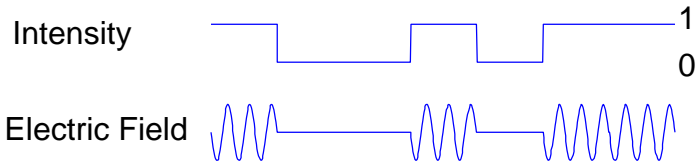
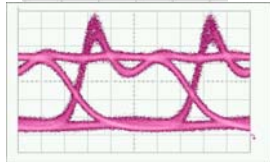
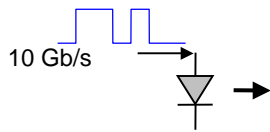


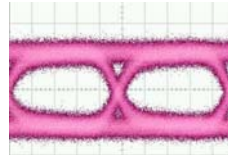
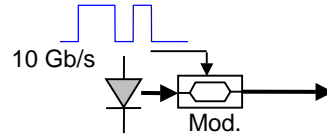
Conventional On-Off Keying



- **Direct Modulation**



- **External Modulation**



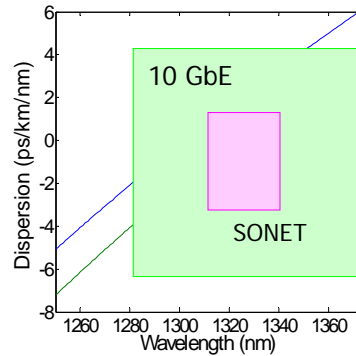
Single-Mode Fiber: 1310 nm

- **Direct-Modulation**
 - Uncooled FP Laser (3 ps/nm)
 - 600 m or 3 km
 - Limited by dispersion and mode partition noise
 - Uncooled or cooled DFB laser (340 ps/nm)
 - Up to 80 km
 - Limited by dispersion and fiber loss
- **Electro-Absorption Modulated Laser (EML)**
 - Up to 80 km
 - Limited by fiber loss

Dispersion @ 1310 nm

Fiber (SMF-28)

- Zero dispersion wavelength
 - $1302 < \lambda_0 < 1322$ nm
 - Zero dispersion slope
 - $S_0 = 0.092$ ps/nm²/km
- Wavelength**
- 1260 to 1355 nm (10 GbE)
 - 1260 to 1360 nm (OIF)
 - 1290 to 1320 nm (GR-253)



Mode-Partition Noise

- Two-mode laser

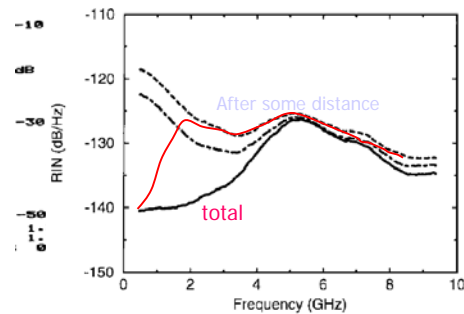
$$\alpha_1 + \alpha_2 = 1 + n$$

$$\alpha_1 = \frac{1}{2} + n_1 + n_c$$

$$\alpha_2 = \frac{1}{2} + n_2 - n_c$$

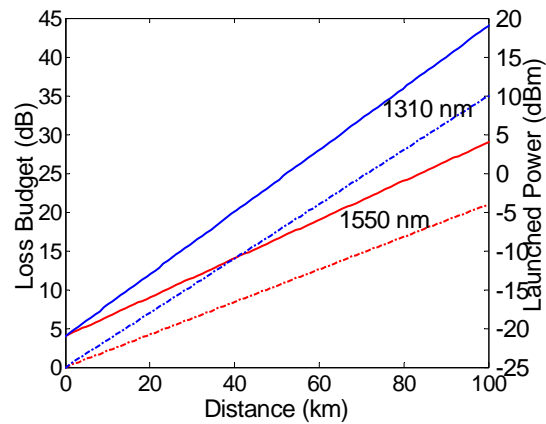
- With dispersion

$$1 + n_c(t) - n_c(t - \tau)$$



Fiber Loss

- 1550 nm
 - Lab: 0.21 dB/km
 - Field: 0.25 dB/km
 - Extra: 4 dB
- 1310 nm
 - Lab: 0.35 dB/km
 - Field: 0.40 dB/km
 - Extra: 4 dB



Beyond 40 km

- Optical Amplifiers
 - Semiconductor optical amplifier (SOA)
 - Must be Linear SOA
- Wavelength Control
 - DFB, fixed temperature

Outline

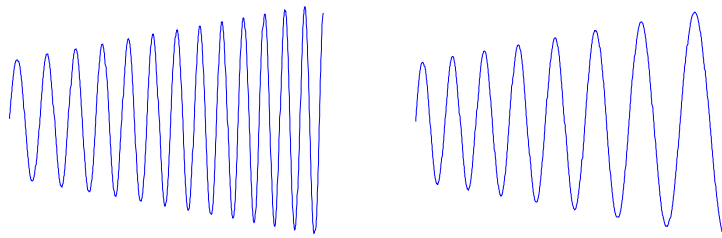
- Current Standards
- Multimode Fiber
- Single Mode Fiber: 1310 nm
- **Single Mode Fiber: 1550 nm**

Single-Mode Fiber: 1550 nm

- Dispersion coefficient of 17 ps/km/nm
- Direct-Modulation
 - FP Laser (3 ps/nm)
 - 300 m
 - DFB laser (340 ps/nm)
 - Up to 20 km (higher for low-chirp DFB)
- Electro-Absorption Modulated (EAM) Laser
 - 20 or 40 km (80 km for low chirp EAM)
- LiNbO₃ Modulator
 - Up to 80 km

Frequency Chirp

- Positive Chirp
 - Frequency **increase** with intensity
 - Wavelength **decrease** with intensity
- Negative Chirp
 - Frequency **decrease** with intensity
 - Wavelength **increase** with intensity



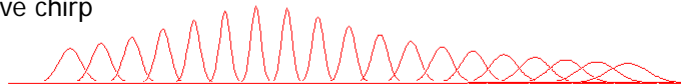
Effects of chirp

Positive Dispersion Coefficient

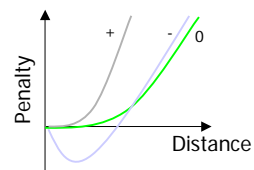
Positive chirp



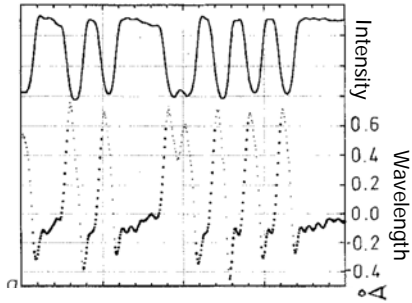
Negative chirp



Laser: Positive chirp ($\alpha \sim 3$ to 4)
EAM: Small variable chirp ($\alpha \sim -2$ to $+1$)
MZ Mod.: Fixed chirp ($\alpha \sim -1$ to $+1$)

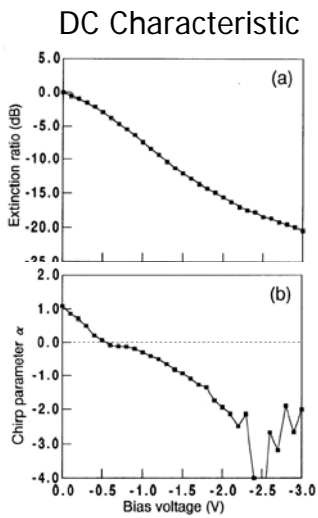


Chirp of DFB Laser

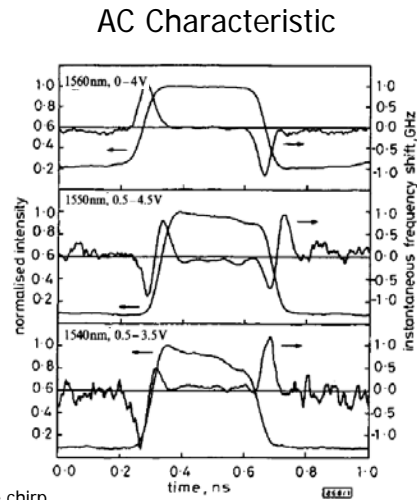


Positive chirp ($\alpha \sim 3$ to 4)
 Almost fixed chirp coefficient
 Large dispersion penalty
 Short distance

Chirp of Electro-Absorption Modulator (EAM)



Small variable chirp
 ($\alpha \sim -2$ to $+1$)



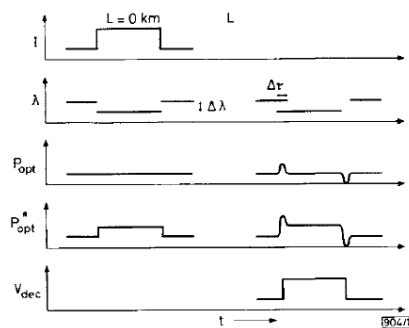
Simple Solution: New Fiber

- Dispersion-shifted fiber
 - More than 300 km
- MetroCor fiber
 - 300 km or up for direct-modulated laser

Chung *et al.* PTL, 9/03 and Jinno *et al.* PTL, 3/98.

Dispersion-Supported Transmission

- Direct FSK Modulation



Phase-mod. to Intensity-mod. conversion

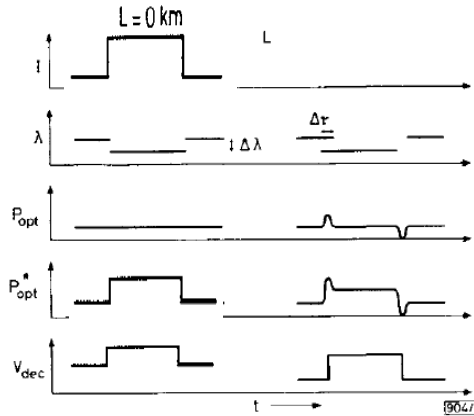
250 km of fiber

Very bad extinction ratio at short distance

Just good for certain distance

Wedding, EL, July 92.

Dispersion-Supported Intensity Modulation



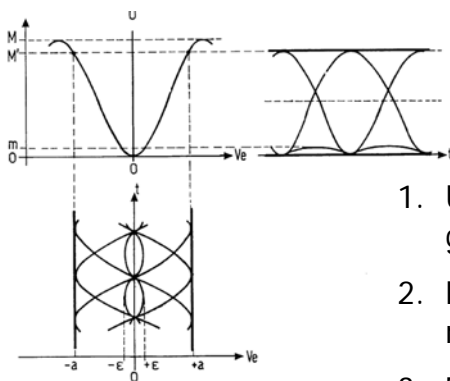
Goal: 80 km

Problems:

Bad Extinction Ratio @ 0 km

Duobinary Modulation

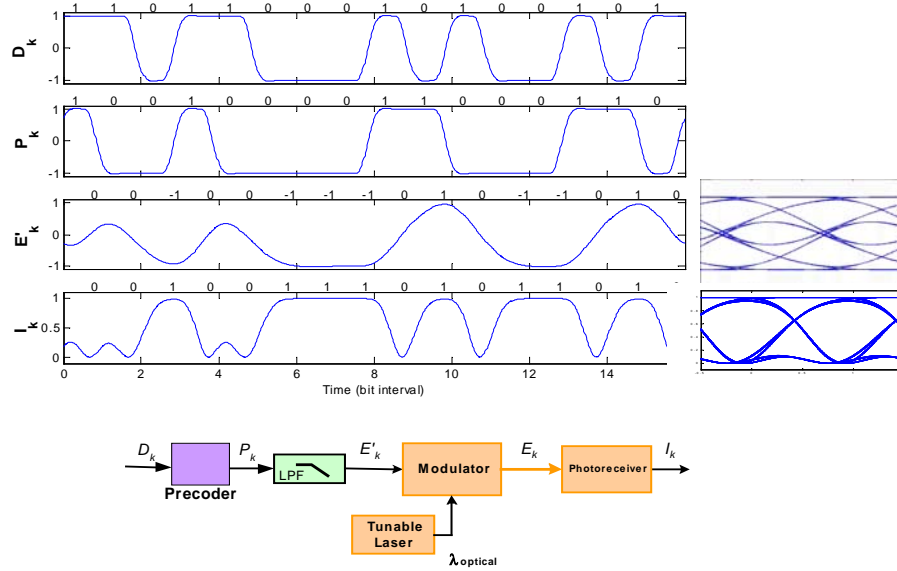
Operation of Modulator



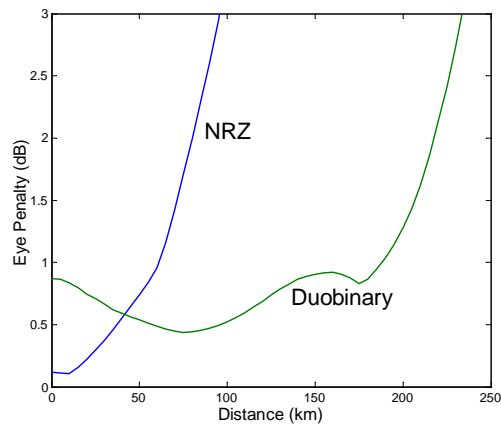
1. Using a low-pass filter to generate 3-level signal
2. Biased the modulator at minimum transmitted point.
3. Modulator converts 3-level signal to binary signal.

Price et al. US 5,867,534

Operation of the duobinary transmitter



Duobinary Modulation Dispersion Tolerance



Distance of ~200 km
Compared with ~60 km
of NRZ

Duobinary/polarization modulation

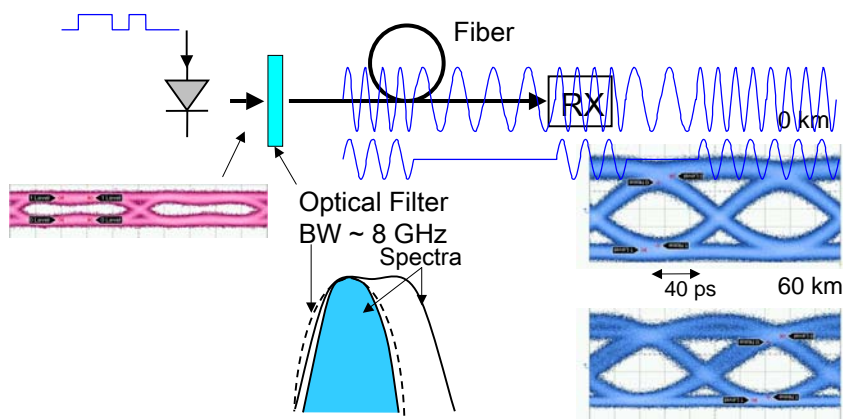
Duobinary



Duobinary/polarization



Recently Invented Low-Cost Transmitter FSK/OOK Conversion



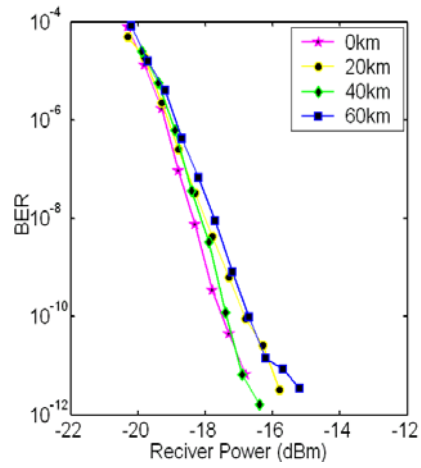
Conventional direct-modulation

- Limited by frequency chirp
- Distance to only 20 km

FSK to OOK conversion

- Reduced semiconductor laser chirp
- High dispersion tolerance

Low-Cost Transmitter BER Measurement



Up to **60 km**
Penalty ~ 1 dB
Conventional scheme:
~20 km