ECEN721: Optical Interconnects Circuits and Systems Spring 2024

Lecture 7: Transmitter Analysis

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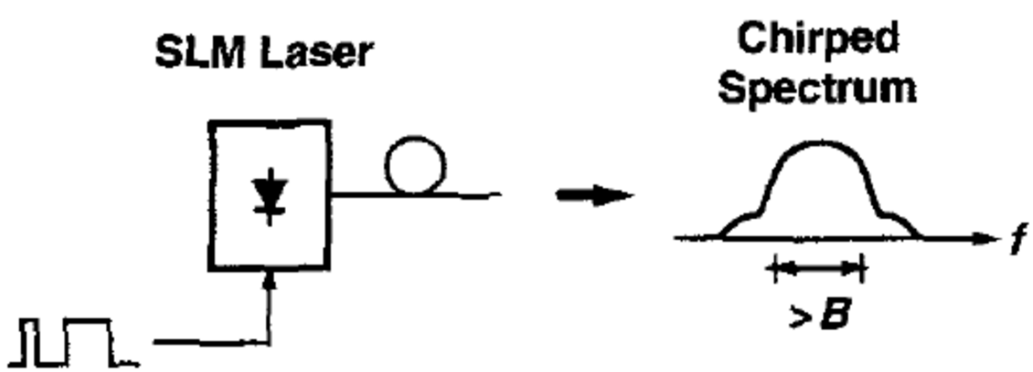
Announcements

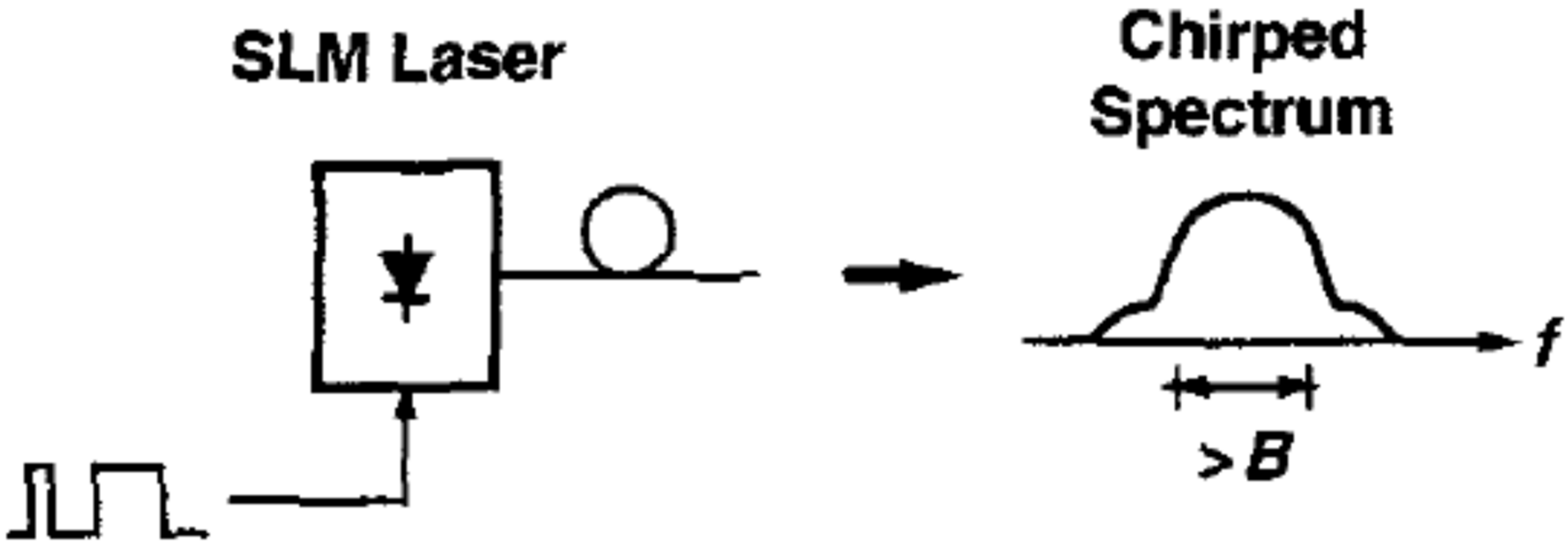
- Exam 1 Mar 7
  - In class
  - One double-sided 8.5x11 notes page allowed
  - Bring your calculator
  - Covers through Lecture 6
- Homework 3 is due Mar 21
- Reading
  - Sackinger Chapter 7

Optical Modulation Techniques

- Due to it's narrow frequency (wavelength) spectrum, a single-longitudinal mode (SLM) laser source often generates the optical power that is modulated for data communication
- Two modulation techniques
  - Direct modulation of laser
  - External modulation of continuous-wave (CW) "DC" laser with absorptive or refractive modulators

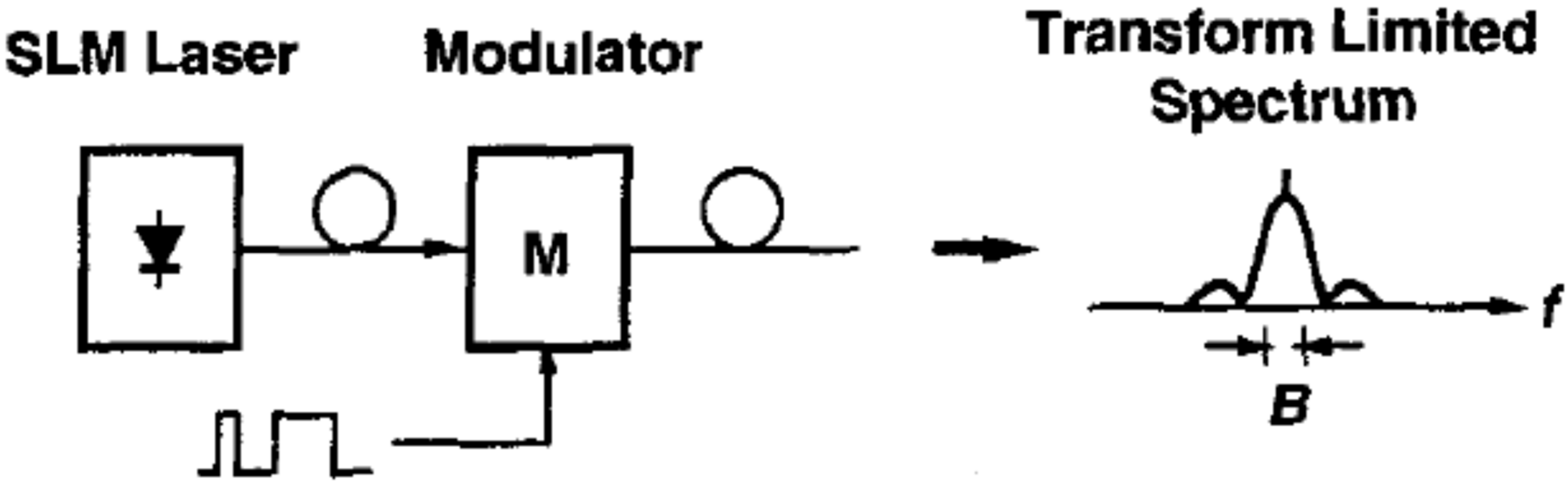


Directly Modulated Laser



- Directly modulating laser output power
- Simplest approach
- Introduces laser "chirp", which is unwanted frequency (wavelength) modulation
- This chirp causes unwanted pulse dispersion when passed through a long fiber

Externally Modulated Laser

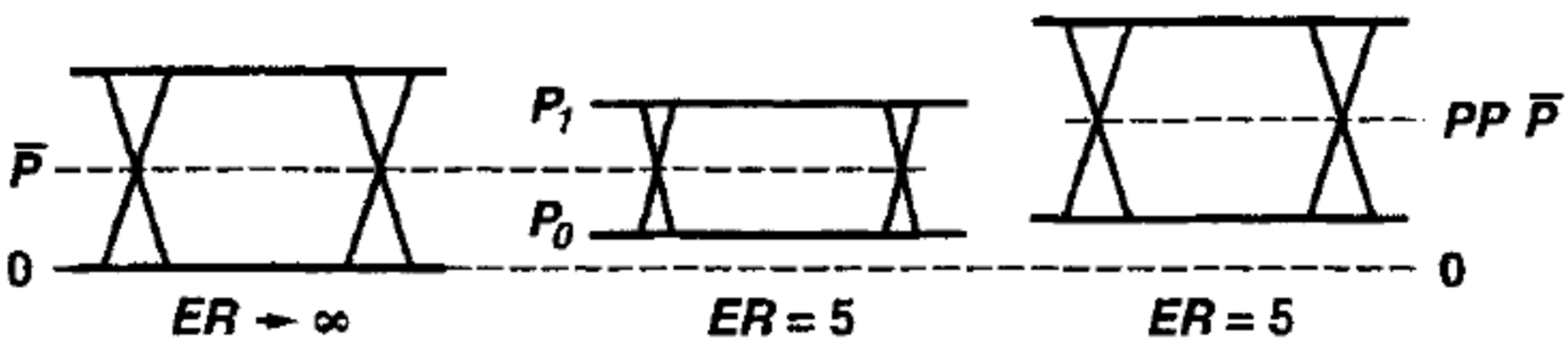


- External modulation of continuous-wave (CW) "DC" laser with absorptive or refractive modulators
  - Adds an extra component
  - Doesn't add chirp, and allows for a transform limited spectrum

Extinction Ratio

- In optical communication systems, a finite optical power is generally transmitted for a "zero" symbol due to
  - Laser turn-on delay below threshold current
  - External modulator non-idealities and driver voltage swing limitations
- The ratio between the "one", P_1, and "zero", P_0, power is the extinction ratio

$$\text{Extinction Ratio} \quad ER = \frac{P_1}{P_0}$$



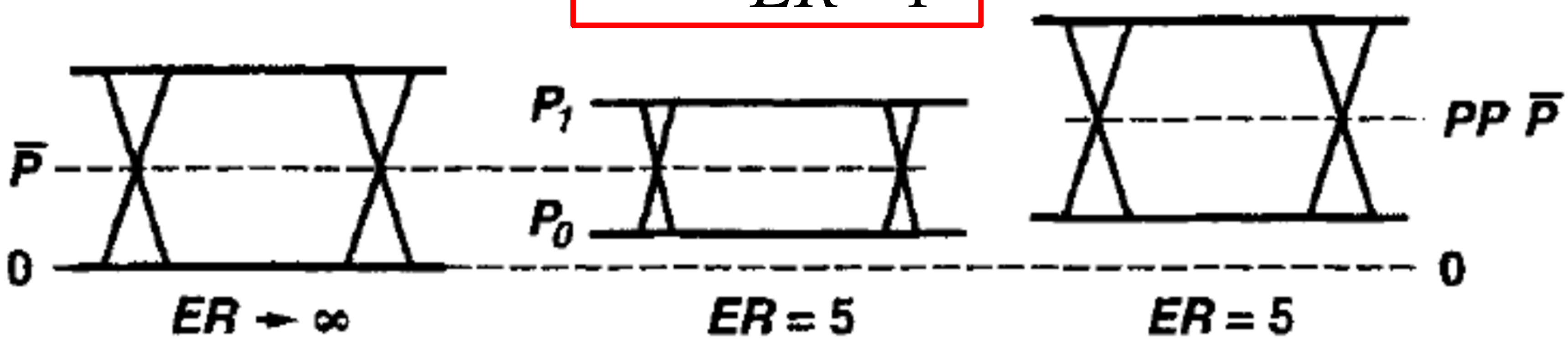
Extinction Ratio Power Penalty

- Optical receiver sensitivity is often specified in terms of the average optical power necessary for the target BER

$$\overline{P} = \left(P_1 + P_0\right)/2$$

- For the same average optical power, a finite extinction ratio reduces the signal swing that the receiver sees, which is what really determines the BER
- To restore the original signal swing, more average transmitted power is necessary, quantified by an extinction ratio power penalty

$$PP = \frac{ER+1}{ER-1}$$

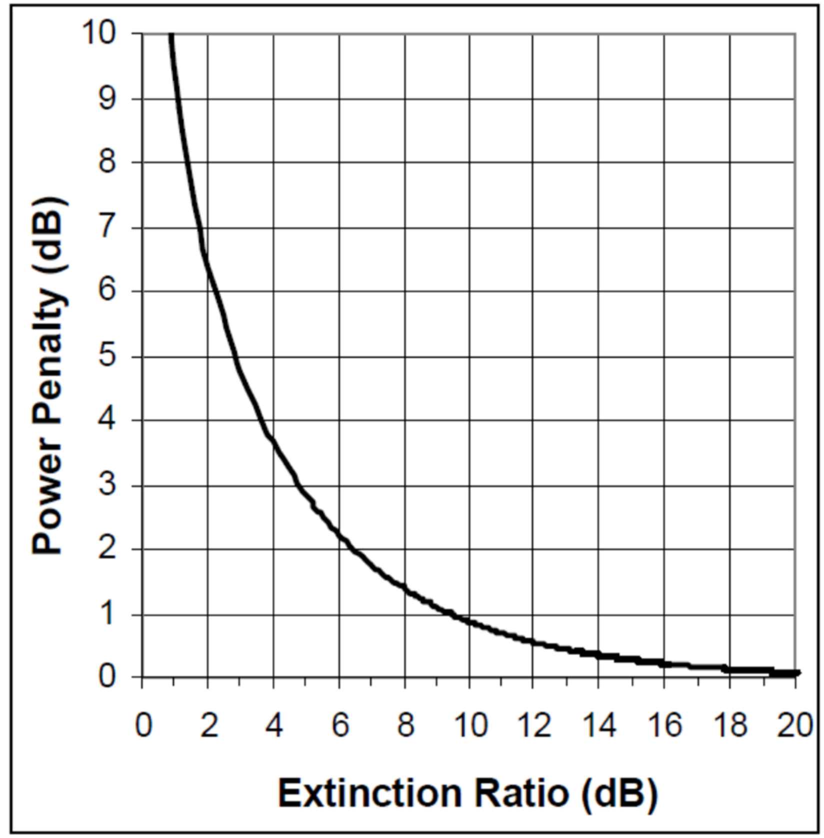


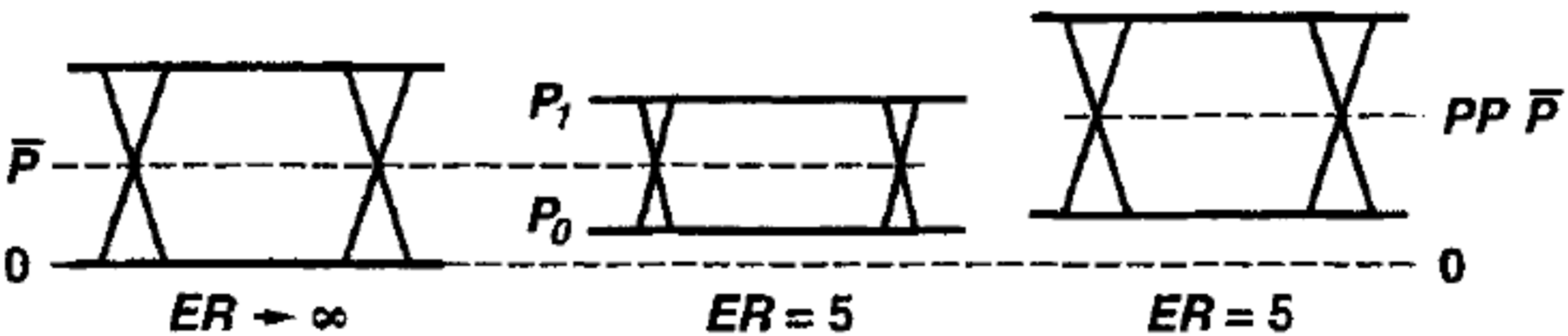
Extinction Ratio Power Penalty

$$PP = \frac{ER+1}{ER-1}$$

An $ER = 5$ (6.99dB) results in

$$\mathrm{PP} = \frac{5+1}{5-1} = 1.5 \;\; (1.76\mathrm{dB})$$





What About the Extra Zero-Level Noise?

- Note the that the most commonly used extinction ratio power penalty expression neglects the increased zero level noise, which is OK for p-i-n receivers

$$PP = \frac{ER+1}{ER-1}$$

- However, if we have an APD or optical amplifier in the system the power penalty will be larger
- In the limit where the detector noise dominates over the amplifier noise the power penalty becomes much worse

$$PP = \left(\frac{\sqrt{ER}+1}{\sqrt{ER}-1}\right)\left(\frac{ER+1}{ER-1}\right)$$

Average Power vs Optical Modulation Amplitude (OMA) Sensitivity

- If we specify receiver sensitivity as an average power quantity, then the extinction ratio power penalty must be calculated in link budgeting
- Another approach is to specify receiver sensitivity in terms of optical modulation amplitude (OMA)

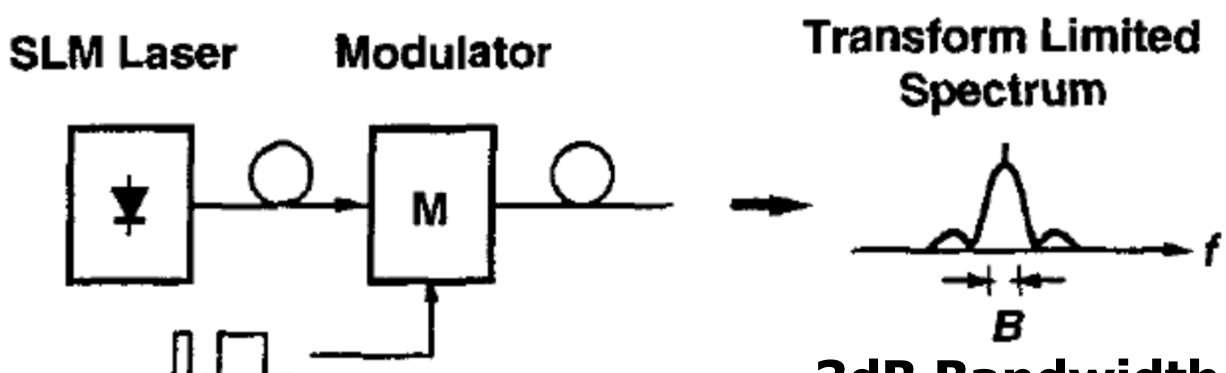
$$OMA = P_1 - P_0$$

- This ideally obviates any extinction ratio penalty in the case of constant noise
- As data rate rise and lower extinction ratios are in use, more systems are specifying receiver sensitivity in terms of OMA

Spectral Linewidth

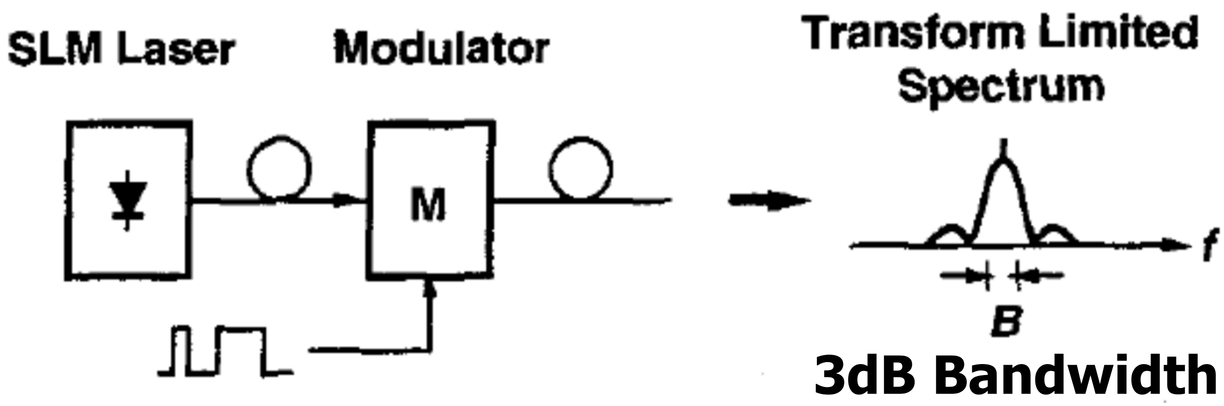
- An ideal optical TX consisting of a monochromatic laser and perfect intensity modulator produces a signal with an ideal AM spectrum
  - Carrier wavelength plus two sidebands

- The commonly-used baseband NRZ signaling has a sinc^2 shape with full 3dB-bandwidth of ~B and a distance between the first two nulls of 2B



3dB Bandwidth

Transform Limited Pulses



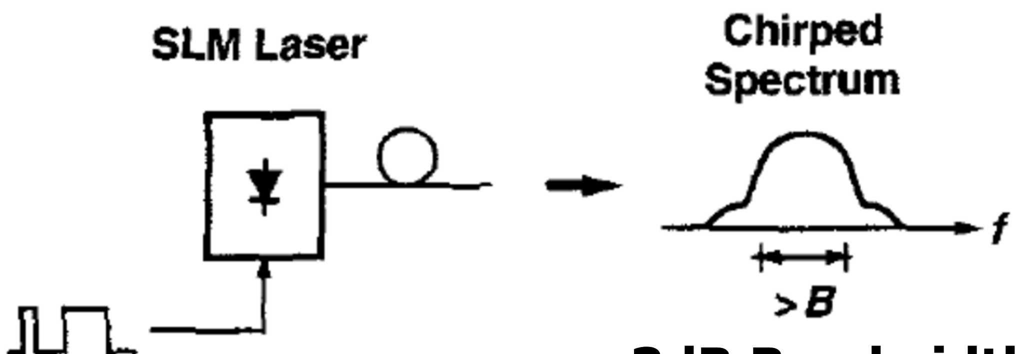
- In this ideal modulation case, we have what are called transform limited pulses
- The optical spectral linewidth can be computed as

$$\Delta\lambda = \frac{\lambda^2}{c}\Delta f \approx \frac{\lambda^2}{c}B$$

10Gb/s modulation in a 1550nm system produces the following transform - limited spectral linewidth

$$\Delta\lambda = \frac{(1550nm)^2}{3\times10^8 \frac{m}{s}}(10GHz) = 80\,pm$$

Chirp



3dB Bandwidth

- Most real transmitters also have additional unwanted frequency modulation called chirp
- The linewidth in this case can be approximated as

$$\Delta\lambda \approx \frac{\lambda^2}{c} B\sqrt{\alpha^2 + 1}$$

where α is the *chirp parameter* or *linewidth enhancement factor*.

10Gb/s modulation in a 1550nm system with $\alpha = 4$ produces the following spectral linewidth

$$\Delta\lambda \approx \frac{(1550nm)^2}{3\times10^8 \frac{m}{s}}(10GHz)\sqrt{4^2+1} = 330\,pm$$

Source-Limited Linewidth

- The previous two cases of transform-limited and chirp-limited linewidth assumed that the laser had a much smaller linewidth than the modulation signal
- Single-longitudinal mode (single-mode) lasers can satisfy this condition
- However, many systems use multiple-longitudinal mode (multi-mode) lasers where the linewidth (>1nm) can be much wider than the modulation
- Here the TX linewidth is simply approximated by the linewidth of the unmodulated source $\Delta\lambda_S$

$$\Delta\lambda \approx \Delta\lambda_S$$

Chromatic Dispersion Limits: Transform-Limited Pulses

- We try and limit the chromatic dispersion spreading of Gaussian pulses to

$$\Delta T = |D| \cdot \Delta\lambda \cdot L \le \frac{1}{2B}$$

$$L \le \frac{1}{2|D| \cdot \Delta\lambda \cdot B}$$

- For the transform-limited pulses case $$L \le \frac{c}{2|D| \cdot \lambda^2 \cdot B^2}$$

- However, given the nonlinear communication channel, this is only an approximation. A more useful expression for 1dB dispersion penalty (1550nm) is

$$L \le \frac{17\, ps/(nm \cdot km)}{|D|} \frac{6000 (Gb/s)^2}{B^2} \text{ km}$$

- Transmission distance decreases as $1/(B^2)$

Chromatic Dispersion Limits: Chirped Pulses

- If we have a transmitter with chirp, then the linewidth increases and the maximum distance reduces

$$L \le \frac{c}{\sqrt{\alpha^2+1} \cdot 2|D| \cdot \lambda^2 \cdot B^2}$$

- Again, given the nonlinear communication channel, this is only an approximation. A more useful expression for 1dB dispersion penalty (1550nm) is

$$L \le \frac{1}{\sqrt{\alpha^2+1}} \cdot \frac{17\,ps/(nm \cdot km)}{|D|} \cdot \frac{6000(Gb/s)^2}{B^2} \ \text{km}$$

- Transmission distance decreases as $1/(B^2)$

Chromatic Dispersion Limits: Source-Limited Linewidth

- If the optical source's linewidth is much wider than the modulation bandwidth, the maximum length is

$$L \leq \frac{1}{2|D| \cdot \Delta\lambda_S \cdot B}$$

- Now the transmission distance only decreases as 1/(B)

Table 7.1 Maximum (unrepeatered) transmission distances over an SMF at 1.55 μm for various transmitter types based on Eqs. (7.19), (7.18), and (7.16) with $D = 17$ ps/(nm · km).

Transmitter Type	2.5 Gb/s	10 Gb/s	
Fabry-Perot laser ($\Delta\lambda = 3$ nm)	4 km	1 km	Source-Limited
Distributed feedback laser ($\alpha = 4$)	230 km	15 km	Chirped-Pulses
External modulator ($\alpha = 0$)	960 km	60 km	Transform-Pulses

Optical Sources for Chip-to-Chip Links

- Vertical-Cavity Surface-Emitting Laser (VCSEL)
- Mach-Zehnder Modulator (MZM)
- Electro-Absorption Modulator (EAM)
- Ring-Resonator Modulator (RRM)