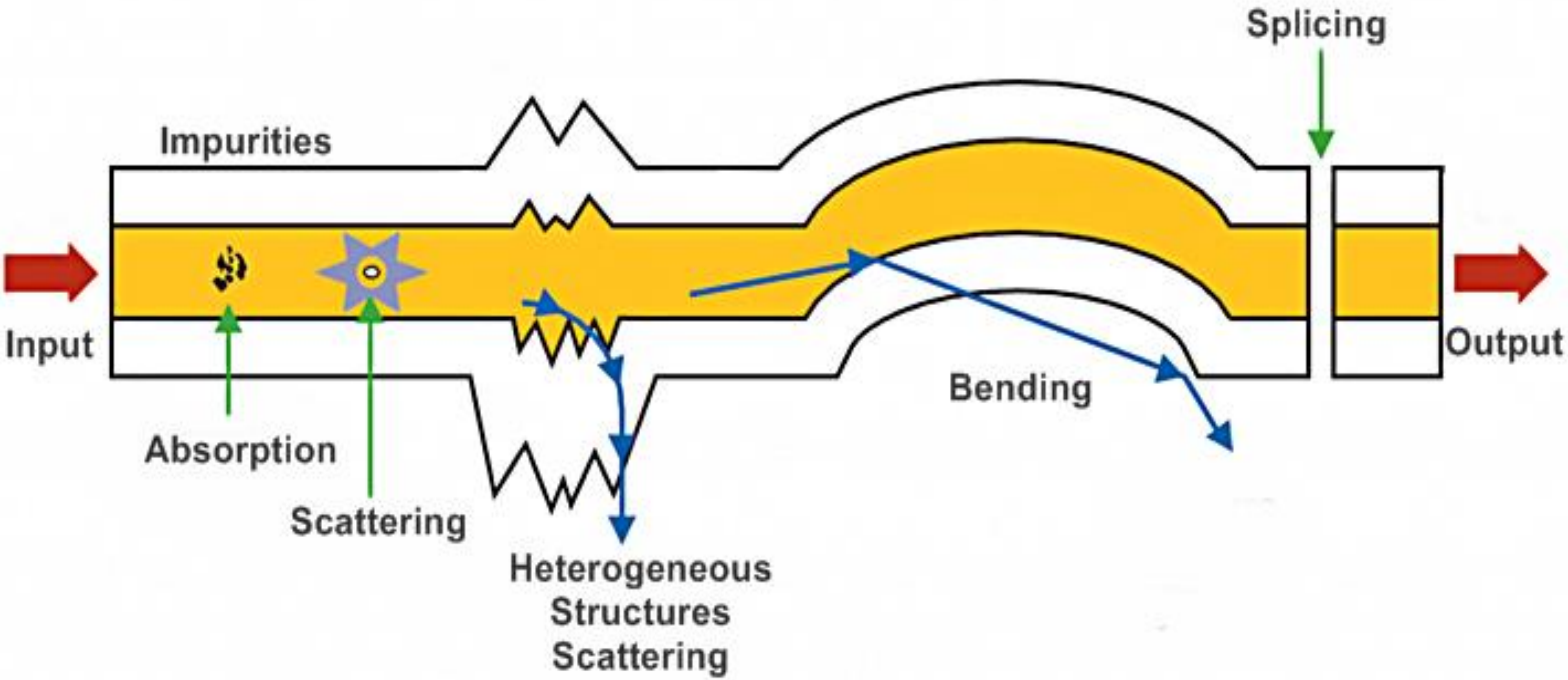
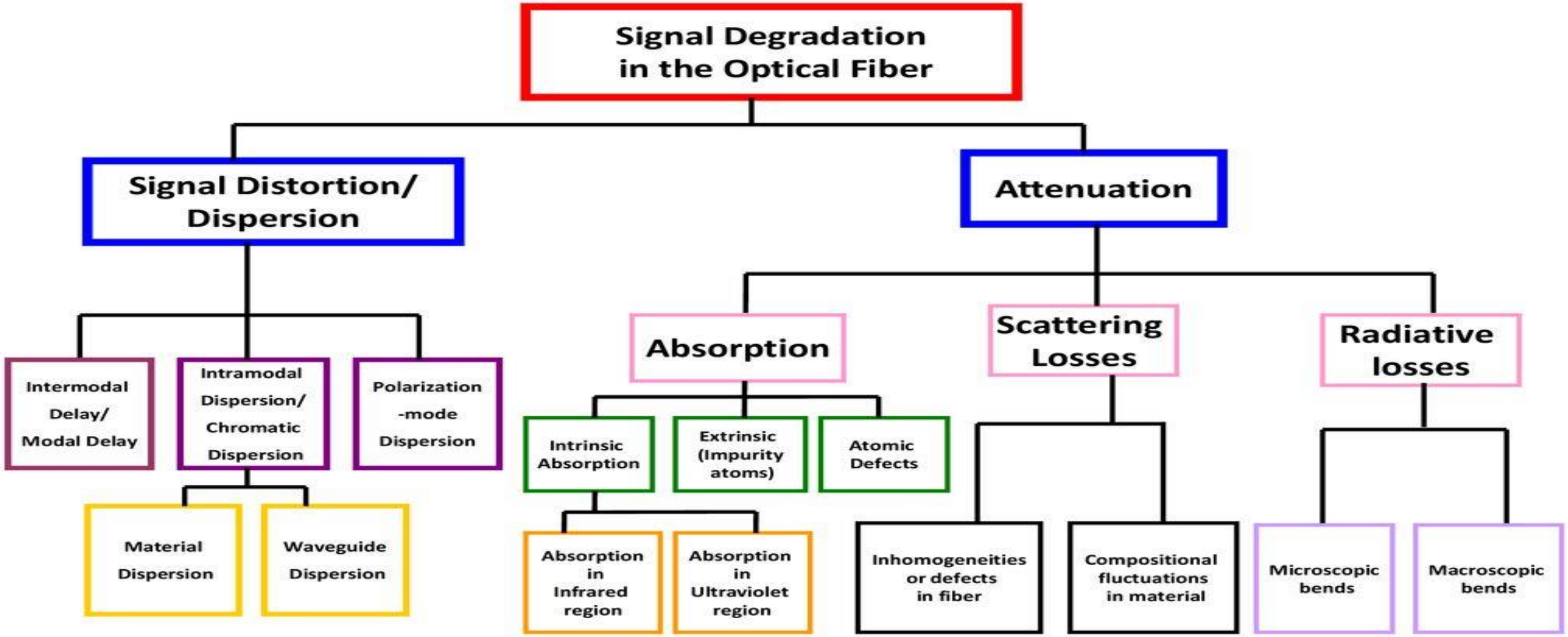


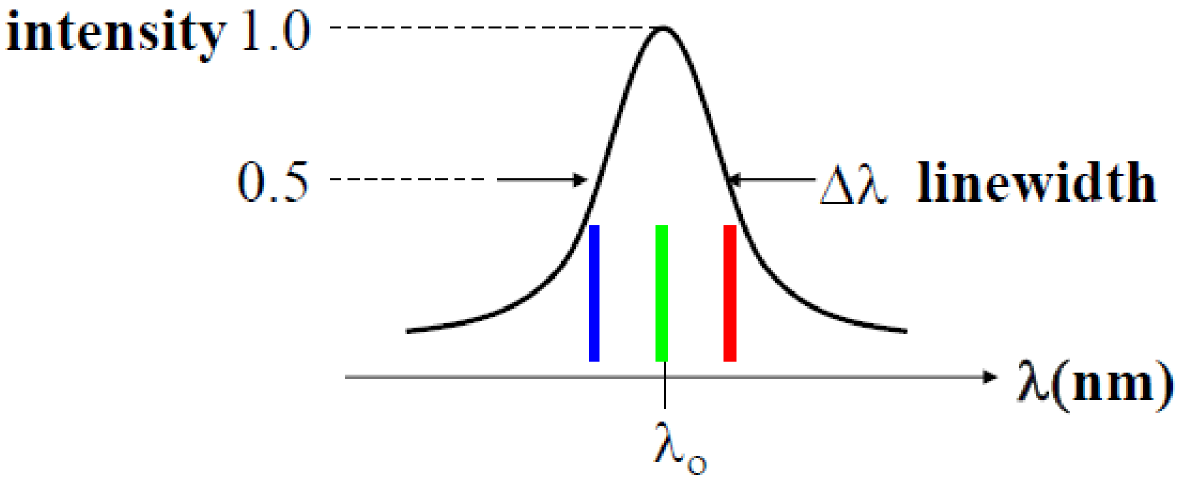
Module – 2
Signal Degradation

Signal degradation in fiber cable



Chromatic Dispersion

- Chromatic dispersion (CD) may occur in all types of optical fiber. The optical pulse broadening results from the finite spectral linewidth of the optical source and the modulated carrier.
- Origin is frequency dependence of the refractive index $n(\omega)$



- In the case of the semiconductor laser, $\Delta\lambda$ corresponds to only a fraction of % of the centre wavelength λ_o. For LEDs, $\Delta\lambda$ is likely to be a significant percentage of λ_o.

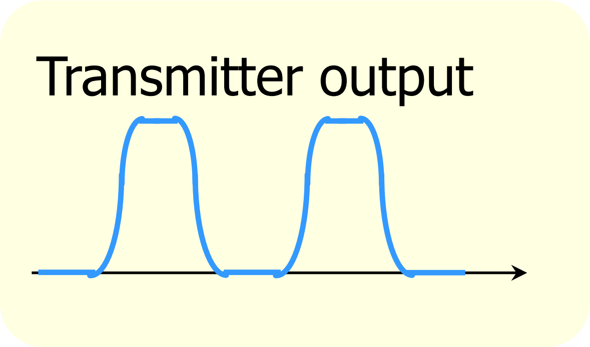
Chromatic Dispersion

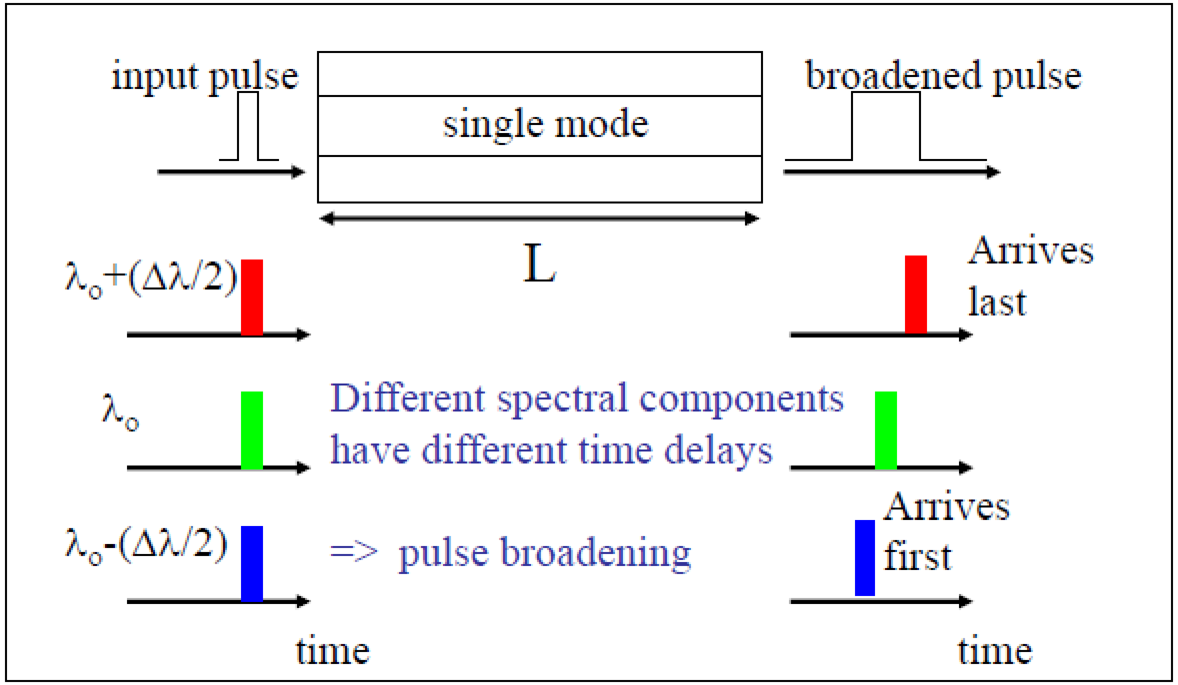
- Real sources emit over a range of wavelengths. This range is the source linewidth or spectral width.
- The smaller is the linewidth, the smaller is the spread in wavelengths or frequencies, the more coherent is the source.
- An ideal perfectly coherent source emits light at a single wavelength.
- It has zero linewidth and is perfectly monochromatic.

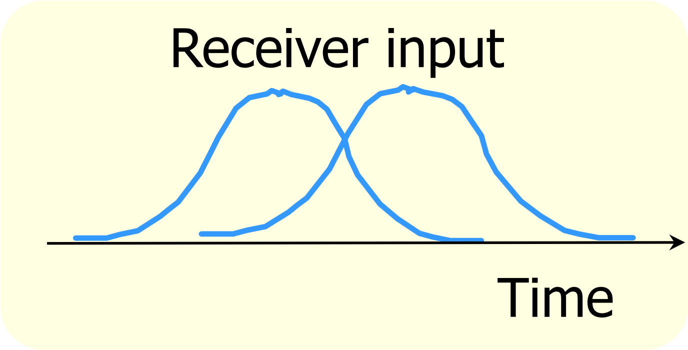
Light sources	**Linewidth (nm)**
Light-emitting diodes	20 nm – 100 nm
Semiconductor laser diodes	1 nm – 5 nm
Nd:YAG solid-state lasers	0.1 nm
HeNe gas lasers	0.002 nm

Chromatic Dispersion

- Pulse broadening occurs because there may be propagation delay differences among the spectral components of the transmitted signal.







- Chromatic dispersion (CD): Different spectral components of a pulse travel at different group velocities. This is known as group velocity dispersion (GVD).

Phase velocity

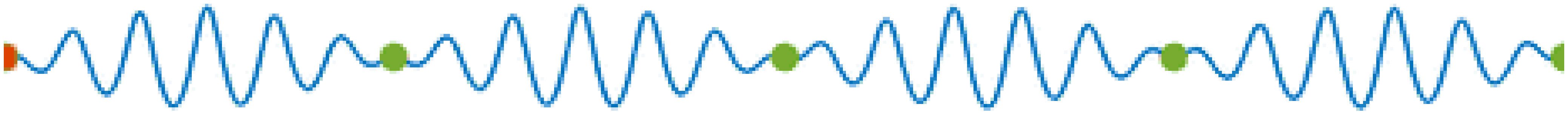
- When the optical waves are propagating through the fiber, there are certain points having constant phase

- These points of constant travels with a velocity called as phase velocity

$$\boxed{v_p = \omega / \beta}$$

$$\omega = \frac{2\pi c}{\lambda} \qquad \beta = \frac{2\pi n}{\lambda}$$

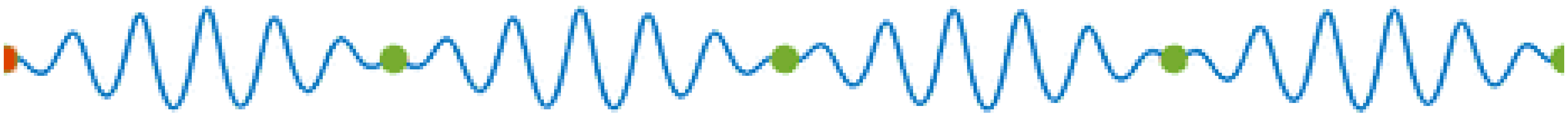
$$\boxed{v_p = c / n}$$



Group velocity

- Optical waves are travelling as wave packets
- A group of waves with closely similar wavelengths (or frequencies) always combine to form a packet of wave
- The rate at which envelope of the waves propagates called as group velocity

$$V_g = \frac{\partial \omega}{\partial \beta} \quad = 2\pi c \frac{\partial}{\partial \beta}\left(\frac{1}{\lambda}\right)$$



Remarks on group velocity

- Because the energy of a harmonic wave is proportional to the square of its field amplitude, the energy carried by a wave packet that is composed of many frequency components is concentrated in regions where the amplitude of the envelope is large.

- Therefore, the energy in a wave packet is transported at group velocity v_g.

- The constant-phase wavefront travels at the phase velocity, but the group velocity is the velocity at which energy (and information) travels.

- Any information signal is a wave packet, and thus travels at the group velocity, not at the phase velocity.

Light pulse in dispersive medium

- When a light pulse with a spread in frequency δw and a spread in propagation constant δβ propagates in a dispersive medium n(λ), the group velocity:

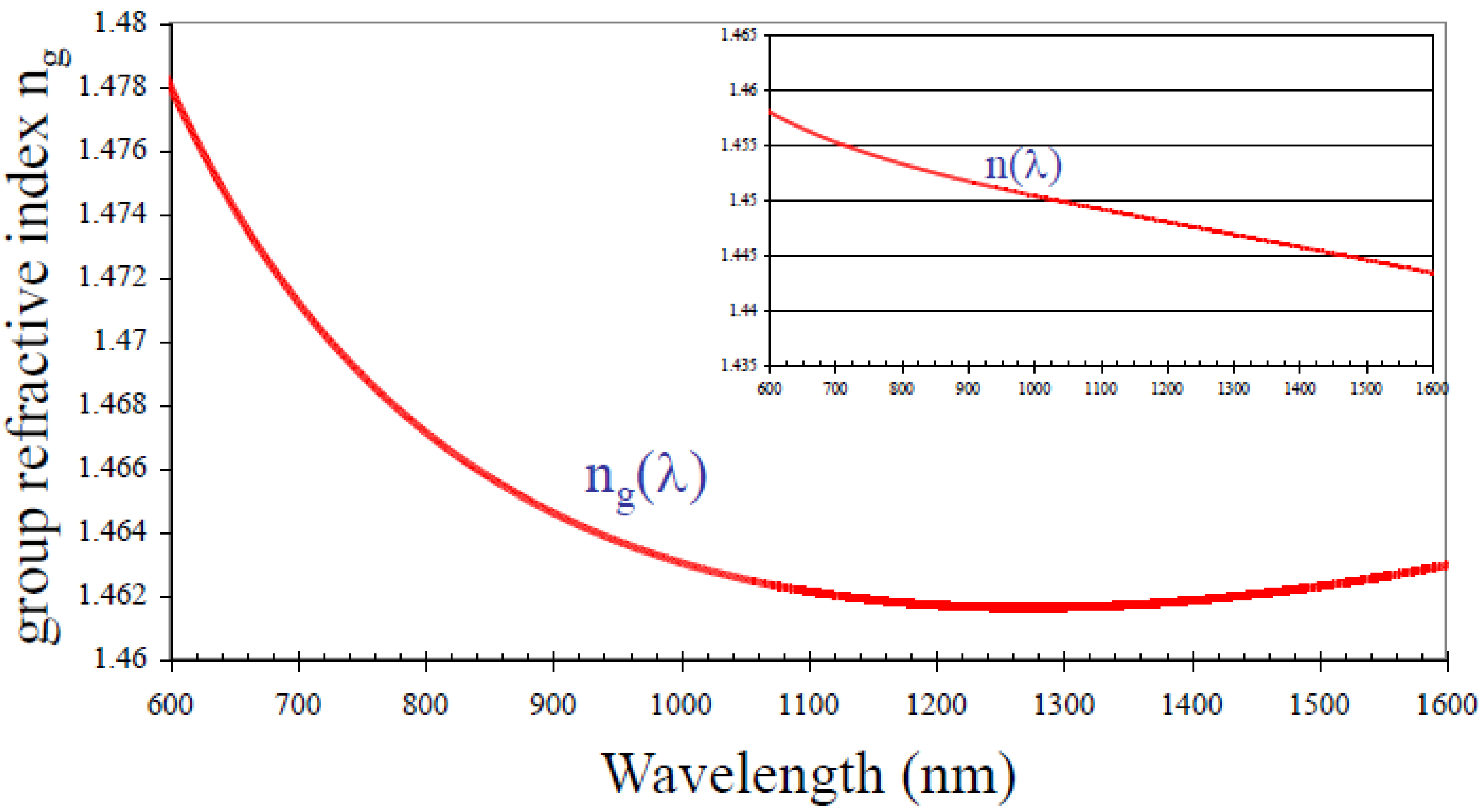
$$V_g = \frac{\partial \omega}{\partial \beta}$$

$$V_g = \frac{\partial \omega}{\partial \lambda} \cdot \frac{\partial \lambda}{\partial \beta}$$

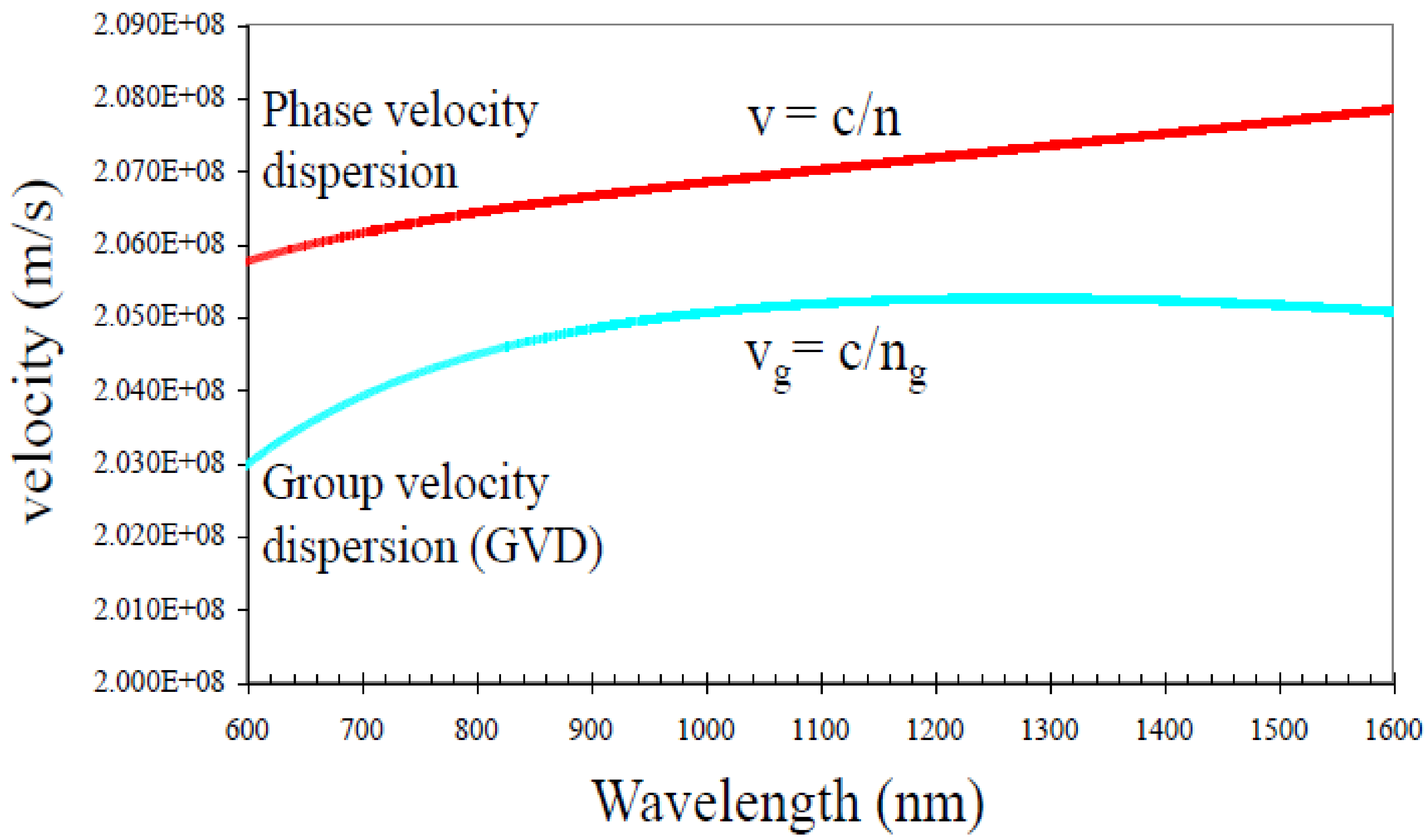
$$\frac{\partial \omega}{\partial \lambda} = -\frac{\omega}{\lambda} \qquad \frac{\partial \lambda}{\partial \beta} = \left(\frac{\partial \beta}{\partial \lambda}\right)^{-1} \qquad \beta = \frac{2\pi n}{\lambda}$$

$$V_g = -\frac{2\pi c}{\lambda^2}\left(\frac{\partial \beta}{\partial \lambda}\right)^{-1} \qquad V_g = \frac{c}{n_g} = \frac{c}{n - \lambda\left(\frac{dn}{d\lambda}\right)}$$

Group refractive index n_g vs. λ for fused silica



Phase velocity c/n and group velocity c/n_g vs. λ for fused silica



Group-Velocity Dispersion (GVD)

- Consider a light pulse propagates in a dispersive medium of length L

- A specific spectral component at the frequency ω (or wavelength λ) would arrive at the output end of length L after a time delay:

$$T = \frac{L}{V_g}$$

- If Δλ is the spectral width of an optical pulse, the extent of pulse broadening for a material of length L is given by

$$\Delta T = \left(\frac{dT}{d\lambda}\right)\Delta\lambda = L\left[\frac{d\left(\frac{1}{V_g}\right)}{d\lambda}\right]\Delta\lambda$$

Group-Velocity Dispersion (GVD)

- Hence the pulse broadening due to a differential time delay:

$$\Delta T = L\left|D_{mat}\right|\Delta\lambda$$

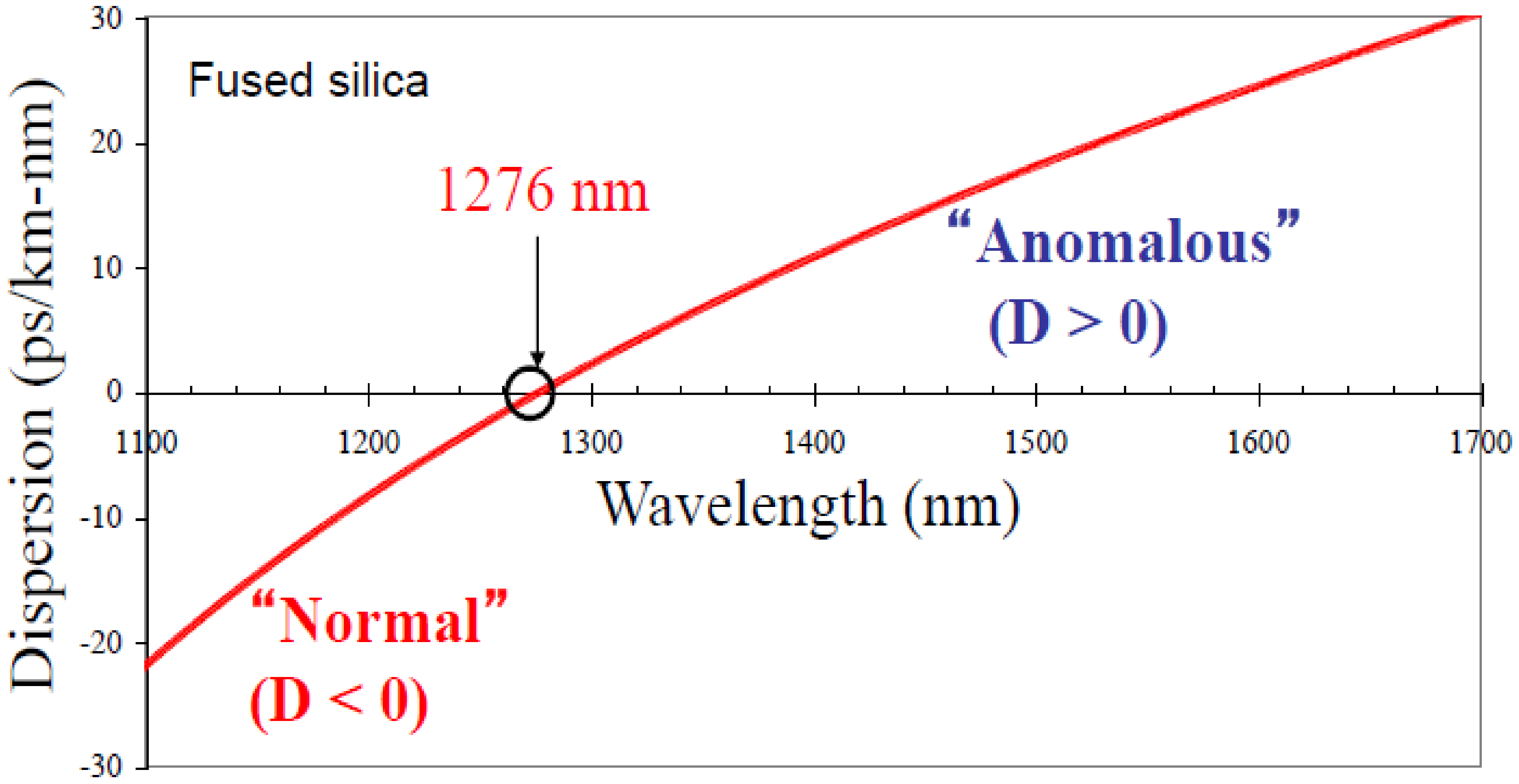
- where D_{mat} = d(1/vg)/dλ is called the material dispersion parameter and is expressed in units of ps/(km-nm).

$$D_{mat} = \frac{d\left(\frac{1}{V_g}\right)}{d\lambda} = -\left(\frac{\lambda}{c}\right)\frac{d^2 n}{d\lambda^2}$$

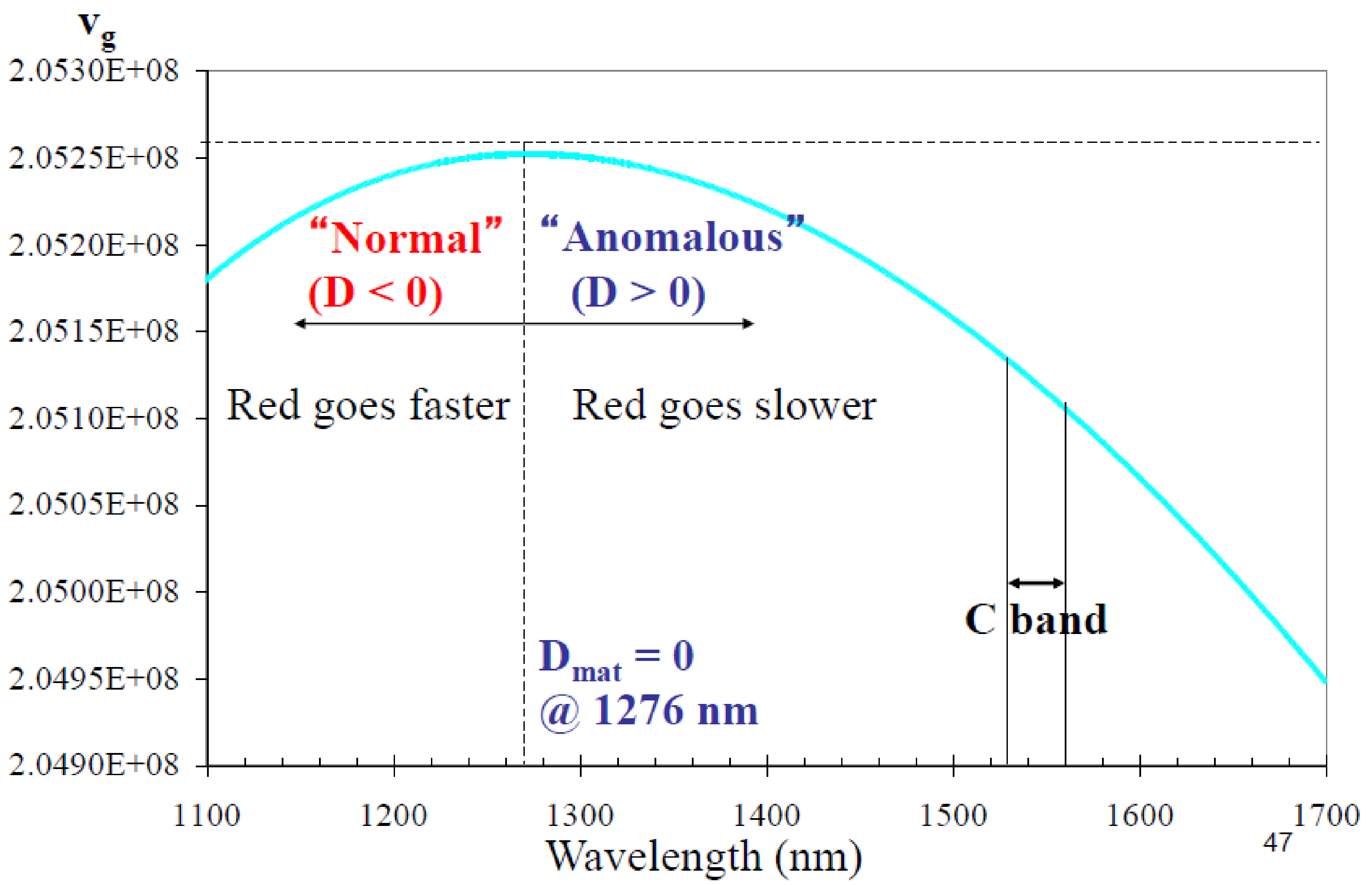
- Suppose, we take, $V_g = -\frac{2\pi c}{\lambda^2}\left(\frac{\partial\beta}{\partial\lambda}\right)^{-1}$ then D_{mat} becomes

$$D_{mat} = \frac{d\left(\frac{1}{V_g}\right)}{d\lambda} = -\left(\frac{2\pi c}{\lambda^2}\right)\frac{d^2\beta}{d\lambda^2}$$

Dispersion parameter $D = -(\lambda/c)\, d^2n/d\lambda^2$



Variation of Vg with wavelength for fused silica



Zero-dispersion wavelength

- Material dispersion $D_{mat} = 0$ at $\lambda \sim 1276$ nm for fused silica.
- This λ is referred to as the zero-dispersion wavelength λ_{ZD}.
- Chromatic (or material) dispersion $D(\lambda)$ can be zero;
  - or negative => longer wavelengths travel faster than shorter wavelengths;
  - or positive => shorter wavelengths travel faster than longer wavelengths.

Material and Waveguide Dispersion

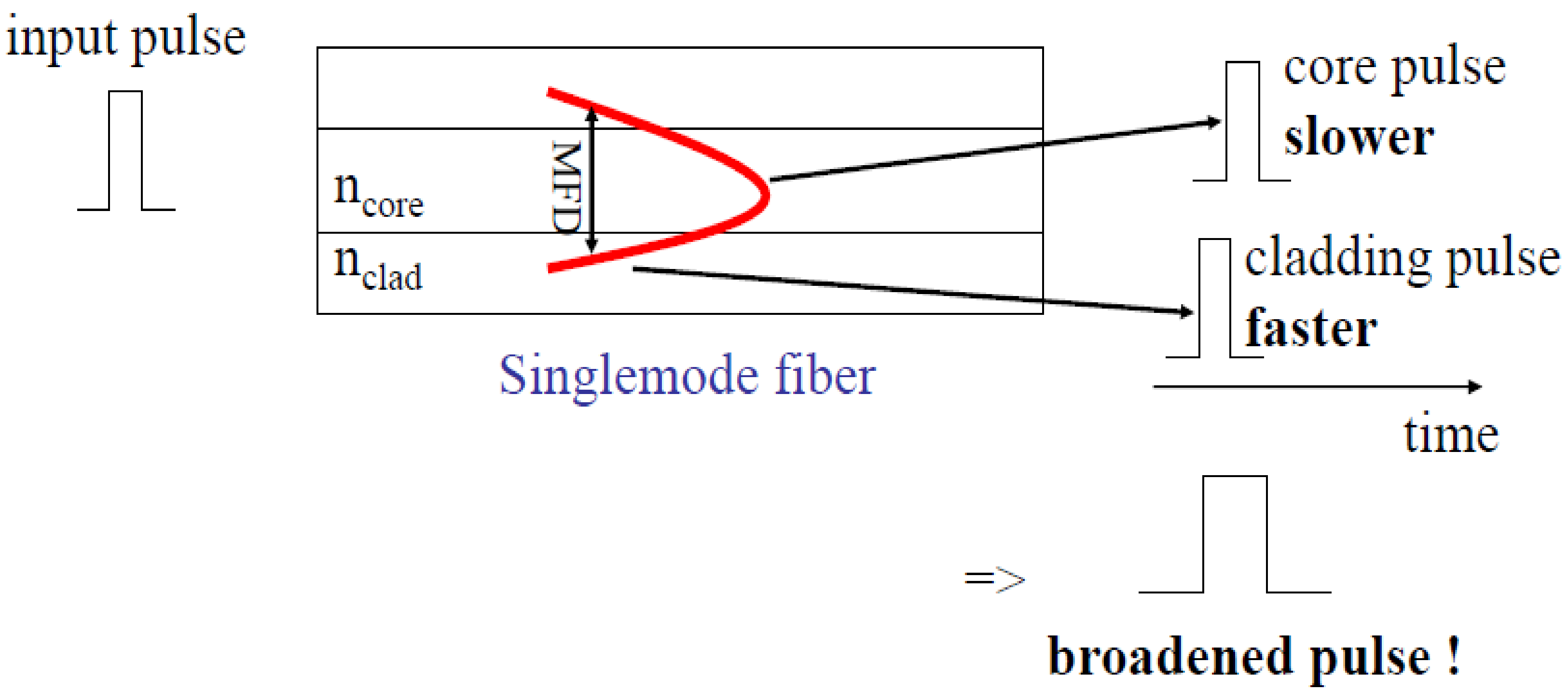
- In fact there are two mechanisms for chromatic dispersion in a fiber:

(a) Silica refractive index n is wavelength dependent (i.e. $n = n(\lambda)$) => different wavelength components travel at different speeds in silica. This is known as material dispersion.

(b) Light energy of a mode propagates partly in the core and partly in the cladding of a fiber. The mode power distribution between the core and the cladding depends on λ. This is known as waveguide dispersion.

$$D(\lambda) = D_{mat}(\lambda) + D_{wg}(\lambda)$$

Waveguide Dispersion



Waveguide Dispersion

- The effect of waveguide dispersion on pulse spreading can be approximated by assuming that the refractive index of the material is independent of the wavelength

- The group velocity in terms of normalized propagation constant b:

$$V_{g,eff} = \frac{\partial \omega}{\partial \beta} \qquad \beta \approx n_2 k (b\Delta + 1)$$

$$V = \frac{2\pi a}{\lambda} NA \approx k a n_2 \sqrt{2\Delta}$$

$$V_g = \frac{c}{n_{g,eff}} = \frac{c}{n_2 + n_2 \Delta \frac{d(Vb)}{dV}}$$

Waveguide Dispersion

- Consider a light pulse propagates in a dispersive medium of length L
- A specific spectral component at the frequency ω (or wavelength λ) would arrive at the output end of length L after a time delay:

$$T = \frac{L}{V_{g,eff}}$$

- If Δλ is the spectral width of an optical pulse, the extent of pulse broadening in a waveguide of length L is given by

$$\Delta T = \left(\frac{dT}{d\lambda}\right)\Delta\lambda = L\left[\frac{d\left(\frac{1}{V_{g,eff}}\right)}{d\lambda}\right]\Delta\lambda$$

Waveguide Dispersion

- Hence the pulse broadening due to a differential time delay:

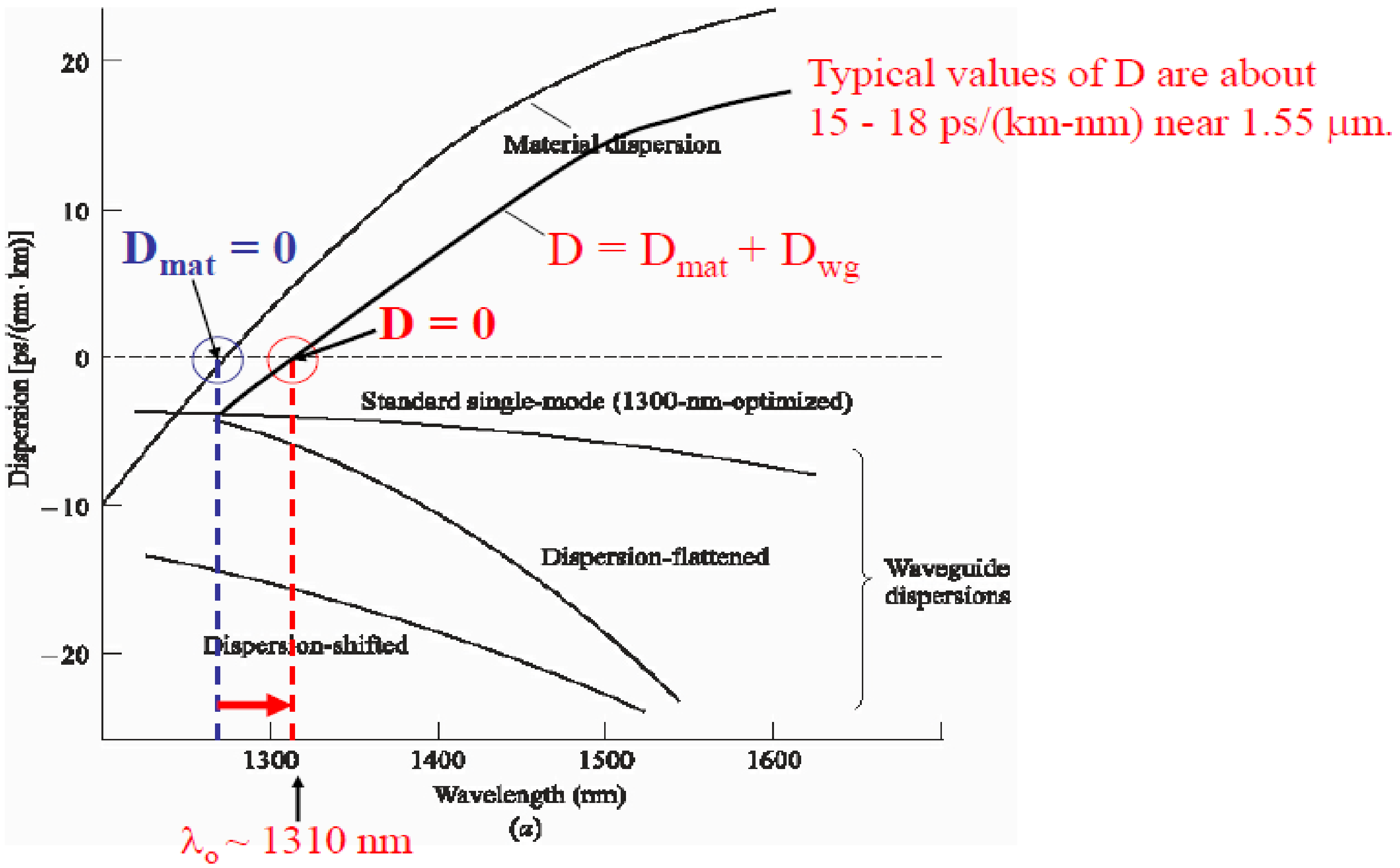
$$\Delta T = L\left|D_{wg}\right|\Delta\lambda$$

- where $D_{wg} = d(1/v_{g,eff})/d\lambda$ is called the waveguide dispersion parameter and is expressed in units of ps/(km-nm).

$$D_{wg} = \frac{d\left(\dfrac{1}{V_{g,eff}}\right)}{d\lambda} = -\frac{n_2\Delta}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right]$$

- The dependence of D_{wg} on λ may be controlled by altering the core radius, the NA, or the V number

Zero Dispersion @ 1310 nm

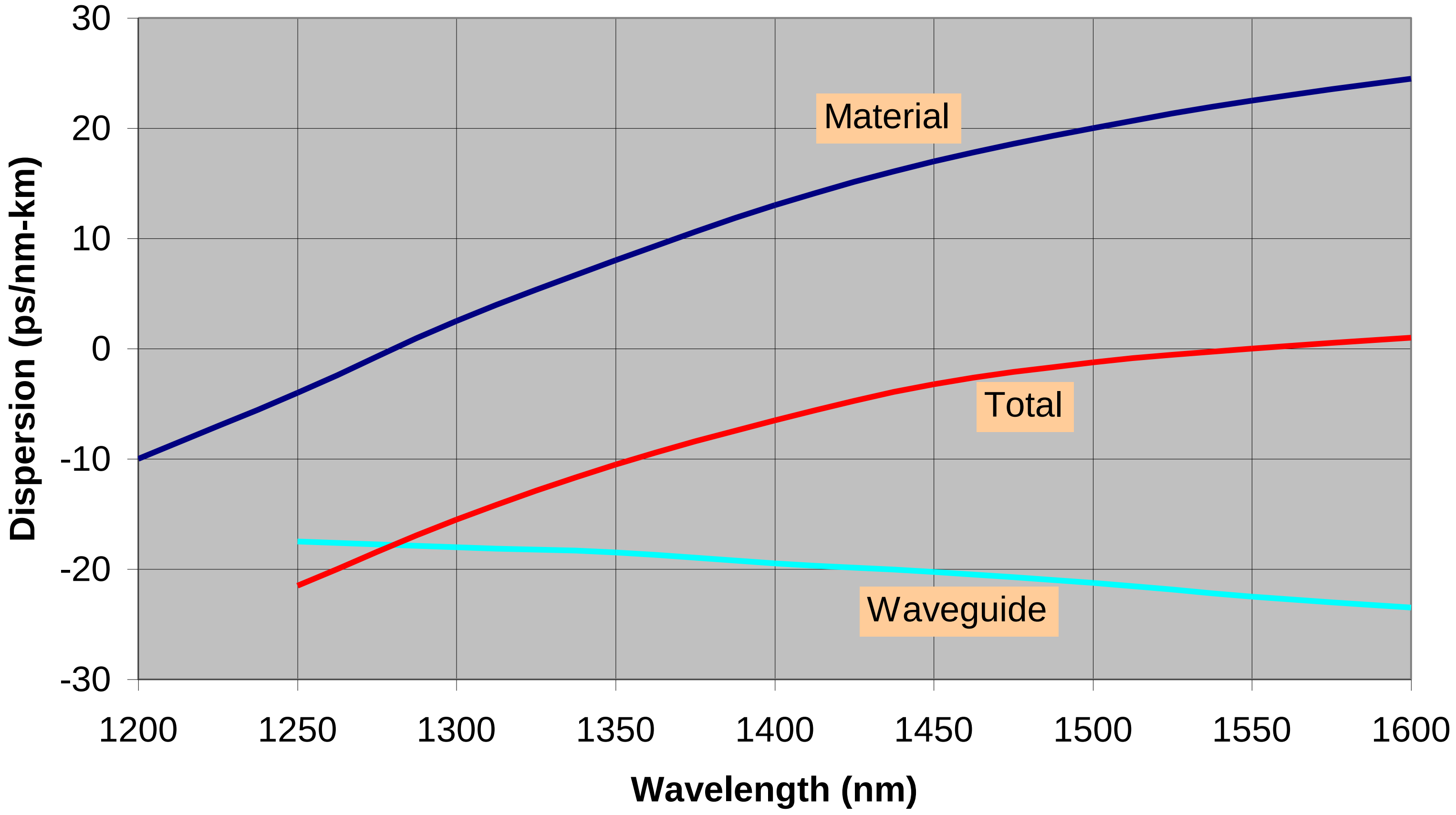


Dispersion tailored fibers

- As the waveguide contribution D_{wg} depends on the fiber parameters such as the core radius a and the index difference D, it is possible to design the fiber such that λ_{ZD} is shifted into the neighborhood of 1.55 mm. Such fibers are called dispersion-shifted fibers.

- It is also possible to tailor the waveguide contribution such that the total dispersion D is relatively small over a wide wavelength range extending from 1.3 to 1.6 mm. Such fibers are called dispersion- flattened fibers.

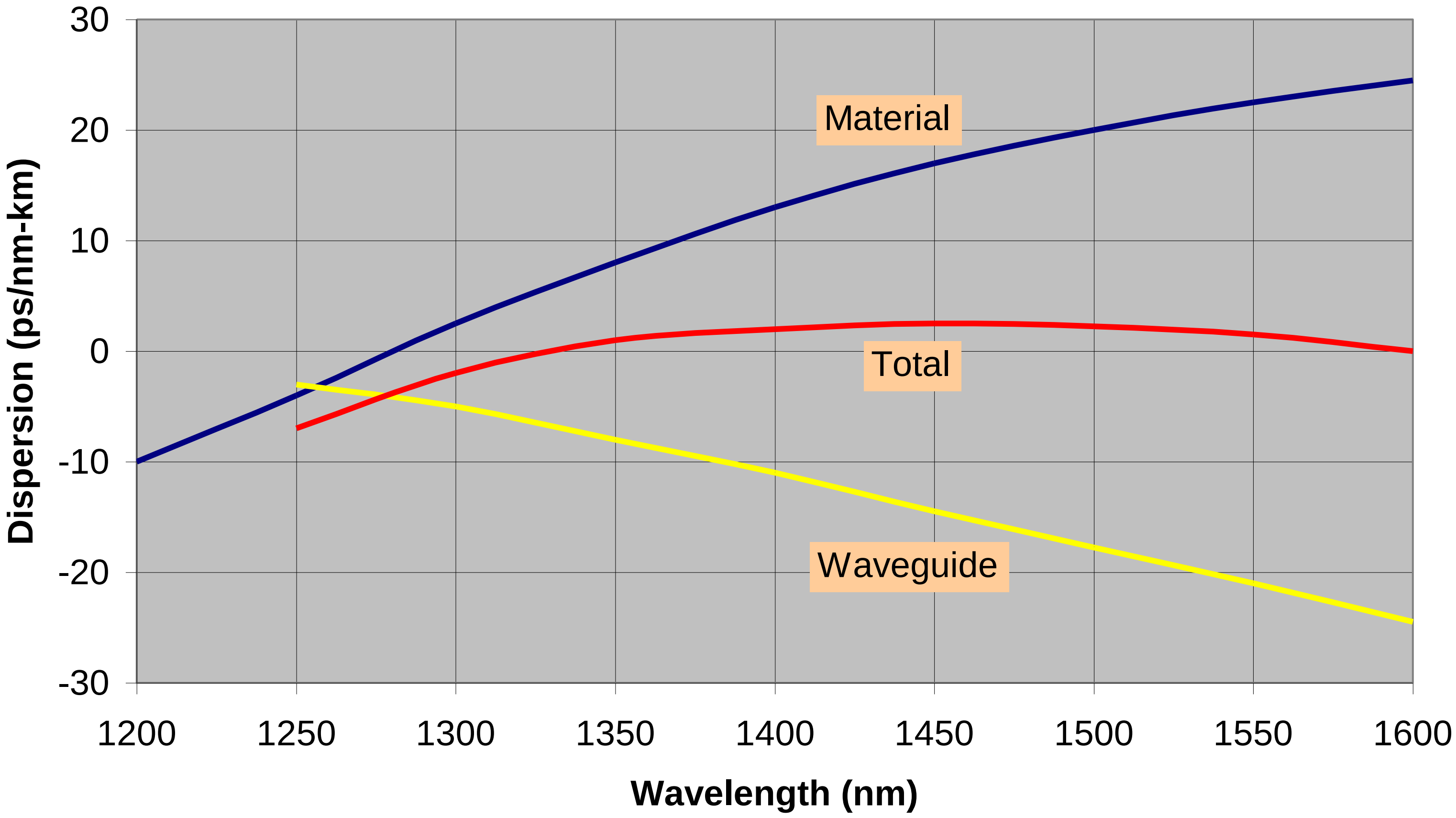
Dispersion-Shifted Fibers



Zero dispersion around 1550 nm!

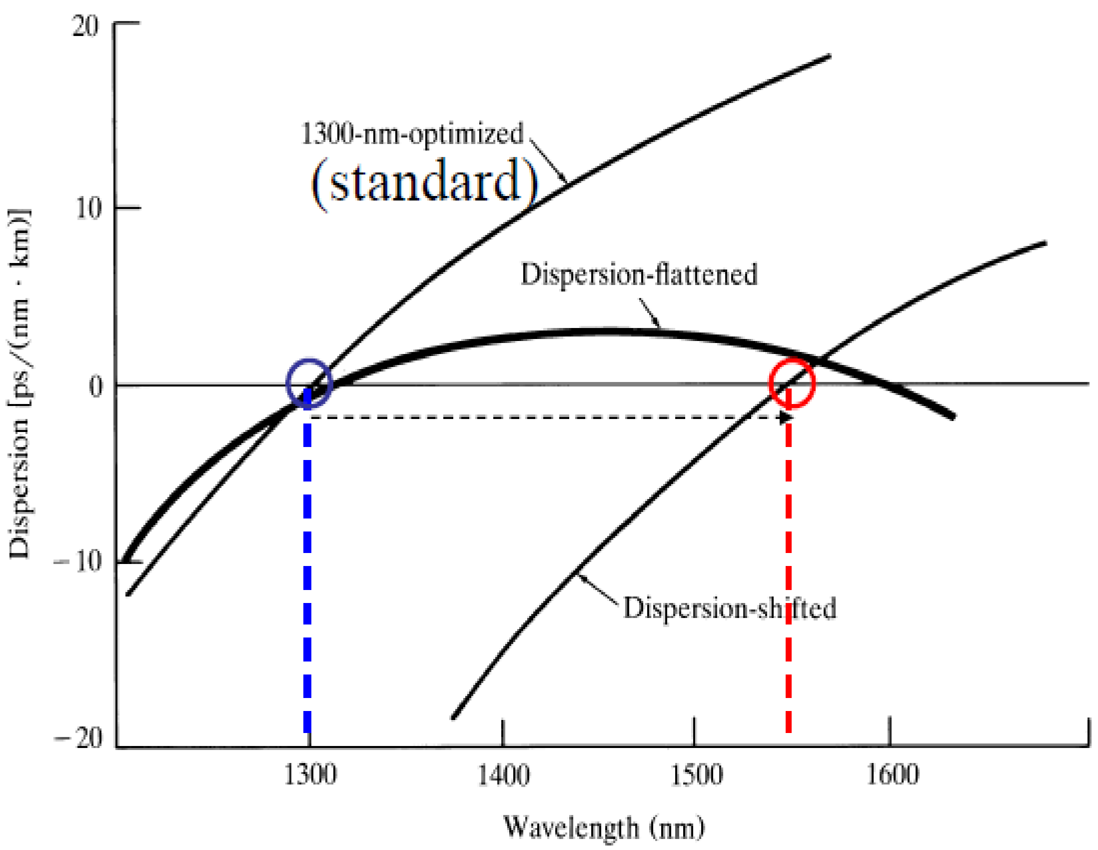
Dr. T.Ilavarasan, Associate Professor,SENSE, VIT

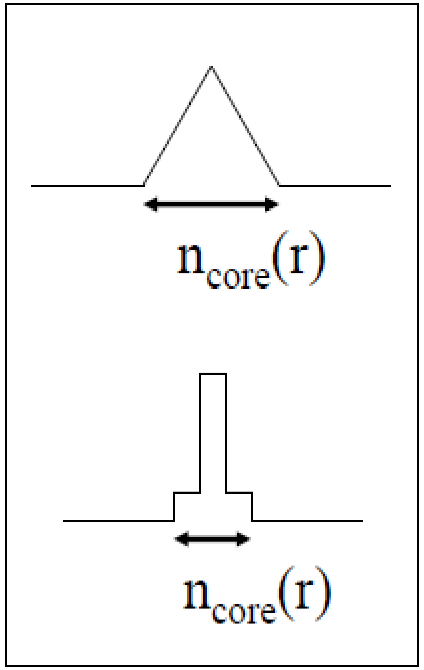
Dispersion-Flattened Fibers



Near-Zero dispersion around 1300-1550 nm!

Dispersion tailored fibers





- The design of dispersion-modified fibers often involves the use of multiple cladding layers and a tailoring of the refractive index profile.

Chromatic dispersion in low-bit-rate systems

- Broadening of the light pulse due to Chromatic Dispersion

$$\Delta T = LD\Delta\lambda$$

- Consider the maximum pulse broadening equals to the bit time period 1/B, then the dispersion-limited distance:

$$L_D = \frac{1}{DB\Delta\lambda}$$

- e.g. For D = 17 ps/(km•nm), B = 2.5 Gb/s and $\Delta\lambda$= 0.03 nm

$$L_D = 784km$$

- (It is known that dispersion limits a 2.5 Gbit/s channel to roughly 800 km! Therefore, chromatic dispersion is not much of an issue in low-bit-rate systems deployed in the early 90s!)

Chromatic dispersion in low-bit-rate systems

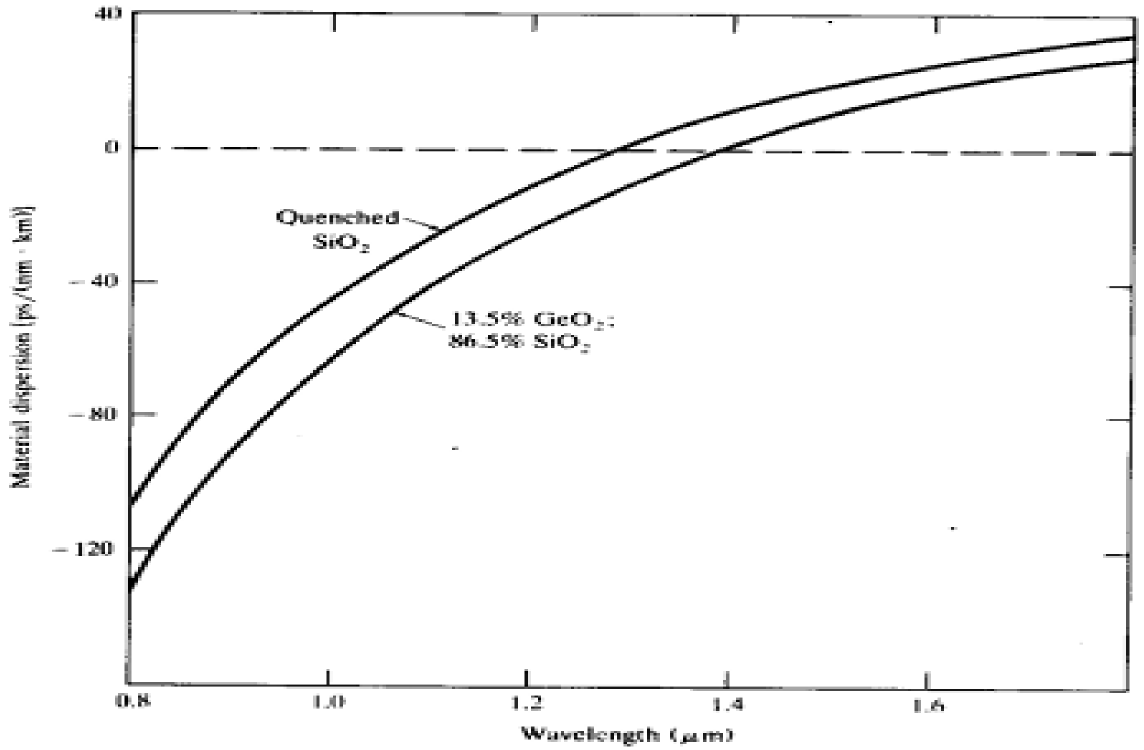
- When upgrading from 2.5- to 10-Gbit/s systems, most technical challenges are less than four times as complicated and the cost of components is usually much less than four times as expensive.
- However, when increasing the bit rate by a factor of 4, the effect of chromatic dispersion increases by a factor of 16!
- For 10 Gb/s system,

$$L_D = 784km/16 = 50km$$

- This is why chromatic dispersion compensation must be employed for systems operating at 10 Gbit/s (now at 40 Gbit/s and beyond.)

Numerical Problems

- An LED operating at 850 nm has a spectral width of 45 nm. What is the pulse spreading in ns/km due to material dispersion in a silica fiber ? What is the pulse spreading when a laser diode having a 2 nm spectral width is used ?



Numerical Problems

- An LED operating at 850 nm has a spectral width of 45 nm. What is the pulse spreading in ns/km due to material dispersion in a silica fiber ? What is the pulse spreading when a laser diode having a 2 nm spectral width is used ?

Solution:

$|D_{mat}(\lambda)|$ at 850 nm = 100 ps / (nm.km) from graph

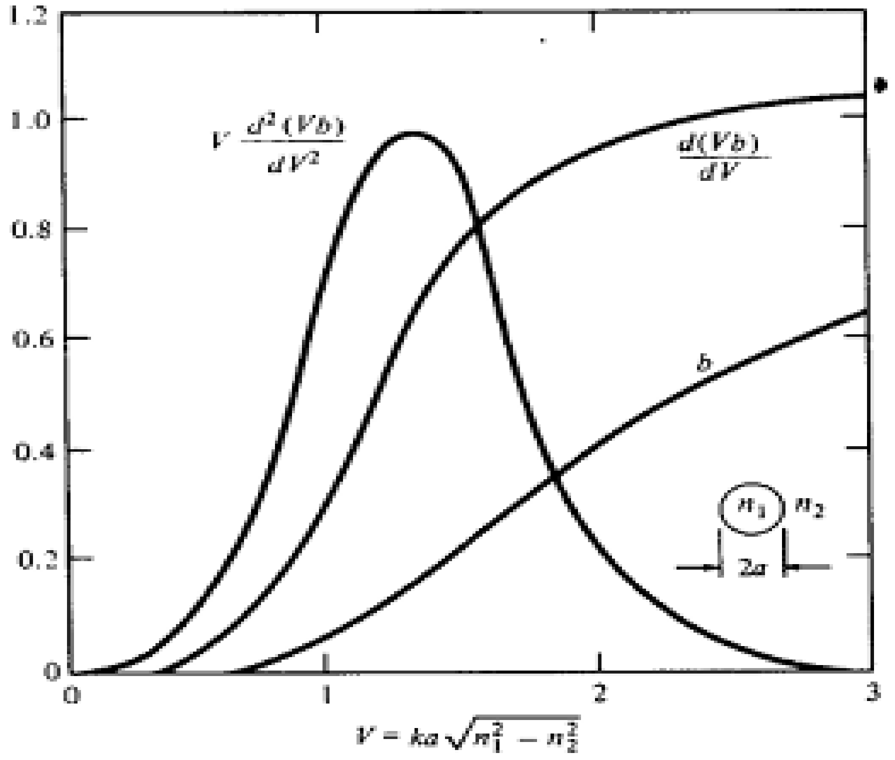
L = 1 km

$\sigma_{mat} = \sigma\lambda\, L\ |D_{mat}(\lambda)|$ = 4.5 ns / km for LED

$\sigma_{mat} = \sigma\lambda\, L\ |D_{mat}(\lambda)|$ = 0.2 ns / km for LD

Numerical Problems

- Calculate the waveguide dispersion at 1320 nm in units of ps /(nm . km) for a single mode fiber with core and cladding diameters of 9 μm and 125 μm, respectively. Let the core index n_1 = 1.48 and the relative index difference Δ = 0.22 %.



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$$D_{wg} = \frac{d\left(\frac{1}{V_{g,eff}}\right)}{d\lambda} = -\frac{n_2\Delta}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right]$$

$$n2 \approx n1\,(1 - \Delta) = 1.477$$

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} = 1.86$$

$Vd^2(Vb)/dV^2 = 0.50$; from graph

$Dwg\,(\lambda) = -4.1$ ps / (nm. km)

Numerical Problems

- A step-index single-mode fiber exhibits material dispersion of 6 ps nm^{-1} km^{-1} at an operation wavelength of 1.55 μm. Assume that $n_1 = 1.45$ and $\Delta = 0.5$ %. Calculate the $Vd^2(Vb)/dV^2$ value to make the total dispersion of the fiber zero at this wavelength.

Numerical Problems

- A step-index single-mode fiber exhibits material dispersion of 6 ps nm^{-1} km^{-1} at an operation wavelength of 1.55 µm. Assume that n_1 = 1.45 and Δ = 0.5 %. Calculate the $Vd^2(Vb)/dV^2$ value to make the total dispersion of the fiber zero at this wavelength.

$$D(\lambda) = D_{mat}(\lambda) + D_{wg}(\lambda)$$

$$D_{wg} = -\frac{n_2\Delta}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right]$$

$$\left[V\frac{d^2(Vb)}{dV^2}\right] = 0.3869$$

Numerical Problems

- Consider an optical link consisting of a 5 Km long step index fiber with core index n_1 = 1.49 and relative index difference Δ = 1 %.

a. Find the delay difference at the fiber end between the slowest and the fastest modes and also the rms pulse broadening caused by intermodal dispersion.
b. If the fiber is coupled to an LED operating at 1550 nm having a 75 nm spectral width, calculate the rms pulse spreading due to material dispersion. Dmat = 20 ps / nm.Km.
c. Calculate the rms pulse spreading due to waveguide dispersion if $V\, d^2(Vb)/\, dV^2 = 0.1$.
d. Calculate the maximum bit rate B_T that can be transmitted over the fiber without significant errors.
e. What is the Bandwidth - Distance product for this fiber ?

Numerical Problems

$$\sigma_s = \Delta T_{mod} / (2\sqrt{3}) = L\, n_1\, \Delta / (c\, 2\sqrt{3}) = 72\text{ ns}$$

$$\sigma_{mat} = \sigma\lambda\, L\, |\, Dmat\,(\lambda)\,| = 7.5\ \text{ns/km}$$

$$D_{wg} = -\frac{n_2\Delta}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right] \qquad \sigma_{wg} = \left|-\frac{n_2\Delta}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right]\right|\sigma_\lambda L = 1.2ns$$

$$B_T = \frac{0.2}{\sigma} = 2.76Mbps$$

$$\sigma = \sqrt{\sigma_{\text{mod}}^2 + \sigma_{mat}^2 + \sigma_{wg}^2}$$

B. L = 13.812155 ≈ 14 MHz . Km