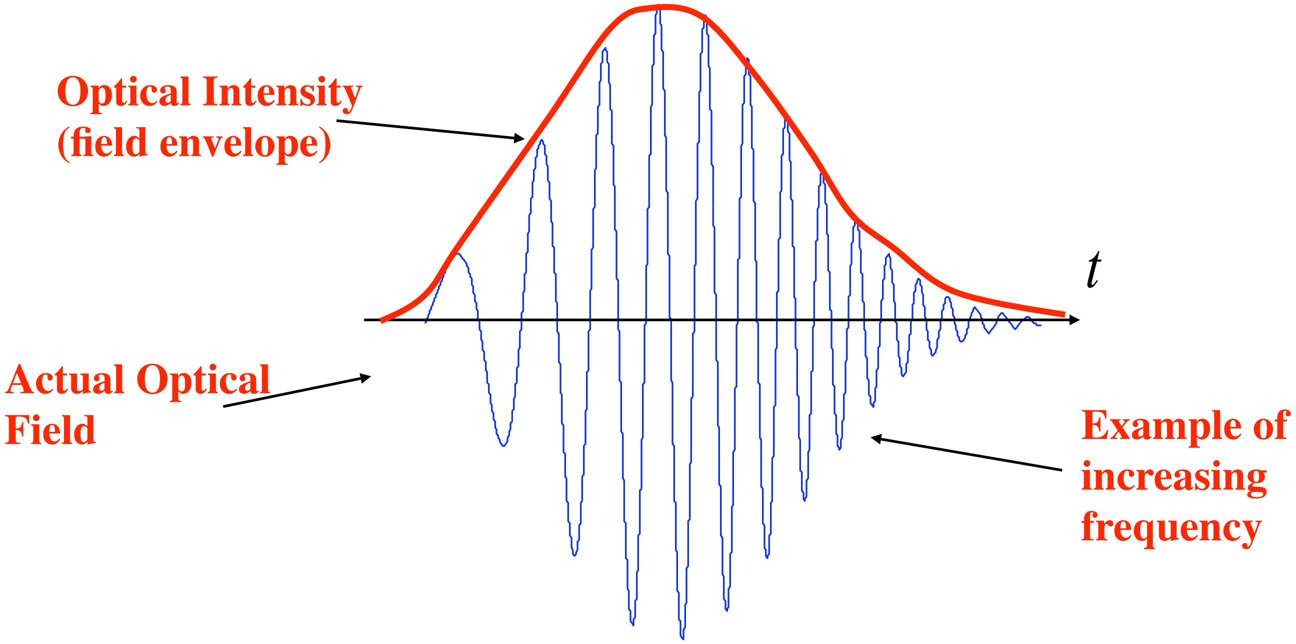
Lecture 8 - Chirp and Dispersion Compensation

Laser Chirp

- Another important parameter is the laser frequency chirp (frequency shift)
- Chirp will limit the bit-rate-distance product that a link can support
- Chirp occurs when directly driving a laser, the change in carrier density changes the effective index of refraction, and thus the oscillation optical frequency
  - This can be interpreted as a bit-synchronous phase or frequency modulation



Optical Intensity (field envelope)

Actual Optical Field

Example of increasing frequency

Laser Frequency Chirping

- Coupled to carrier density modulation ($n_1(\omega_m)$) via Kramers-Kronig, is frequency modulation via phase modulation.
- We define time varying frequency (modulation) as ***"Chirp"***
- Solving the frequency domain rate equations for $n_1(\omega_m)$ including gain suppression and converting back to the time domain (by replacing $i\omega_m$ with d/dt) and defining $N(t) = N_0 + \Delta N(t)$

$$n_1(\omega_m) = \frac{\left(i\omega_m + \dfrac{\varepsilon P_0}{\tau_p}\right)}{\Gamma A P_0} p_1(\omega_m)$$

$$\Delta N(t) = \frac{1}{\Gamma A}\left(\frac{1}{P_0}\frac{dP_0}{dt} + \frac{\varepsilon}{\tau_p}\Delta P(t)\right)$$

Laser Frequency Chirping

- The complex refractive index of a gain medium can be used to derive the ***Henry α-factor*** and the resulting change in phase $\Delta n_0'$ resulting from a carrier density change ΔN(t)

$$n_0(t) = n_0'(t) - i n_0''(t)$$

$$\Delta n_0'' = -\frac{n_0'}{4\pi\nu} A \Delta N(t)$$

$$\alpha = \Delta n_0' \big/ \Delta n_0'' = \frac{dn}{dN} \Big/ \frac{dg}{dN}$$

$$\Delta n_0' = -\frac{\alpha n_0' A}{4\pi\nu} \Delta N(t)$$

- The change in index via carrier density modulation causes the laser frequency to change from its unperturbed value

$$\frac{\Delta\nu}{\nu} = -\frac{\Delta n_0'}{n_0'} \Gamma_a = \frac{\alpha \Gamma_a A}{4\pi\nu} \Delta N(t)$$

$$\Delta\nu(t) = \frac{\alpha}{4\pi} \left(\frac{1}{P_0} \frac{dP}{dt} + \frac{\varepsilon}{\tau_p} \Delta P(t) \right)$$

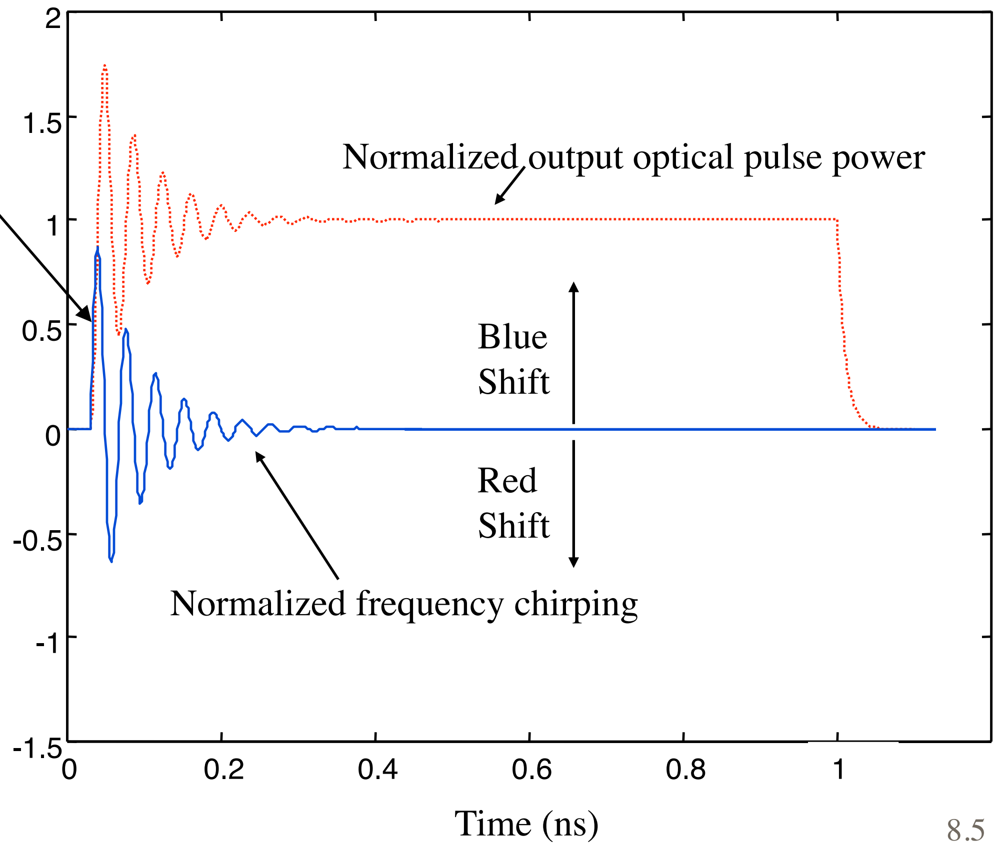
SC Laser direct modulation

- As the laser current is changed between the low and high states, the laser carrier density changes and there is a resulting time dependent phase change.
- The time dependent phase changes leads to an instant frequency shift called **frequency chirp**.

$$\Delta\nu(t) = -\frac{\alpha}{4\pi}\left(\underbrace{\frac{1}{P}\frac{dP}{dt}}_{(1)} + \underbrace{\frac{2\Gamma\varepsilon}{V\eta h\nu}\Delta P(t)}_{(2)}\right)$$

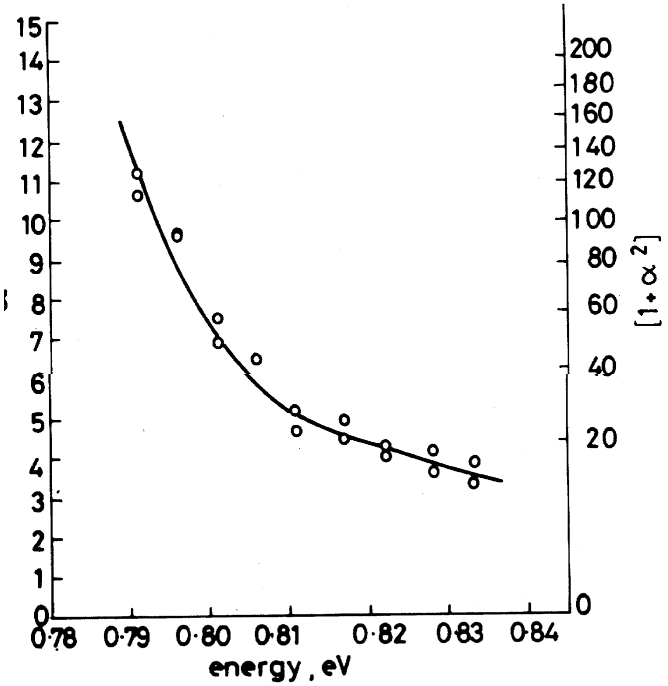
(1) Dynamic chirp: wavelength shift associated with on-off modulation

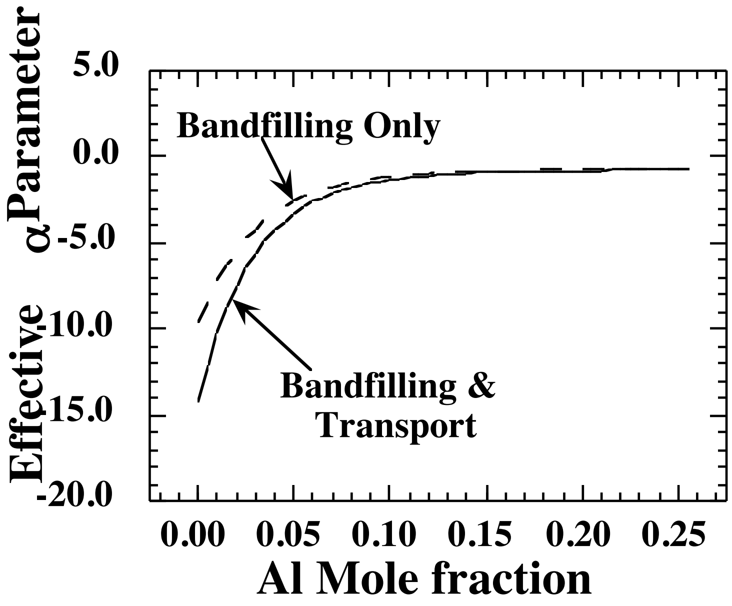
(2) Adiabatic chirp: Steady-state emission frequency difference between on and off states



Chirp

The linewidth enhancement factor changes with wavelength, and can also depend on the structure



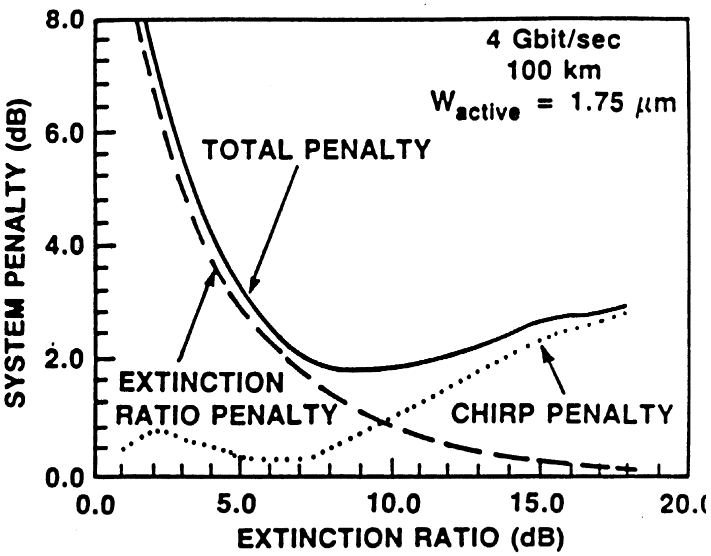


L.D. Westbrook, Electron. Lett., vol. 21, no. 22, 1018 (1984)

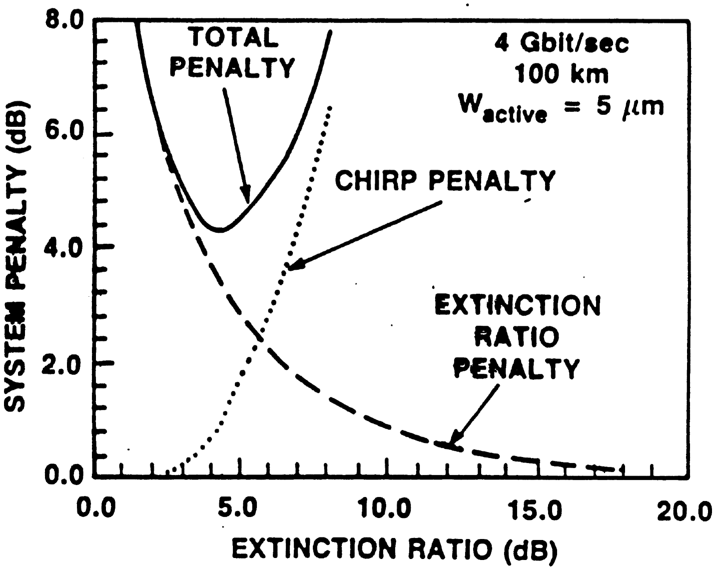
R. Nagarajan, J. Quantum Electronics, vol. 29, no. 6, 1601 (1993)

Chirp

Low chirp laser is a requirement to achieve the full potential of an optical communication system



DCPBH Laser



Ridge Waveguide Laser

P.J. Corvini et al., J. Lightwave Technol., vol. LT-5, 1591 (1987)

Chirped Pulse Propagation

- Chirp: A linear change in frequency with time.
- Pulse width varies as

$$\left(\frac{T_1}{T_0}\right)^2 = (1 + \frac{C\beta_2 z}{T_0^2})^2 + (\frac{\beta_2 z}{T_0^2})^2$$

- For C<0, pulse becomes narrower under propagation.

Compression of Chirped Pulses

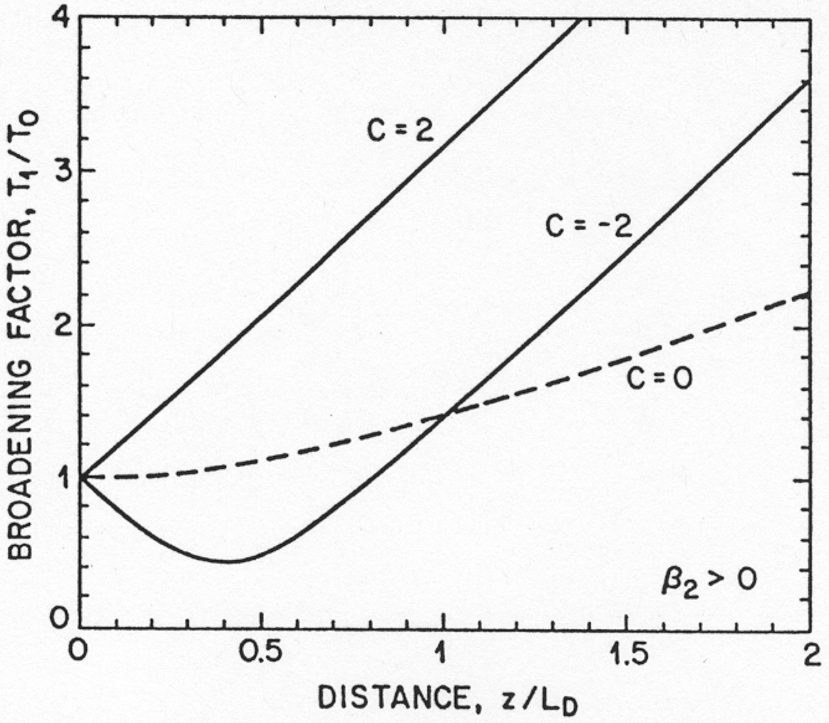
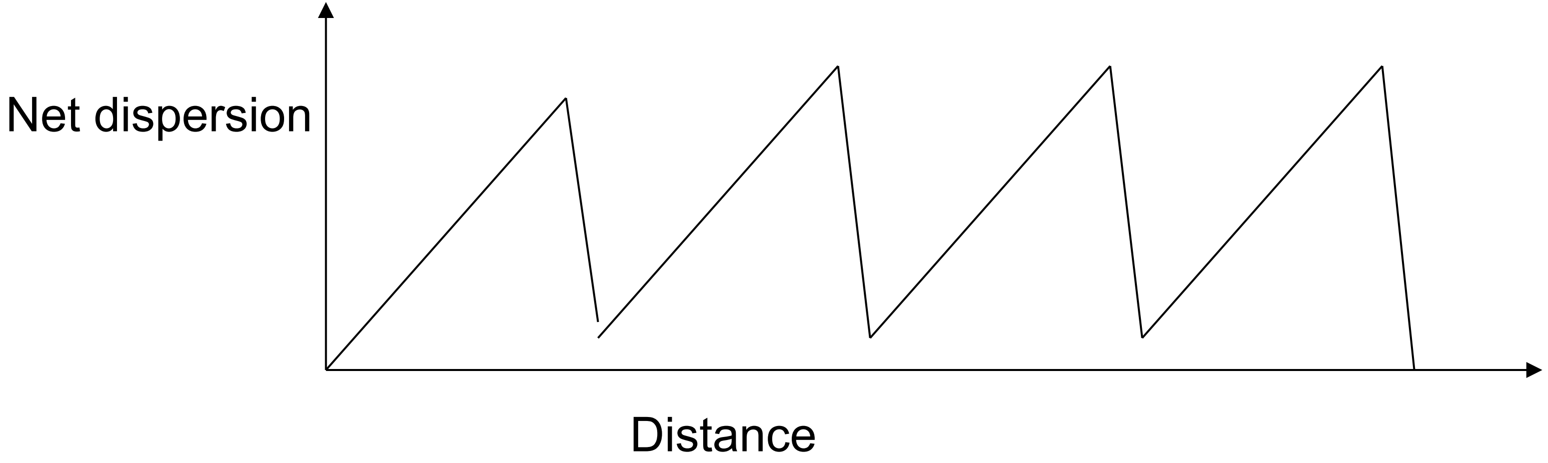


Figure 2.12: Variation of broadening factor with propagated distance for a chirped Gaussian input pulse. Dashed curve corresponds to the case of an unchirped Gaussian pulse. For $\beta_2 < 0$ the same curves are obtained if the sign of the chirp parameter C is reversed.

Dispersion Management

- We’ve discussed
  - Material dispersion
  - Waveguide dispersion
  - Modal dispersion
- Modal dispersion is solved by using single mode fiber.
- The fiber dispersion (material plus waveguide) is solved by dispersion management: Use low dispersion fiber and compensate at the end for zero total dispersion.



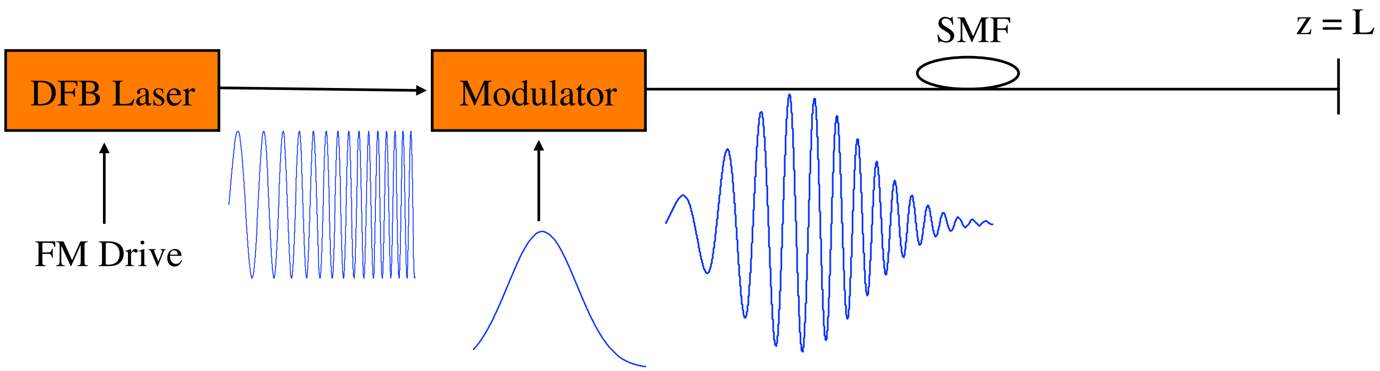
This can be repeated many times over a long distance. The final compensation amount differs for each wavelength.

Dispersion Compensation Motivation

- Optical amplifiers have removed optical loss as the primary limitation. Transmission system bit rates are now “Dispersion Limited”
- Operating at the zero dispersion wavelength is good for single channel but makes nonlinearities a primary limitation for WDM
- Dispersion accumulates over multiple fiber/amplifier spans
- Fiber nonlinear effects decreases when increasing the value of the dispersion parameter D
- The solution: find a way to have
  - high local dispersion along the link, to reduce nonlinear effect
  - Reduced dispersion effects
  - Approaches
    - Pre-chirp
    - Post compensation
    - Dispersion management

Dispersion Pre-Compensation

- **Pre-Chirping and Pulse Shaping:** Pre-distort the pulse so that dispersion produces a close to ideal pulse at the output of a fiber of length L with dispersion β_2. For example, prechirping the laser with parameter +C in a fiber with dispersion $-\beta_2$.

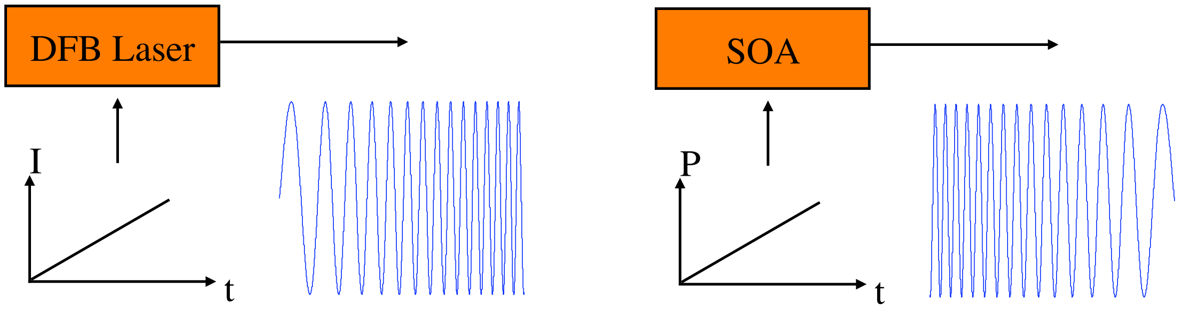


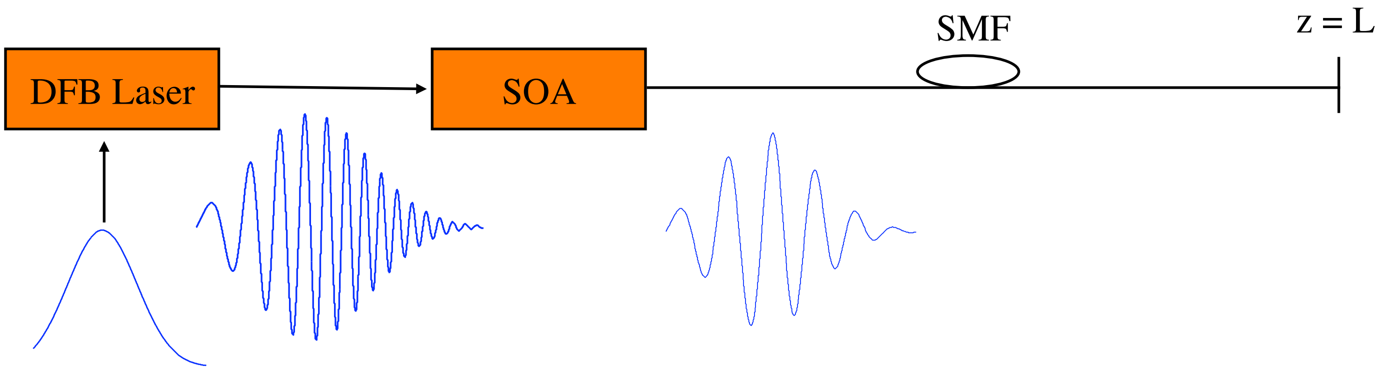
$$L = \frac{C + \sqrt{1+2C^2}}{1+C^2}\frac{T_0^2}{|\beta_2|}, \text{ for } \frac{T(L)}{T_0} = \sqrt{2} \quad ^{\dagger}$$

† G. P. Agrawal, Fiber Optic Communications Systems, Wiley-Interscience

Dispersion Pre-Compensation

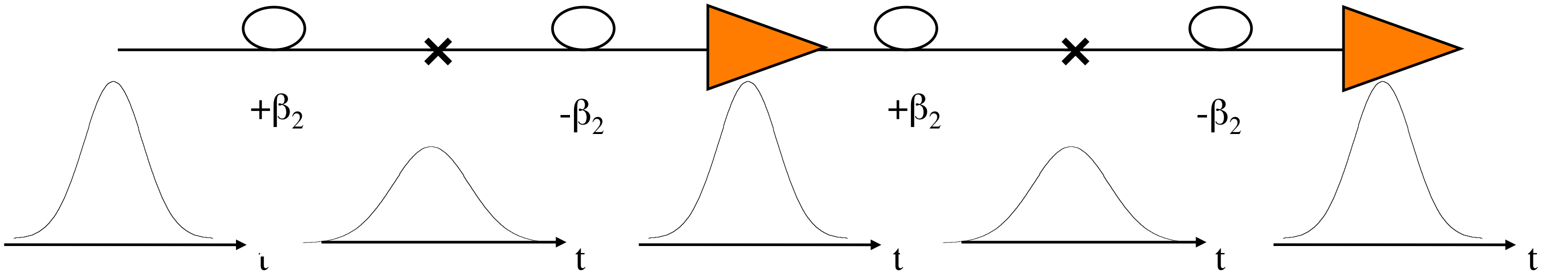
- **Optical Amplifier Induced Chirp:** The sign of chirp induced by directly modulating a semiconductor laser is opposite in sign to the chirp induced by a semiconductor optical amplifier on an input optical bit when operated in gain saturation.





Mid-Span Compensation

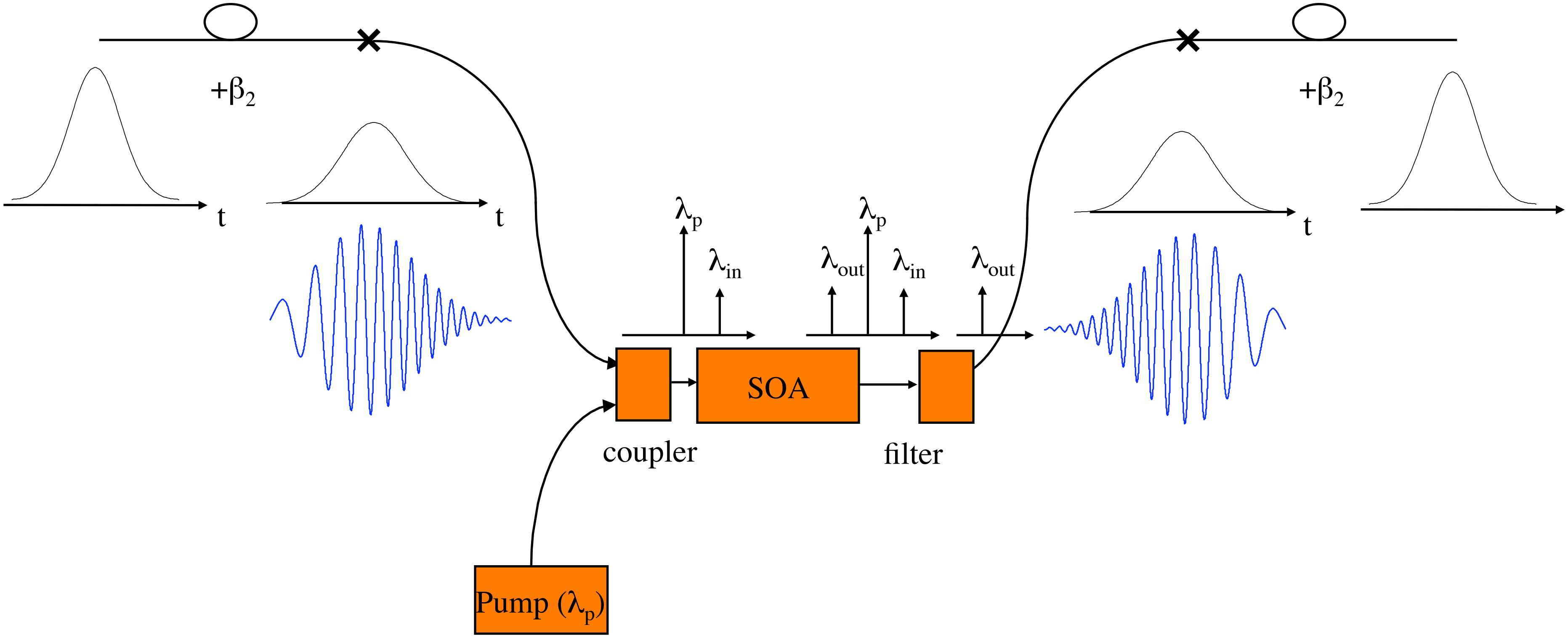
- Dispersion Management. Basic idea:
  - Alternating lengths of fiber with opposite dispersion sign with net zero dispersion at end of link.
- This was the initial approach, developed 5-6 years ago



- It was then realized that much better results in terms of nonlinearity reduction can be achieved by properly designed dispersion maps

Mid-Span Compensation

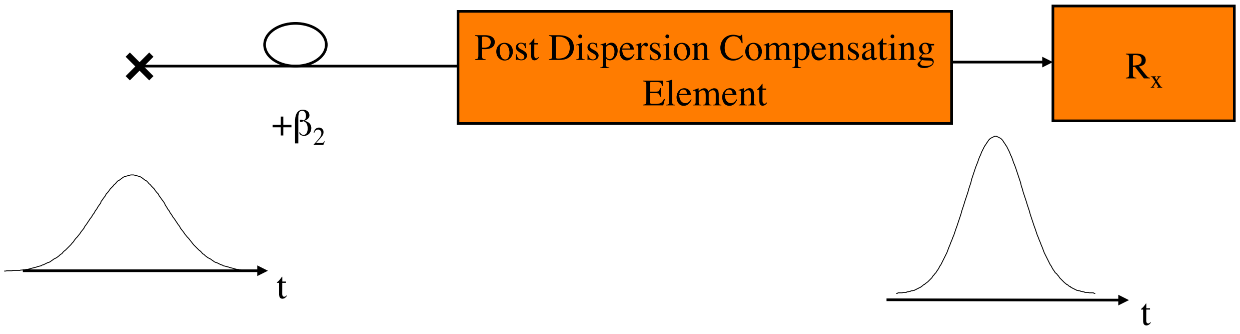
- Phase Conjugation via Four-Wave Mixing (FWM)



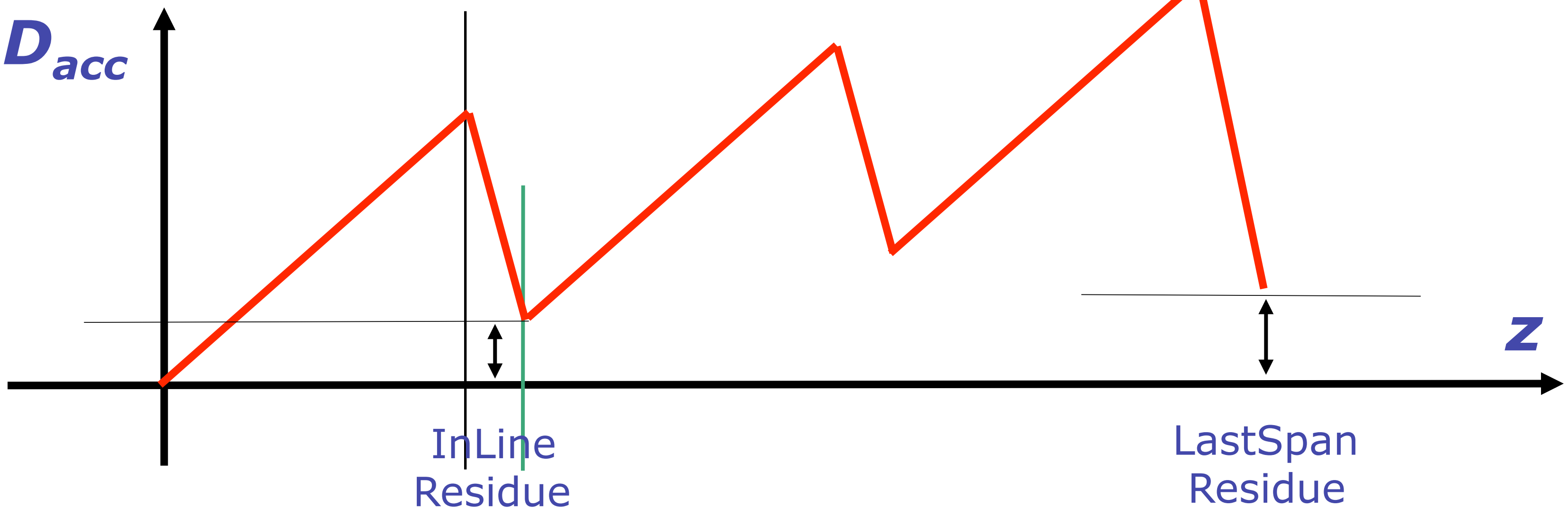
Post Compensation

- Dispersion is compensated at the end of the link, usually with a concentrated optical device, such as a suitable Bragg grating

  - High Dispersion Fibers
  - Optical Filters
  - Fiber Bragg Gratings



Dispersion management

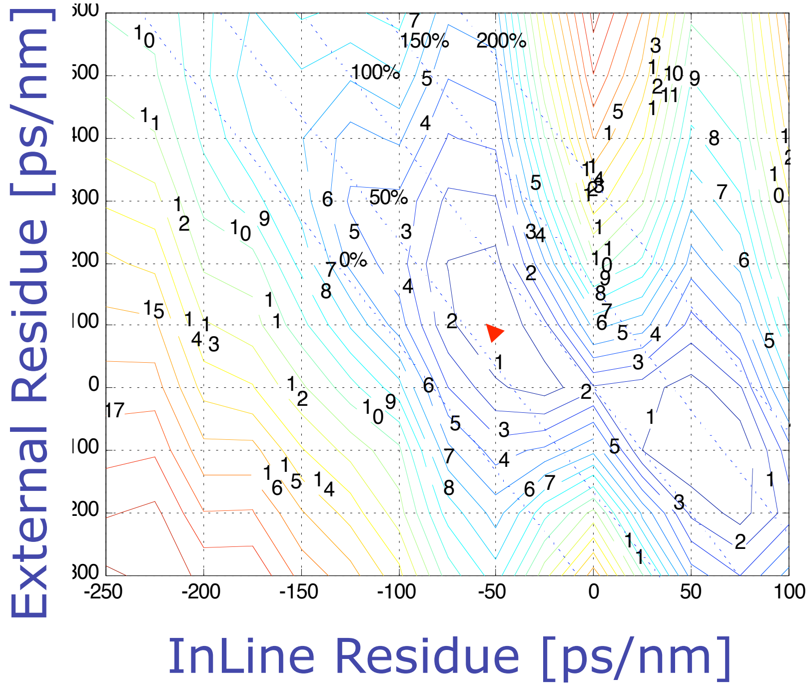


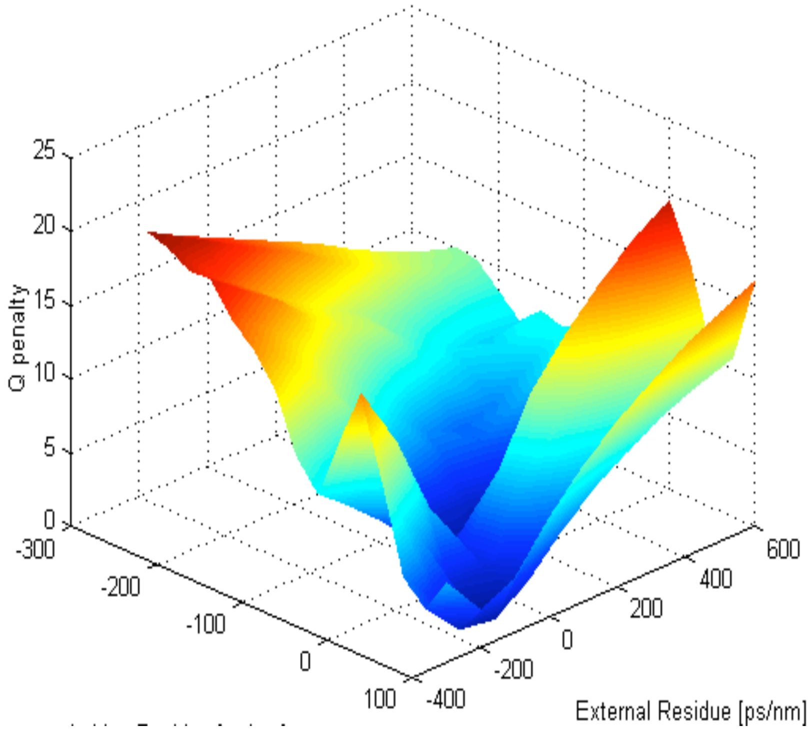
- Optimal dispersion maps are extremely difficult to be studied
- The optimization is usually performed by a mix of simulation and experiments

Dispersion maps

- ⇨ Optimization of the dispersion map of a 400 km long terrestrial systems
- ⇨ Results obtained using the commercial simulator OptSim

http://www.artis.it/products/home.html





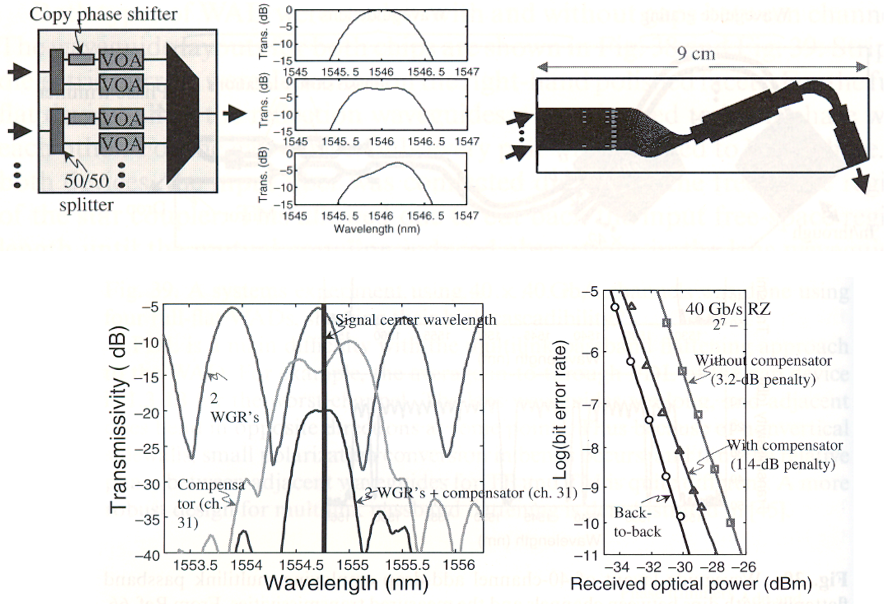
Optimal dispersion region

Dispersion Maps and Optical Networks

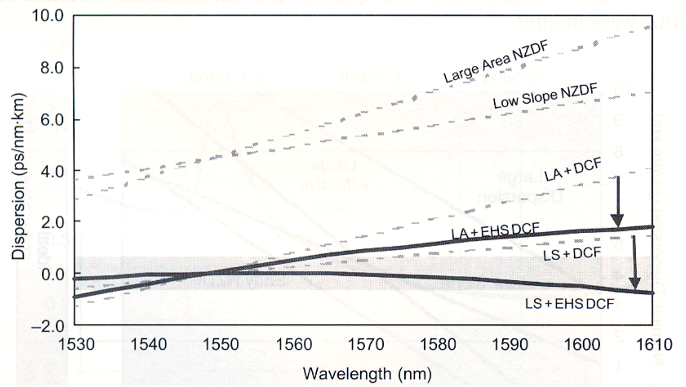
- Optimal dispersion map design yields closer to the ultimate fiber capacity of point-to-point systems
  - All transmission records uses (among other techniques) a careful choice of dispersion map
- In a reconfigurable all-optical networks, signals may follow different path, with different power levels
  - Dispersion optimization is even more complex
  - Several approaches are currently being studied
- Several research groups have studied electrical or optical adaptive receivers
  - Same technique as in electronic adaptive equalizing filters

Broadband Dispersion Compensation

- Since dispersion is wavelength dependent ($\beta_2(\lambda)$), compensation at one WDM channel may not be adequate at another channel
- Can use parallel bank of dispersion compensators (one for each channel)
- Can design a single broadband compensator



From Kaminow, page 452



From Kaminow, page 24