Nonlinear Optics

$$P = \varepsilon_0 \chi^1 E + \varepsilon_0 \chi^2 E^2 + \varepsilon_0 \chi^3 E^3 + \cdots$$

Nonlinear relationship between P and E,
where P and E are scalars.

Third Order Optical Susceptibility

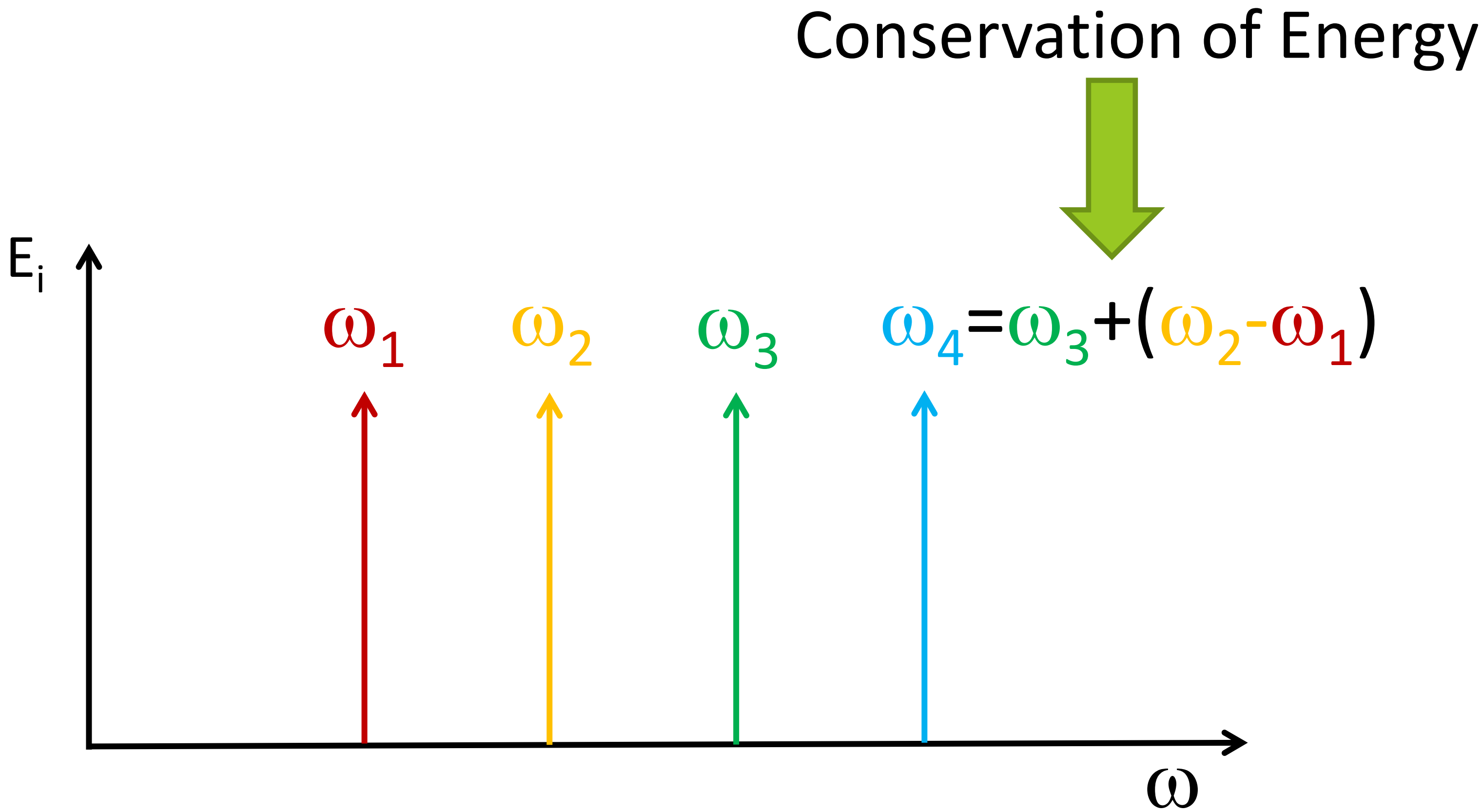
$$P_i^3(\omega_4) = \varepsilon_0 D^3 \sum_{jkl} \chi_{ijkl}^3(-\omega_4 : \omega_1, \omega_2, \omega_3) E_j(\omega_1) E_k(\omega_2) E_l(\omega_3)$$

$$D^3 = \begin{cases} 1 & \text{all fields indistinguishable} \\ 3 & \text{two fields indistinguishable} \\ 6 & \text{all fields indistinguishable} \end{cases}$$

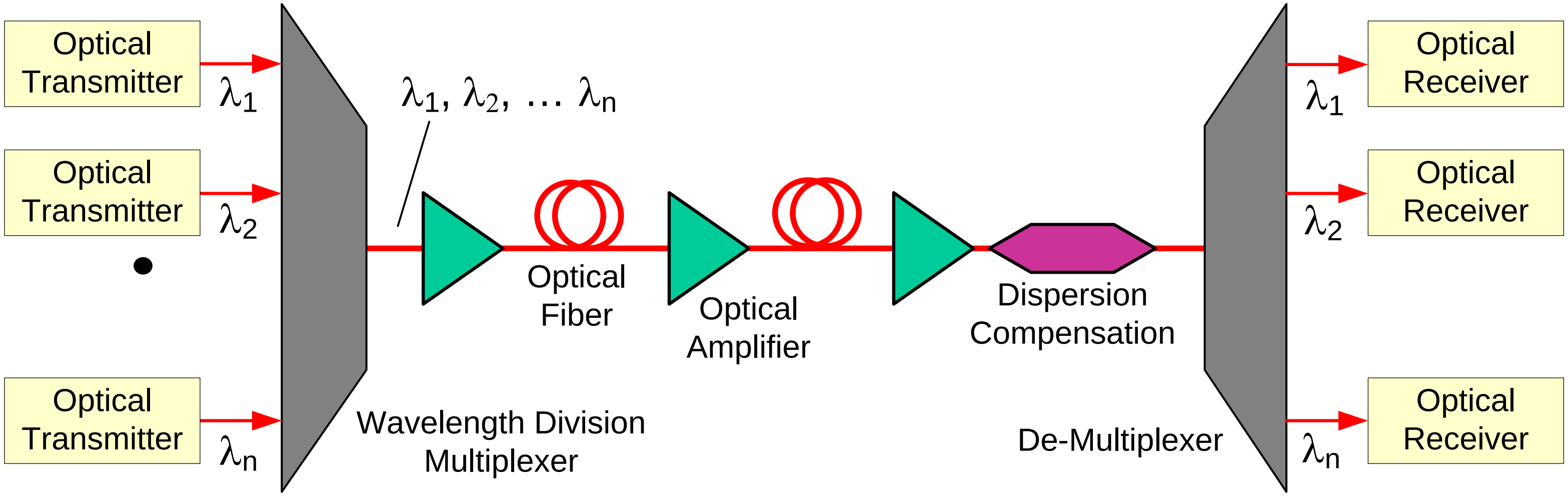
- E and P are generalized to vectors
- The stimulating fields and response (polarization) are monochromatic

This is the convention introduced in "Handbook of Nonlinear Optics," Richard L. Sutherland (Marcel Dekker, 1996)

Four Wave Mixing (FWM)

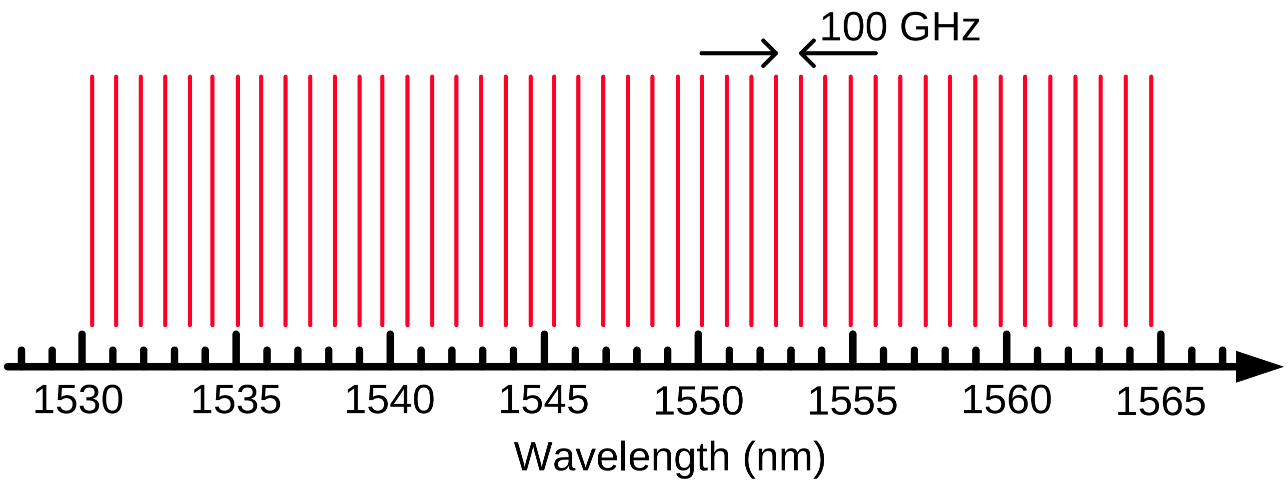


Wavelength Division Multiplexing



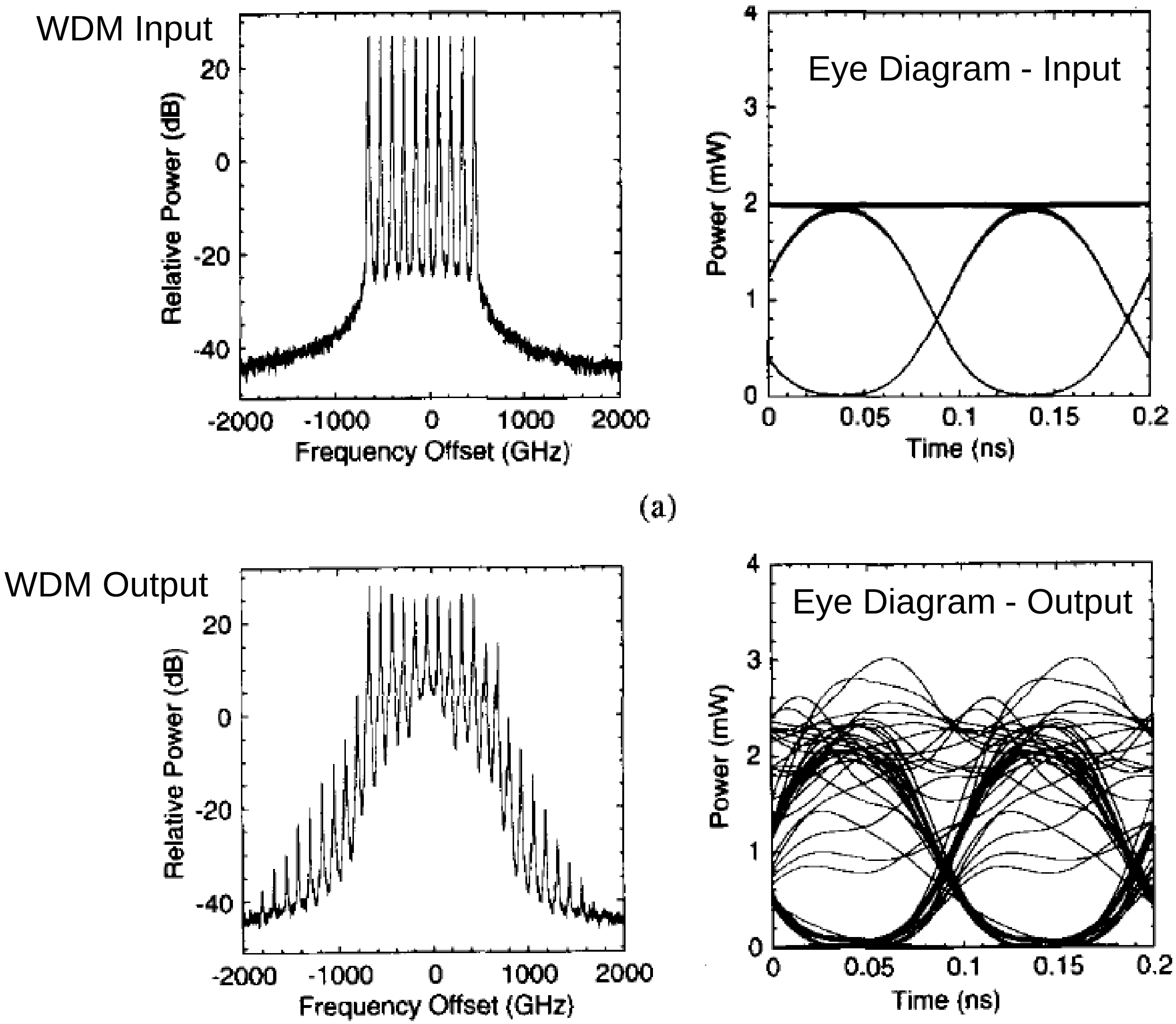
- A wavelength division multiplexed (WDM) link with 80 OC-192 wavelength channels operates at close to 1 Terabit per second and carries just over 10,000,000 simultaneous phone calls

The International Telecommunication Union (ITU) Grid



- The ITU specifies wavelengths centered at 193.1 THz spaced by 50 GHz to be used for WDM.

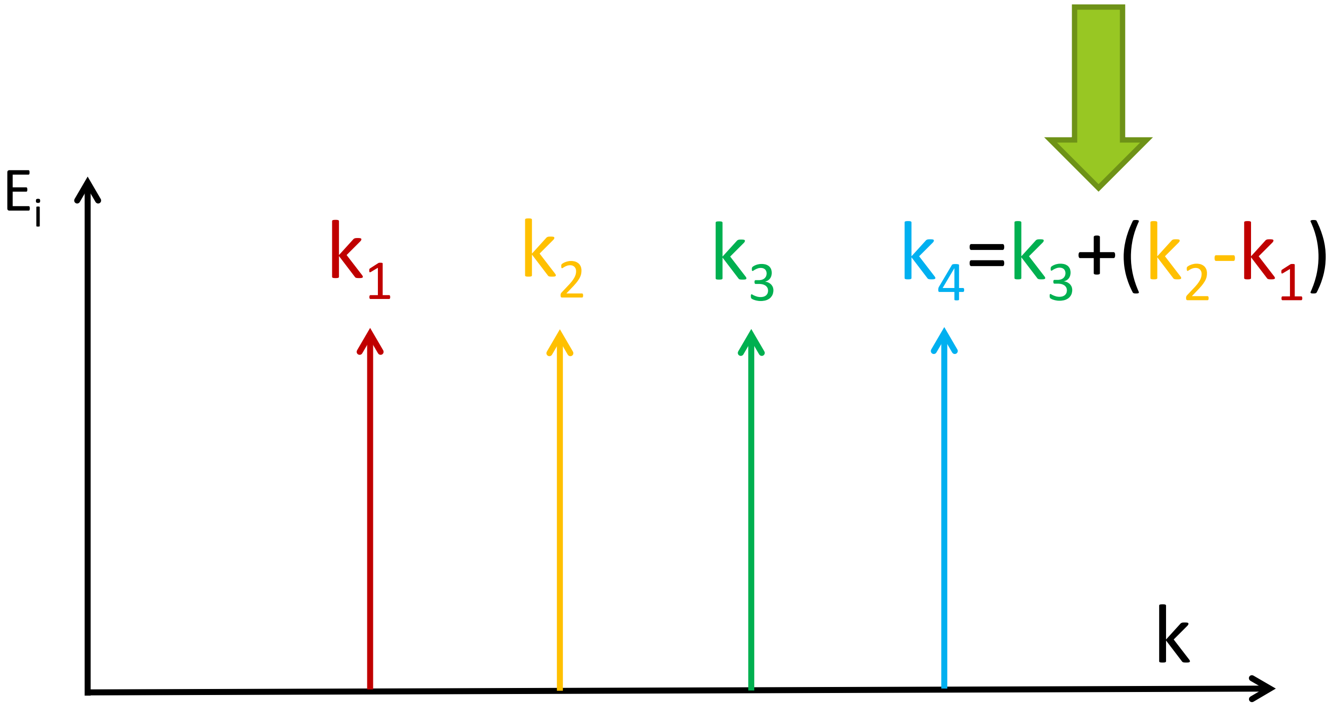
FWM as an Impairment



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

Mitigating FWM Impairment

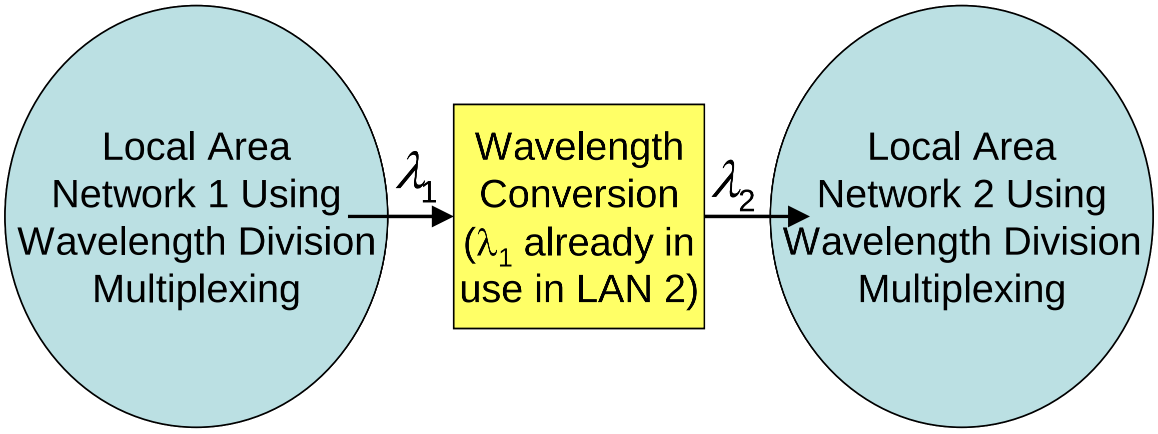
Conservation of Momentum



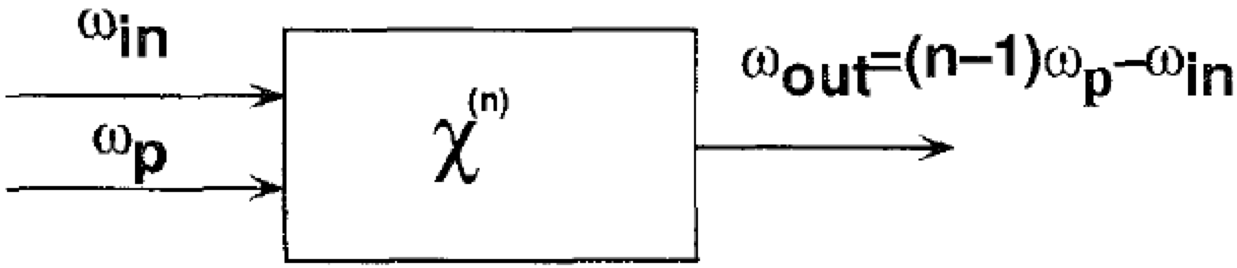
- For efficient wave mixing, we must have "phase matching" (momentum conservation in the photon picture)
- Large group velocity dispersion may make this less likely
- There is a trade-off – we want high GVD for low FWM, but low GVD for low pulse spreading

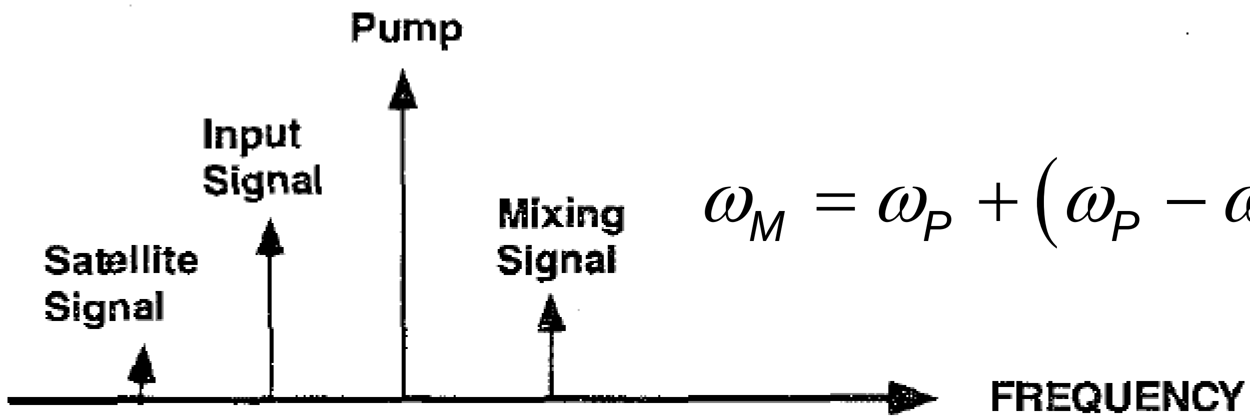
When is FWM a Good Thing?

- When sub-networks, trying to communicate with each other, share the same set of optical wavelengths.



Wavelength Conversion with FWM





$$\omega_M = \omega_P + \left(\omega_P - \omega_M\right)$$

From "Wavelength Conversion Techniques for WDM Network Applications," S. J. B. Yoo, J. Lightwave Technology, Vol. 14 (6) p. 955 (1996)

Wavelength Conversion with FWM

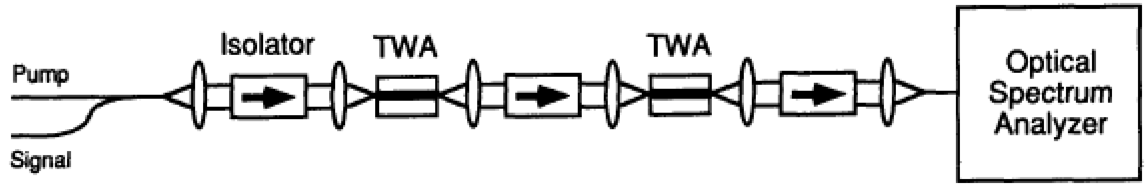


Fig. 1. FWM wavelength conversion setup showing a tandem amplifier geometry.

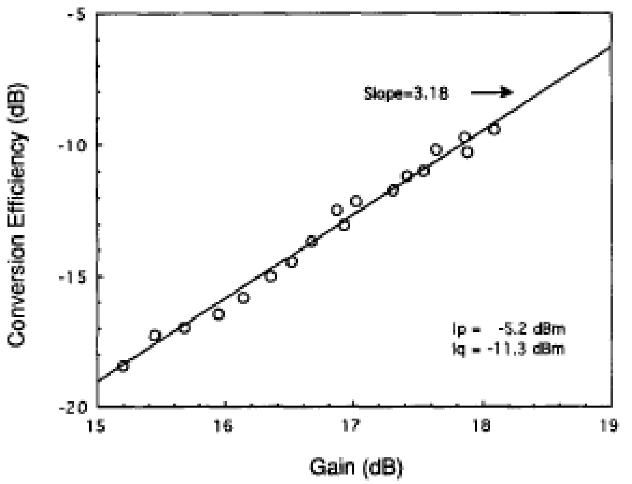


Fig. 2. Measured conversion efficiency η versus saturated single-pass TWA optical gain, showing cubic dependence of efficiency on gain.

"Four-wave Mixing Wavelength Conversion Efficiency in Semiconductor Traveling-Wave Amplifiers Measured to 65 nm of Wavelength Shift," Zhou et al., IEEE Photonics Technology Letters, Vol. 6 (8) p. 984 (1994)

- Wavelength conversion by FWM has relatively low efficiency