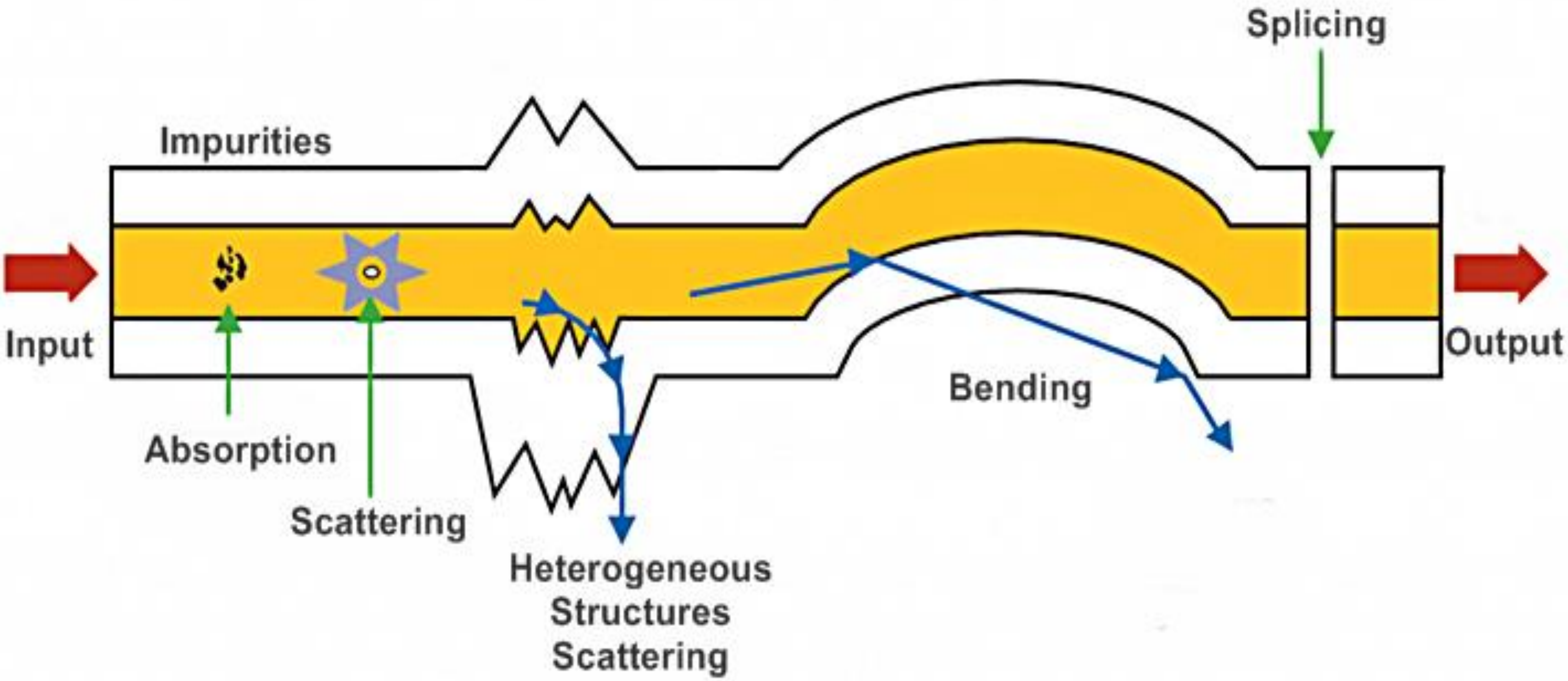
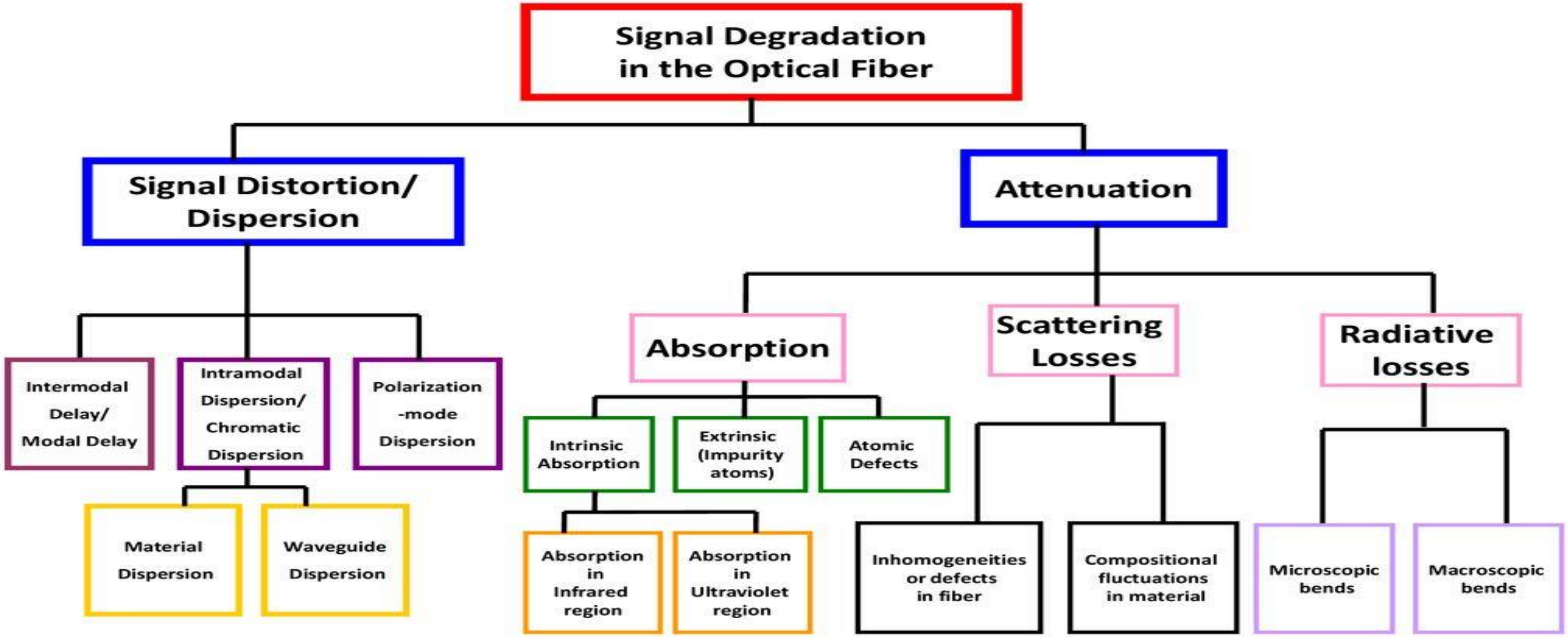


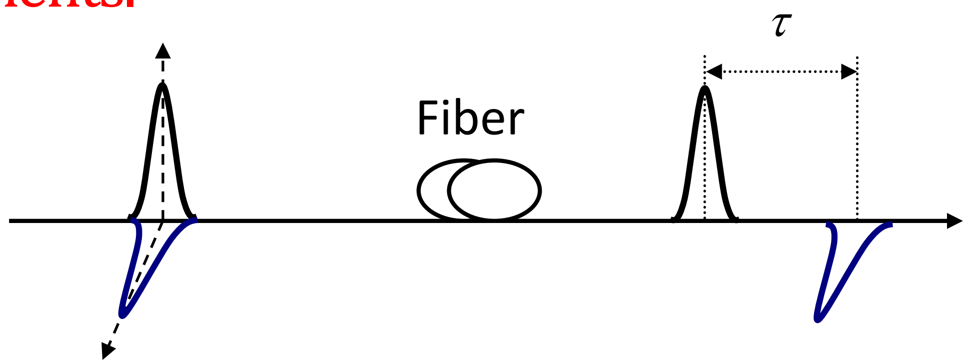
Module – 2
Signal Degradation

Signal degradation in fiber cable

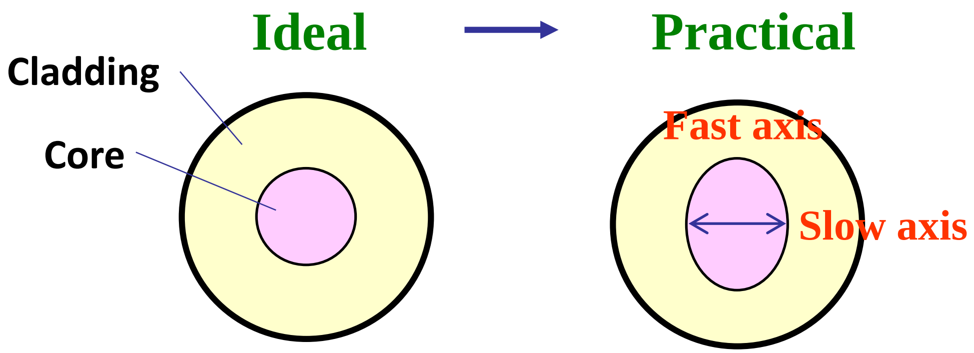


Polarization Mode Dispersion (PMD)

- PMD is the broadening of a pulse due to the time delay (in picoseconds) of one of the two polarization components.



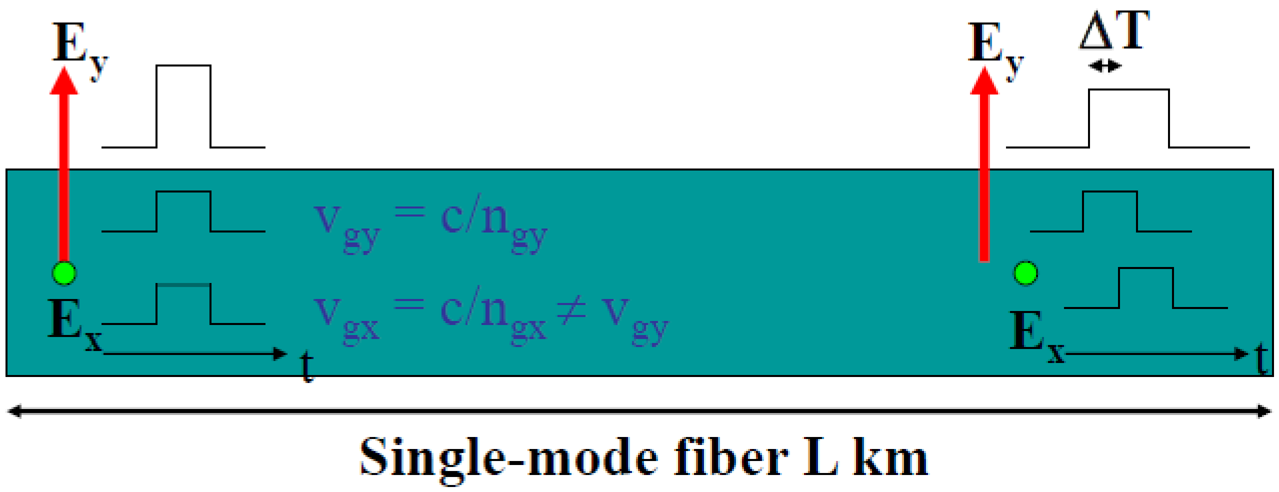
Cross-section of optical fiber



Polarization Mode Dispersion (PMD)

- Pulse broadening due to the orthogonal polarization modes (The time delay between the two polarization components is characterized as the differential group delay (DGD))

- Polarization varies along the fiber length



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

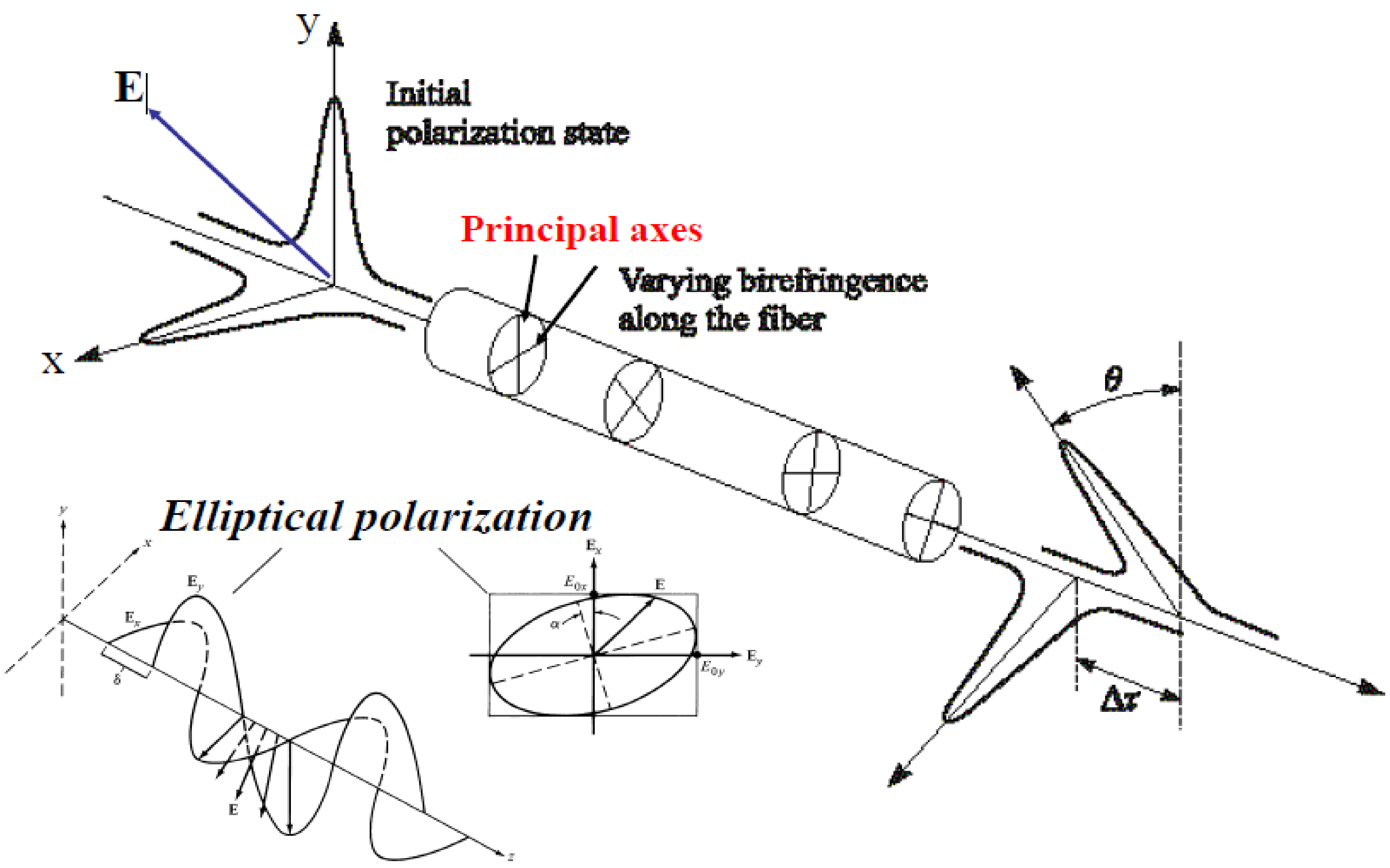
Birefringence

- The refractive index difference is known as birefringence.

$$B = n_x - n_y$$

- Assuming $n_x > n_y$ => y is the fast axis, x is the slow axis.
- B varies randomly because of thermal and mechanical stresses over time(due to randomly varying environmental factors in submarine, terrestrial, aerial, and buried fiber cables).
- => PMD is a statistical process !

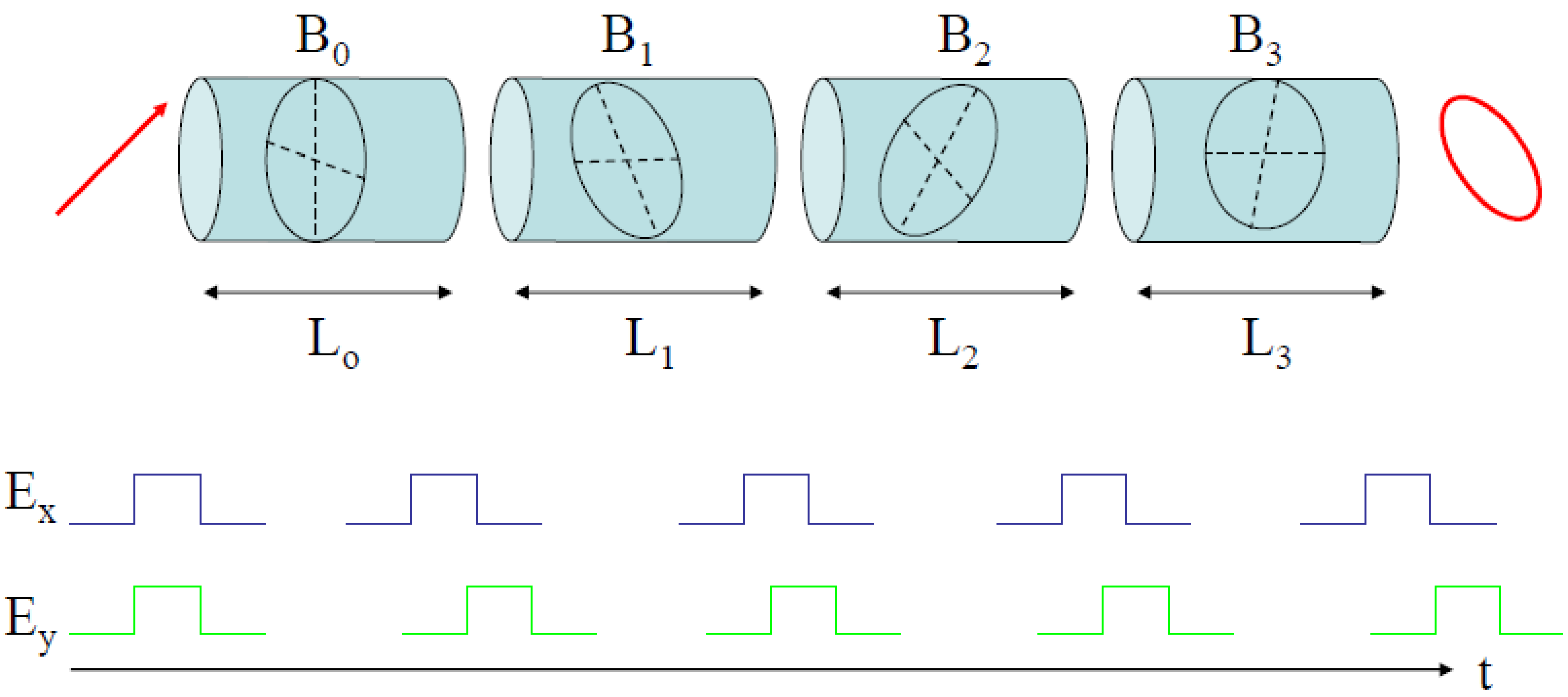
Randomly varying birefringence along the fiber



Polarization Mode Dispersion (PMD)

- The polarization state of light propagating in fibers with randomly varying birefringence will generally be elliptical and would quickly reach a state of arbitrary polarization
- However, the final polarization state is not of concern for most lightwave systems as photodetectors are insensitive to the state of polarization.
- A simple model of PMD divides the fiber into a large number of segments. Both the magnitude of birefringence B and the orientation of the principal axes remain constant in each section but changes randomly from section to section.

A simple model of PMD



Randomly changing differential group delay (DGD)

A simple model of PMD

- Pulse broadening caused by a random change of fiber polarization properties is known as polarization mode dispersion (PMD).

$$\text{PMD pulse broadening} \quad \Delta T_{PMD} = D_{PMD} \sqrt{L}$$

- D_{PMD} is the PMD parameter (coefficient) measured in ps/√km.

- $\sqrt{L}$ models the "random" nature (like "random walk")

- D_{PMD} does not depend on wavelength

- Today's fiber (since 90's) PMD parameter is 0.1 - 0.5 ps/√km. and the Legacy fibers deployed in the 80's have $D_{PMD} > 0.8$ ps/√km.

Numerical - PMD

- Calculate the pulse broadening caused by PMD for a singlemode fiber with a PMD parameter $D_{PMD} \sim 0.5$ ps/√km and a fiber length of 100 km.

Numerical - PMD

- Calculate the pulse broadening caused by PMD for a singlemode fiber with a PMD parameter DPMD ~ 0.5 ps/√km and a fiber length of 100 km.

$$\Delta T = 5\,ps$$

- Recall that pulse broadening due to chromatic dispersion for a 1 nm linewidth light source was ~ 15 ps/nm.km, which resulted in 1500 ps for 100 km of fiber length.

- PMD pulse broadening is orders of magnitude less than chromatic dispersion !

- PMD is relatively small compared with chromatic dispersion. But when one operates at zero-dispersion wavelength (or dispersion compensated wavelengths) with narrow spectral width, PMD can become a significant component of the total dispersion.

So why do we care about PMD?

- Recall that chromatic dispersion can be compensated to ~ 0, (at least for single wavelengths, namely, by designing proper -ve waveguide dispersion) but there is no simple way to eliminate PMD completely.

- It is PMD that limits the fiber bandwidth after chromatic dispersion is compensated!

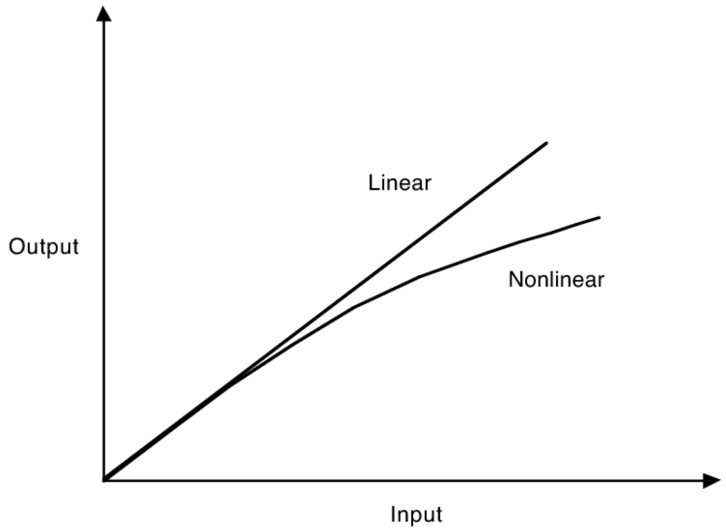
- PMD is of lesser concern in lower data rate systems. At lower transmission speeds (up to and including 10 Gb/s), networks have higher tolerances to all types of dispersion, including PMD.

- As data rate increases, the dispersion tolerance reduces significantly, creating a need to control PMD as much as possible at the current 40 Gb/s system.

Nonlinear Effects

- The response of any dielectric to light becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception

- Even though silica is intrinsically not a highly nonlinear material, the waveguide geometry that confines light to a small cross section over long fiber lengths makes nonlinear effects quite important in the design of modern lightwave systems



Nonlinear Effects

- The total polarization P induced by electric dipoles is given by

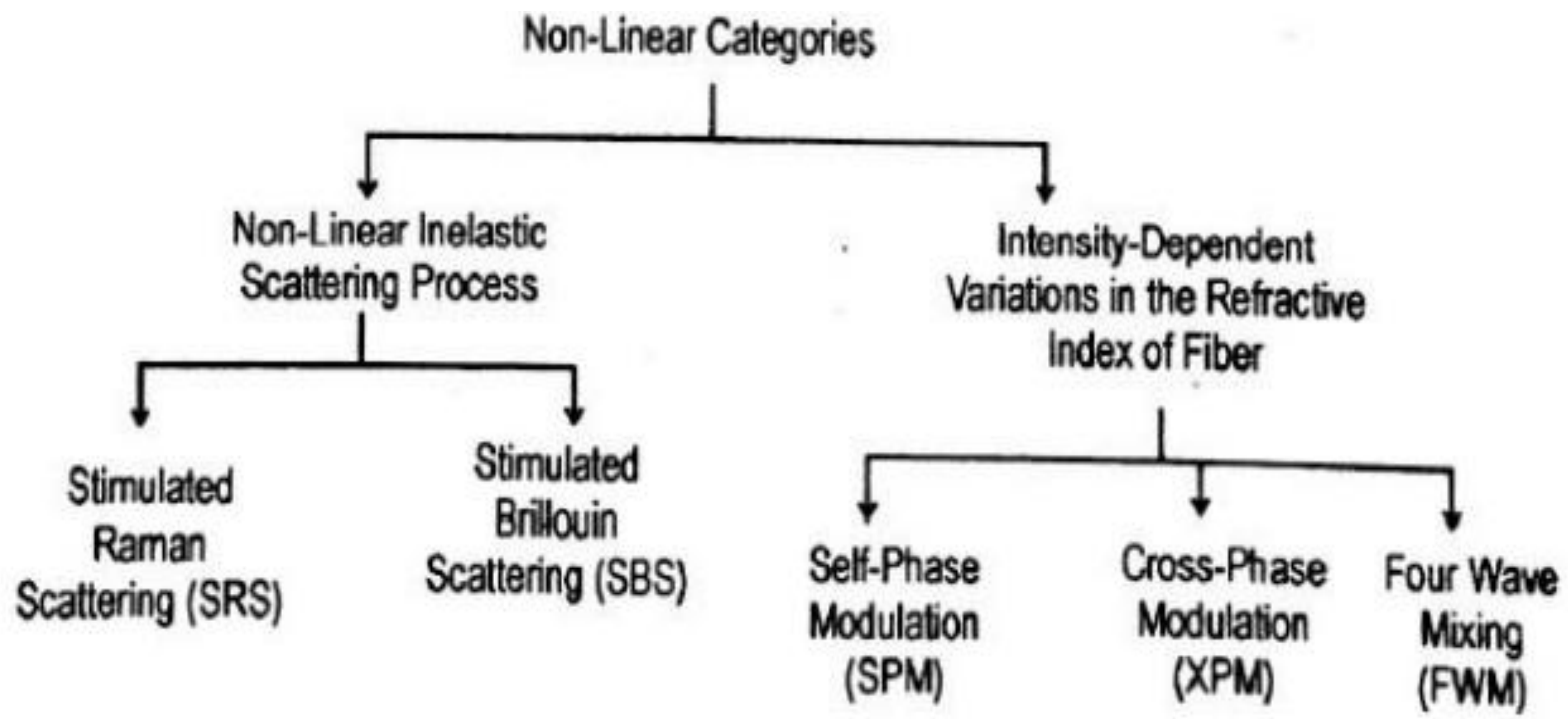
$$P = \varepsilon_0 \left(\chi^{(1)} . E + \chi^{(2)} . EE + \chi^{(3)} . EEE \right)$$

- The linear susceptibility $\chi^{(1)}$ represents the dominant contribution to P and it is responsible for refractive index (n) and attenuation coefficient (α).

- The second order susceptibility $\chi^{(2)}$ is responsible for nonlinear effects such as second harmonic generation and sum frequency generation.

- However, these kind of non linearities are negligible in silica glass fibers. The nonlinear effects occurs due to third order susceptibility $\chi^{(3)}$ are more dominant in case of optical fiber cables

Different types of Nonlinear Effects



Self Phase Modulation (SPM)

- SPM refers to self induced phase shift experienced by an optical field during its propagation in optical fibers.
- The non linear phase shift due to SPM effect is given by

$$\phi_{NL} = n_2 k_0 L |E|^2$$

- where n_2 is the nonlinear index coefficient, ko = $2\pi/\lambda$, L is the fiber length and $|E|^2$ is the optical intensity inside the fiber.
- SPM is responsible for symmetrical spectral broadening of optical pulses and formation of optical solitons in anomalous dispersion regime of fibers.
- Even though the SPM effect can be used for various applications such as fast optical switching, passive mode locking and soliton formation, it will be considered as a serious issue and should be compensated in long haul light wave systems

Cross Phase Modulation (XPM)

- XPM refers to nonlinear phase shift of an optical field induced by another co-propagating field having a different wavelength, direction, or state of polarization.
- The non linear phase shift due to XPM effect can be given by

$$\phi_{NL} = n_2 k_0 L\left(|E_1|^2 + 2|E_2|^2\right)$$

- where $|E_1|^2$ and $|E_2|^2$ represents the optical intensities of two co-propagating field of different wavelength.
- Due to difference in wavelength, the parameters β_2 (GVD) and n_2 (nonlinear index coefficient) are also different for the two co-propagating beams.
- XPM is always accompanied by SPM and is responsible for asymmetrical spectral broadening of co-propagating optical pulses.

Four Wave Mixing(FWM)

- The nonlinear interaction among three different optical waves under proper phase matching conditions, will lead to the creation of new optical wave called Four Wave Mixing (FWM) which can be mathematically represented as

$$\omega_4 = \omega_1 + \omega_2 - \omega_3$$

- where ω_1, ω_2 and ω_3 are the frequencies which can copropagate inside the fiber and ω4 is the frequency of newly generated optical wave.
- The following phase matching condition Δ_k has to be satisfied for the effect of FWM to occur.

$$\Delta_k = k_3 + k_4 - k_1 - k_2 = 0$$

- where k_1, k_2, k_3 and k_4 are the propagation constants.
- The effect of FWM will be minimal in standard optical fiber cables due to the need for phase matching conditions to prevail.

Four Wave Mixing(FWM)

- However for long haul dispersion compensated fiber transmission systems carrying OFDM kind of signals, its effect could be considered serious due to the compact distribution of a large number of subcarriers as well as the near phase matched condition brought out due to dispersion compensation.

Comparison of various dispersion and nonlinear effects

Parameter	CD	PMD	SPM	XPM	FWM	SRS	SBS
Bit rate	Dependent	Dependent	Dependent	Dependent	Independent	Dependent	Dependent
Optical intensity/ power	Independent	Independent	Dependent	Dependent	Dependent	Dependent	Dependent
Transmission length	Dependent	Dependent	Dependent	Dependent	Dependent	Dependent	Dependent
Fiber type	Single mode	Single mode	Single mode	Single mode	Single mode	Single mode	Single mode (bidirectional fibers only)
Origin	$n(\omega)$	$n_x \neq n_y$	Real part of χ^3	Real part of χ^3	Real part of χ^3	Img part of χ^3	Img part of χ^3
Effect	Pulse broadening due to delay in arrival of different wavelengths	Pulse broadening due to delay between two polarization components	Self induced phase shift	Phase shift is due to co-propagating pulses of different wavelengths	New waves are generated	Raman crosstalk due to amplif-ication of low frequency signals by high frequency signals	Brillouin crosstalk due to amplif-ication of low frequency signals by high frequency signals
Shape of broadening	Asymmetric	Symmetric	Symmetric	Asymmetric/ Symmetric	No broadening	No broadening	No broadening
Channel Spacing	Increases by decreasing the spacing	Increases by decreasing the spacing	No effect	Increases by decreasing the spacing	Increases by equal spacing	Do not match with Ramam shift	Do not match with Brillouin shift