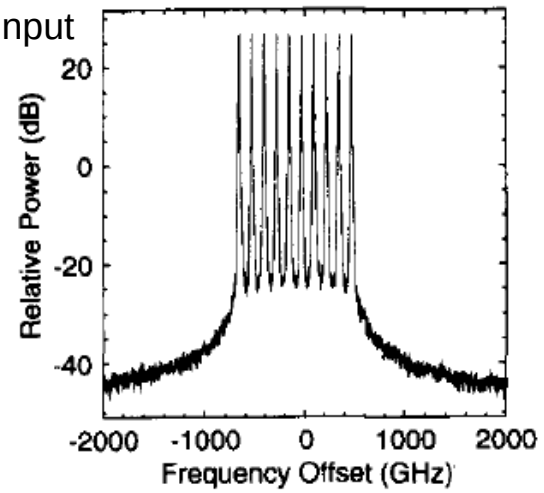
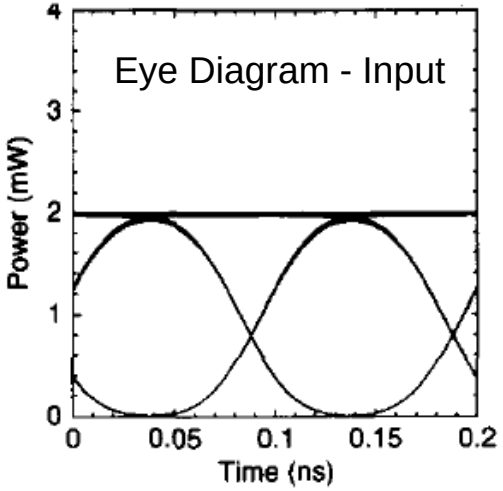
FWM as an Impairment

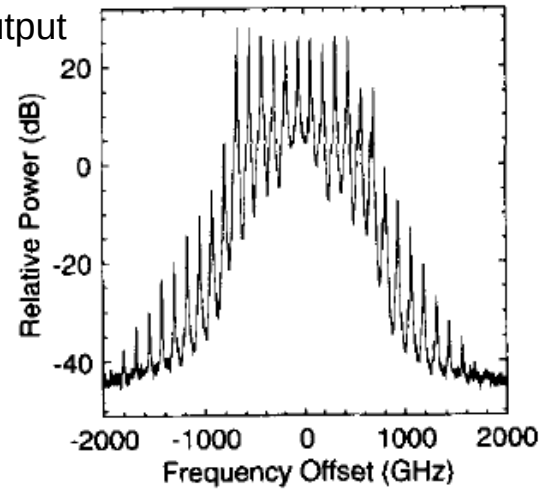
WDM Input

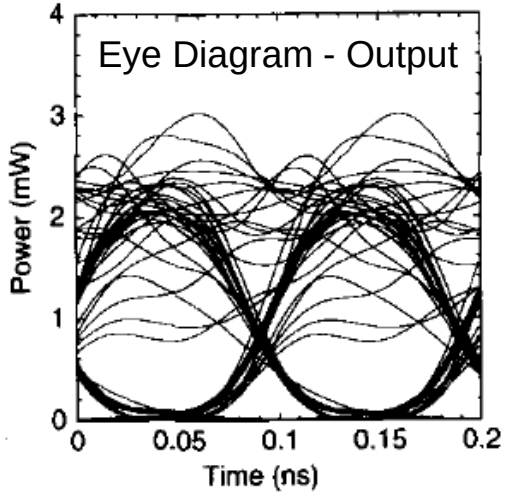




(a)

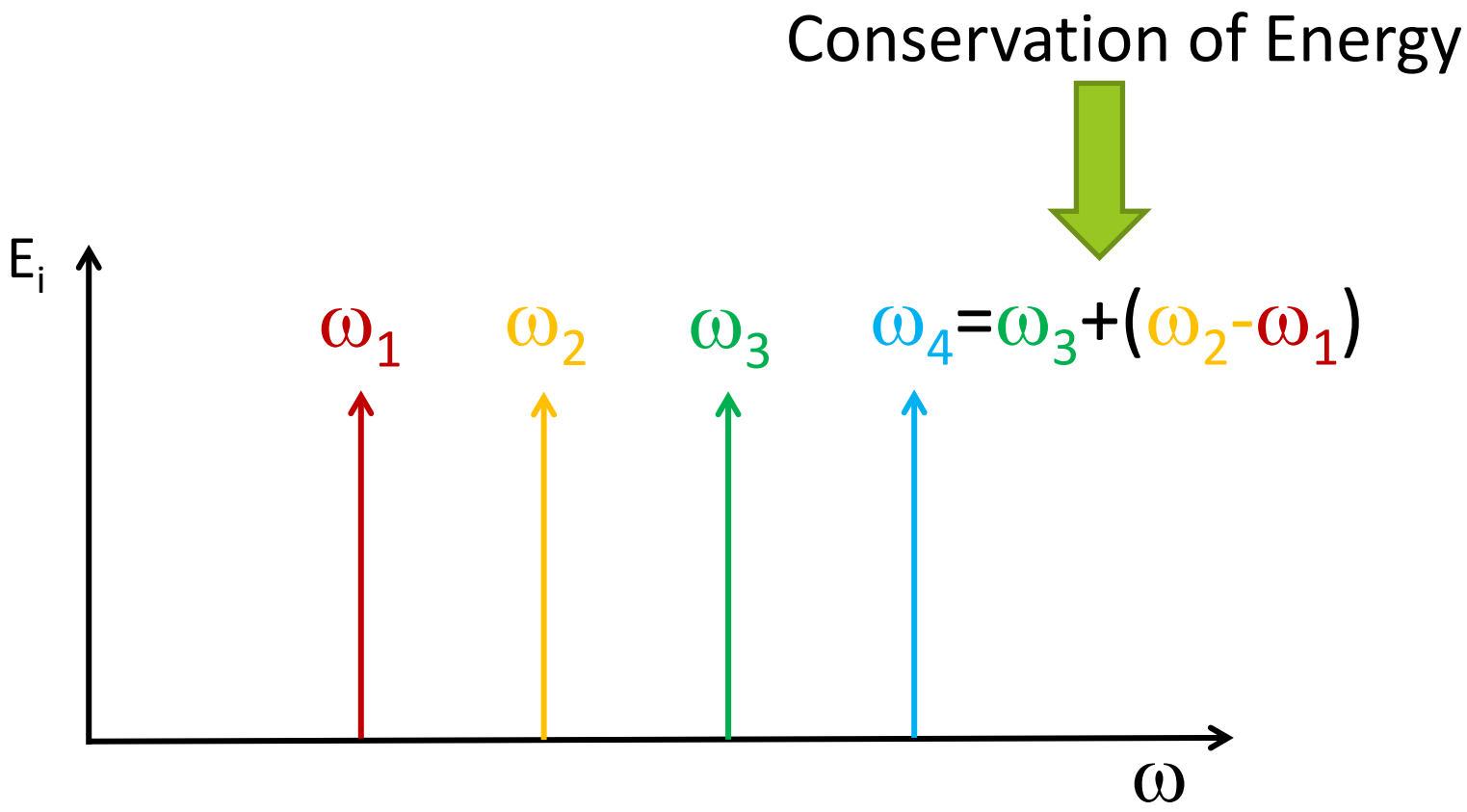
WDM Output



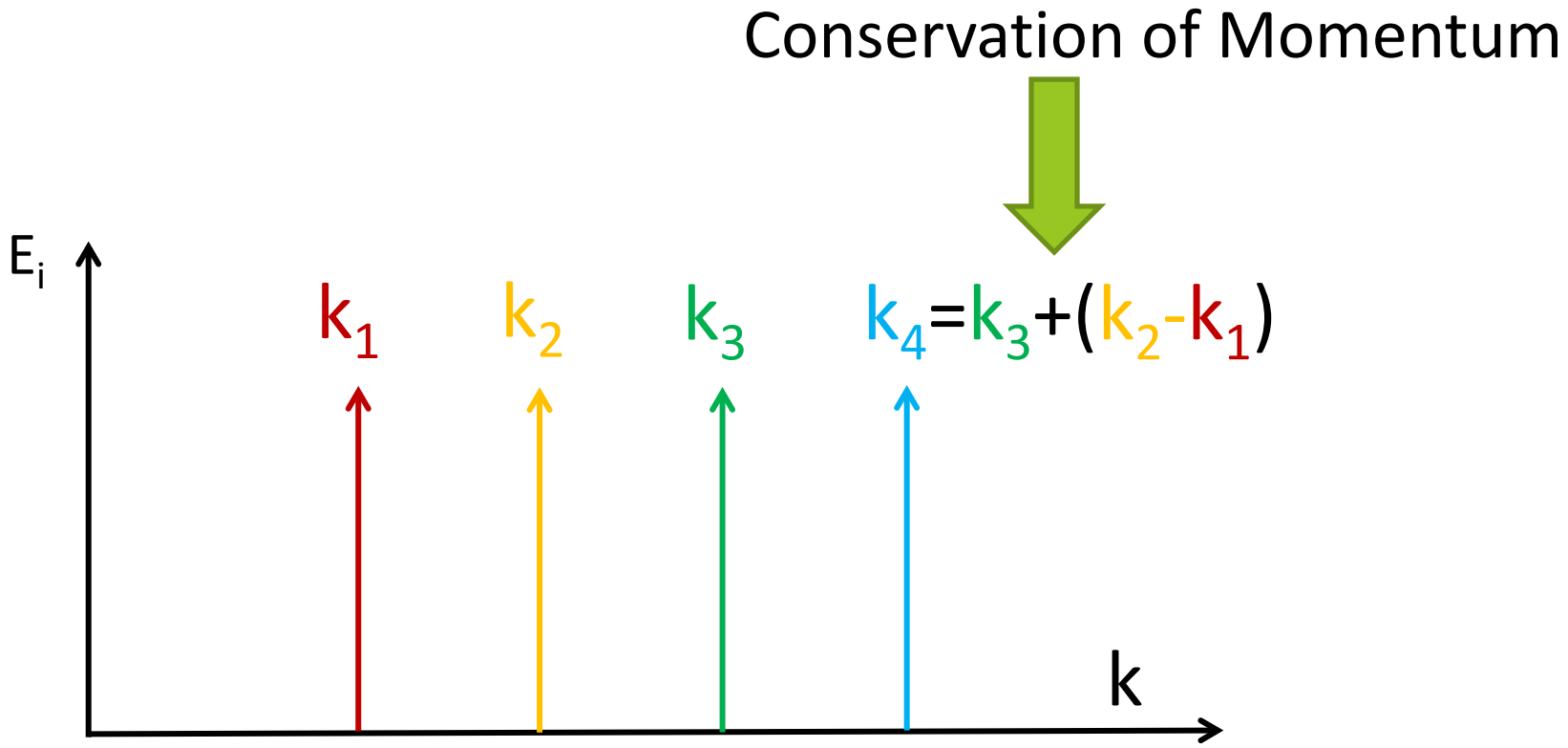


Simulations from "Four-Photon Mixing and High-Speed WDM Systems, Tkach et al. J. Lightwave Tech. Vol. 13 (5) 1995, p. 841

Four Wave Mixing (FWM)

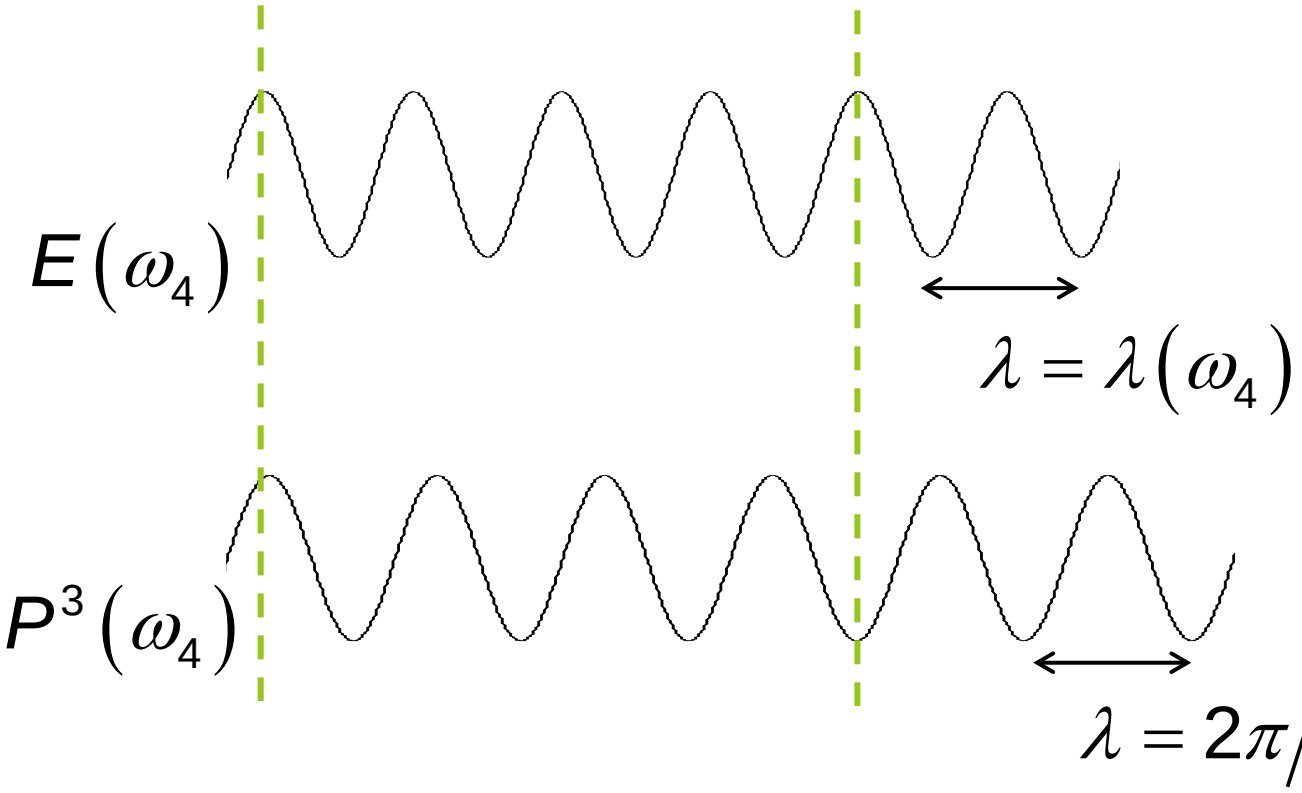


Mitigating FWM Impairment



- For efficient wave mixing, we must have "phase matching" (momentum conservation in the photon picture)
- Large group velocity dispersion may make this less likely
- There is a trade-off – we want high GVD for low FWM, but low GVD for low pulse spreading

Phase Matching



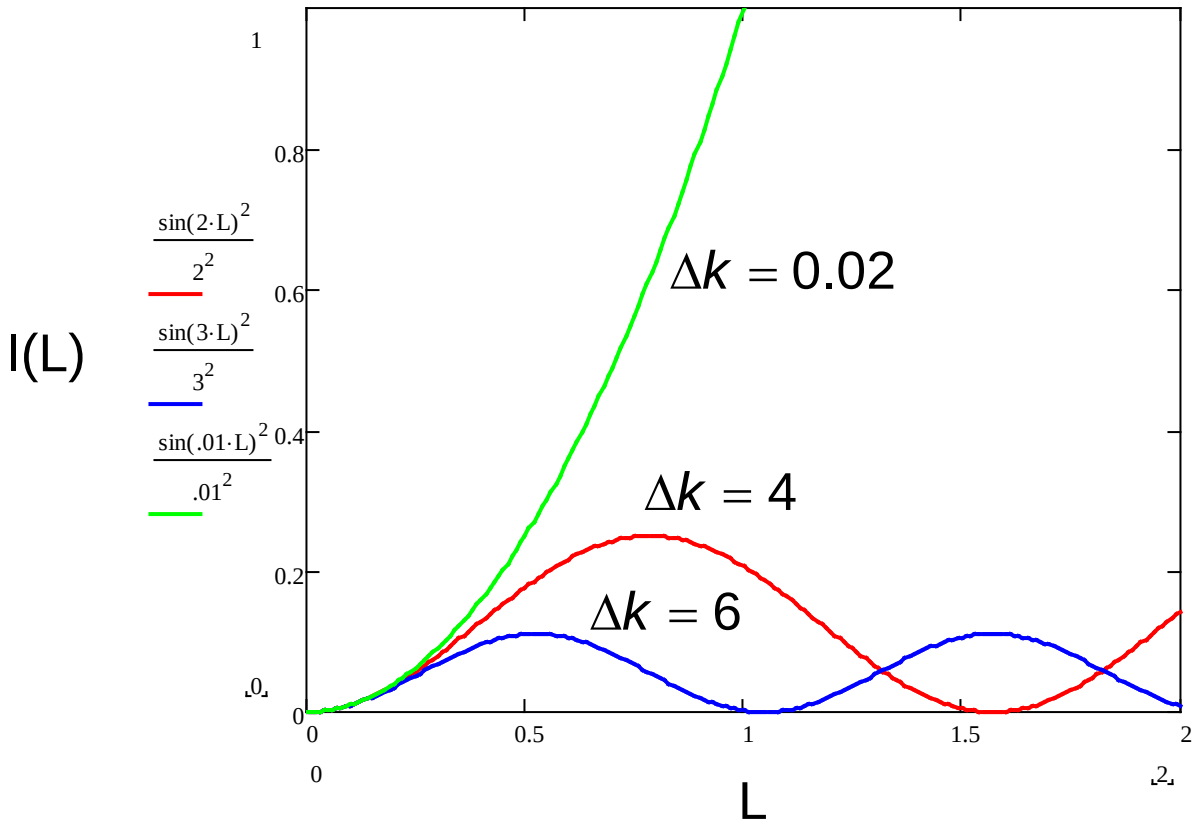
$$I(L) \propto E(L)^2$$

$$\propto L^2 \left[\frac{\sin(\Delta kL/2)}{\Delta kL/2} \right]^2$$

- Phase matching is required to maintain energy transfer into the new wave

Phase Matching

$$I(L) \propto E(L)^2 \propto L^2 \left[\frac{\sin(\Delta kL/2)}{\Delta kL/2} \right]^2$$



FWM and Group Velocity Dispersion

$$\Delta\beta = \beta_g + \beta_k - \beta_j - \beta_i = \frac{2\pi\lambda^2}{c}\Delta f^2\left(D + \Delta f\frac{\lambda^2}{c}\frac{dD}{d\lambda}\right)$$

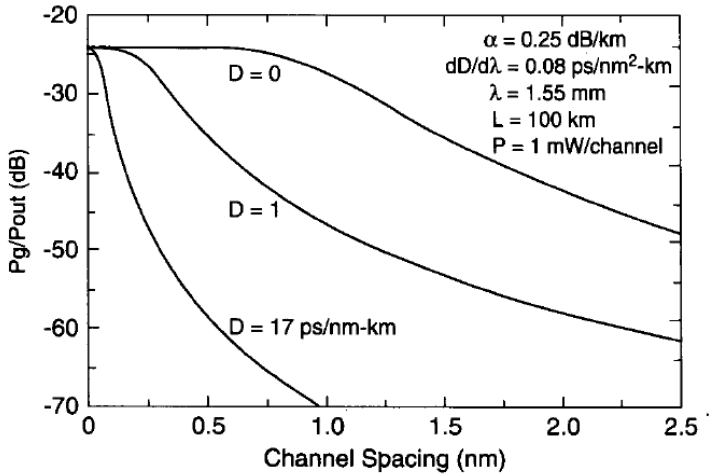


Fig. 1. Plot of the ratio of generated mixing-product power to transmitted channel power versus channel spacing for two equal-power channels. Curves are shown for three different values of fiber chromatic dispersion.

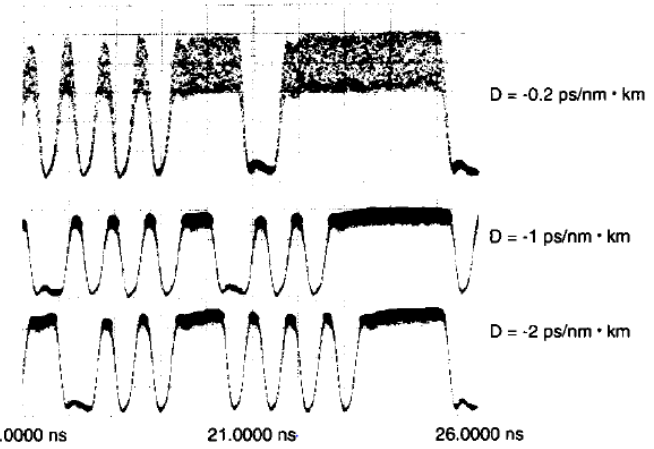
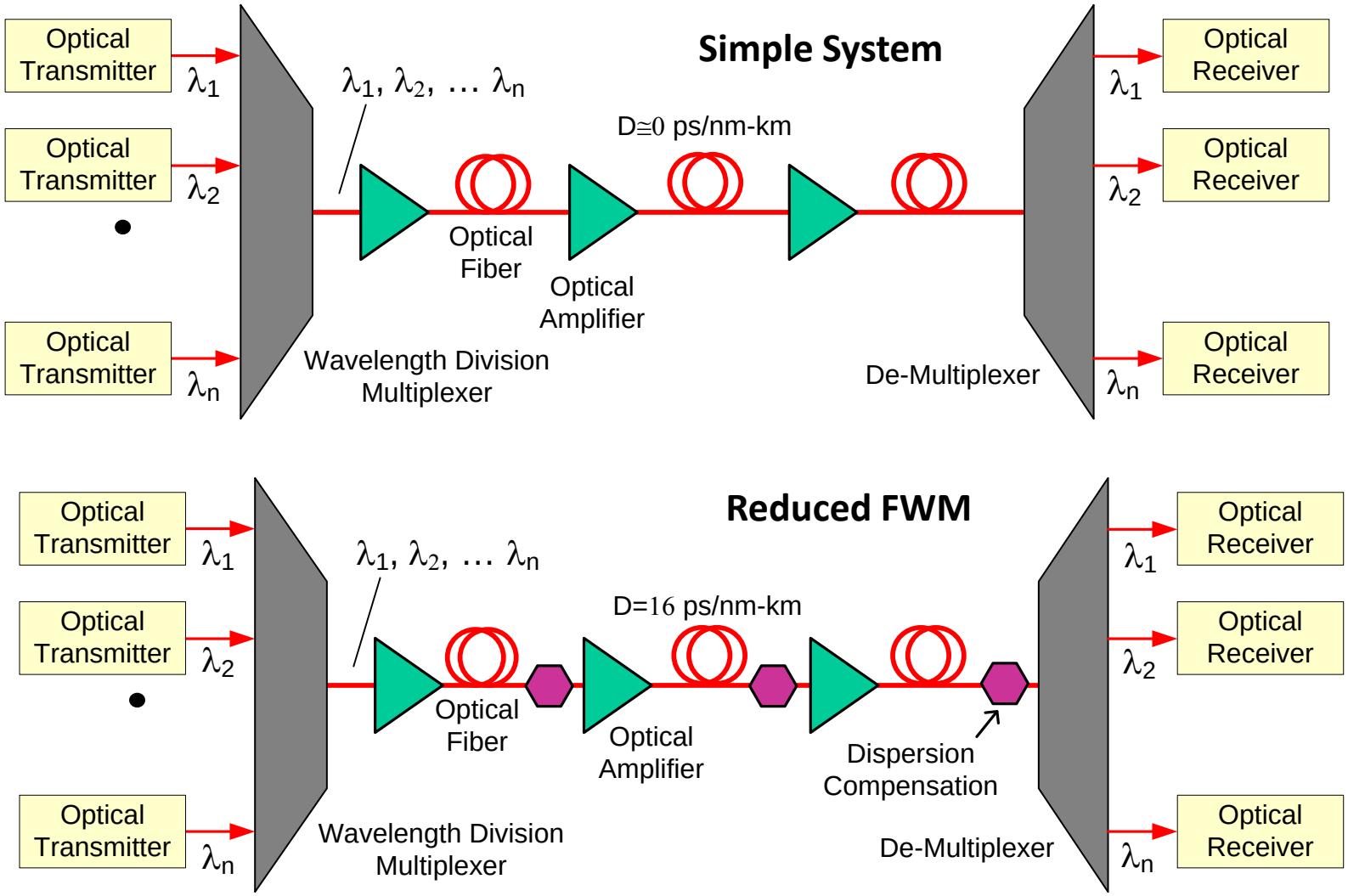


Fig. 3. Bit patterns observed for the central channel when the three channels are equally spaced so that the largest mixing product falls on the central channel. Shown for three different values of fiber chromatic dispersion. Launched power was 3 mW/channel.

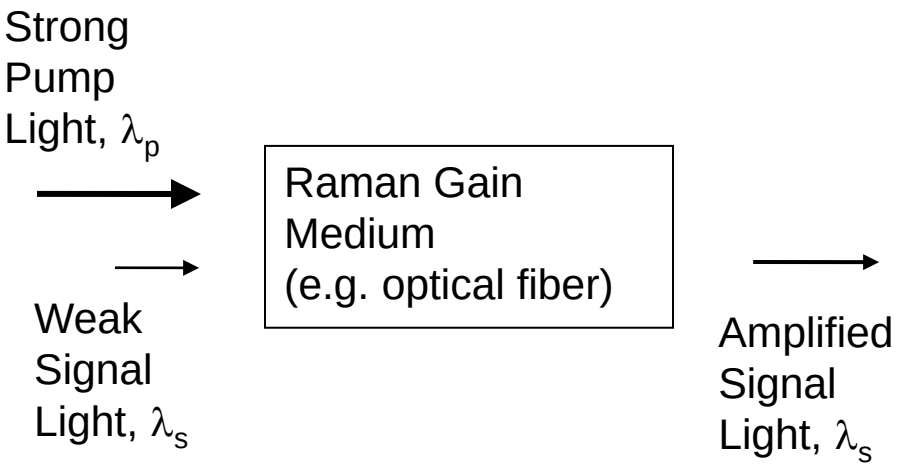
Simulations from "Four-Photon Mixing and High-Speed WDM Systems, Tkach et al. J. Lightwave Tech. Vol. 13 (5) 1995, p. 841

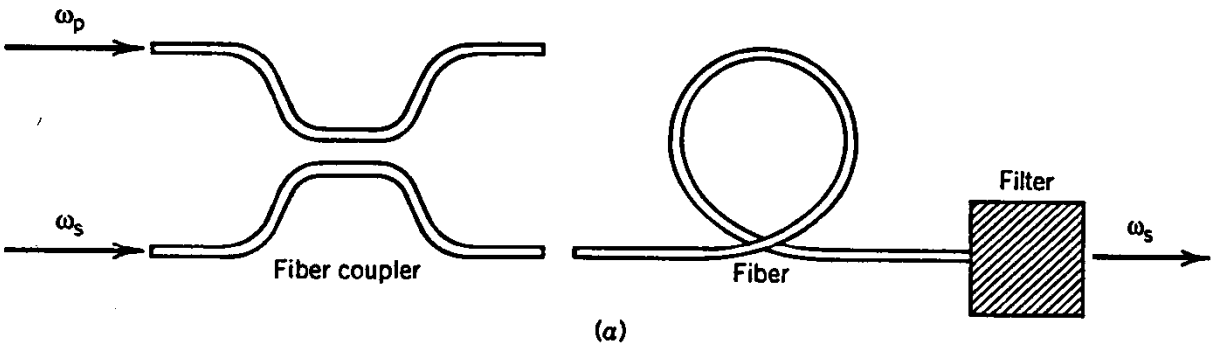
- Larger GVD means less FWM

Using Dispersion "Maps" to Reduce FWM



Raman Amplifiers





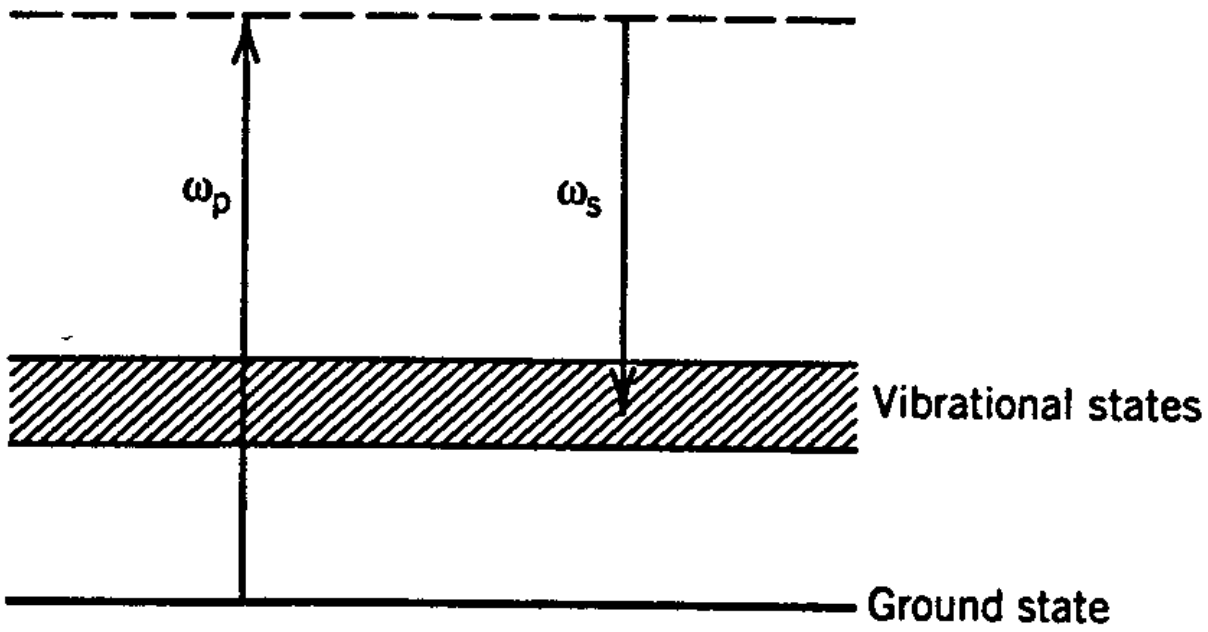
From Fiber-Optic Communications, 2nd Edition, Govind Agrawal, Figure 8.10a

Raman Amplifiers

Stimulated Raman amplification is described by

$$P = \varepsilon_0 \left(\chi^1 + \chi^3 E_{pump}{}^2 \right) E_{signal}$$

The Photon Picture of Stimulated Raman Scattering



From Fiber-Optic Communications, 2nd Edition, Govind Agrawal, Figure 8.10a

Raman Gain

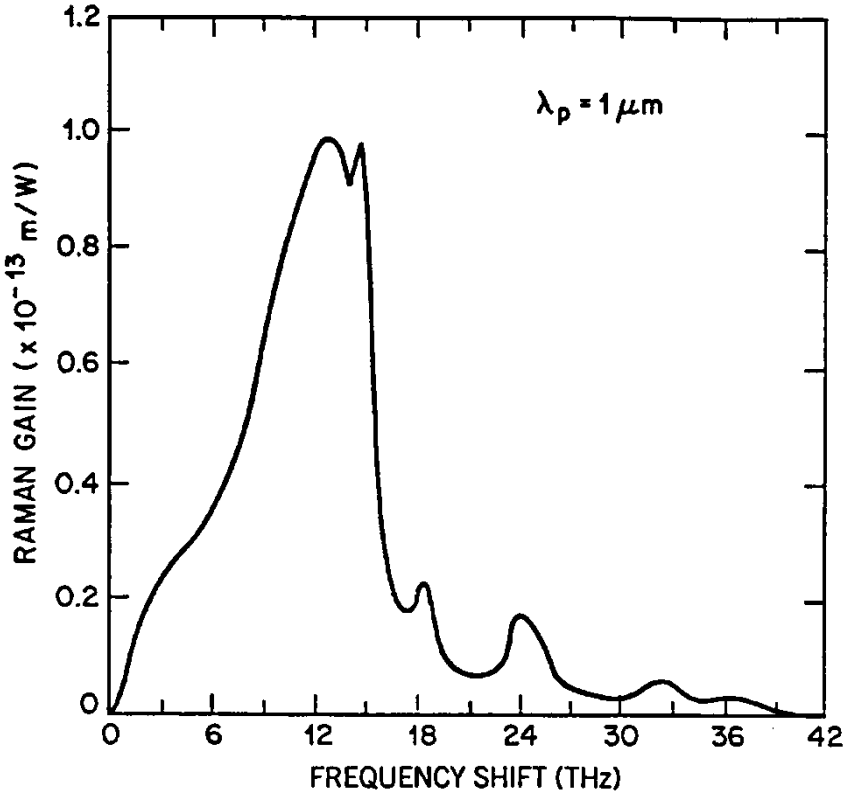


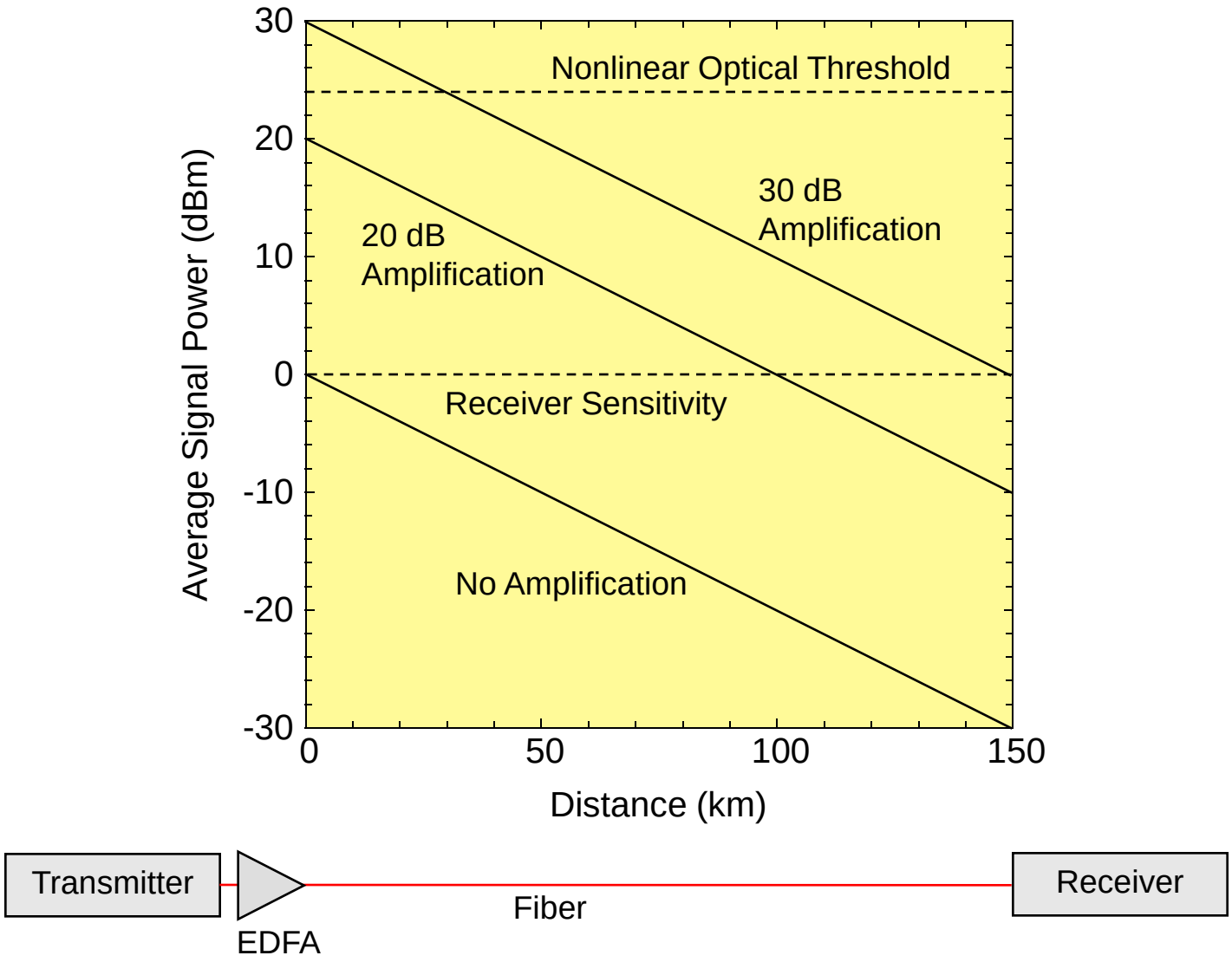
Figure 8.11 Measured Raman gain spectrum for fused silica. Raman gain scales inversely with the pump wavelength λ_p. (After Ref. [29]. ©1972 AIP. Reprinted with permission.)

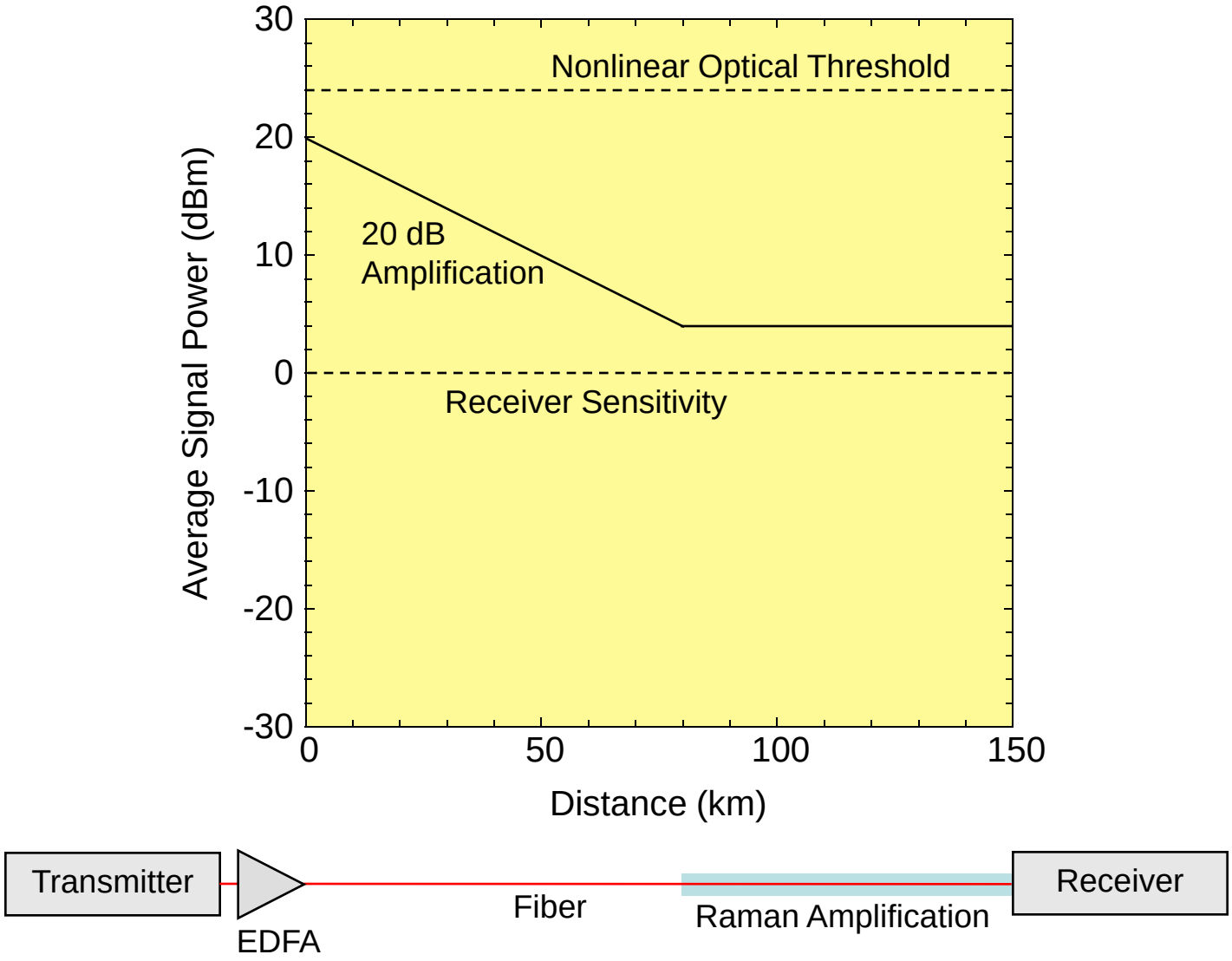
From Fiber-Optic Communications, 2nd Edition, Govind Agrawal

Near 1550 nm, a frequency shift of 6 Thz corresponds to a wavelength shift of 48 nm.

When should we use a Raman amplifier?

Erbium-doped fiber amplifiers work very well in optical communications, and people don't think Raman amplifiers will replace them. However, systems designers particularly like the idea of using both amplifiers to increase the spacing between repeaters. The idea is to use an EDFA to boost the signal at the beginning of a length of optical fiber, and to use a Raman amplifier to keep the signal from dropping into the noise before it reaches the end of the fiber.


30
20
10
0
-10
-20
-30
Average Signal Power (dBm)
Nonlinear Optical Threshold
30 dB
Amplification
20 dB
Amplification
Receiver Sensitivity
No Amplification
0
50
100
150
Distance (km)
Transmitter
EDFA
Fiber
Receiver


30
20
10
0
-10
-20
-30
Average Signal Power (dBm)
Nonlinear Optical Threshold
20 dB
Amplification
Receiver Sensitivity
0
50
100
150
Distance (km)
Transmitter
EDFA
Fiber
Raman Amplification
Receiver