Fiber Nonlinearities

By
Dr.A.Brintha Therese

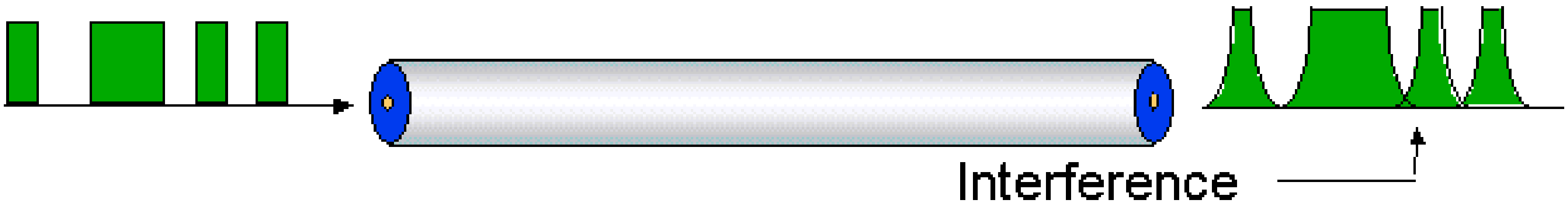
Fiber Nonlinearities

- As long as optical power within an optical fiber is small, the fiber can be treated as a linear medium; that is the loss and refractive index are independent of the signal power

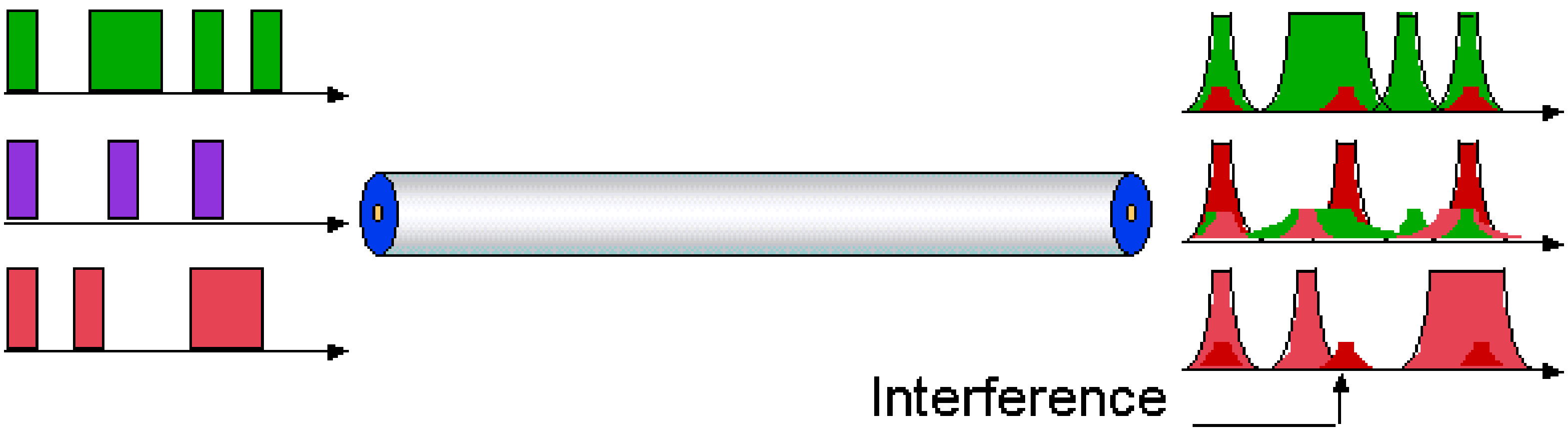
- When optical power level gets fairly high, the fiber becomes a nonlinear medium; that is the loss and refractive index depend on the optical power

Effects of Nonlinearites

- A single channel's pulses interact as they travel (Self-Phase)



- Multiple channels interact as they travel (Cross Phase, FWM)



- Degradation scales as (channel power)^2

Nonlinear Effects

- Stimulated Raman scattering
- Stimulated Brillouin scattering
- Four-wave Mixing
- Self-phase Modulation
- Cross-phase Modulation

FIBER EFFECTIVE LENGTH

•Nonlinear interaction depends on transmission length and cross-sectional area of the fiber

•The longer the length, the more the interaction and the worse the effect of the nonlinearity.

•BUT, signal propagates along link and experiences loss (from fiber attenuation) …
...complicated to model.

Simple model: Assume power is constant over a certain effective length

P denotes power transmitted into fiber. L denotes actual fiber length

$P(z) = P\, e^{-\alpha z}$ power at distance z along link.

$$PL_e = \int_{z=0}^{L} P(z)\,dz$$

$$L_e = \frac{1-e^{-\alpha L}}{\alpha}$$

Typical:
α = 0.22 dB/km at 1.55um
if L>>1/ α ,then L_e approx 20 km

EFFECTIVE CROSS SECTIONAL AREA

Effect of nonlinearity grows with intensity in the fiber. This is inversely proportional to the area of the core (for a given power).

Power not evenly distributed in the cross section.
Use effective cross sectional area (for convenience).

A = actual cross sectional area
I(r, θ) = actual cross sectional distribution of the intensity.

$$A_e = \frac{\left[\int_r \int_\theta r dr d\theta I(r,\theta)\right]^2}{\int_r \int_\theta r dr d\theta I(r,\theta)}$$

Most cases of interest:

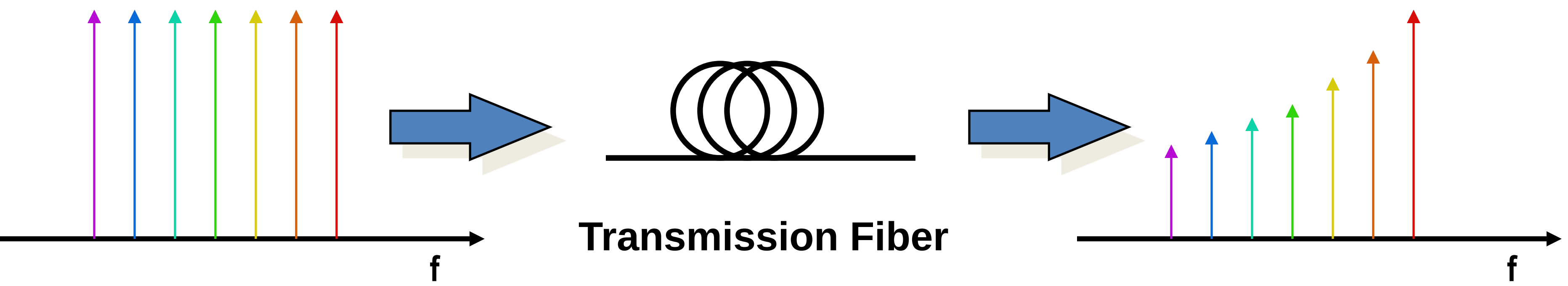
$$A_e \approx \text{area of single mode fiber}$$

Stimulated Raman Scattering

•Scattering of light from vibrating silicon molecule
•If two or more signals at different wavelengths are injected into a fiber, SRS causes
power to be transferred from the lower wavelength channels to the higher-wavelength
channels.
•Has a broadband effect (unlike SBS)
•Gain coefficient g_R as function of channel separation.
•Both forward and reverse traveling Stokes wave.
•Coupling between channels occurs only if both channels sending a "1".
•SRS penalty is therefore reduced by dispersion.

SRS Cont…

- N Channels equally spaced
- Channel 0 lowest wavelength is affected worst



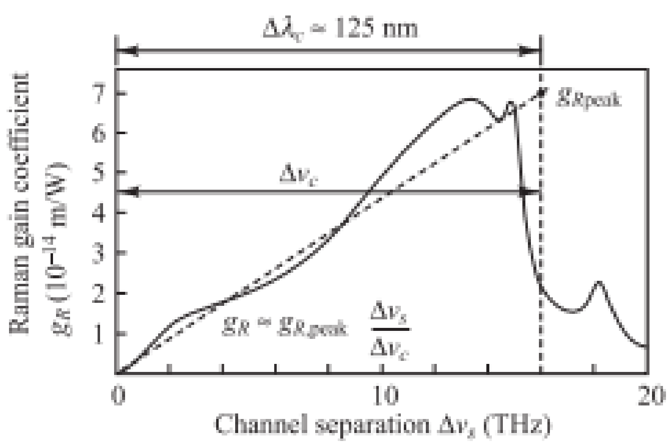
SRS Cont...

Consider a WDM system that has N channels equally spaced in a 30-nm band centered at 1545 nm. Assume that the transmitted power P is the same on all channels, that the.

If Fout(j) is the fraction of power coupled from channel 0 to channel j, then the total fraction of power coupled out of channel 0 to all the other channels is

$$F_{\text{out}} = \sum_{j=1}^{N-1} F_{\text{out}}(j) = \sum_{j=1}^{N-1} g_{R,\text{peak}} \frac{j\Delta v_s}{\Delta v_c} \frac{PL_{\text{eff}}}{2A_{\text{eff}}} = \frac{g_{R,\text{peak}} \Delta v_s PL_{\text{eff}}}{2\Delta v_c A_{\text{eff}}} \frac{N(N-1)}{2}$$

Raman gain increases linearly as shown by the dashed line in Figure



Stimulated Raman Scattering (SRS)

1) Effect and consequences

- **SRS causes a signal wavelength to behave as a “pump” for longer wavelengths, either other signal channels or spontaneously scattered Raman-shifted light. The shorter wavelengths is attenuated by this process, which amplifies longer wavelengths**
- **SRS takes place in the transmission fiber**

2) SRS could be exploited as an advantage

- **By using suitable Raman Pumps it is possible to implement a Distributed Raman Amplifier into the transmission fiber. This helps the amplification of the signal (in co-operation with the localized EDFA). The pumps are depleted and the power is transferred to the signal**

Stimulated Brillouin Scattering

- Arises when a strong optical signal generate acoustic waves(Sound waves represent alternating regions of compressed material and expanded material)
- Produce refractive index variation
- Scattering is induced by index discontinuities
- Cause backwards scattering in fiber

SBS, continued

- Brillouin frequency shift equal to

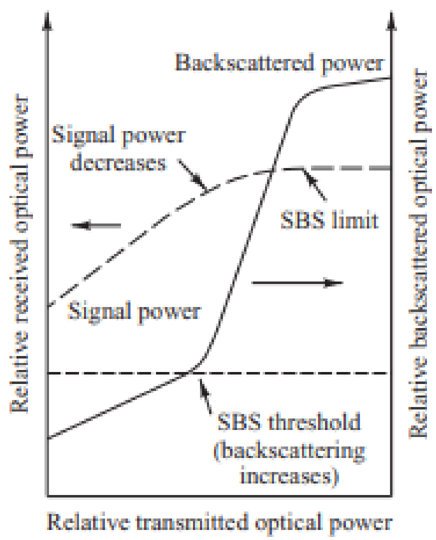
  $2nV_s/\lambda$, where n is the mode index and v is the speed of sound in the material
- For fiber, scattered light is 11 GHz lower in frequency than signal wavelength (speed of sound is 5.96 km/s)
- System impairment starts when amplitude of the scattered wave is comparable to the signal power

SBS

- SBS threshold Power

$$P_{th} = 21 \frac{A_{eff} b}{g_B L_{eff}} \left(1 + \frac{\Delta v_{source}}{\Delta v_B} \right)$$

- The effect of SBS on signal power in an optical fiber



Schemes for reducing the SBS

- Optical isolators
- Keeping optical power per WDM below thershold
- Increasing the linewidth

Self Phase Modulation

- The refractive index of many materials depends on optical intensity I
- $n = n_o + n_2 I$

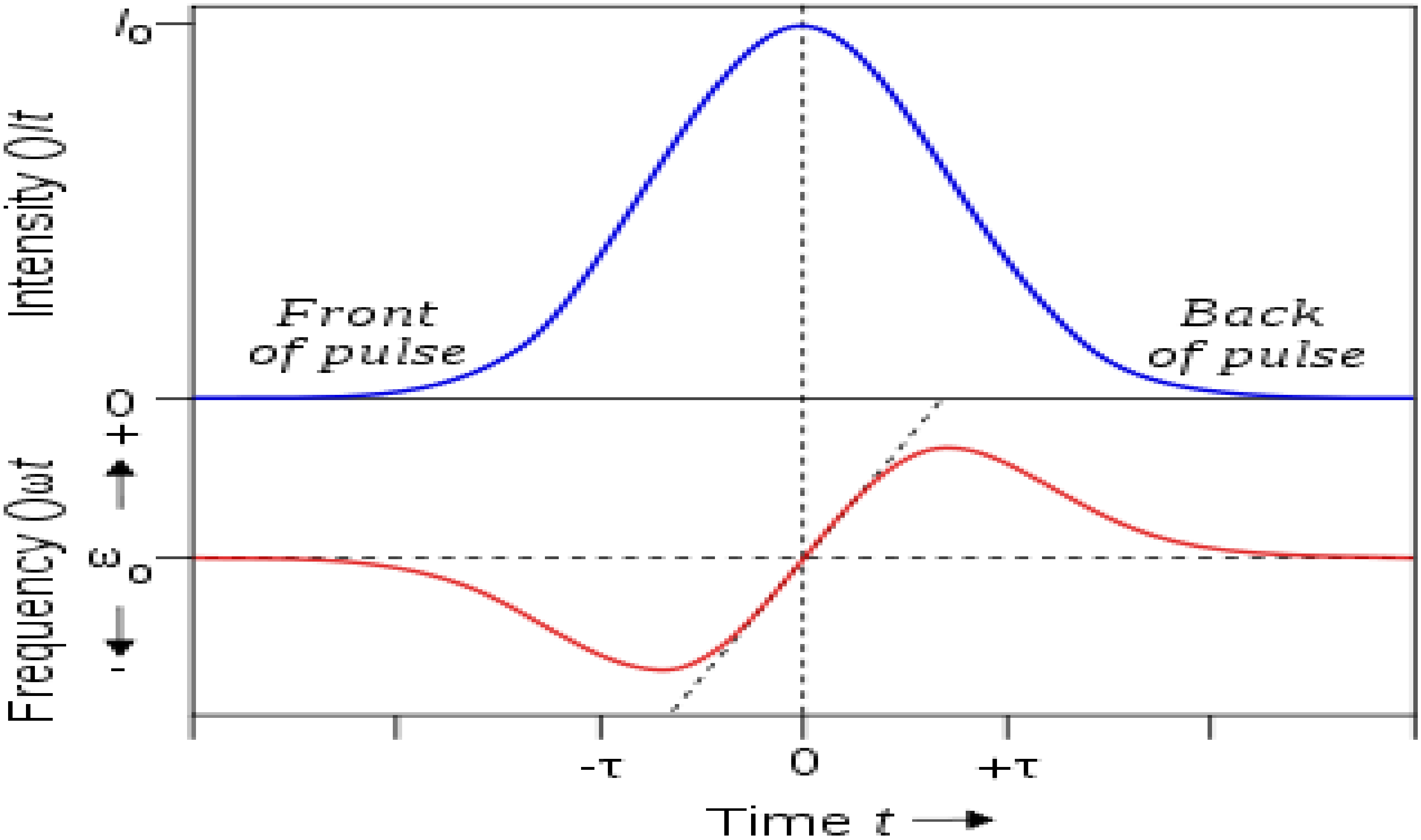
  $= n_o + n_2 P/A_{eff}$

n_o = ordinary refractive index

n_2 = nonlinear index coefficient

Kerr nonlinearity produce self phase modulation called kerr effect

SPM Frequency Chirping



SPM

- Magnitude of nonlinear effect in SPM

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}}$$

- The frequency shift

$$\Delta\varphi = \frac{d\varphi}{dt} = \gamma L_{eff}\frac{dP}{dt}$$

Cross Phase modulation

- Similar to SPM appear in WDM
- Refractive index nonlinearity converts optical intensity fluctuation in one wavelength chanel to phase fluctuation in another channel

$$\Delta\varphi = \frac{d\varphi}{dt} = 2\gamma L_{eff} \frac{dP}{dt}$$

SPM

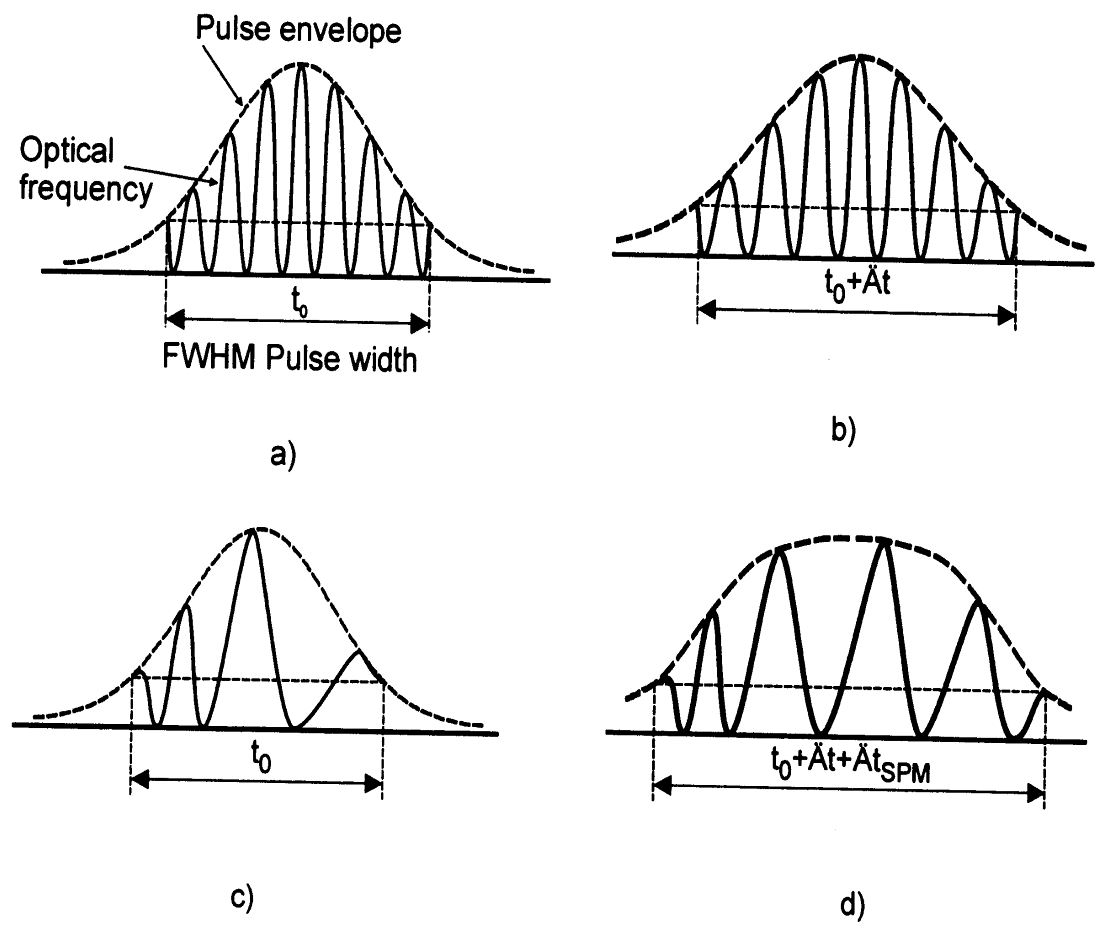
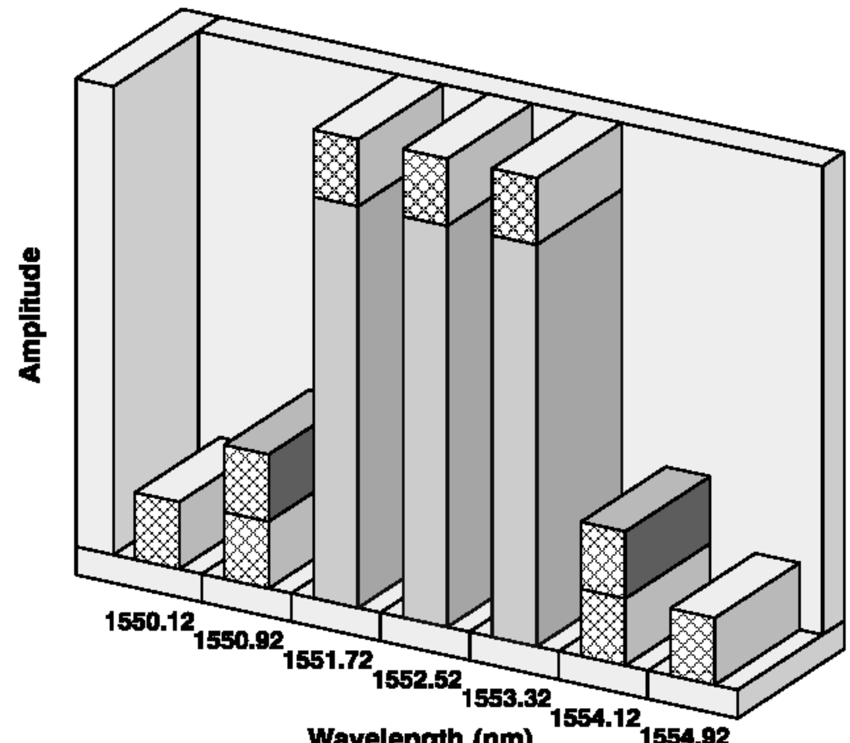


Figure 6.22 Self-phase modulation effect: spreading of chirped pulse: (a) Regular unchirped pulse entering the link; (b) the same pulse distorted after traveling distance *L* along the fiber; (c) chirped pulse entering the link; (d) chirped pulse broadens after traveling distance *L*.

Non Linear Effects:
Four Wave Mixing (FWM) cont…

- **Consider a simple three wavelength (λ1, λ2 & λ3)**
- **Let's assume that the input wavelengths are λl = 1551.72 nm, λ2 = 1552.52 nm & λ3 = 1553.32 nm. The interfering wavelengths that are of most concern in our hypothetical three wavelength system are:**
  - **λ1 + λ2 - λ3 = 1550.92 nm**
  - <u>**λ1 - λ2 + λ3 = 1552.52 nm**</u>
  - **λ2 + λ3 . λ1 = 1554.12 nm**
  - **2λ1 - λ2 = 1550.92 nm**
  - **2λ1 - λ3 = 1550.12 nm**
  - <u>**2λ2 - λ1 = 1553.32 nm**</u>
  - <u>**2λ2 - λ3 = 1551.72 nm**</u>
  - **2λ3 - λ1 = 1554.92 nm**
  - **2λ3 - λ2 = 1554.12 nm**



FWM

- K nonlinear interation constant

$$P_{ijk}(L) = \eta(Dk)^2 P_i(0)\, P_j(0) P_k(0) \exp(-\alpha L)$$

$$K = \frac{32\pi^3 X_{1111}}{n_2 \lambda c}\left(\frac{Leff}{Aeff}\right)$$