

# ECEN689: Special Topics in Optical Interconnects Circuits and Systems

## Spring 2022

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### Lecture 7: Transmitter Analysis



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# Announcements

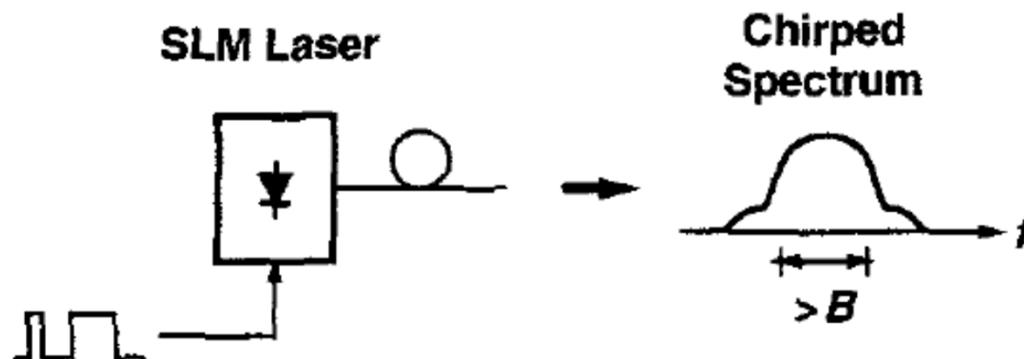
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- Homework 3 is due Mar 31
- Reading
  - Sackinger Chapter 7

# Optical Modulation Techniques

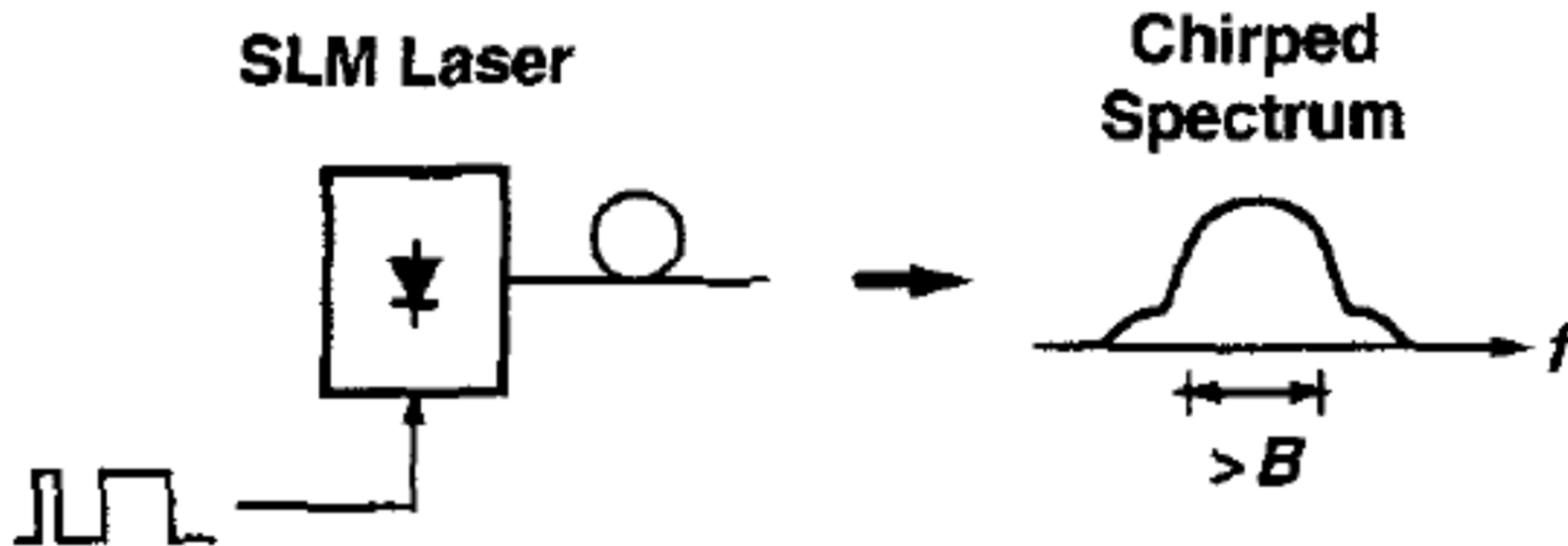
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- Due to its narrow frequency (wavelength) spectrum, a single-longitudinal mode (SLM) laser source often generates the optical power that is modulated for data communication
- Two modulation techniques
  - Direct modulation of laser
  - External modulation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



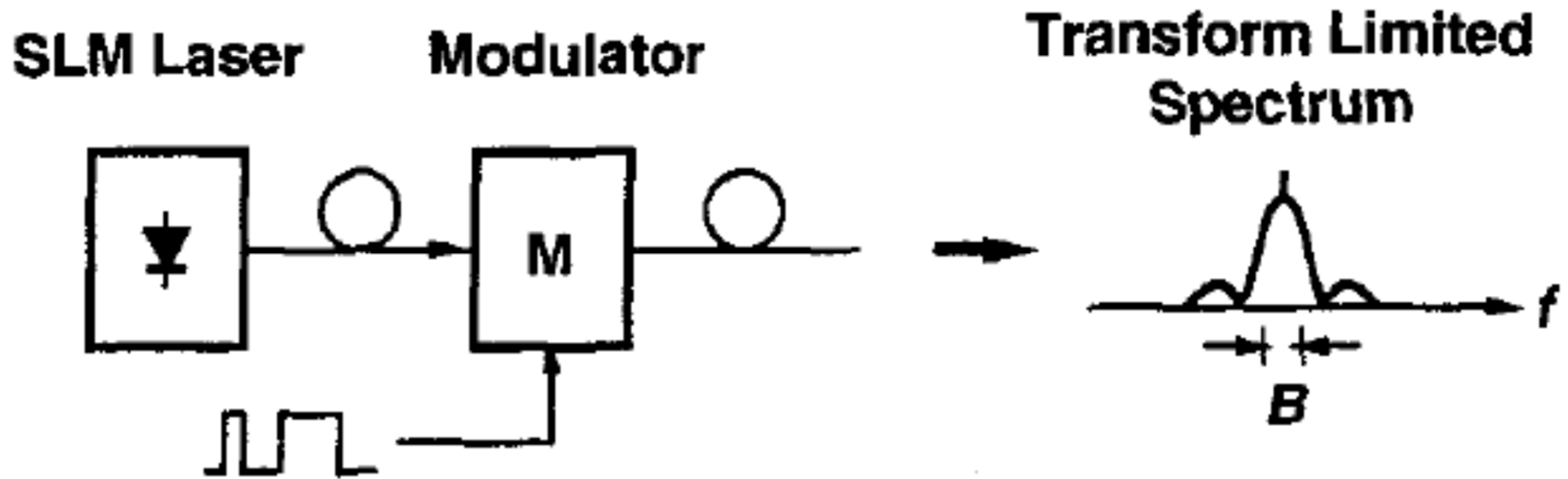
# Directly Modulated Laser

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- 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

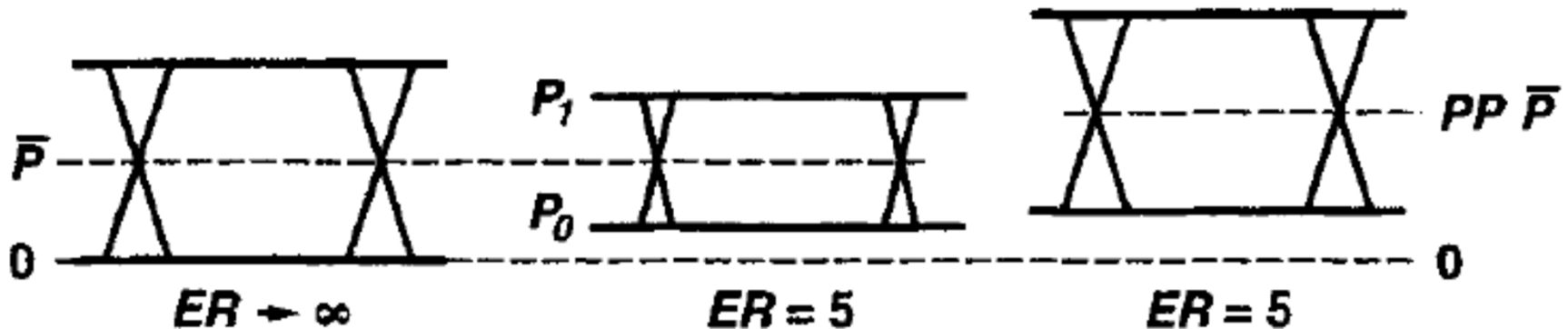


- External modulation of continuous-wave (CW) "DC" laser with absorptive or refractive modulators
  - Adds an extra component
  - Doesn't add chirp, and allows for a transform limited spectrum

# 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

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



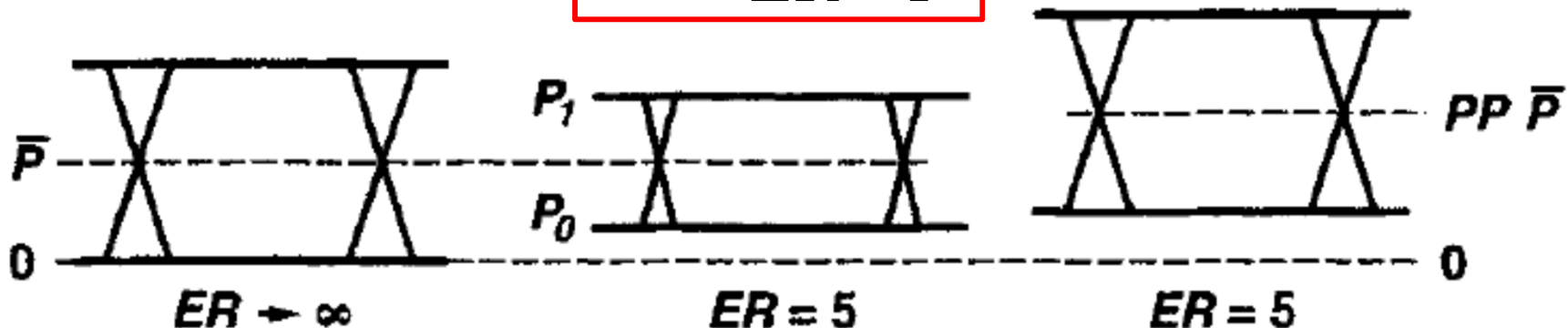
# Extinction Ratio Power Penalty

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

$$\bar{P} = (P_1 + P_0)/2$$

- 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

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

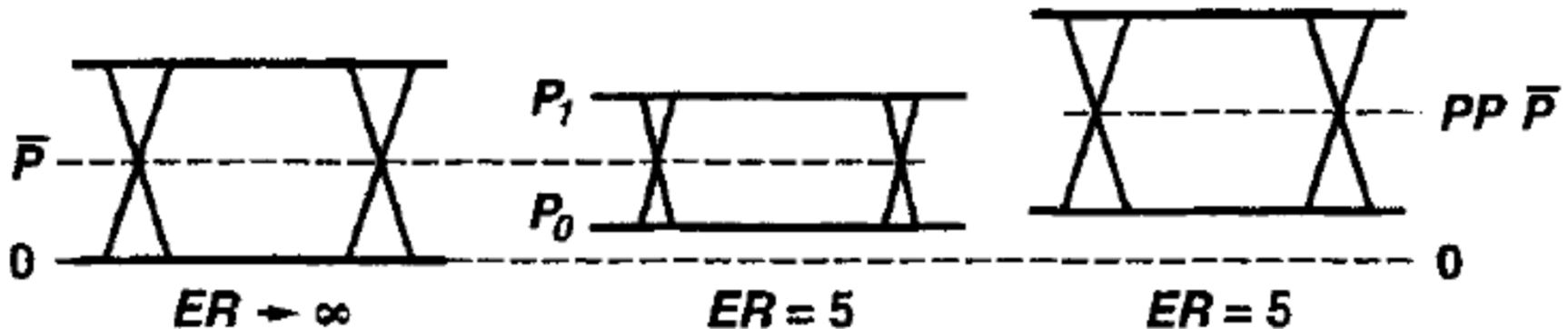
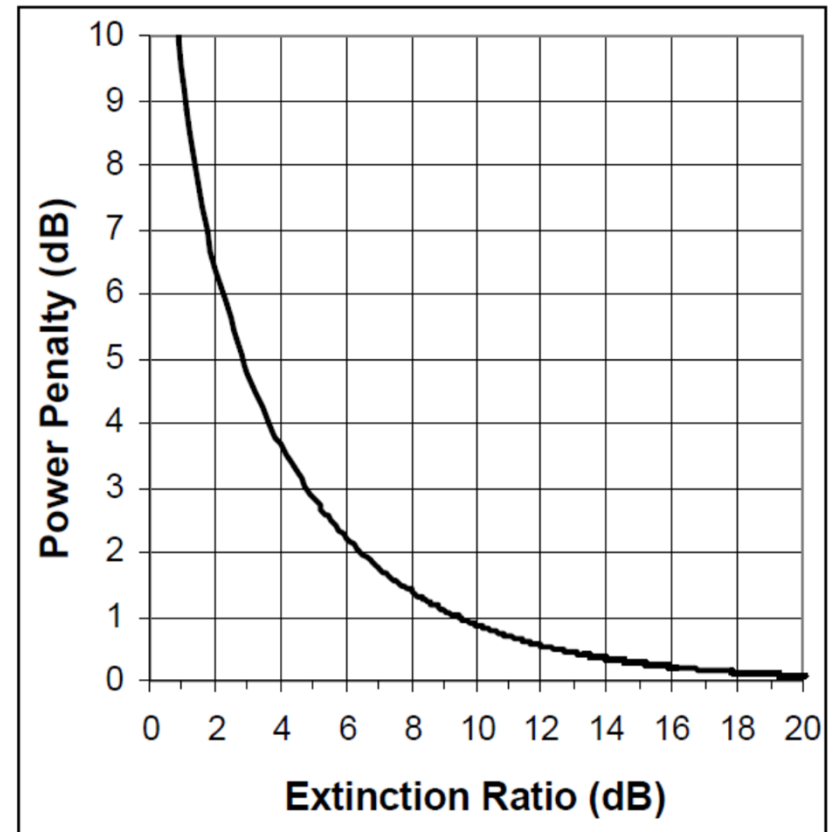


# Extinction Ratio Power Penalty

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

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

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





# What About the Extra Zero-Level Noise?

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- Note 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

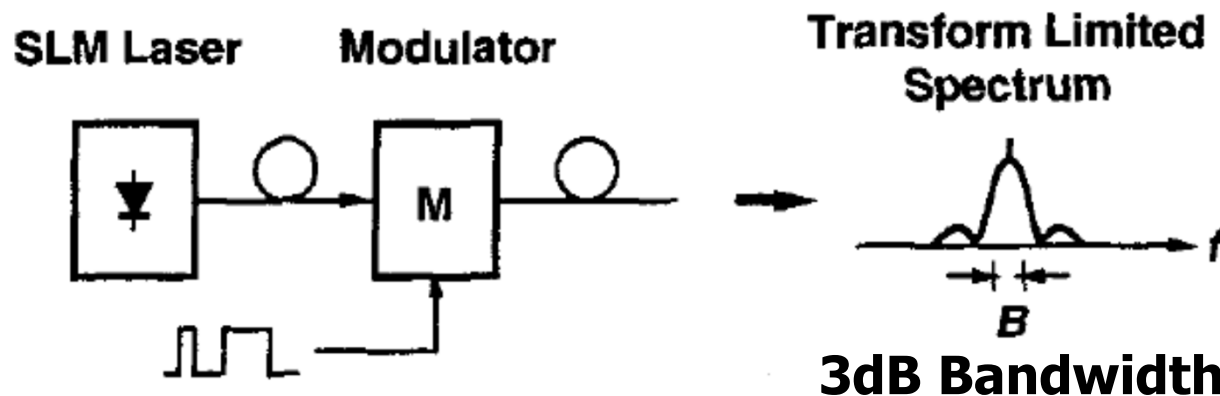
- If we specify receiver sensitivity as an average power quantity, then the extinction ratio power penalty must be calculated in link budgeting
- Another approach is to specify receiver sensitivity in terms of **optical modulation amplitude (OMA)**

$$OMA = P_1 - P_0$$

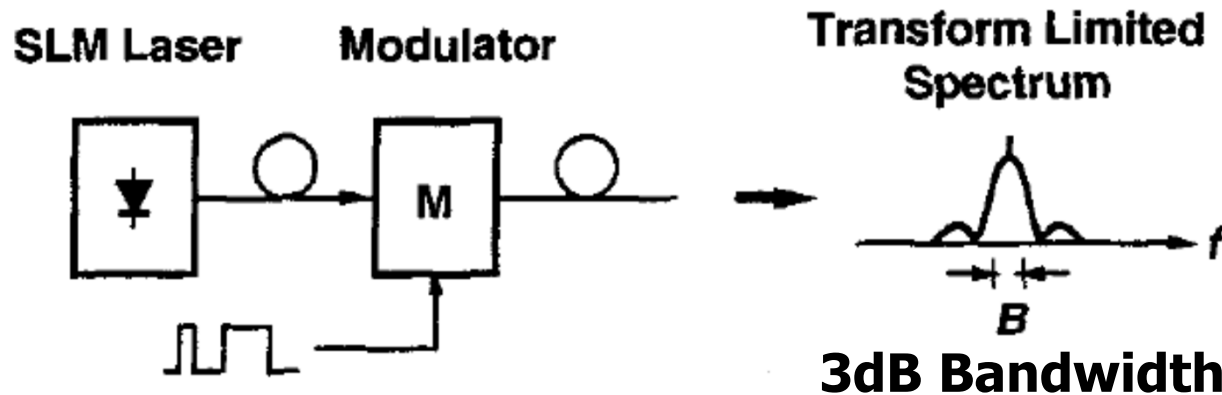
- This ideally obviates any extinction ratio penalty in the case of constant noise
- As data rate rise and lower extinction ratios are in use, more systems are specifying receiver sensitivity in terms of OMA

# 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  $\text{sinc}^2$  shape with full 3dB-bandwidth of  $\sim B$  and a distance between the first two nulls of  $2B$



# Transform Limited Pulses



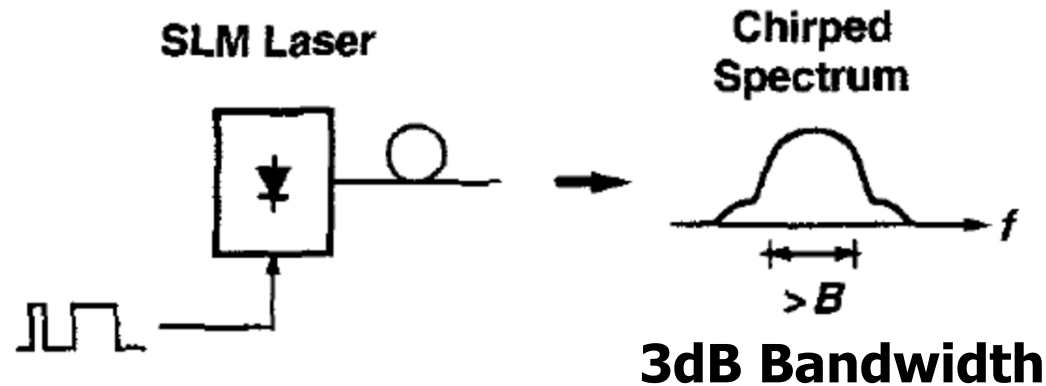
- In this ideal modulation case, we have what are called **transform limited pulses**
- The optical spectral linewidth can be computed as

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

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

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

# Chirp



- 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  $\alpha$  is the *chirp parameter* or *linewidth enhancement factor*.

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

following spectral linewidth

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

# Source-Limited Linewidth

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- 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 ( $>1\text{nm}$ ) 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

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

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

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

- For the transform-limited pulses case  $L \leq \frac{c}{2|D| \cdot \lambda^2 \cdot B^2}$
- However, given the nonlinear communication channel, this is only an approximation. A more useful expression for 1dB dispersion penalty (1550nm) is

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

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

# Chromatic Dispersion Limits: Chirped Pulses

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

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

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

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

- 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 (unrepeated) transmission distances over an SMF at  $1.55 \mu\text{m}$  for various transmitter types based on Eqs. (7.19), (7.18), and (7.16) with  $D = 17 \text{ ps}/(\text{nm} \cdot \text{km})$ .

Transmitter Type	2.5 Gb/s	10 Gb/s	
Fabry-Perot laser ( $\Delta\lambda = 3 \text{ nm}$ )	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

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