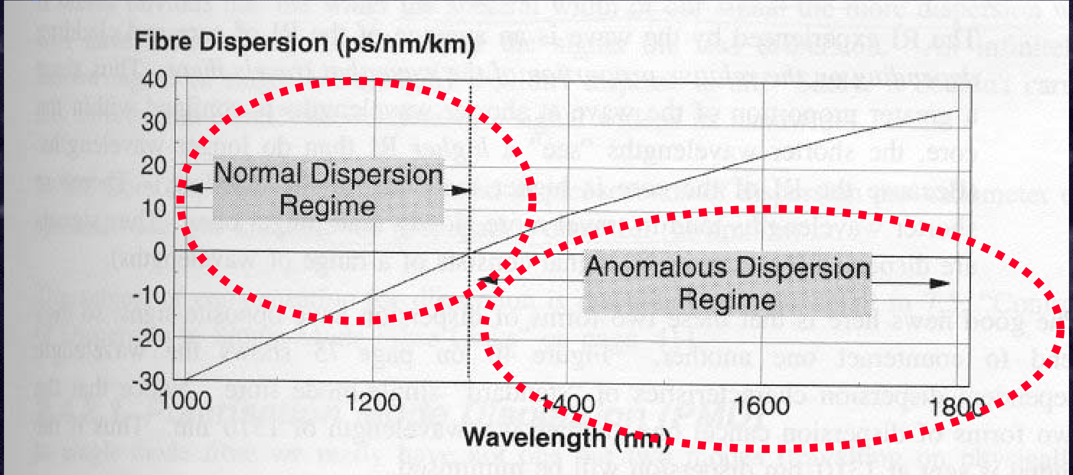


Figure 40. Dispersion of "Standard" Single-Mode Fibre

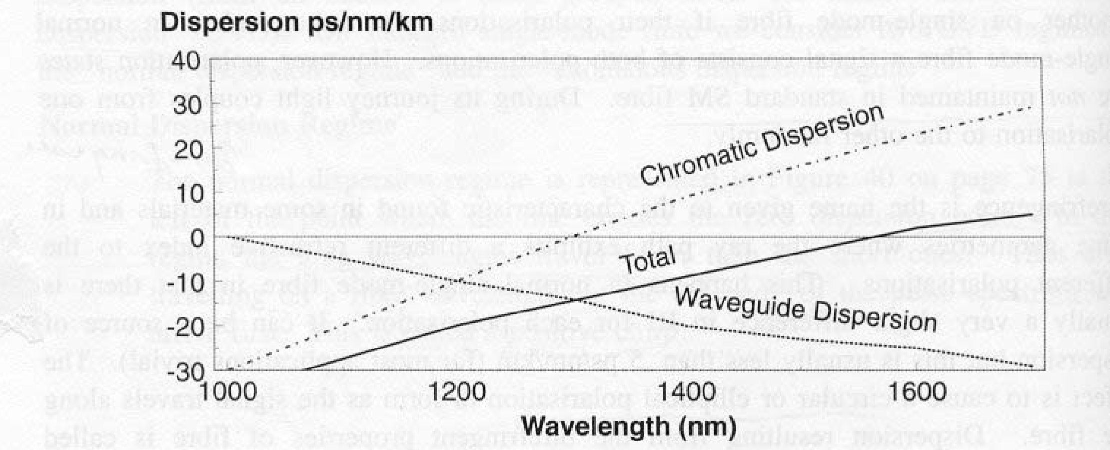


Figure 41. Dispersion Shifted Fibre

Though material dispersion cannot be attacked, waveguide dispersion can be reduced (aka "shifted") => DSF fiber

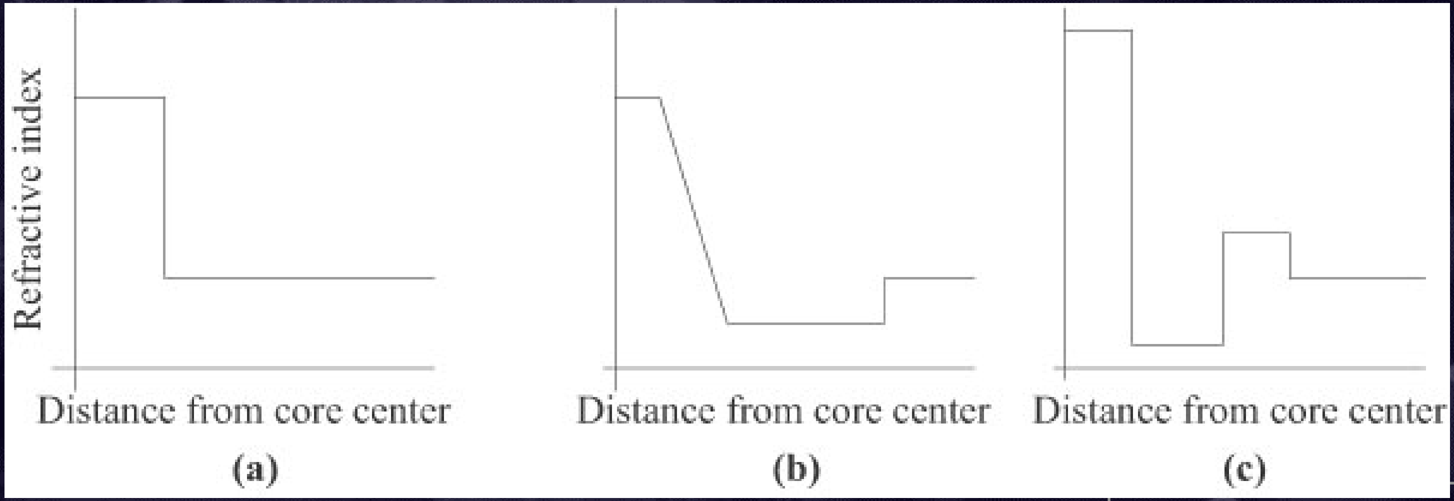
- *Deployed a lot in Japan*
- *RI profile can also be varied to combat residual C-dispersion*

Dispersion Shifted Fiber (contd)

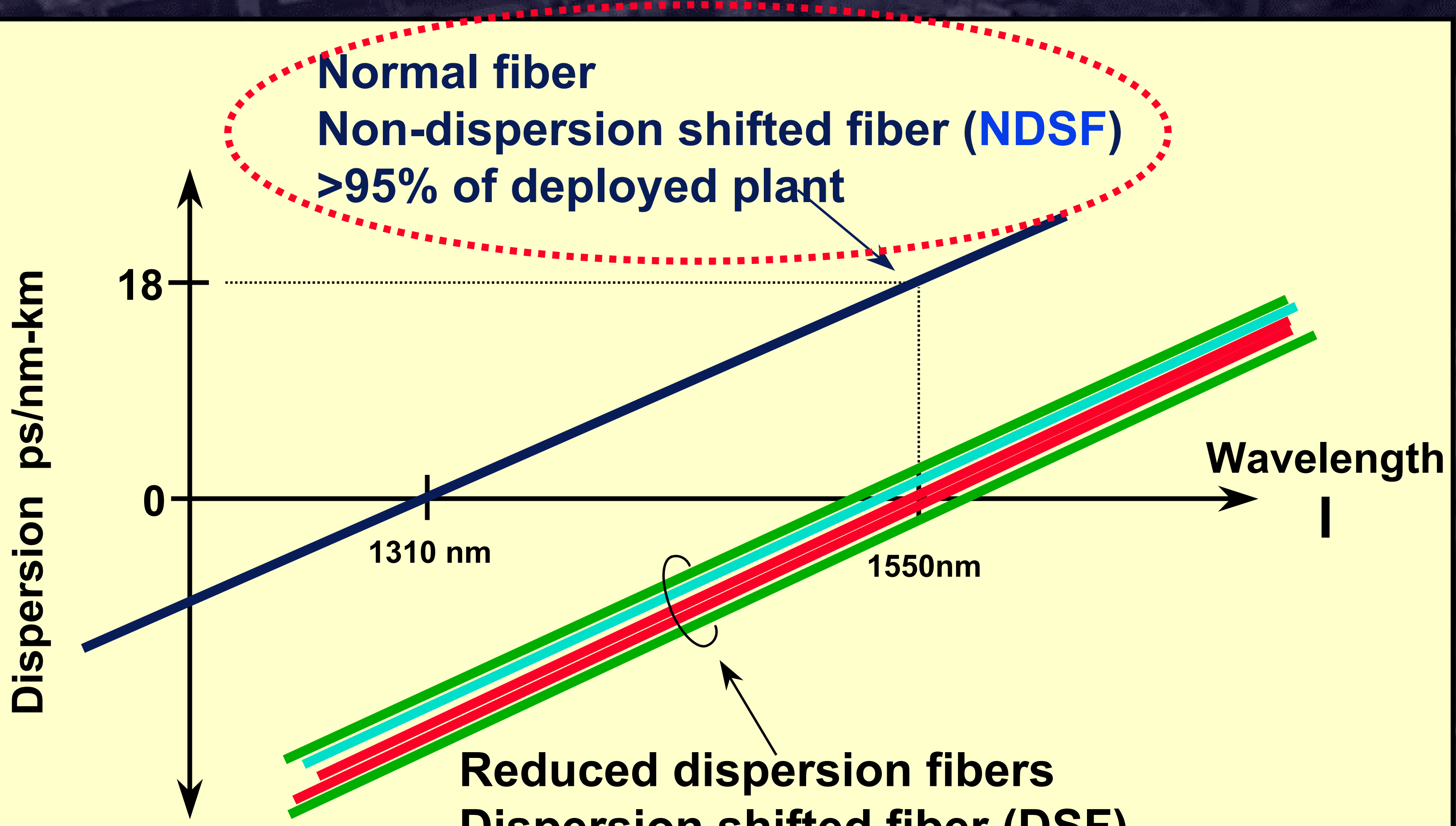
* Waveguide dispersion may be reduced by changing the RI-profile of the single-mode fiber from a step-profile to a trapezoidal profile (see below)

* This operation effectively "*shifts*" the zero-chromatic dispersion point to 1550nm & the average value in the band is 3.3 ps/nm/km

* Alternatively a length of "*compensating*" fiber can be used



Fiber *Dispersion*



Normal fiber
Non-dispersion shifted fiber (NDSF)
>95% of deployed plant

Reduced dispersion fibers
Dispersion shifted fiber (DSF)
Non-zero dispersion shifted fibers (NZDSF)

Dispersion Compensation Modules

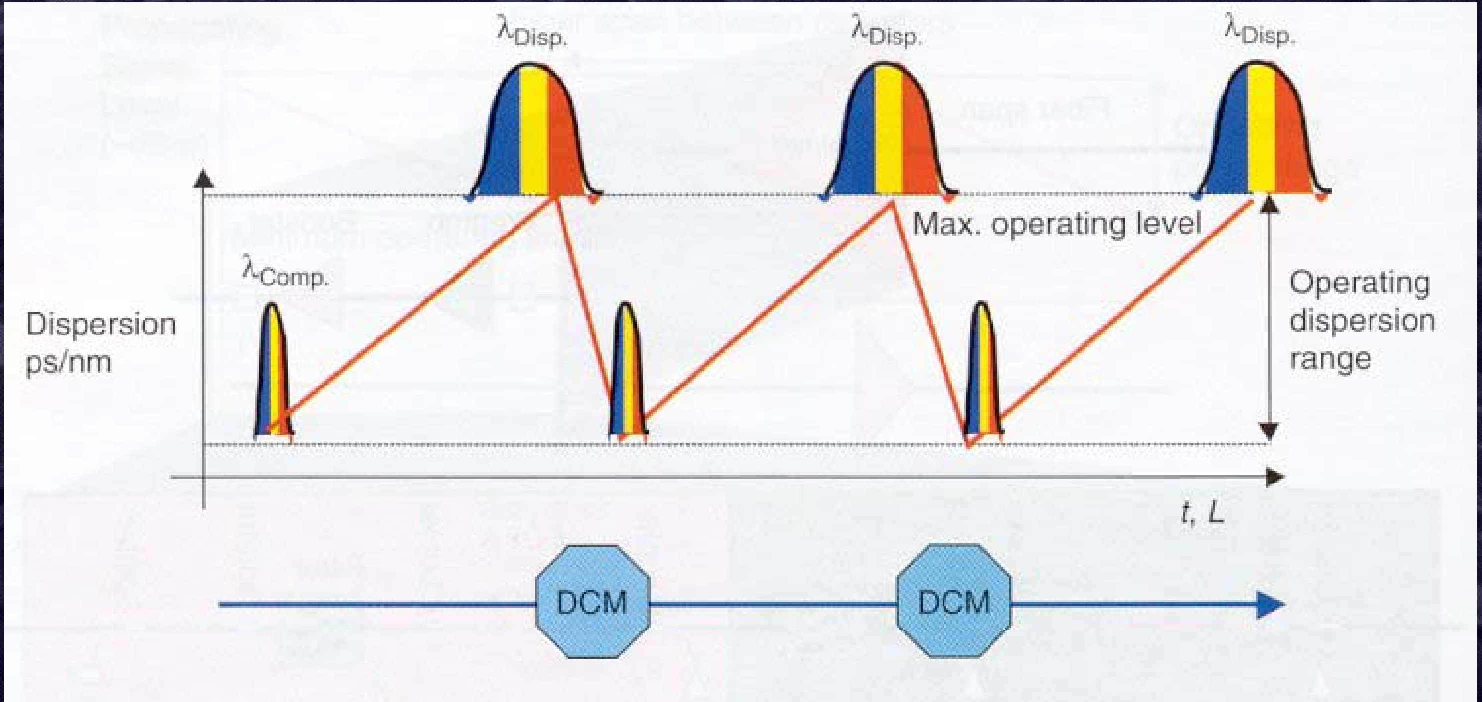


Figure 4.22 Dispersion compensation action.

Instead of DSF fibers, use dispersion compensation modules

Eg: *In-fiber chirped bragg gratings* (carefully reflect selected λs and make then travel a longer path segment) to compensate for C-dispersion

Residual Dispersion after DCMs

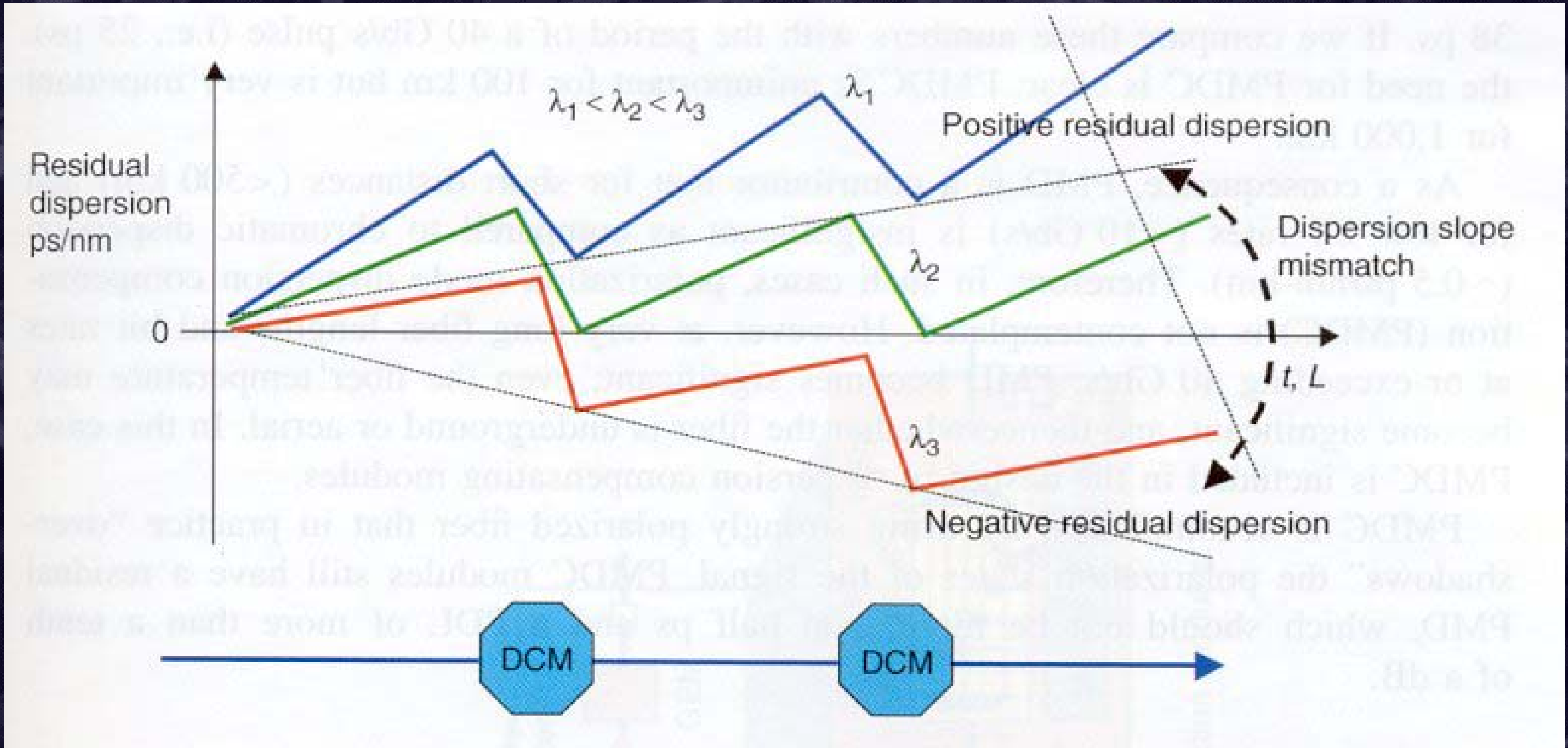
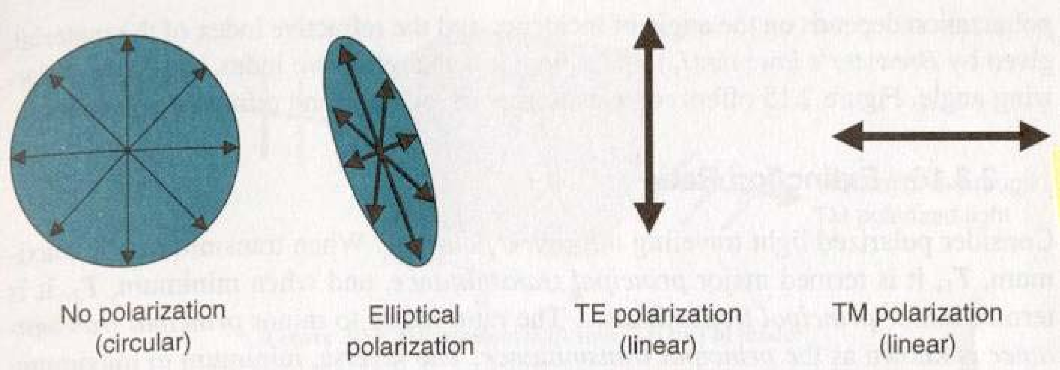


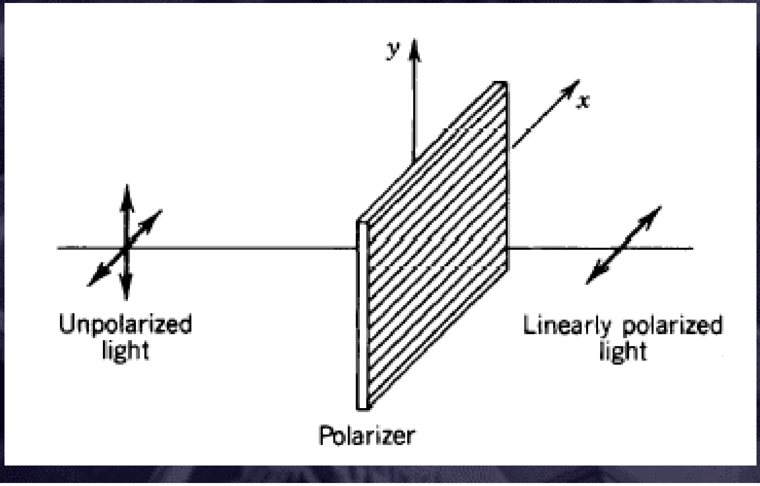
Figure 4.23 Residual dispersion in a path with DCMs.

Role of 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)



Linearly Polarized Light



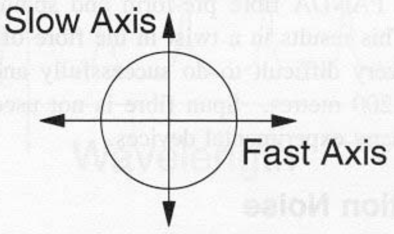
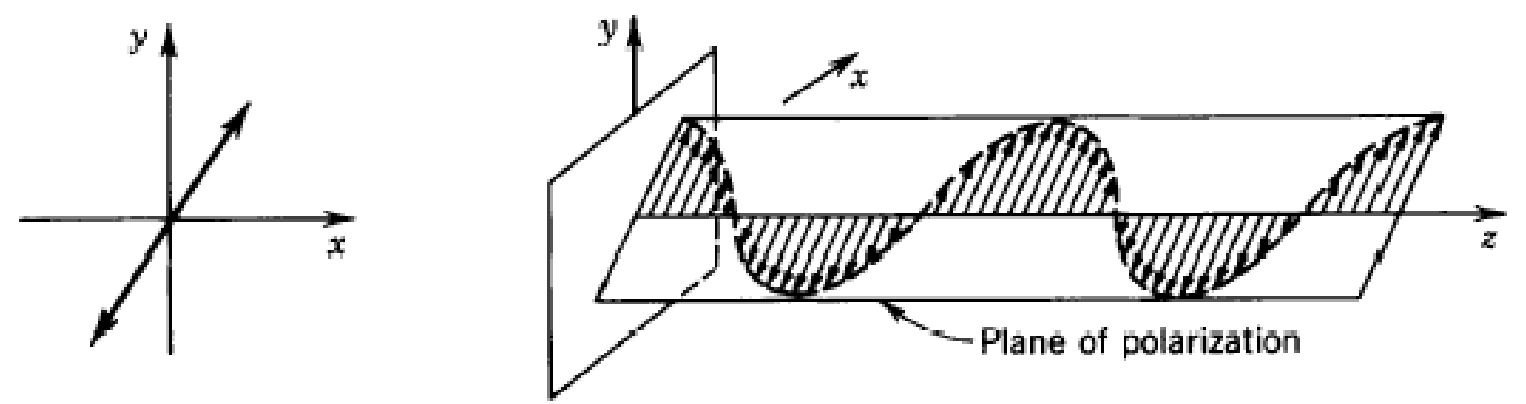
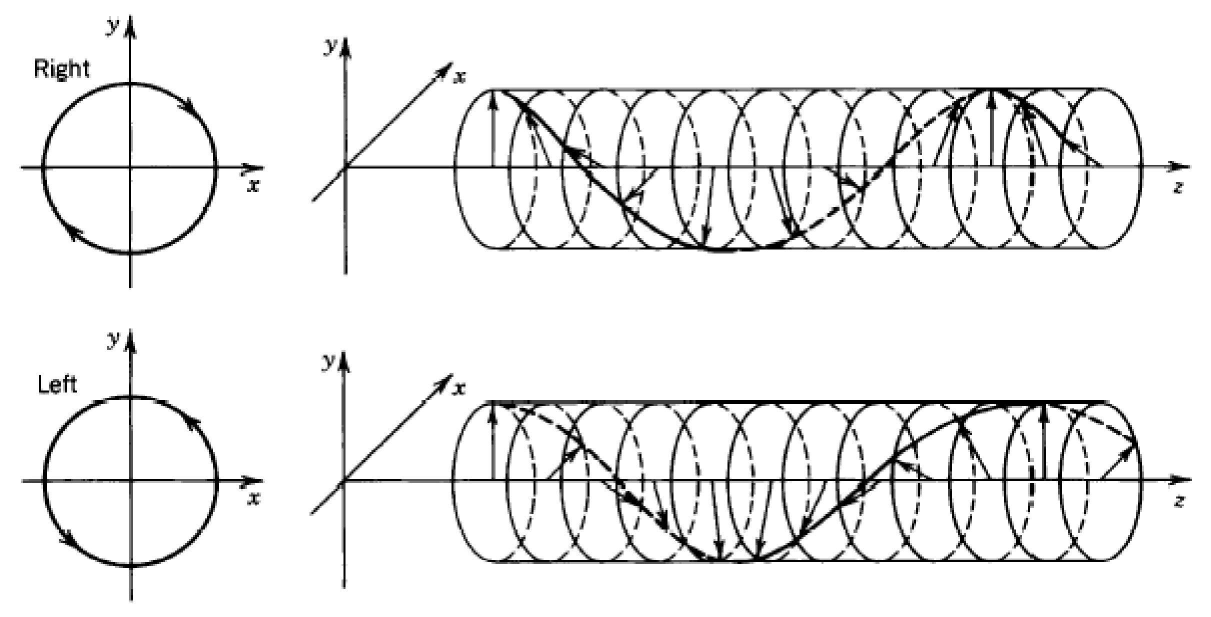


Figure 45. Axes of Polarisation in PMF



Circularly Polarized Light



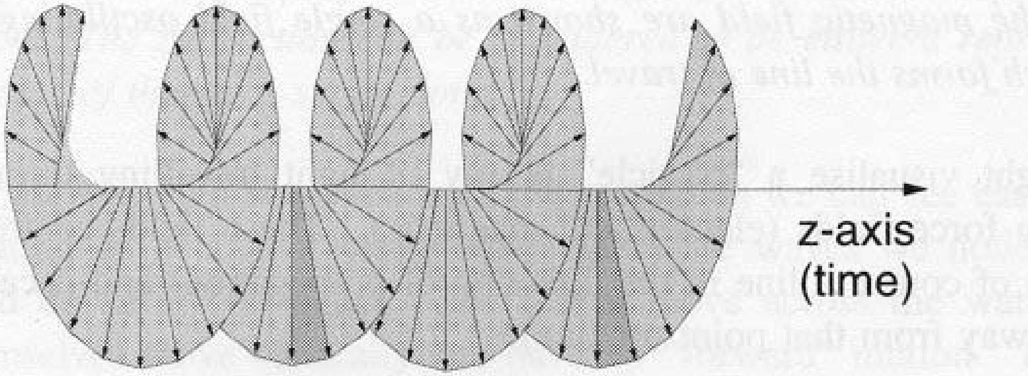


Figure 5. *Circular Polarisation. The direction of the electric field vector is represented by the arrows. As time passes (along the z-axis) the electric field rotates by 360 degrees in each wavelength period. Four cycles are illustrated.*

Polarizing Filters

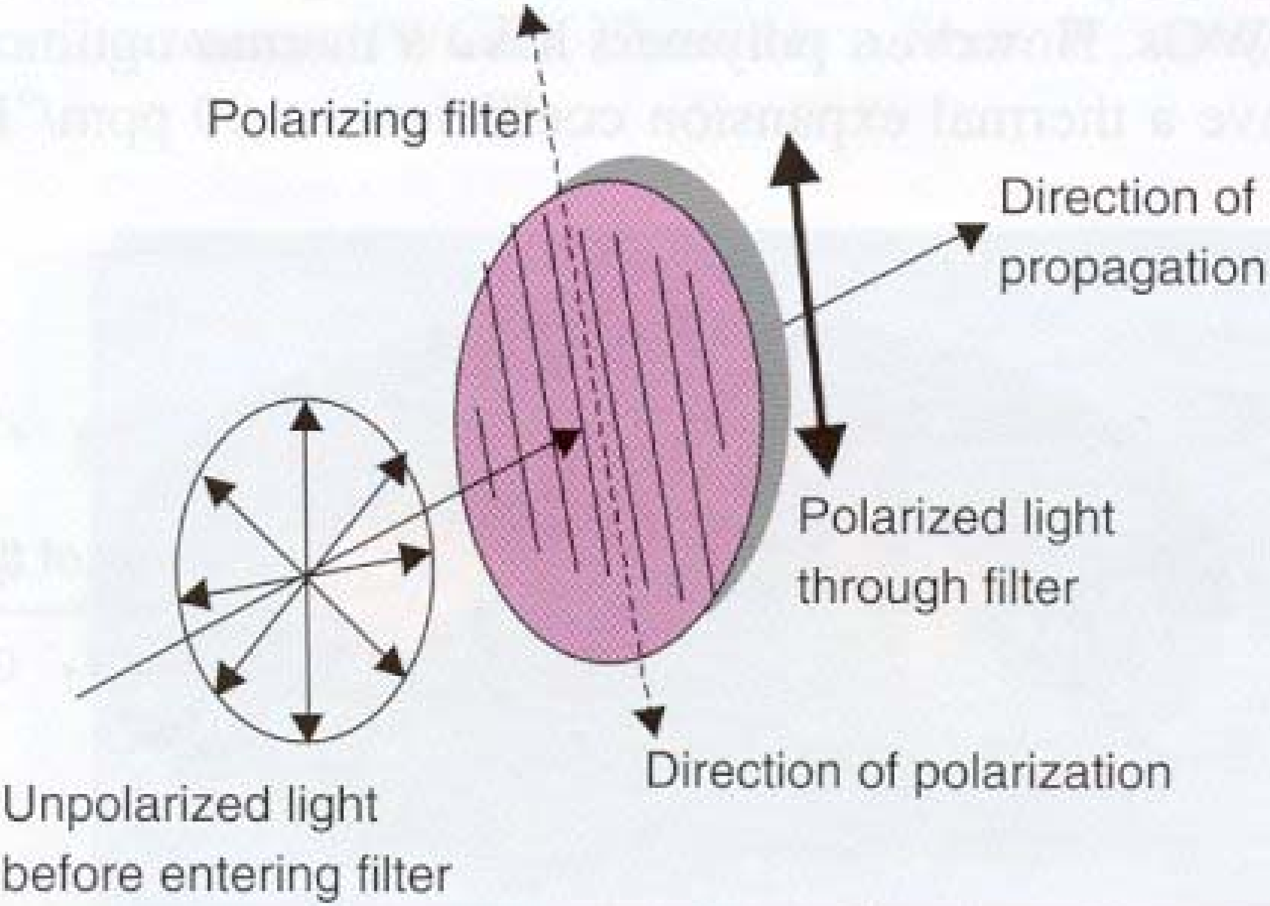


Figure 2.23 Polarizing filter.

Rotating Polarizations

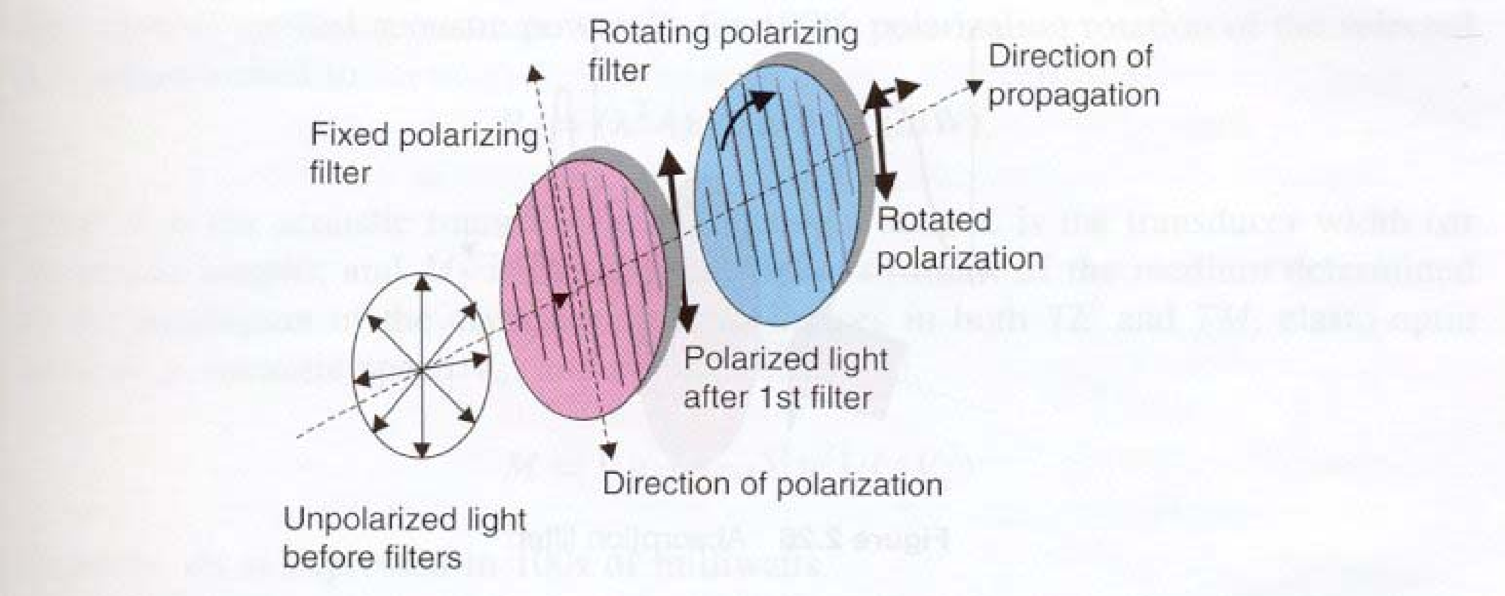


Figure 2.24 An assembly of a fixed and a rotating polarizing filter to rotate the polarization direction.

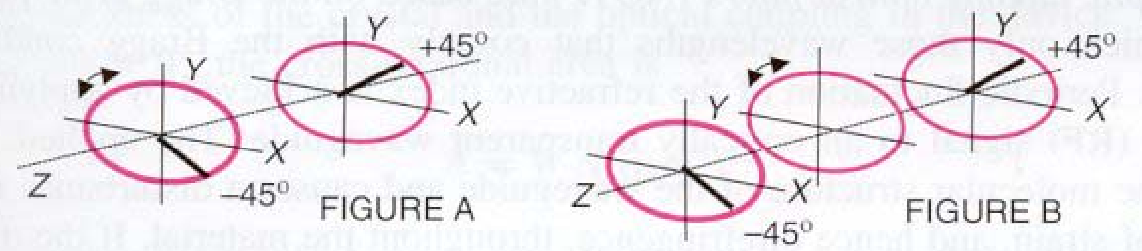


Figure 2.25 Birefringent plates construct fixed optical filters, A, or tunable filters, B.

Optical Isolator

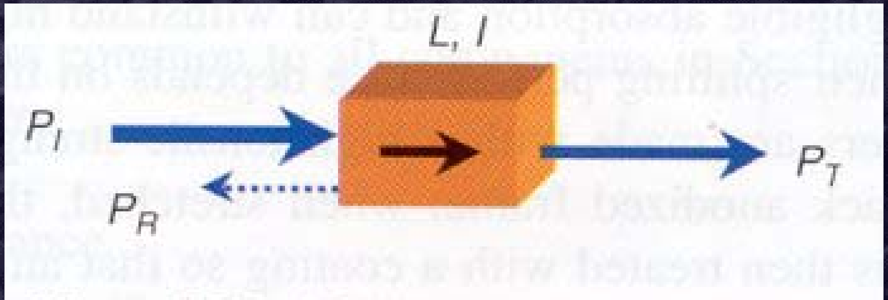
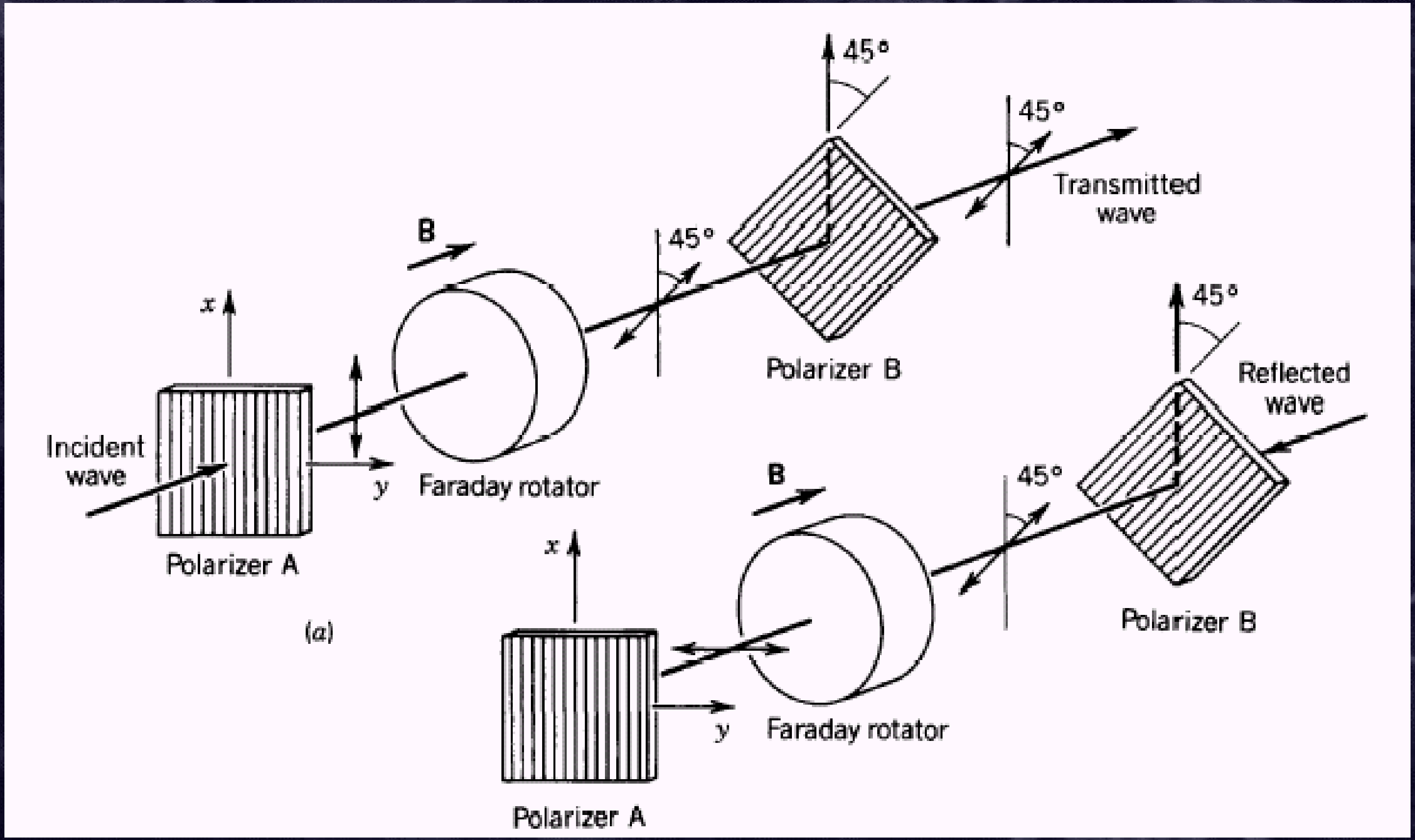


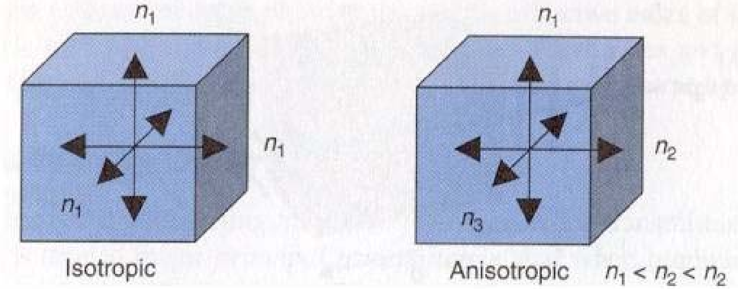
Figure 2.30 Model of an optical isolator.

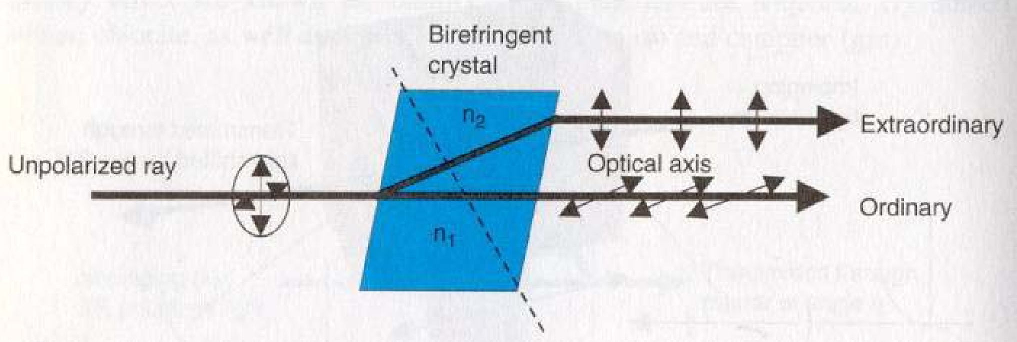


Single Mode Issues: Birefringence, PMD

- Even in single mode, there are 2 linearly independent solutions for every λ (to maxwell's equations)
- State of polarization (SOP): distribution of light energy between the (two transverse) polarization modes Ex and Ey
- Polarization Vector: The electric dipole moment per unit volume
- In perfectly circular-symmetric fiber, the modes should have the same velocity
- Practical fibers have a slight difference in these velocities (birefringence): separate un-polarized light into two rays with different polarizations
- This leads to pulse-spreading called Polarization Mode Dispersion (PMD)

AnIsotropy and Birefringence





Silica used in fiber is isotropic

Birefringence can also be understood as different refractive indices in different directions

It can be exploited (eg: Lithium niobate) for tunable filters, isolators, modulators etc

Birefringence

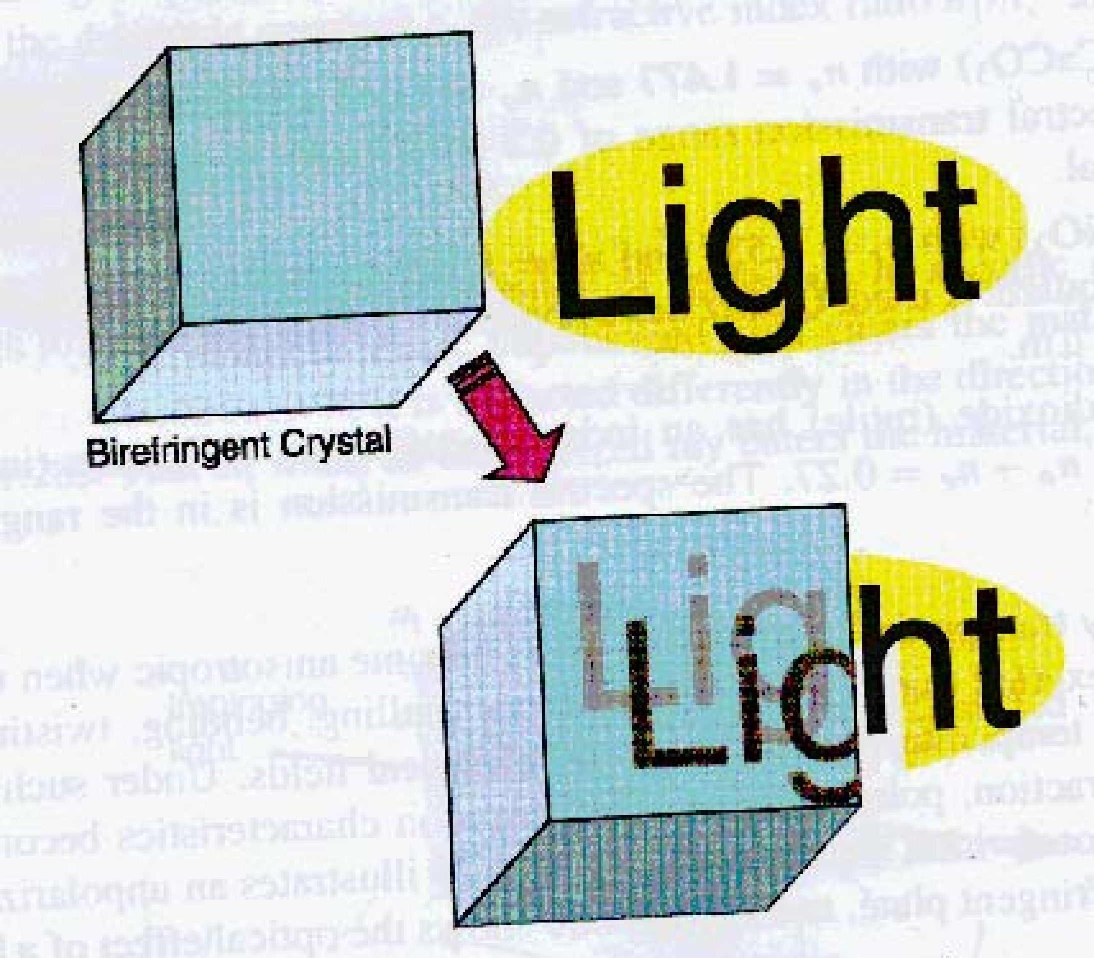
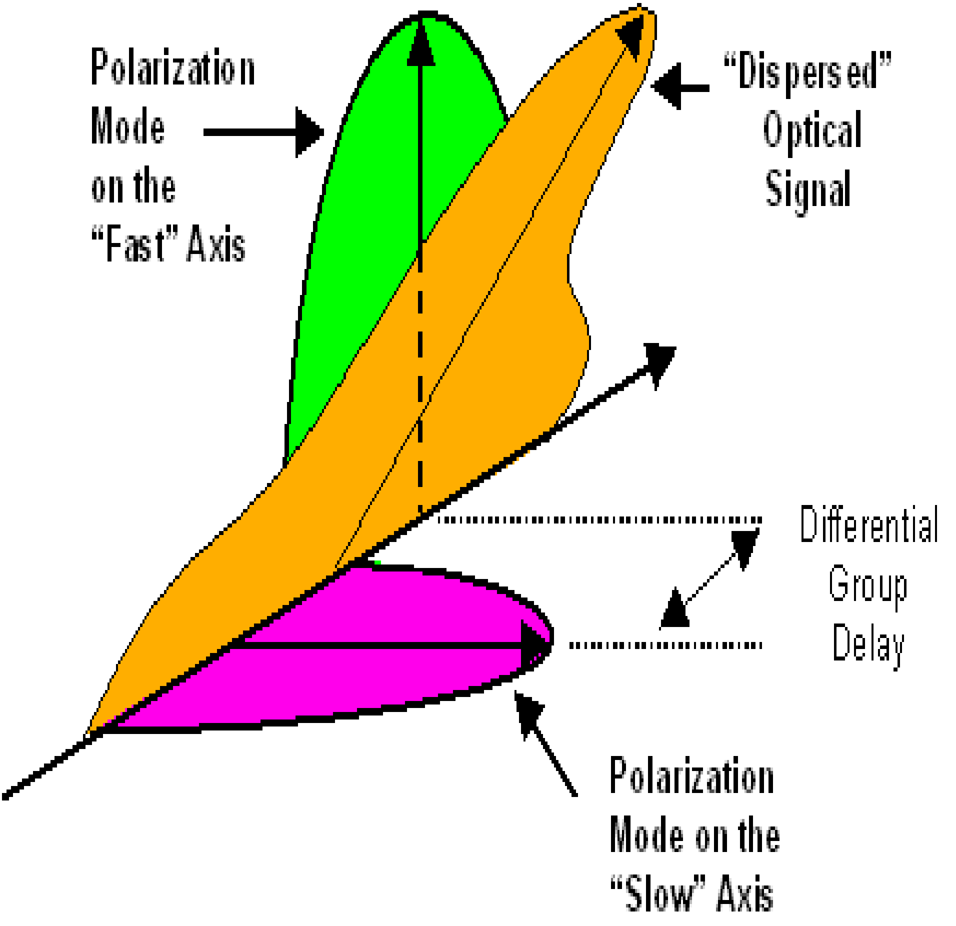


Figure 1.30 Effect of a birefringence crystal.

Polarization Mode Dispersion (PMD)



- Most severe in older fiber
- Caused by several sources
  - Core shape
  - External stress
  - Material properties
- Note: another issue is polarization-dependent loss (PDL)
- Both become dominant issue at OC-192 and OC-768

Polarization Mode Dispersion

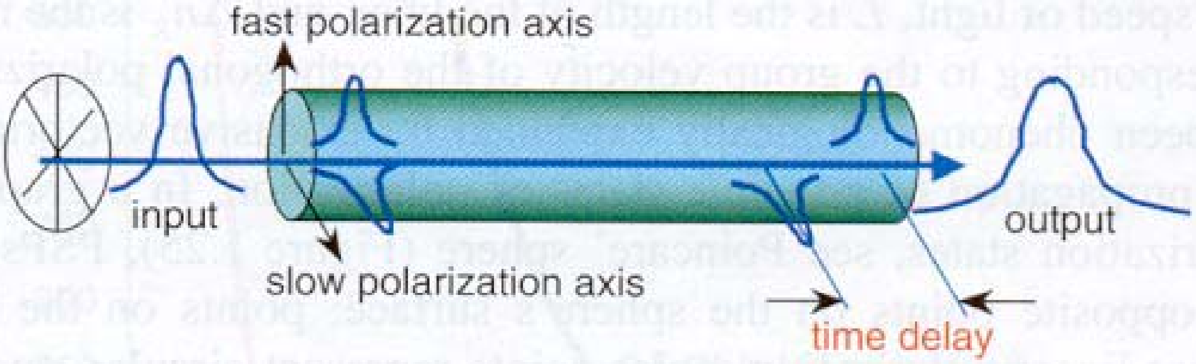


Figure 1.55 Polarization-mode dispersion.

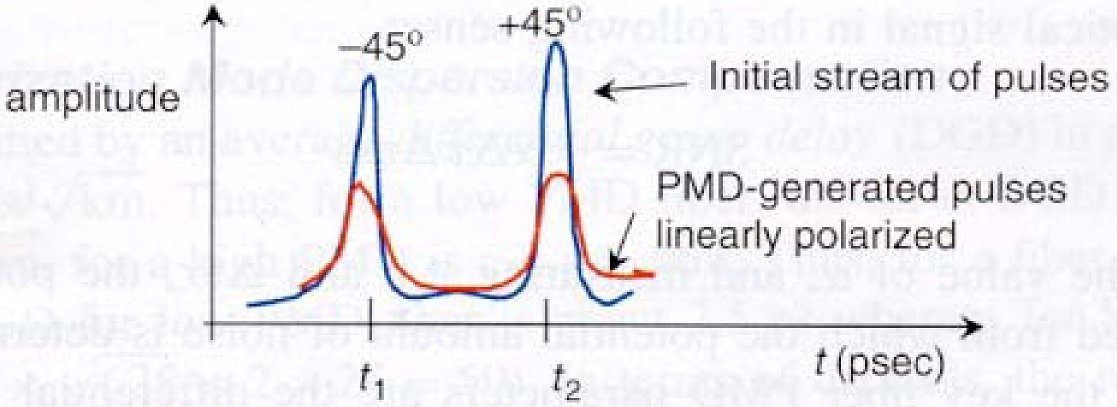


Figure 1.56 In polarization mode dispersion, sequential orthogonally polarized pulses interact to generate another stream of linearly polarized pulses.

Non-linear Effects

- Linearity: a light-matter interaction assumption
  - Induced dielectric polarization is a convolution of material's susceptibility (χ) and the electric field (E)
- Linearity: low power (few mW) & bit rates (2.4 Gbps)

- Non-linearity:
  - ↑ bit rates (10 Gbps) and ↑ power => non-linearities
  - ↑ channels (eg: DWDM) => more prominent even in moderate bit rates etc

- Two categories:
  - A) λ-phonon interaction & scattering (SRS, SBS)
  - B) RI-dependence upon light intensity (SPM, FWM)

Non-linearity Scattering Effects

- Stimulated Raman or Brillouin Scattering (SRS or SBS)
  - Energy transferred from one λ to another at a longer λ (or lower energy)
  - The latter wave is called the "*Stokes wave*"
  - Former wave is also called the "*pump*"
  - Pump loses power as it propagates and Stokes wave gains power
- SBS: pump is signal wave & Stokes is unwanted wave
- SRS: pump is high-power wave, and Stokes wave is signal wave that is amplified at the expense of the pump
- Parameters:
  - g: gain coefficient (strength of the effect)
  - Δf: Spectral width over which the gain is present

SRS: Photon Emission Mechanics

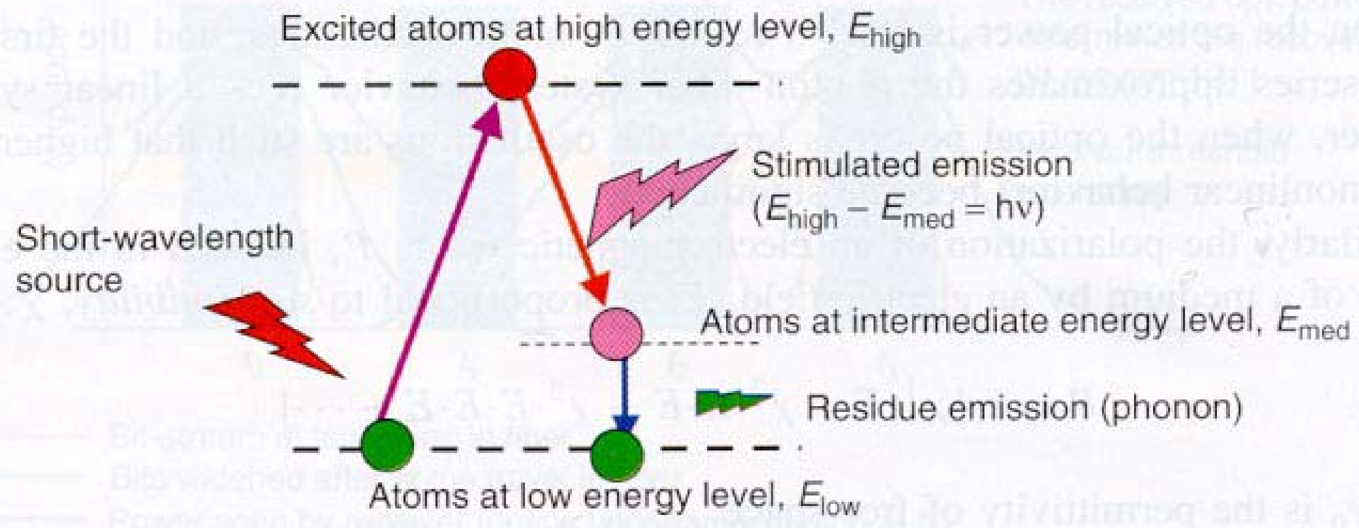
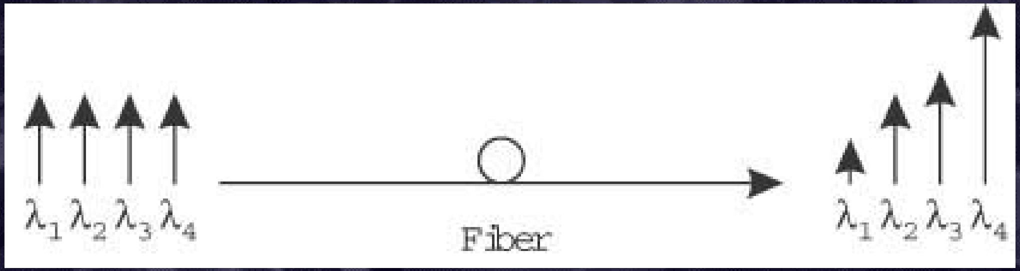
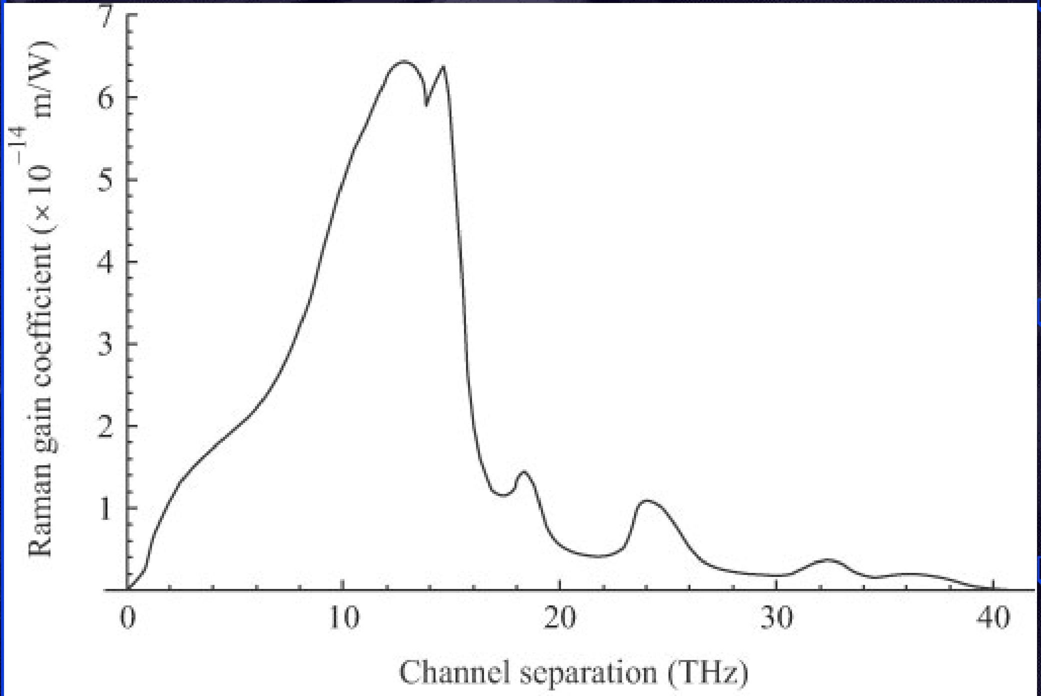


Figure 1.62 A short-wavelength source excites atoms to a higher-energy level. When the atom is stimulated, it releases photonic energy of a longer wavelength.

- Photons interact with atoms: eg: May be absorbed to reach an “excited” state (“meta-stable”, I.e. cant hang around!)
- In the excited state, certain photons may trigger them to fall back, and release energy in the form of photons/phonons
- Photon-Atom vs Photon-Atom-Photon interactions
- Most of these effects are “third order” effects

Stimulated Raman Scattering (SRS)





- Power transferred from lower-λ to higher-λ channels
- Can be used as basis for optical amplification and lasers!
- Photons of lower-λ have higher energy (aka “pump”) that excite atoms and lead to stimulate emission at higher-λ
- Effect smaller than SBS, but can affect both forward and reverse directions
- Effect is also wider: I.e a broadband effect (15 Thz)

Raman Scattering

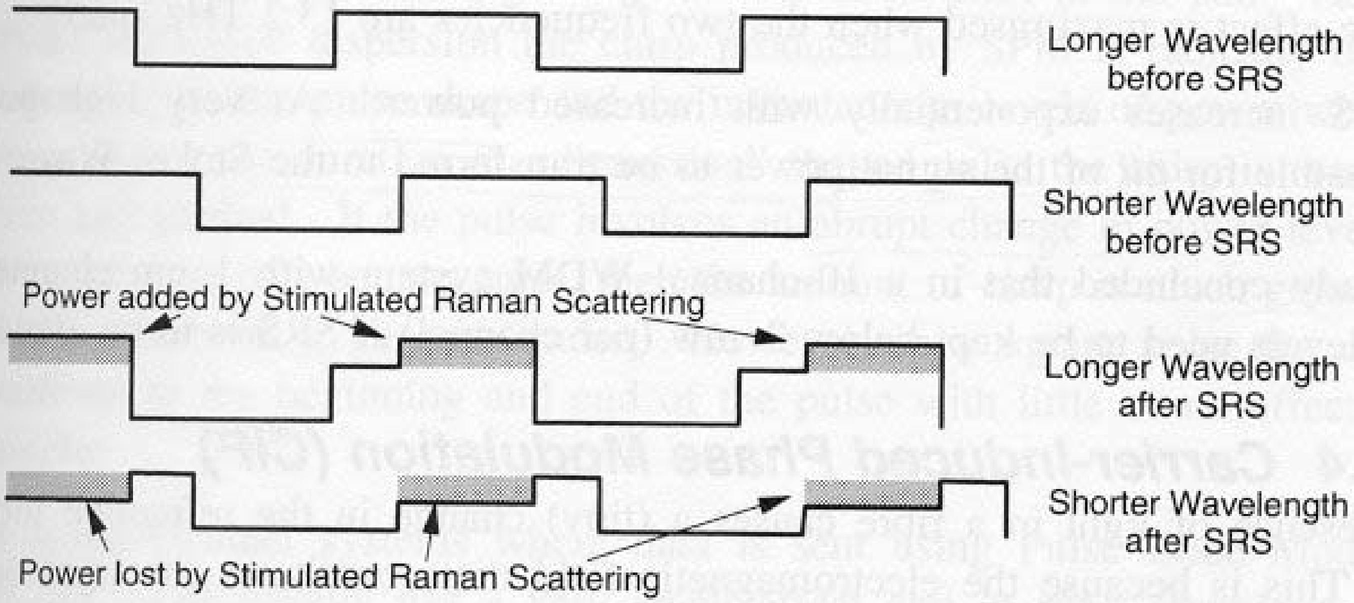


Figure 49. Stimulated Raman Scattering

Stimulated Brillouin Scattering (SBS)

- Triggered by interaction between a photon and an acoustic phonon (I.e. molecular vibrations)
- Affects a narrowband: 20 Mhz (compare with 15 Thz effect in SRS)
  - Can combat it by making source linewidth wider
- The downshifted wavelength waves propagate in the opposite direction (reverse gain): need isolation at source!
- Dominant when the spectral power (brightness) of the source is large and abruptly increases beyond a threshold (5-10 mW)
- Limits launched power per channel, but may be used in amplification

SBS: Threshold Variation

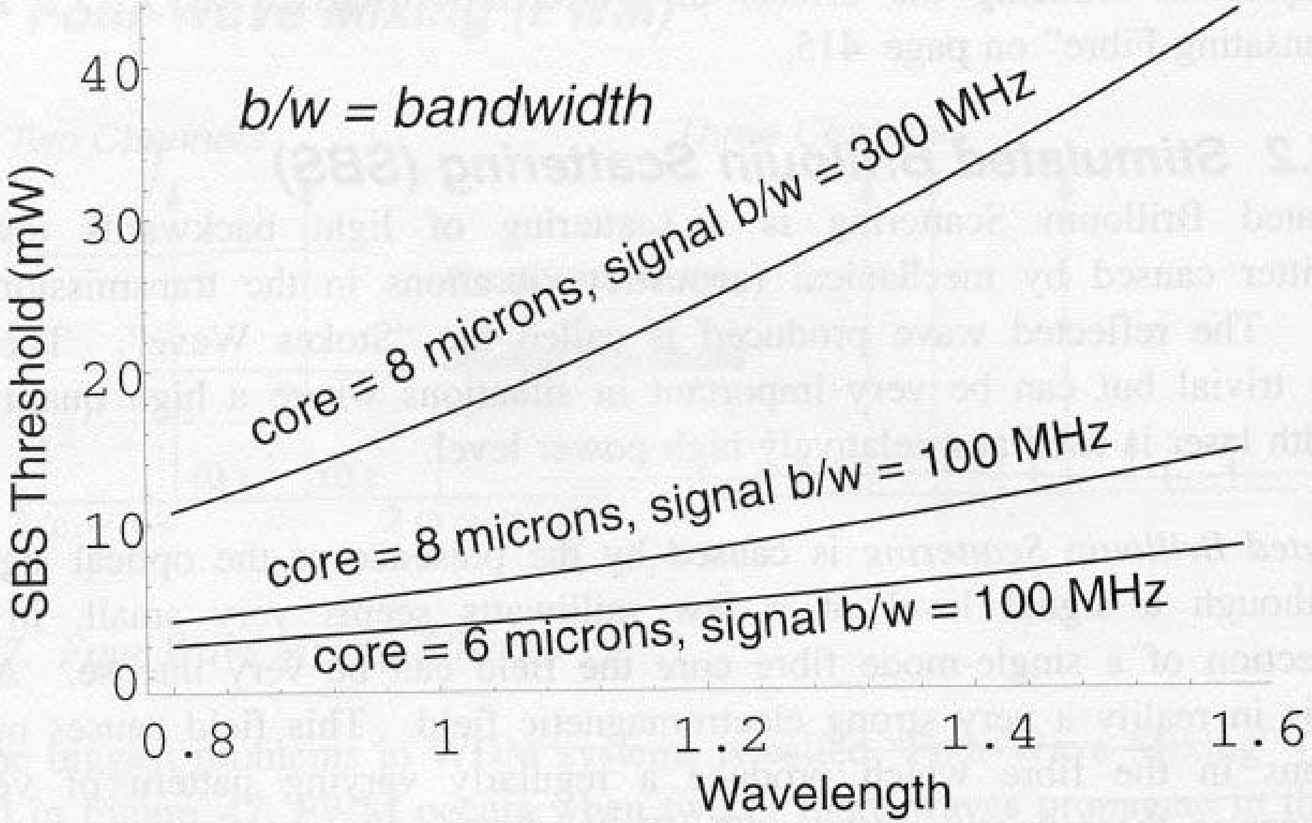


***Figure 48.** SBS Threshold Variation with Wavelength. The threshold value is the power level above which SBS causes a significant effect.*

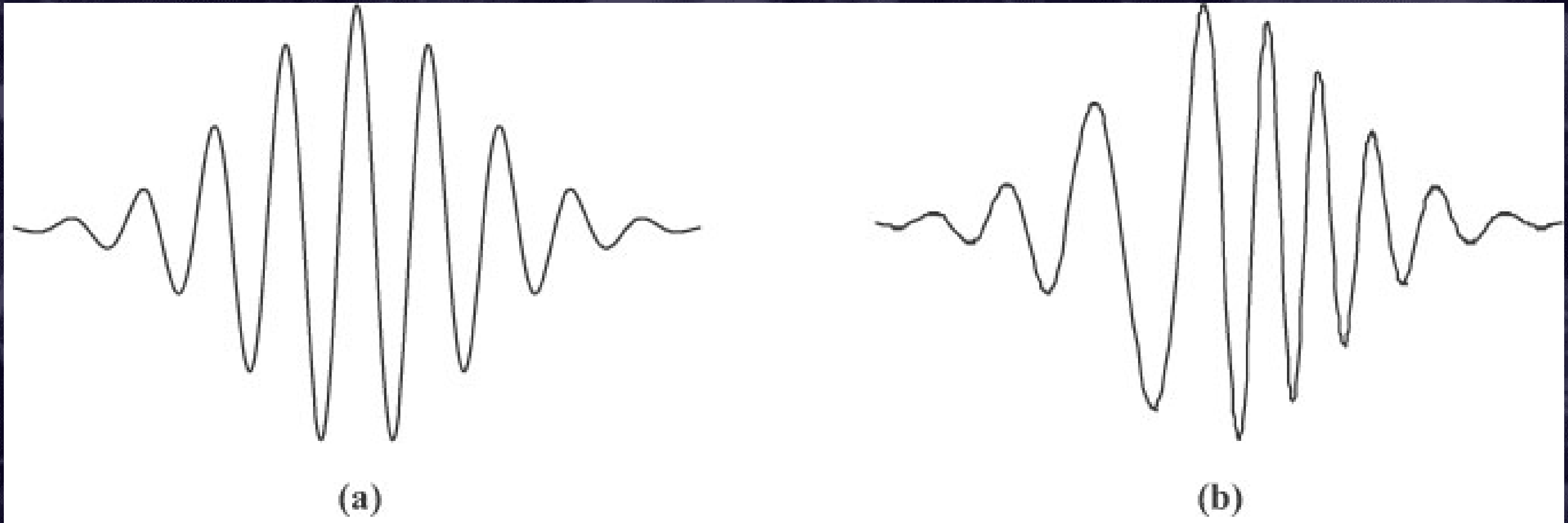
Electro-Optic RI Effects

- Electro-optic effects:
  - Refractive index (RI) depends upon amplitude (and hence intensity) of electric field (E)
  - Result: induced birefringence, dispersion
- Pockels Effect: $\Delta n = (a_1)E$
- Kerr Effect: (second order) $\Delta n = (\lambda K)E^2$
- The second order magnification in Kerr effect may be used to create ultra high speed modulators (> 10Gbps)

Intensity-dependent RI Effects

- Self-phase Modulation (SPM), Cross-Phase Modulation (CPM) & Four-wave mixing (FWM)
- SPM: Pulses undergo induced chirping at higher power levels due to RI variations that depend upon intensity
- In conjunction with chromatic dispersion, this can lead to even more pulse spreading & ISI
  - But it could be used to advantage depending upon the sign of the GVD parameter
- CPM: Multiple channels: induced chirp depends upon variation of RI with intensity in *other* channels!
- FWM: A DWDM phenomena: tight channel spacing
  - Existence of f1, … fn gives rise to new frequencies 2fi – fj and fi + fj – fk etc
  - In-band and out-of-band crosstalk

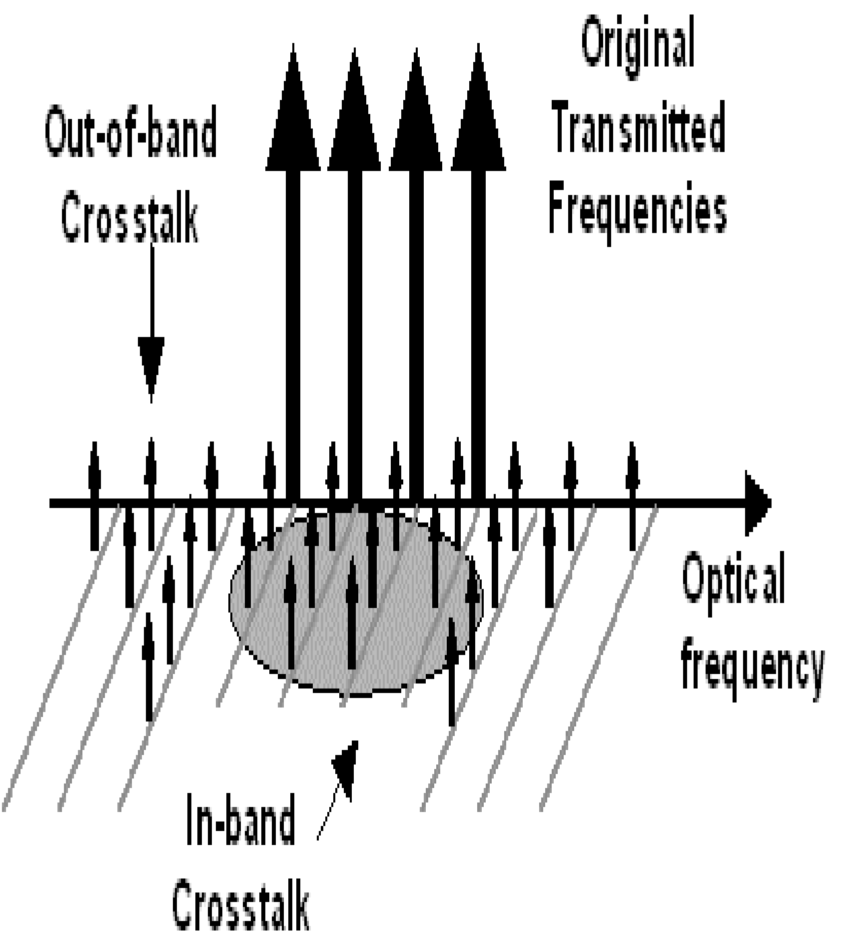
Self-Phase Modulation



Example of (positive) chirp or frequency fluctuations induced by self-phase modulation

Modulation instability or self-modulation: In the frequency domain, we see new sidelobes

Four-Wave Mixing (FWM)



- **Creates in-band crosstalk** (superposition of uncorrelated data) that can not be filtered
- Signal power depletion
- SNR degradation
- Problem increases geometrically with
  - Number of λs
  - Spacing between λs
  - Optical power level
- Chromatic dispersion minimizes FWM (!!)
- Need to increase channel spacing and manage power carefully

Four-Wave Mixing Effects

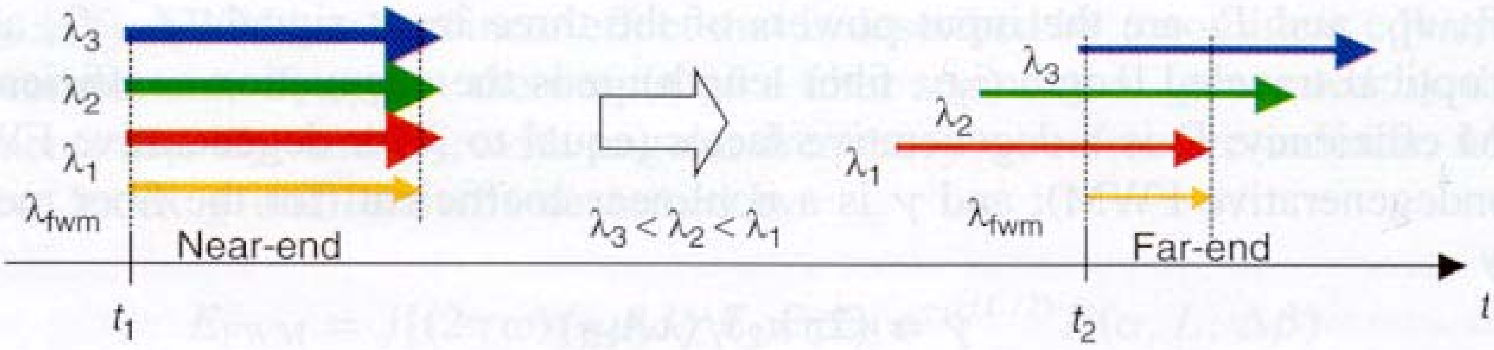


Figure 1.64 The effect of FWM is strongest at the near-end of synchronized channels, and it is diminished at the far-end where channels are weakest due to attenuation and dispersion.

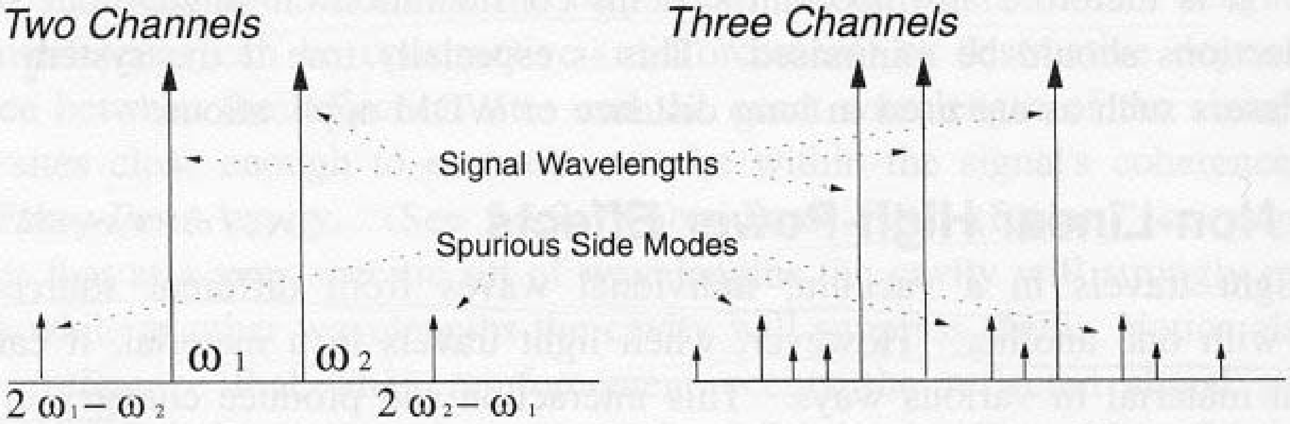
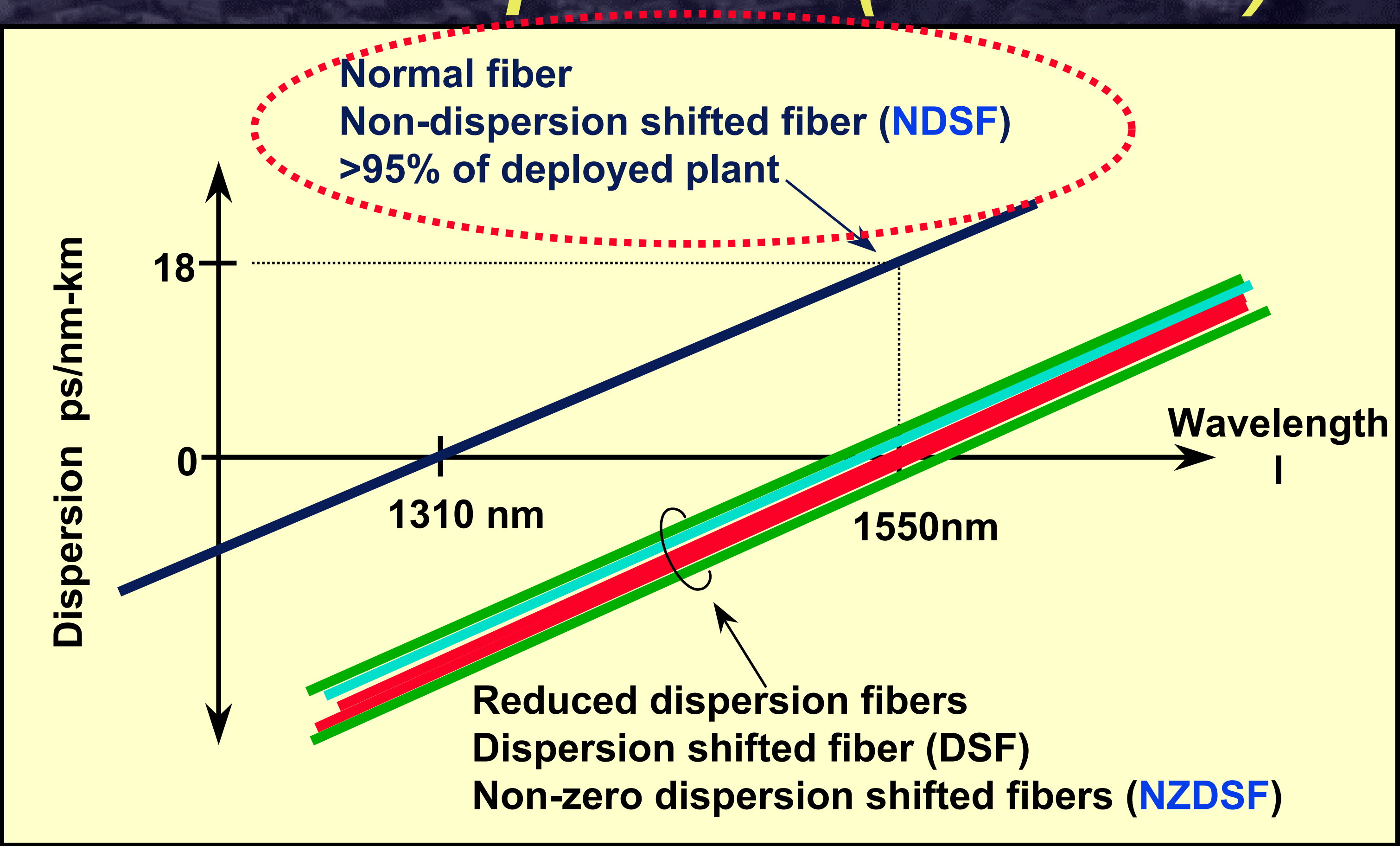


Figure 47. *Four Wave Mixing Effects*

Fiber *Dispersion (revisited)*



Normal fiber
Non-dispersion shifted fiber (**NDSF**)
>95% of deployed plant

Reduced dispersion fibers
Dispersion shifted fiber (DSF)
Non-zero dispersion shifted fibers (**NZDSF**)

** Dispersion-shifted (DSF) is good for chromatic dispersion but bad for non-linear effects.*

** NZ-DSF: puts back a small amount of C-dispersion!*

Non-Zero Dispersion Shifted Fiber

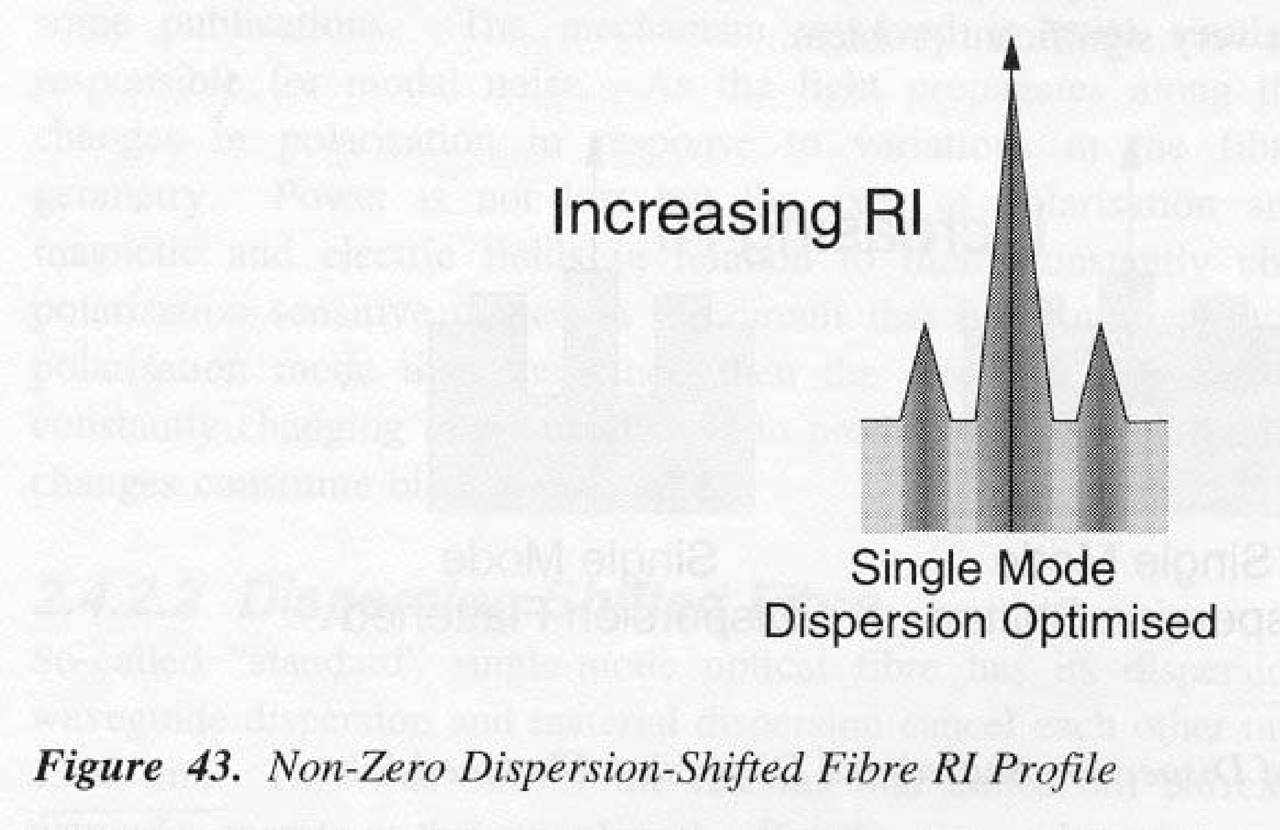


Figure 43. Non-Zero Dispersion-Shifted Fibre RI Profile

- *NZ-DSF: puts back a small amount of C-dispersion!*
- *Note: The goal of RI-profile shaping is different here than graded-index in multimode fiber*

Fibers: chromatic dispersion story…

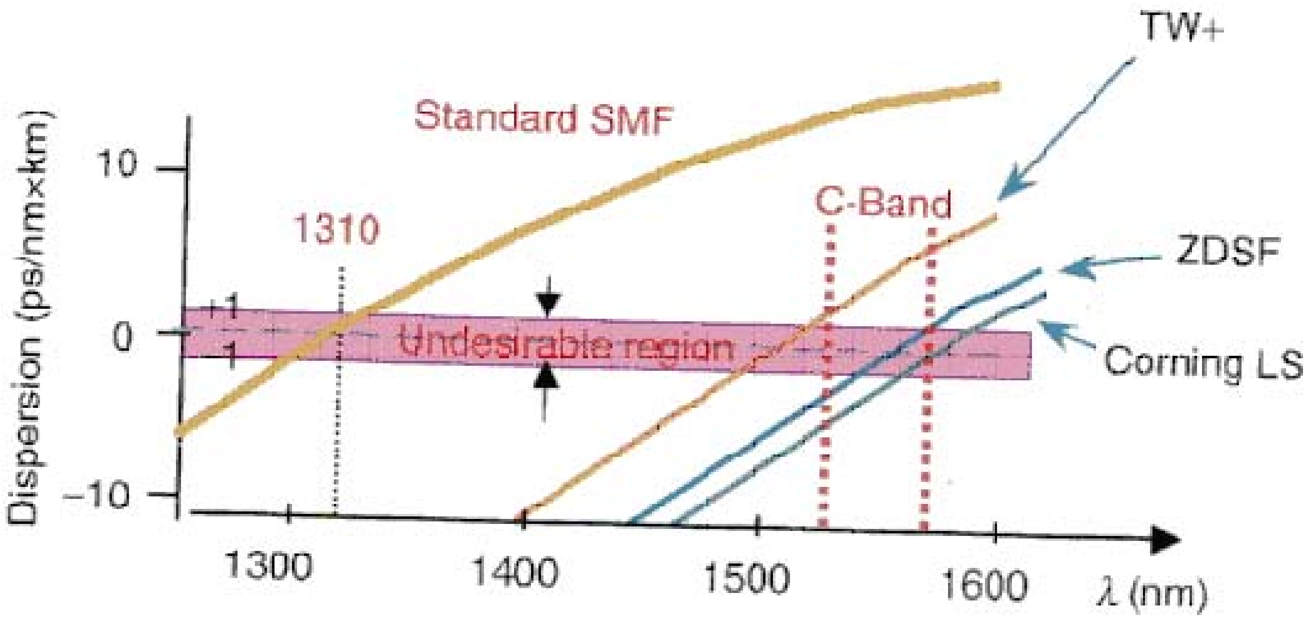
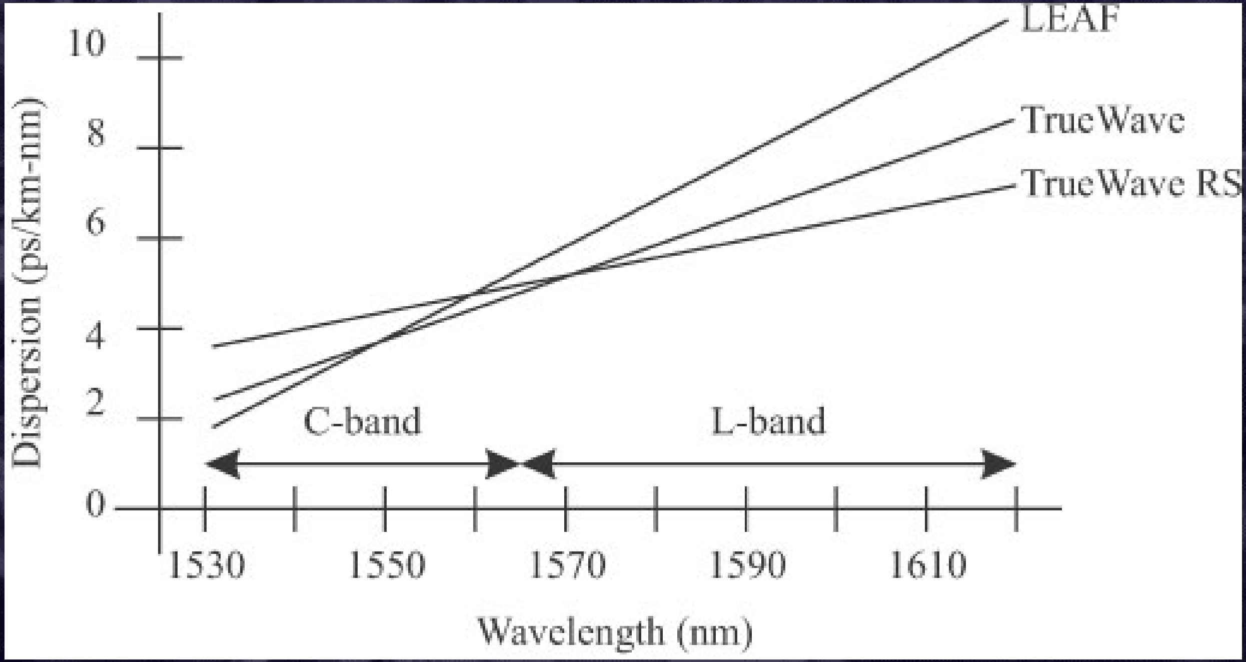


Figure 1.48 Chromatic dispersion (approximate) and zero-dispersion wavelength for different fibers types.

Latest Fibers & Bands

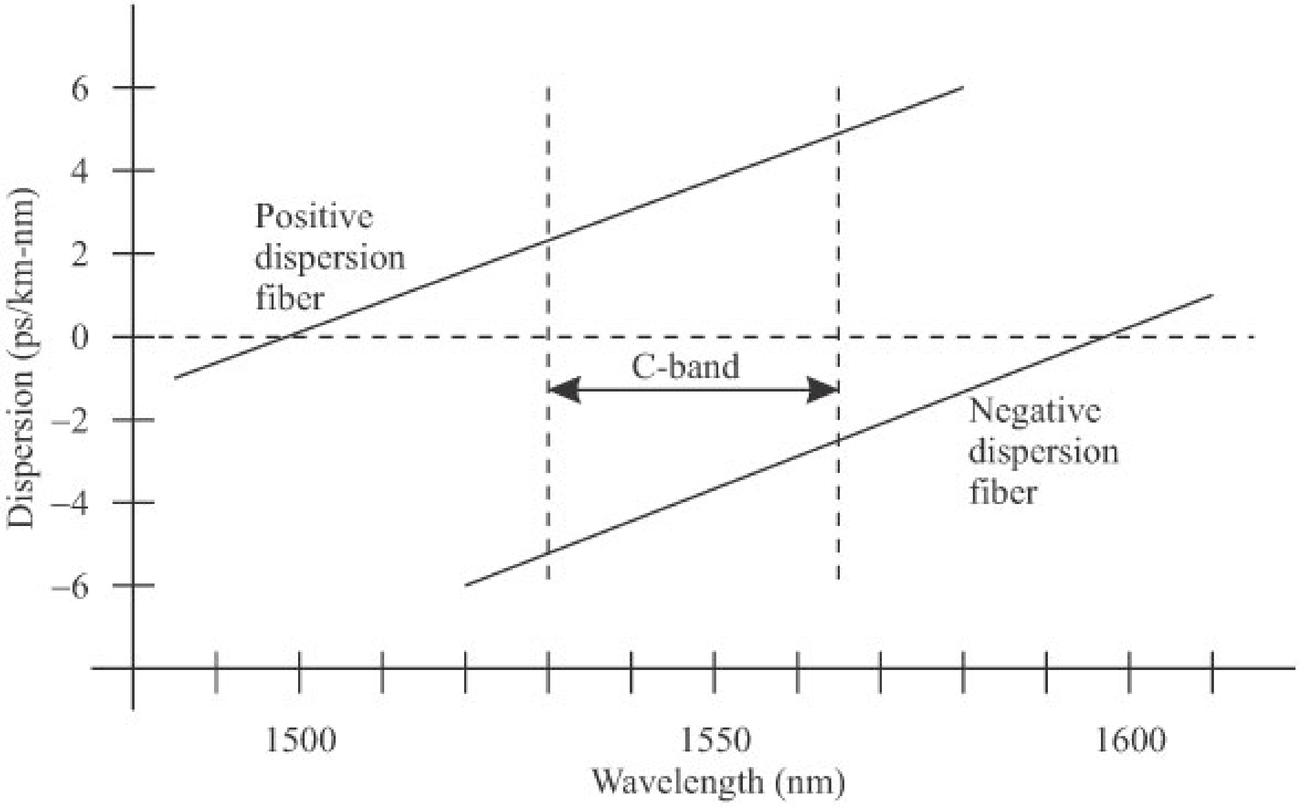


LEAF fibers have larger effective area=> better tradeoff for non-linearities

Fiber Bands:

O-band: (Original) 1260-1360nm
E-band: (Extended) 1360-1460nm
S-band: (Short) 1460-1530nm
C-band: (Conventional): 1530-1565nm
L-band: (Long) 1565-1625nm
U-band: (Ultra-long): 1625-1675nm

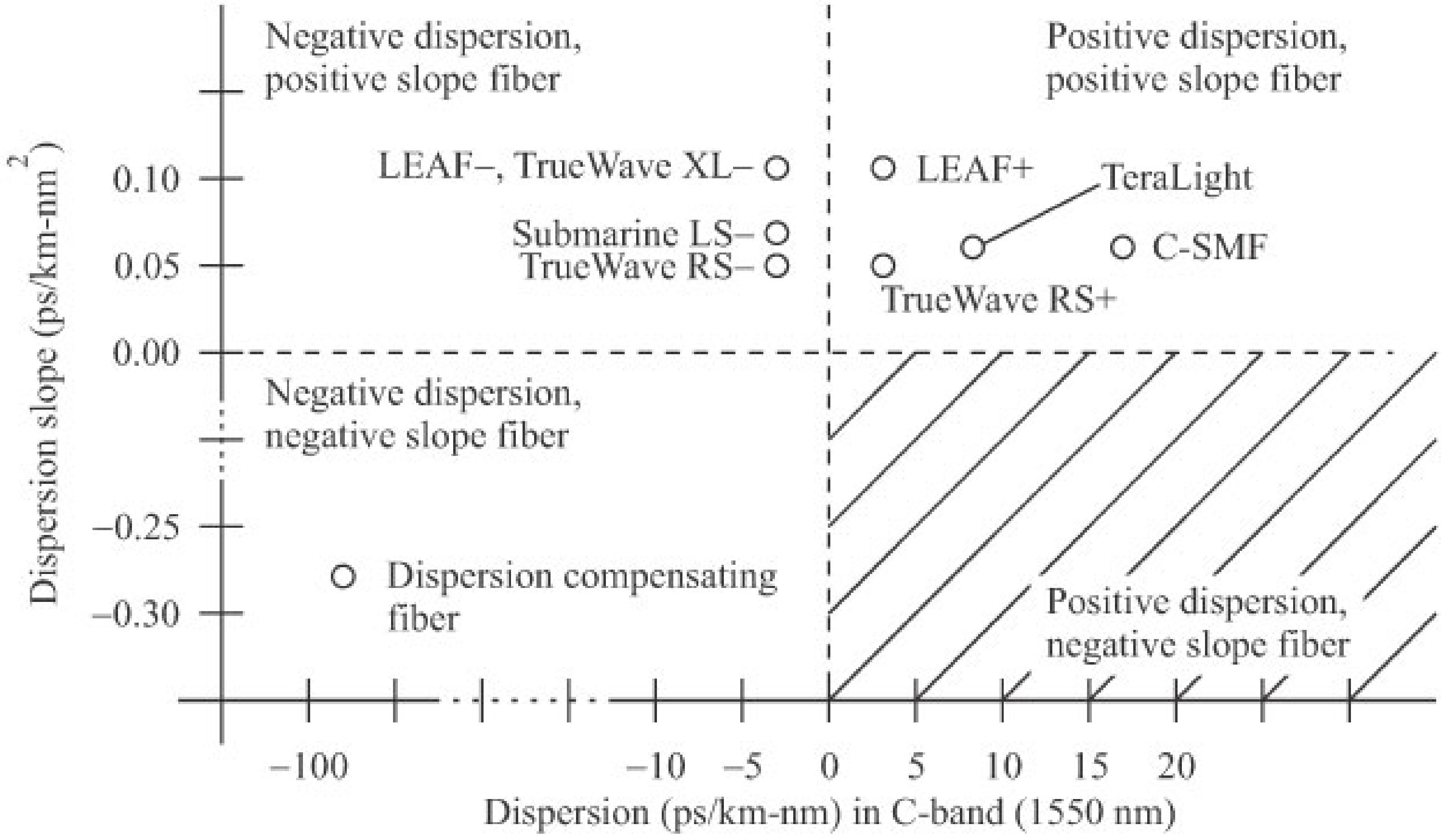
Terrestrial vs Submarine Fibers



* Positive (chromatic) dispersion fibers (CDF) used in terrestrial, and negative CDF used in submarine apps.

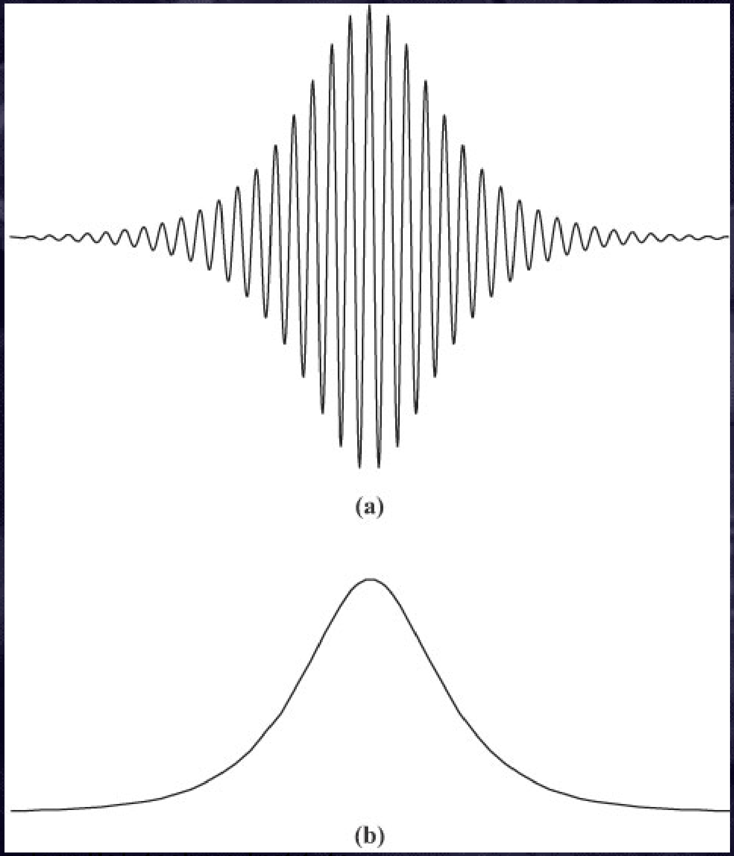
* Due to *modulation instability* (interaction between SPM and chromatic dispersion at high power levels)

Fiber *Dispersion (contd)*



Solitons

- Key idea: SPM induced chirping actually *depends upon the time-domain envelope of the pulse*!
- If pulse envelope right, SPM induced chirping will exactly combat the chromatic dispersion (GVD) chirping!



- *Soliton Regime:* input power distribution shape, effective area/cross-section of fiber core and fiber type
- DWDM with pure solitons not practical since solitons may "*collide*" and exchange energy over a length of fiber

Solitons (contd)

- *Family of pulse shapes* which undergo *no change or periodic changes*
- Fundamental solitons: no change in shape
- Higher-order solitons: periodic changes in shape
- Significance: completely *overcome chromatic dispersion*
- With optical amplifiers, high powers, the properties maintained => long, very high rate, repeaterless transmission
- Eg: 80 Gb/s for 10,000km demonstrated in lab (1999)!
- Dispersion-managed solitons:
  - An approximation of soliton pulse, but can operate on existing fiber
  - This can be used for DWDM: 25-channel, 40 Gbps, 1500km has been shown in lab (2001)

Summary: Fiber and Optical Amplifier Trends

- Bandwidth-span product:
  - SMF: 1310 nm, 1983 => 2.5Gbps for 640 km w/o amplification or 10 Gbps for 100 km
  - Recent SMF: 2.5 Gbps for 4400 km; 10 Gbps for 500 km
  - Multiply these by # of DWDM channels! (eg: 40-160)…
- Fiber amplifiers:
  - Erbium doped (EDFA): 1550 nm range
  - Praseodymium-doped flouride fiber (PDFFA): 1310 nm
  - Thorium-doped (ThDFA): 1350-1450nm
  - Thulium-doped (TmDFA): 1450-1530 nm
  - Tellerium-erbium-doped (Te-EDFA): 1532-1608 nm
  - Raman amplifiers: address an extended spectrum using standard single-mode fiber… (1150 –1675 nm!)

Optical Amplifier: Limitations on Practical Bandwidths

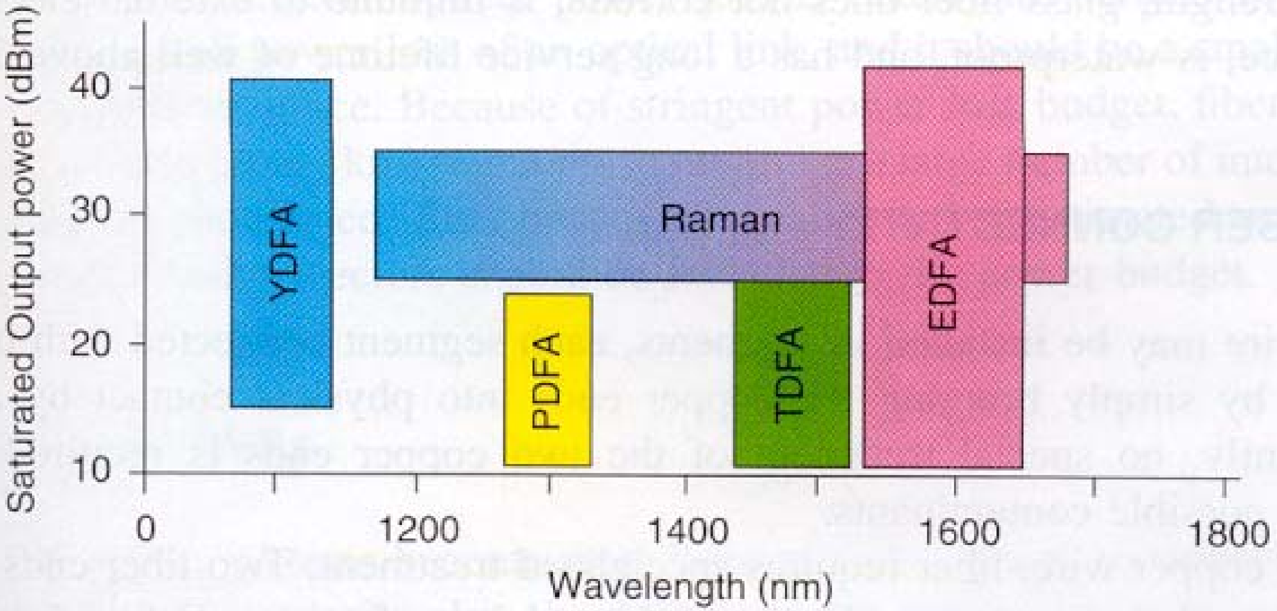


Figure 1.66 Optical amplifiers are many, each suitable for a different spectral range.

EDFAs popular in C-band
Raman: proposed for S-band
Gain-shifted EFDA for L-band

Future: Hollow Nano-tube Waveguides

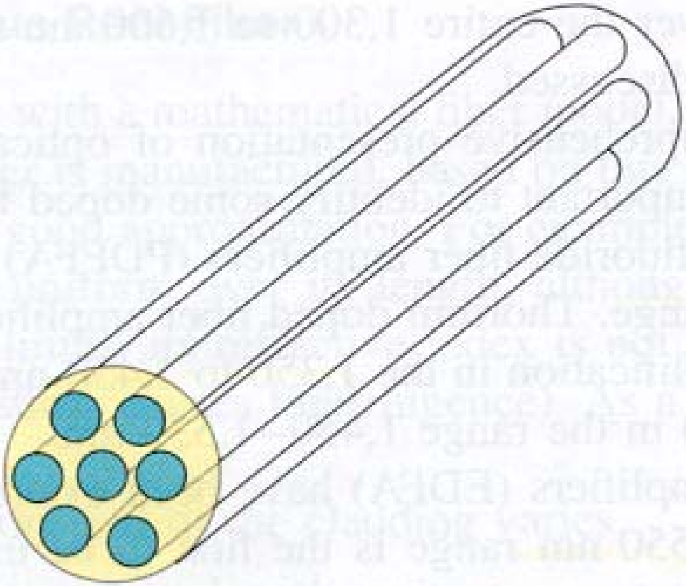


Figure 1.67 Hollow nano-tube optical waveguides (light may travel in each tube for ultra long distances, many hundreds of Km).

Perhaps carbon nanotubes developed at RPI could be used? ☺

Summary: Interaction of Light with Matter

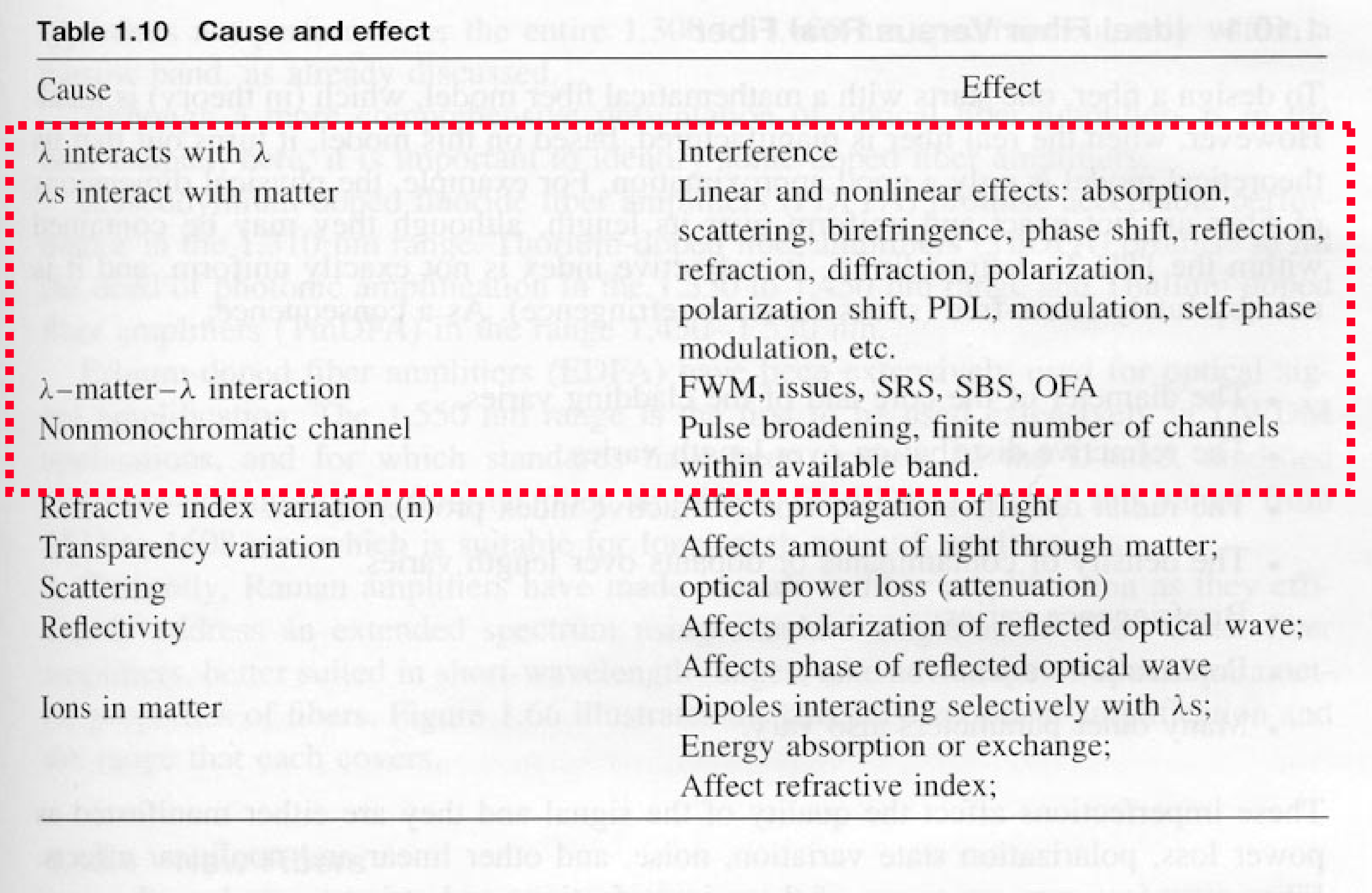


Table 1.10 Cause and effect

Cause	Effect
λ interacts with λ	Interference
λs interact with matter	Linear and nonlinear effects: absorption, scattering, birefringence, phase shift, reflection, refraction, diffraction, polarization, polarization shift, PDL, modulation, self-phase modulation, etc.
λ–matter–λ interaction	FWM, issues, SRS, SBS, OFA
Nonmonochromatic channel	Pulse broadening, finite number of channels within available band.
Refractive index variation (n)	Affects propagation of light
Transparency variation	Affects amount of light through matter;
Scattering	optical power loss (attenuation)
Reflectivity	Affects polarization of reflected optical wave; Affects phase of reflected optical wave
Ions in matter	Dipoles interacting selectively with λs; Energy absorption or exchange; Affect refractive index;

Metrics and Parameters in Optics

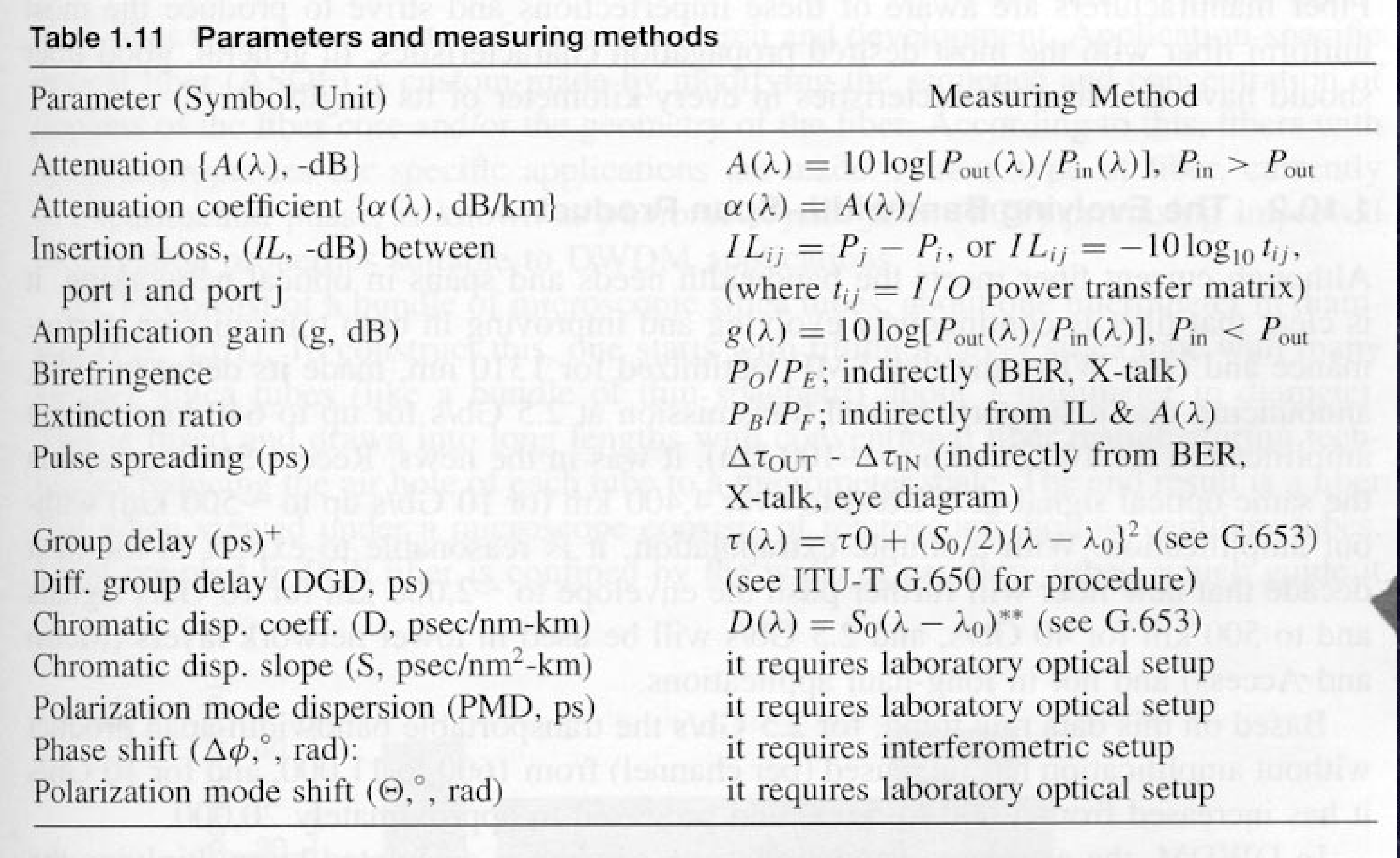


Table 1.11 **Parameters and measuring methods**

Parameter (Symbol, Unit)	Measuring Method
Attenuation {$A(\lambda)$, -dB}	$A(\lambda) = 10\log[P_{\mathrm{out}}(\lambda)/P_{\mathrm{in}}(\lambda)]$, $P_{\mathrm{in}} > P_{\mathrm{out}}$
Attenuation coefficient {$\alpha(\lambda)$, dB/km}	$\alpha(\lambda) = A(\lambda)/$
Insertion Loss, (IL, -dB) between port i and port j	$IL_{ij} = P_j - P_i$, or $IL_{ij} = -10\log_{10} t_{ij}$, (where $t_{ij} = I/O$ power transfer matrix)
Amplification gain (g, dB)	$g(\lambda) = 10\log[P_{\mathrm{out}}(\lambda)/P_{\mathrm{in}}(\lambda)]$, $P_{\mathrm{in}} < P_{\mathrm{out}}$
Birefringence	P_O/P_E; indirectly (BER, X-talk)
Extinction ratio	P_B/P_F; indirectly from IL & $A(\lambda)$
Pulse spreading (ps)	$\Delta\tau_{\mathrm{OUT}}$ - $\Delta\tau_{\mathrm{IN}}$ (indirectly from BER, X-talk, eye diagram)
Group delay (ps)$^{+}$	$\tau(\lambda) = \tau 0 + (S_0/2)\{\lambda - \lambda_0\}^2$ (see G.653)
Diff. group delay (DGD, ps)	(see ITU-T G.650 for procedure)
Chromatic disp. coeff. (D, psec/nm-km)	$D(\lambda) = S_0(\lambda - \lambda_0)^{**}$ (see G.653)
Chromatic disp. slope (S, psec/nm^2-km)	it requires laboratory optical setup
Polarization mode dispersion (PMD, ps)	it requires laboratory optical setup
Phase shift ($\Delta\phi$, °, rad):	it requires interferometric setup
Polarization mode shift (Θ, °, rad)	it requires laboratory optical setup