Optical Communication Systems (OPT428)

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▶
Back
Close

Course Outline

- Introduction
- Optical Signal Generation
- Signal Propagation in Fibers
- Nonlinear Impairments in Fibers
- Signal Recovery and Bit Error Rate
- Loss Management: Optical Amplifiers
- Dispersion Management Techniques
- Nonlinearity Management Techniques
- Multichannel Lightwave Systems
- Optical Networks

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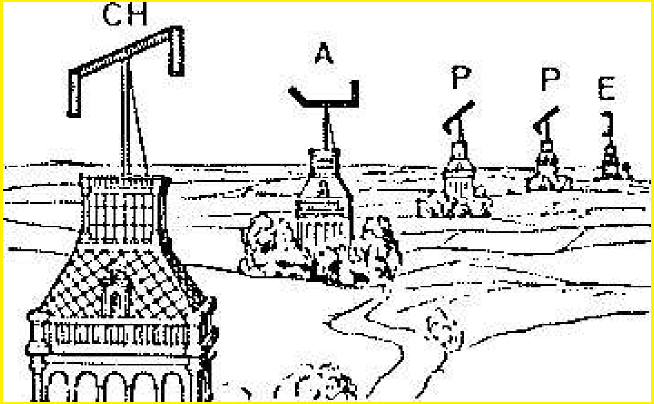
Back
Close

Historical Perspective

- Smoke signals; $<$1500
- Semaphore Devices; 1500-1800
- Mechanical Coding (Chappe); 1792



Back
Close

Historical Perspective

Electrical Era		Optical Era	
Telegraph;	1836	Optical Fibers;	1978
Telephone;	1876	Optical Amplifiers;	1990
Coaxial Cables;	1840	WDM Technology;	1996
Microwaves;	1948	Multiple bands;	2002

- Microwaves and coaxial cables limited to $B \sim 100$ Mb/s.
- Optical systems can operate at bit rate $>$10 Tb/s.
- Improvement in system capacity is related to the high frequency of optical waves ($\sim$200 THz at 1.5 μm).

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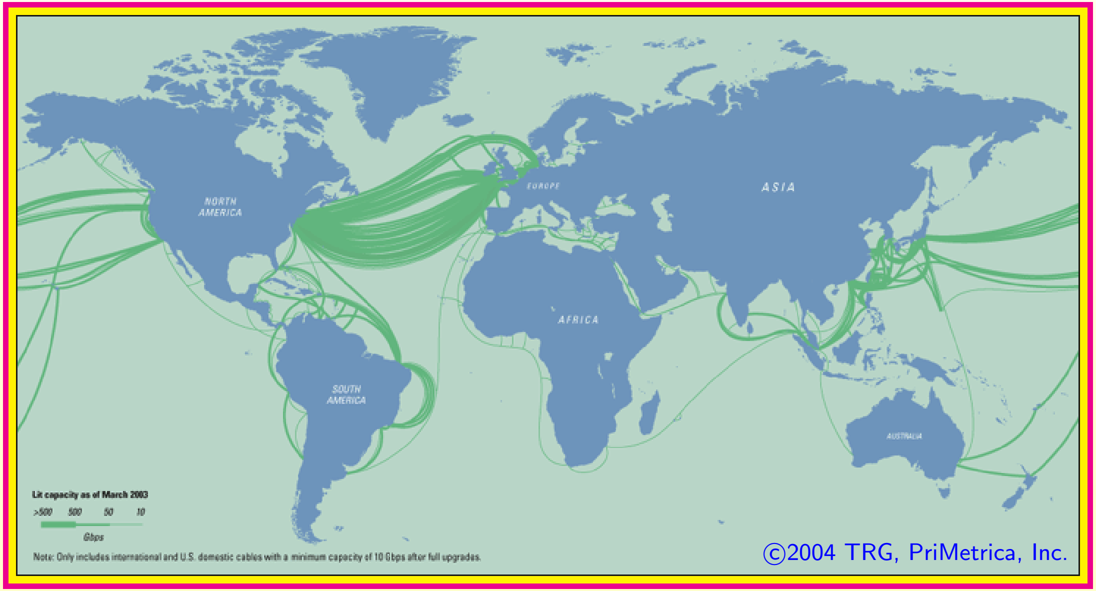
Back
Close

Information Revolution

- Industrial revolution of 19th century gave way to information revolution during the 1990s.
- Fiber-Optic Revolution is a natural consequence of the Internet growth.



Note: Only includes international and U.S. domestic cables with a minimum capacity of 10 Gbps after full upgrades.

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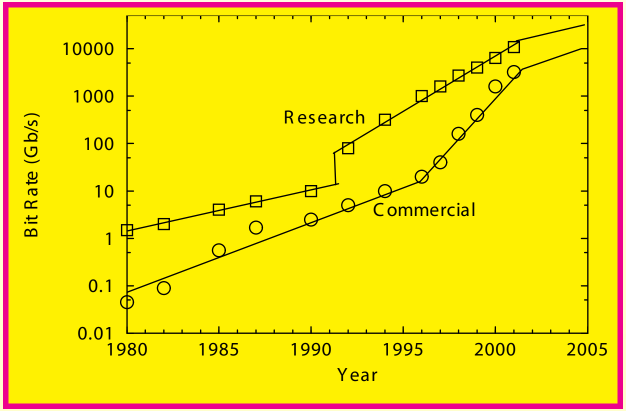
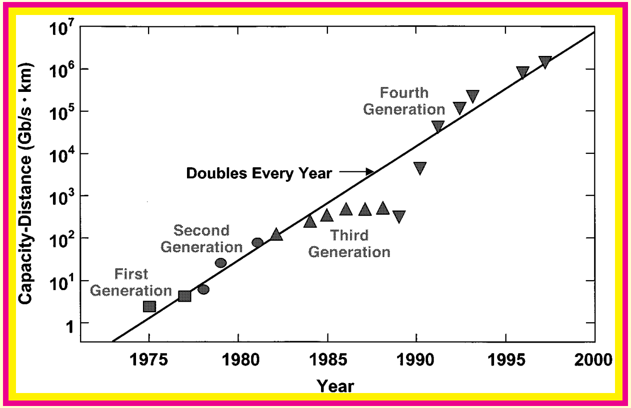
Five Generations

- 0.8-μm systems (1980); Graded-index fibers
- 1.3-μm systems (1985); Single-mode fibers
- 1.55-μm systems (1990); Single-mode lasers
- WDM systems (1996); Optical amplifiers
- L and S bands (2001); Raman amplification





Back
Close

Lightwave System Components

Generic System

- Optical Transmitters:
  Convert electrical data into an optical bit stream suitable for transmission.
- Communication Channel:
  Optical fibers are used for transmitting optical bit streams in most terrestrial networks.
- Optical Receivers:
  Convert optical bit stream into the original electrical form.

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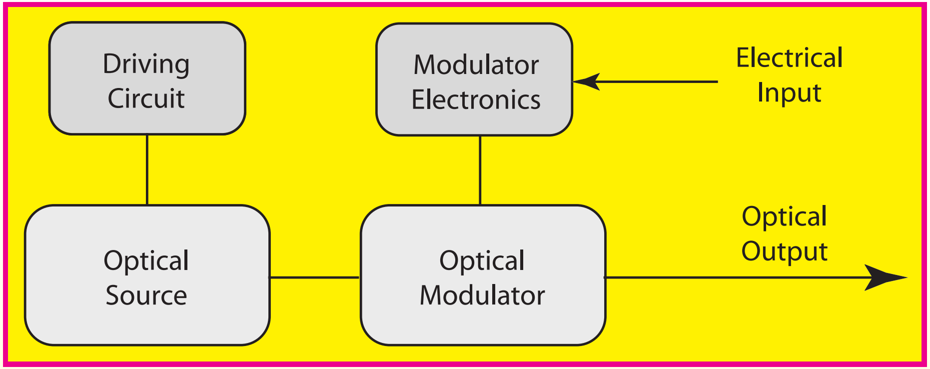
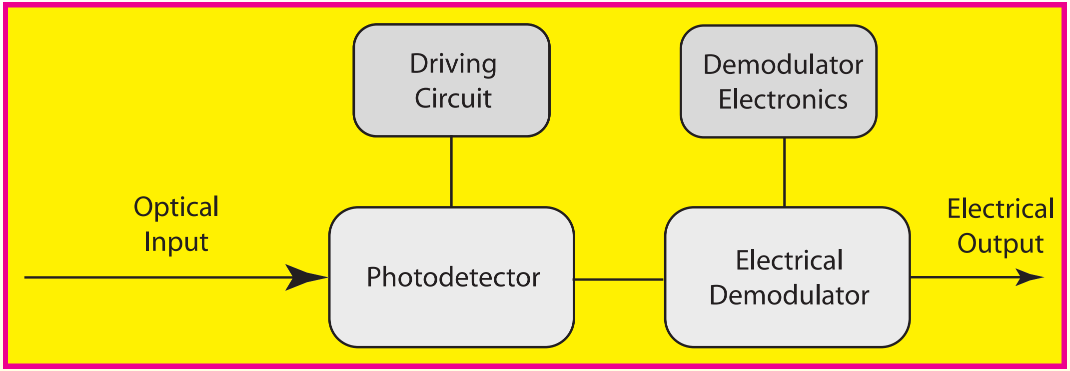
▶
Back
Close

Optical Transmitters



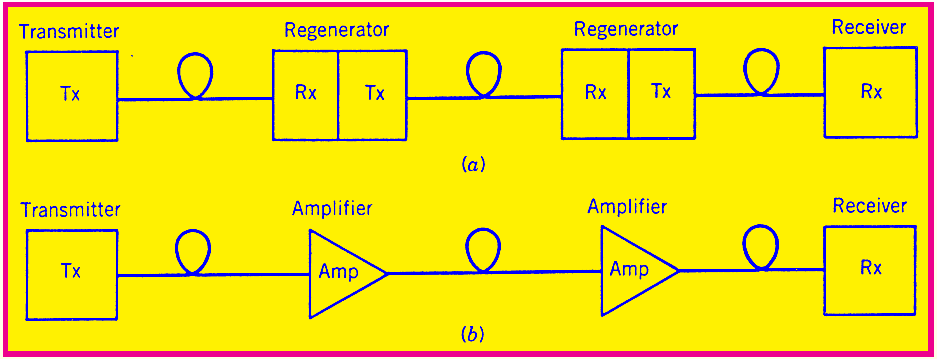
- Optical source (laser or LED) provides the optical carrier.
- Carrier frequency varies from 185 to 200 THz (1520 to 1620 nm).
- C band: 1530 to 1570 nm; L band: 1570 to 1610 nm.
- Modulator creates the optical bit stream.
- Direct modulation technique: laser current modulated to produce the bit stream (no external modulator needed).

Optical Receivers



- Photodetector used for optical-to-electrical conversion.
- Demodulator re-creates the electrical bit stream.
- Noise added during transmission and at receiver leads to errors.
- Bit-error rate (BER) is required to be $< 10^{-9}$.
- All receivers need a certain minimum power to operate reliably.
- This power level is known as the receiver sensitivity.

Fiber-Optic Communication Channel



- Single-mode fibers with low losses (0.2 dB/km near 1550 nm) act as a communication channel.
- Transmission distance is still limited by fiber losses.
- Losses compensated periodically using regenerators or amplifiers.
- Dispersive and nonlinear effects then limit the total distance.

Decibel Units

- Any ratio converted into dB as R (in dB) $= 10\log_{10} R$.
- $R = 1$ corresponds to 0 dB: Ratios smaller than 1 are negative.
- Signal-to-noise ratio is defined as

$$\mathrm{SNR} = 10\log_{10}(P_S/P_N).$$

- Loss of an optical fiber is expressed in dB units.
- If a 1-mW signal reduces to 1 μW after 100 km of fiber, 30-dB loss translates into a loss of 0.3 dB/km.
- Power (in dBm) $= 10\log_{10}\left(\frac{\text{power}}{1\text{ mW}}\right)$.
- 1 mW corresponds to 0 dBm on the decibel scale.
- 1 μW power corresponds to -30 dBm.

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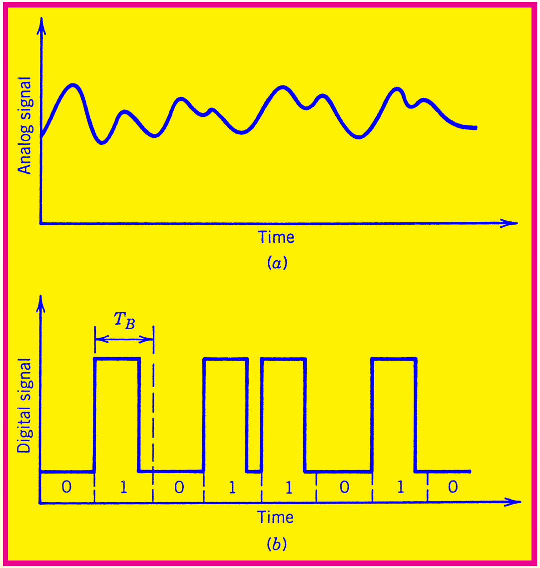
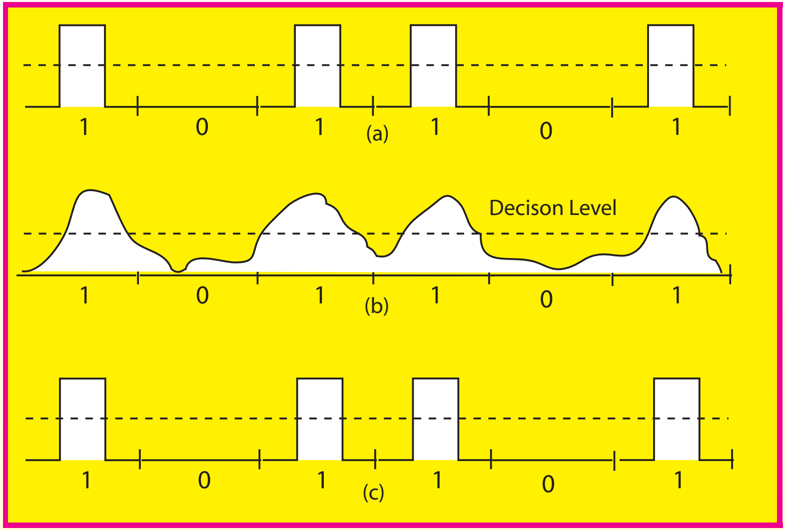
Back
Close

Analog and Digital Signals



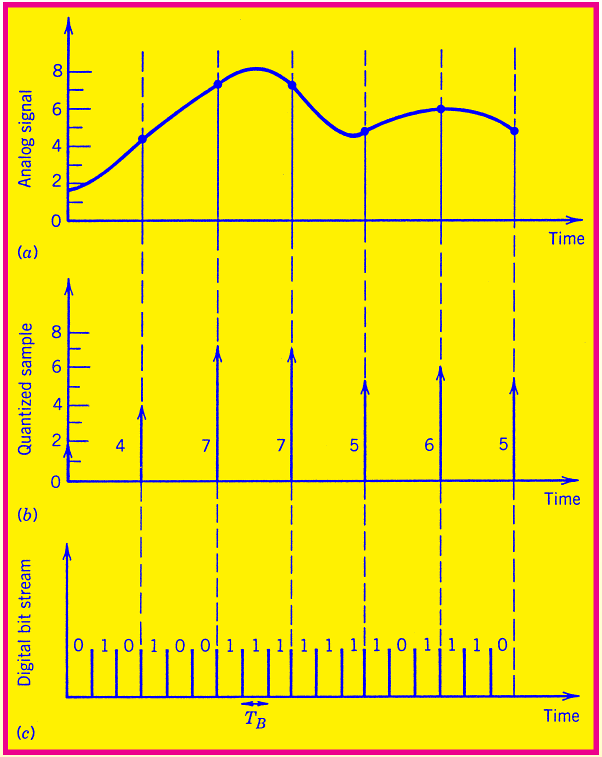
- Lightwave systems use the digital format.
- Optical signal is a stream of 0 and 1 bits.
- Bit rate B determines the time slot $T_B = 1/B$ for each bit.

Advantage of Digital Format



- Signal can be recovered in spite of noise and distortion.
- If the amplitude exceeds the decision level for a 1 bit, it can be recovered in spite of changes in pulse shape.
- Actual shape of the bit is not important.

Analog to Digital Conversion



- Sampling:
  $f_s \geq 2\Delta f$ (sampling theorem).
- Quantization:
  $M > A_{\max}/A_N$ (error $<$ noise).
- Coding:
  $M = 2^m$; m bits/sample (Binary coding).
- Bit rate: $B = mf_s$
  $B \geq (2\Delta f)\log_2 M$
  $B > (\Delta f/3)\mathrm{SNR}$.
  $\mathrm{SNR} = 20\log_{10}(A_{\max}/A_N)$.

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▶
Back
Close

Audio and Video Signals

Digital Audio Signal

- $\Delta f = 3.1$ kHz (0.3 to 3.4 kHz); SNR $=$ 30 dB.
- Minimum $B = (\Delta f/3)$SNR $=$ 31 kb/s.
- In practice, $B = 64$ kb/s ($f_s = 8$ kHz; 8 bits/sample).

Digital Video Signal

- $\Delta f = 4$ MHz; SNR $=$ 50 dB.
- Minimum $B = (\Delta f/3)$SNR $=$ 66 Mb/s.
- In practice, $B = 100$ Mb/s ($f_s = 10$ MHz; 10 bits/sample).

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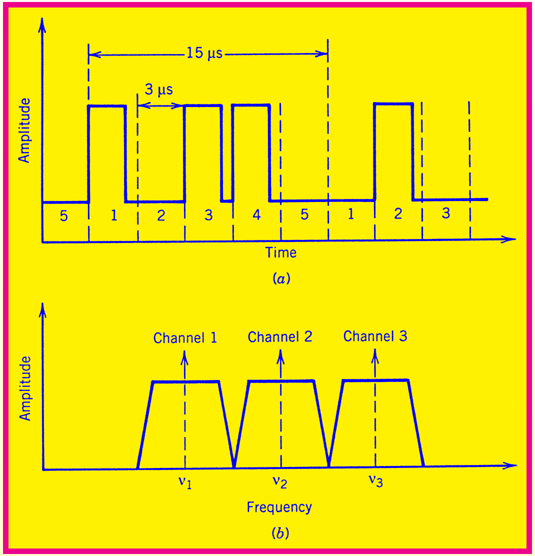
Back
Close

Channel Multiplexing

TDM: Time-division multiplexing

FDM: Frequency-division multiplexing



Optical FDM = WDM (Wavelength-Division Multiplexing)

Time-Division Multiplexing

- No standards until 1988.
- US standard: *synchronous optical network* (SONET).
- ITU standard: *synchronous digital hierarchy* (SDH).

SONET	SDH	B (Mb/s)	Channels
OC-1		51.84	672
OC-3	STM-1	155.52	2,016
OC-12	STM-4	622.08	8,064
OC-48	STM-16	2,488.32	32,256
OC-192	STM-64	9,953.28	129,024
OC-768	STM-256	39,813.12	516,096

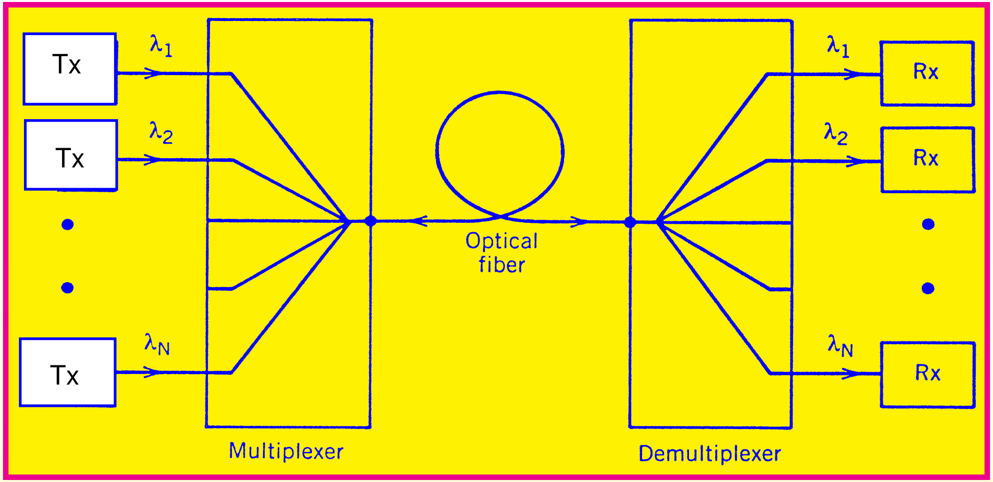
Terrestrial Lightwave Systems

System	Year	λ (μm)	B (Mb/s)	L (km)	Voice Channels
FT–3	1980	0.85	45	< 10	672
FT–3C	1983	0.85	90	< 15	1,344
FT–3X	1984	1.30	180	< 25	2,688
FT–G	1985	1.30	417	< 40	6,048
FT–G-1.7	1987	1.30	1,668	< 46	24,192
STM–16	1991	1.55	2,488	< 85	32,256
STM–64	1996	1.55	9,953	< 90	129,024
STM–256	2002	1.55	39,813	< 90	516,096

- WDM systems commercialized after 1995.
- 160-channel system with 1.6 Tb/s became available by 2000.

Back
Close

Wavelength-Division Multiplexing



- Each channel is assigned a unique carrier frequency (ITU grid).
- An optical source at a precise wavelength is employed.
- Channel spacing 50 GHz or less for dense WDM.

Undersea Lightwave Systems

System	Year	B (Gb/s)	L (km)	Comments
TAT–8	1988	0.28	70	1.3 μm, multimode lasers
TAT–9	1991	0.56	80	1.55 μm, DFB lasers
TAT–10/11	1993	0.56	80	1.55 μm, DFB lasers
TAT–12/13	1996	5.00	50	1.55 μm, optical amplifiers
AC–1	1998	80.0	50	1.55 μm, WDM, amplifiers
TAT–14	2001	1280	50	1.55 μm, dense WDM
AC–2	2001	1280	50	1.55 μm, dense WDM
360Atlantic	2001	1920	50	1.55 μm, dense WDM
Tycom	2002	2560	50	1.55 μm, dense WDM
FLAG	2002	4800	50	1.55 μm, dense WDM

- By 2001, several WDM systems across the Atlantic Ocean provided a combined capacity of more than 10 Tb/s.
- By 2002, cost of calling Europe decreased to <5 cents/min.

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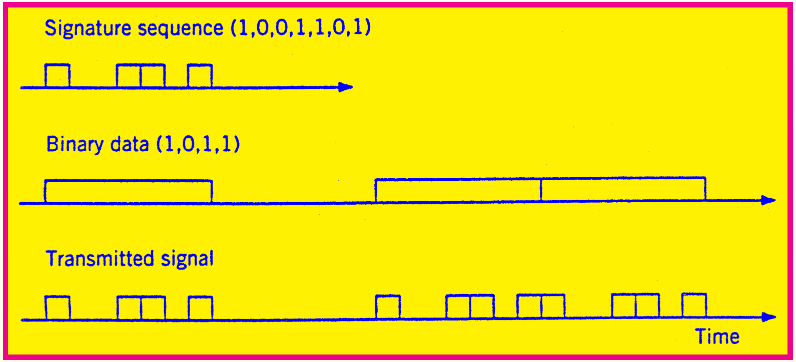
Back
Close

Code-Division Multiplexing



- Borrowed from microwaves (used in cell phones).
- Spectrum of each channel spread over a wide range using codes.
- A signature sequence in time domain increases the bandwidth of each channel.
- Channels overlap *both in time and frequency domains* but can be decoded using the code.

Chapter 2:
Optical Signal Generation

- Modulation formats
- Digital data formats
- Bit-stream generation
- Transmitter design

Modulation Formats

- Optical Carrier:

$$\mathbf{E}(t) = \hat{\mathbf{e}} A_0 \cos(\omega_0 t - \phi_0)$$

- Amplitude-shift keying (ASK): modulate A_0
- Frequency-shift keying (FSK): modulate ω_0
- Phase-shift keying (PSK): modulate ϕ_0
- Polarization-shift keying (PoSK): information encoded in the polarization state $\hat{\mathbf{e}}$ of each bit (not practical for optical fibers).
  - ⋆ Most lightwave systems employ ASK.
  - ⋆ ASK is also called on–of keying (OOK).
  - ⋆ Differential PSK (DPSK) has been employed in recent years.

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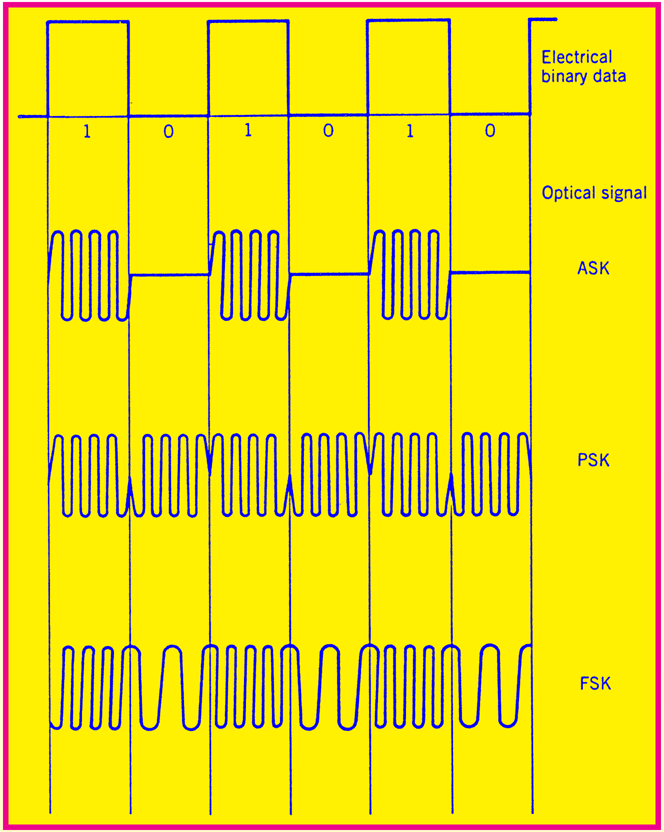
Back
Close

Modulation Formats

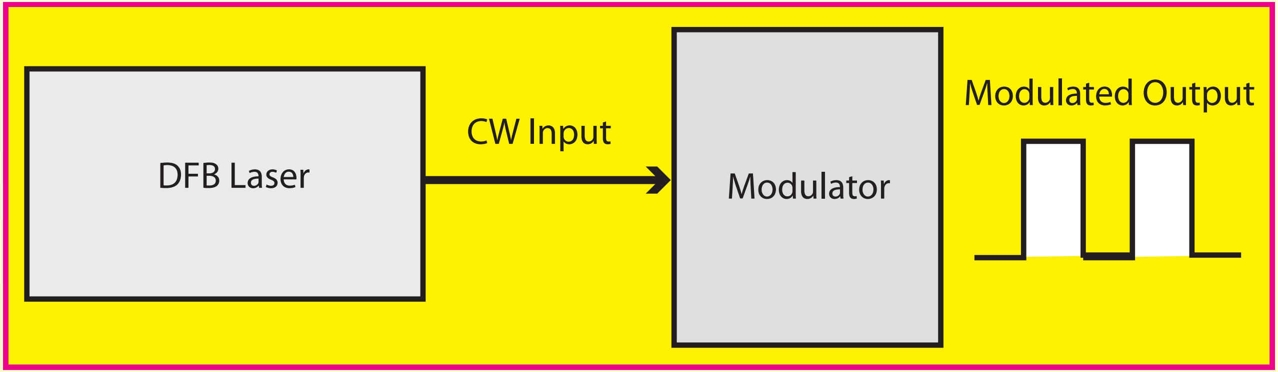


ASK Format

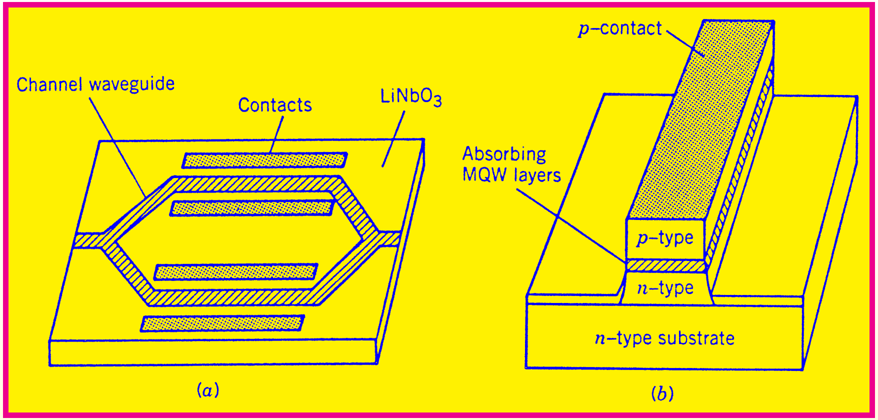
- Optical field: $\mathbf{E}(t) = \mathrm{Re}[A_0(t)\exp(i\phi_0 - i\omega_0 t)]$.
- Only the amplitude A_0 is modulated with data.

$$A_0(t) = \sqrt{P_0}\sum_n b_n f_p(t - nT_b).$$

- Random variable $b_n = 0$ or 1 depending on the bit.
- Direct modulation suffers from the chirping problem.



External Modulators



- LiNbO$_3$ modulators are based on the electro-optic effect.
- Refractive index is changed by applying a voltage across it.
- Phase changes converted into amplitude modulation using a Mach–Zehnder interferometer.
- LiNbO$_3$ modulators can be modulated up to 40 Gb/s.
- Driving voltage can be reduced to 2 to 3 V.

Electro-Absorption Modulators

- Insertion losses can be reduced to <1 dB using an electro-absorption modulator.
- Such modulators make use of the electro-absorption effect.
- Band gap is reduced with an external voltage to make it absorbing.
- Such modulators do not require an interferometer because they change optical power directly in response to an applied voltage.
- Modulator is made with the same material used for lasers.
- It can be integrated with the optical source.
- Optical transmitters with an integrated modulator operate at bit rates of up to 40 Gb/s.

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▶▶
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▶
Back
Close

PSK Format

- Optical field: $\mathbf{E}(t) = \mathrm{Re}[A_0 \exp(i\phi_0(t) - i\omega_0 t)]$.
- Only the phase ϕ_0 is modulated with data:

$$\phi_0(t) = \pi \sum_n b_n f_p(t - nT_b).$$

- Random variable $b_n = 0$ or 1 depending on the bit.
- Optical power remains constant during all bits.
- Information cannot be recovered using just a photodetector.
- Necessary to employ homodyne or heterodyne detection.

Heterodyne Detection

- Optical bit stream combined coherently with the CW output of a local oscillator (a DFB laser) before the signal is detected.

$$E_d(t) = A_0 \exp[i\phi_0(t) - i\omega_0 t] + A_L \exp(i\phi_L - i\omega_L t).$$

- Interference between the two optical fields creates a time-dependent electric current:

$$I_d(t) = R_d(A_0^2 + A_L^2) + 2R_d A_0 A_L \cos[(\omega_0 - \omega_L)t + \phi_0(t) - \phi_L].$$

- R_d is the responsivity of the photodetector.
- Since $I_d(t)$ changes from bit to bit, one can reconstruct the original bit stream.

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▶
Back
Close

Phase-Modulated Bit Stream

- Implementation of PSK requires an external modulator capable of changing optical phase in response to an applied voltage.
- A $\mathrm{LiNbO_3}$ modulator can be used for this purpose.
- Design simpler than that of an amplitude modulator as a MZ interferometer is no longer needed.
- Semiconductors can also be used to make phase modulators if they exhibit the electro-optic effect.
- PSK format rarely used in practice because it requires the phase of optical carrier to remain stable.
- This requirement puts a stringent condition on the tolerable line widths of the DFB lasers.

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▶
Back
Close

DPSK Format

- A variant of the PSK format, known as differential PSK or DPSK, is more practical for lightwave systems.
- Information is coded by using the phase difference between two neighboring bits.
- Phase difference $\Delta\phi = \phi_k - \phi_{k-1}$ is changed by 0 or π, depending on whether the kth bit is a 0 or 1.
- DPSK format does not suffer from the phase stability problem.
- Information can be recovered as long as the carrier phase remains stable over a duration of two bits.
- This condition is easily satisfied at bit rates above 1 Gb/s because line width of a DFB laser is typically <10 MHz.

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Back
Close

QPSK Format

- Another modulation format is known as quaternary PSK (QPSK).
- Phase modulator takes two bits at a time and produces four possible phases of the optical carrier.
- Typically, phase values are 0, $\pi/2$, π, and $3\pi/2$ for bit combinations 00, 01, 11, and 10, respectively.
- Such a signal has half the bandwidth compared with the binary PSK as its bit rate is lower by a factor of 2.
- QPSK format suffers from the same phase-stability issue as binary PSK.
- This problem can be avoided by adopting a differential QPSK (DQPSK) format.

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▶
Back
Close

FSK Format

- Information is coded by shifting the carrier frequency ω_0 itself.

$$E(t) = \mathrm{Re}[A_0 \exp[i\phi_0 - i(\omega_0 \pm \Delta\omega)t].$$

- For a binary digital signal, ω_0 takes values $\omega_0 - \Delta\omega$ and $\omega_0 + \Delta\omega$, depending on whether a 0 or 1 bit is being transmitted.
- The shift $2\Delta f$ is called tone spacing as it represents frequency separation between 0 and 1 bits.
- FSK format can also be viewed as a special kind of PSK modulation for which the carrier phase increases or decreases linearly.
- Similar to the PSK case, one must employ heterodyne detection for decoding an FSK-coded optical bit stream.

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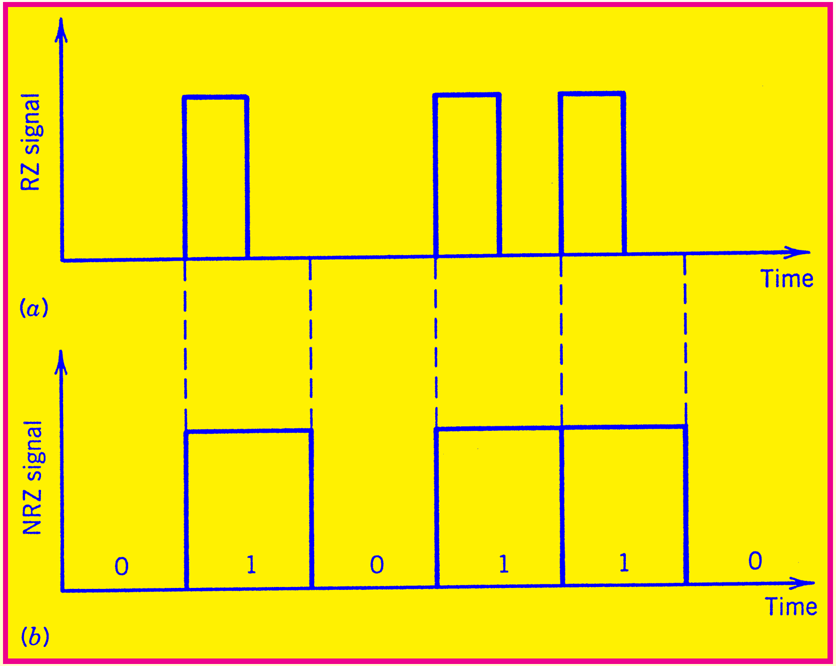
Back
Close

FSK Modulation

- Implementation of FSK format requires modulators capable of shifting frequency of the incident optical signal.
- Electro-optic materials such as $LiNbO_3$ produce a phase shift proportional to the applied voltage.
- They can be used for FSK by applying a triangular voltage pulse.
- A linear phase change corresponds to a frequency shift.
- An alternative technique makes use of Bragg scattering from acoustic waves inside an acousto-optic modulator.
- Such modulators can be fabricated by exciting surface acoustic waves within a $LiNbO_3$ waveguide.
- Simplest method makes use of the direct modulation.

Digital Data Formats

- Return-to-zero (RZ) format
- nonreturn-to-zero (NRZ) format



NRZ Format

- Optical pulse occupies the entire bit slot.
- Optical power does not drop to zero between successive 1 bits.
- Pulses in an NRZ bit stream do not have the same width.
- Pulse width varies depending on the bit pattern.
- If ten 1 bits occur in succession, a single optical pulse of width $10T_b$ is used to represent all 10 bits.
- Main advantage: Signal bandwidth is smaller than the RZ format by about a factor of 2.
- This is the reason why the NRZ format is used whenever bandwidth should be economized as much as possible.
- NRZ format cannot tolerate even a relatively small amount of pulse broadening.

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Back
Close

RZ Format

- Each optical pulse is shorter than the bit slot.
- All pulses are identical in an RZ bit stream but the spacing among them depends on the bit pattern.
- How wide the optical pulse should be compared to the bit slot?
- The ratio T_p/T_b is referred to as the duty cycle.
- Duty cycle is just a design parameter that can be tailored to help meet design goals.
- Several variants of the RZ format used in practice:
  - ⋆ chirped RZ (CRZ) format
  - ⋆ carrier-suppressed RZ (CSRZ) format.

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▶
Back
Close

Power Spectral Density

- Electric field: $E(t) = \mathrm{Re}[A(t)\exp(-i\omega_0 t)]$.
- In the case of the ASK format

$$A(t) = \sum_n b_n A_p(t - nT_b) \equiv \int_{-\infty}^{\infty} b(t')A_p(t-t')\,dt'.$$

- $b(t) = \sum_n b_n \delta(t - nT_b)$ is the impulse response of an filter.
- Power spectral density is found from the Wiener–Khintchine theorem: $S_A(\omega) = \int_{-\infty}^{\infty} \Gamma_A(\tau)\exp(i\omega\tau)\,d\tau$.
- Autocorrelation function $\Gamma_A(\tau) = \langle A^*(t)A(t+\tau)\rangle$. It follows that $S_A(\omega) = |\tilde{A}_p(\omega)|^2 S_b(\omega)$.
- Fourier transform: $\tilde{A}_p(\omega) = \int_{-\infty}^{\infty} A_p(t)\exp(i\omega t)\,dt$.

Autocorrelation Function

- First calculate the autocorrelation function of $b(t)$ using

$$\Gamma_b(\tau) = \langle b(t)b(t+\tau)\rangle = \sum_n \sum_k \langle b_n b_k \rangle \delta(t - kT_b)\delta(t + \tau - nT_b).$$

- Replace ensemble average with a time average. Using $n - k = m$

$$\Gamma_b(\tau) = \frac{1}{T_b}\sum_m r_m \delta(\tau - mT_b), \qquad r_m = \lim_{N\to\infty}\frac{1}{N}\sum_n b_n b_{n+m}.$$

- Power spectral density:

$$S_A(\omega) = |\tilde{A}_p(\omega)|^2 \frac{1}{T_b}\sum_{m=-\infty}^{\infty} r_m \exp(im\omega T_b).$$

- Correlation coefficients r_m calculated noting that b_n equals 1 or 0 with equal probabilities: $r_0 = 1/2$ and $r_m = 1/4$ $(m \neq 0)$.

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▶
Back
Close

Power Spectral Density

- Final expression for power spectral density:

$$S_A(\omega) = \frac{|\tilde{A}_p(\omega)|^2}{4T_b}\left(1 + \sum_{m=-\infty}^{\infty} \exp(im\omega T_b)\right).$$

- Next use the well-known identity

$$\sum_{n=-\infty}^{\infty} \exp(in\omega T_b) = \frac{2\pi}{T_b}\sum_{n=-\infty}^{\infty} \delta\left(\omega - \frac{2\pi n}{T_b}\right).$$

- Power spectral density of $A(t)$ then becomes

$$S_A(\omega) = \frac{|\tilde{A}_p(\omega)|^2}{4T_b}\left[1 + \frac{2\pi}{T_b}\sum_{m=-\infty}^{\infty} \delta\left(\omega - \frac{2\pi m}{T_b}\right)\right].$$

- The spectrum consists of a continuous part and a discrete part resulting from the sum over delta functions.

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▶
Back
Close

Spectral Density of NRZ Bit Stream

- Assuming a rectangular shape, $A_p(t) = \sqrt{P_0}$ within the bit slot of duration T_b and 0 outside of it.
- Pulse spectrum: $|\tilde{A}_p(\omega)|^2 = P_0 T_b^2 \mathrm{sinc}^2(\omega T_b/2)$.
- Spectral density of the entire bit stream:

$$S_A(\omega) = \frac{P_0 T_b}{4} \mathrm{sinc}^2(\omega T_b/2) + \frac{\pi}{2} P_0.$$

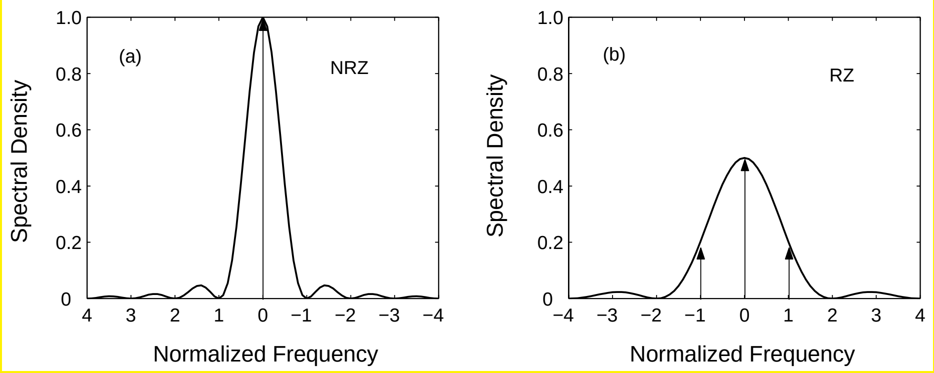
- Only the $m = 0$ term survives in the sum.
- The sinc function vanishes at all frequencies such that $\omega = 2\pi m/T_b$ except when $m = 0$.

Spectral Density of RZ Bit Stream

- Spectral density of an RZ bit stream depends on the duty cycle.
- Each 1 bit occupies a fraction d_c of the bit slot.
- Assuming a rectangular shape for the optical pulse

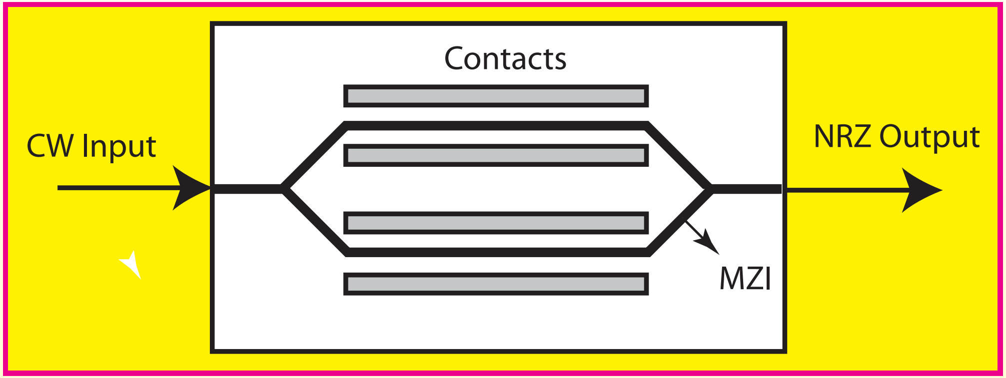
$$|\tilde{A}_p(\omega)|^2 = P_0 T_b^2 d_c \,\mathrm{sinc}^2(\omega T_b d_c/2).$$

- Spectrum wider for RZ pulses and contains discrete spectral components.



Bit-Stream Generation

- NRZ Transmitters: Design relatively simple if the electrical signal is itself in the NRZ format.
- A Mach–Zehnder modulator converts the CW light into an optical bit stream.



- Modulator can be integrated with the DFB laser if the electro-absorption effect is used for modulation.

Transmission of a MZ modulator

- Outputs A_b and A_c from the bar and cross ports:

$$\begin{pmatrix} A_b \\ A_c \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \begin{pmatrix} e^{i\phi_1} & 0 \\ 0 & e^{i\phi_2} \end{pmatrix} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \begin{pmatrix} A_i \\ 0 \end{pmatrix}.$$

- $\phi_j(t) = \pi V_j(t)/V_\pi$ is the phase shift when voltage V_j is applied.
- Transmission: $t_m = A_b/A_i = \cos[(\phi_1 - \phi_2)/2] \exp[i(\phi_1 + \phi_2 + \pi)/2]$.
- $\phi_1 + \phi_2$ constant if $V_2(t) = -V_1(t) + V_b$:

$$T_m(t) = |t_m|^2 = \cos^2\left(\frac{\pi}{2V_\pi}[2V_1(t) - V_b]\right).$$

- To generate NRZ bit stream, modulator is biased with $V_b = -V_\pi/2$.
- $V_1(t)$ varies from $-V_\pi/4$ to $+V_\pi/4$ between 0 and 1 bits.

RZ Transmitters

- Situation different when electrical signal is in the NRZ format.
- One possibility: Use a mode-locked laser.
- Such a laser produces a periodic train of pulses of appropriate width at a repetition rate equal to the bit rate B.
- In essence, laser produces an "$11111\cdots$" bit stream.
- Modulator is then operated such that it blocks the pulse in all slots representing 0 bits.
- Rarely used for commercial lightwave systems because mode-locked lasers are not as reliable as a CW semiconductor laser.

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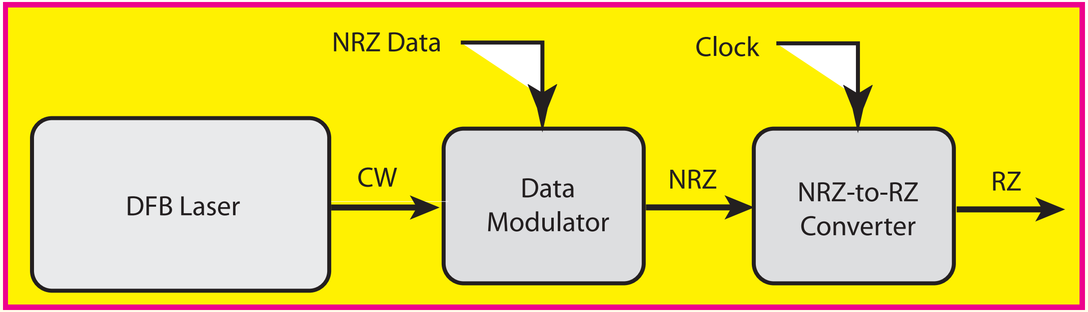
Back
Close

RZ Transmitters



- An alternative approach makes use of the scheme shown above.
- NRZ signal generated first using a data modulator.
- It is converted into an RZ bit stream with a second modulator that is driven by a sinusoidal signal at the bit rate.
- Second modulator is called the pulse carver.

Biasing of Modulators

- Three different biasing configurations can be used to create RZ bit streams with duty cycles ranging from 33 to 67%.
- In one configuration, $V_b = V_\pi/2$ and $V_1(t) = (V_\pi/4)\cos(2\pi Bt)$.
- Since phase shift equals $\pi/2$ once during each cycle, each long pulse representing a string of 1's is split into multiple pulses.
- Such a device acts as an NRZ-to-RZ converter for the optical bit stream by forcing the output to reduce to zero at the boundaries of each bit.
- Transmissivity of the second modulator:

$$T_m(t) = \cos^2[\tfrac{1}{2}\pi\sin^2(\pi Bt)].$$

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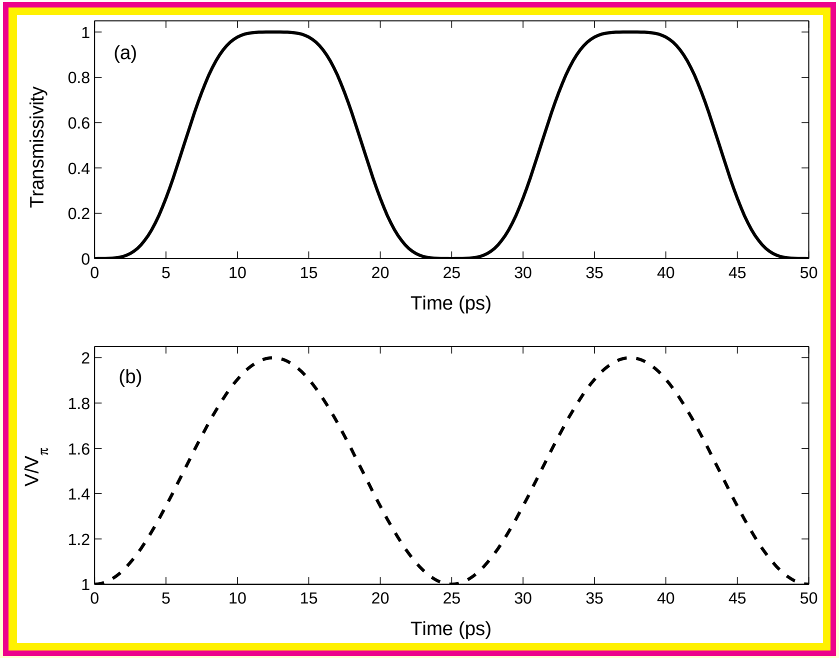
Back
Close

RZ bit Stream



- Duty cycle of RZ pulses is about 50%.
- It can be adjusted by reducing the voltage swing and adjusting the bias voltage applied to the modulator.

Biasing of Modulators

- In the second configuration, bias voltage $V_b = 2V_\pi$ (point of maximum transmission), and $V_1(t)$ is modulated at a frequency equal to $B/2$ with the peak value $V_\pi/2$.
- Resulting RZ pulses are shorter with a duty cycle of 33%.
- In the third configuration, the bias voltage $V_b = V_\pi$ (point of minimum transmission), and $V_1(t)$ is modulated in periodic fashion at a frequency equal to $B/2$.
- This configuration provides a duty cycle of 67%.
- Main drawback: Synchronization required between two RF signals applied to two modulators.

Modified RZ Transmitters

- Bandwidth of RZ bit stream is larger that of the NRZ format.
- Enhancement factor depends on the duty cycle.
- Bandwidth is nearly doubled for a 50% duty cycle.
- This increase forces one to increase wavelength spacing between two neighboring WDM channels (lower spectral efficiency).
- Spectral efficiency can be improved with suitable modifications.
- One approach: Modulate phase in addition to amplitude.
- Chirped RZ (CRZ format): optical pulses representing 1 bits are chirped before they are launched into the fiber.

Back
Close

CSRZ Format

- CSRZ stands for carrier-suppressed RZ.
- Phase modulation is used to introduce a π phase shift between any two neighboring bits.
- This phase alternation modifies signal spectrum such that the central peak located at the carrier frequency is suppressed.
- CSRZ produces a narrower spectrum than that of RZ signal.
- Several other RZ-type formats are possible.
- Figure 2.9 shows experimentally recorded optical spectra at 42.7 Gb/s for several different formats.
- Bit rate is larger than 40 Gb/s because of 7% FEC overhead.
- FEC stands for forward error correction.

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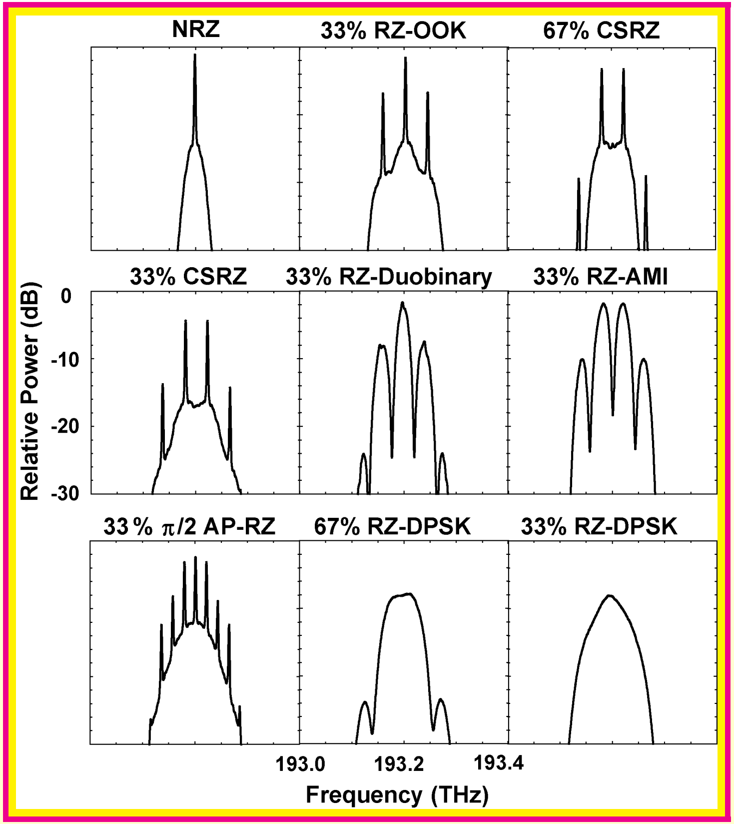
Back
Close

Comparison of Signal Spectra



CSRZ: A Ternary Format

- A π phase shift for alternate bits is equivalent to changing the sign of the pulse amplitude:

$$A(t) = \sum_n (-1)^n b_n A_p(t - nT_b) \equiv \sum_n \bar{b}_n A_p(t - nT_b).$$

- We can absorb $(-1)^n$ in the definition of $\bar{b}$ that is allowed to take three values (-1, 0, and 1) for each bit.
- CSRZ scheme can be implemented with the same two-modulator configuration used for the RZ format.
- Second modulator (pulse carver) is operated at half the bit rate with twice the peak voltage ($V_1 = V_\pi/2$).
- Modulator is biased at the point of minimum transmission ($V_b = V_\pi$) and produces pulses with 67% duty cycle.

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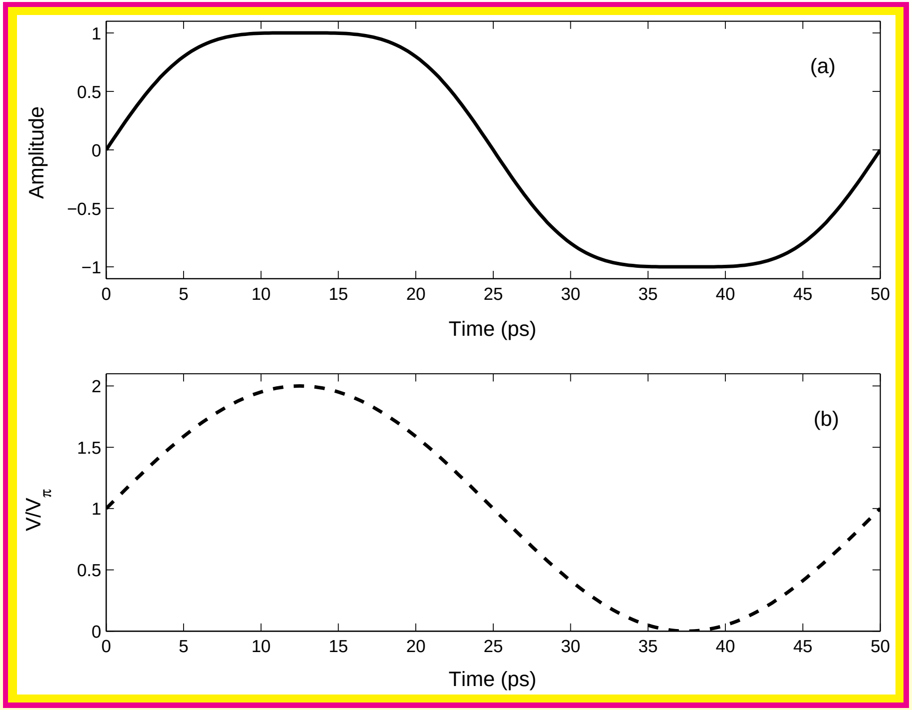
Back
Close

CSRZ Format



- During a single clock cycle, two optical pulses with a relative phase shift of π are created.

RZ-AMI Format

- A variant of CSRZ is format known as the alternate-mark-inversion.
- Spectrum for the RZ-AMI format is quite different.
- A π phase shift is introduced only for 1's so that alternate 1 bits have their amplitudes inverted.
- Power spectral density is given by

$$S_A(\omega) = \frac{1}{2T_b}|\tilde{A}_p(\omega)|^2[(1-\cos(\omega T_b)].$$

- For a 50% duty cycle, $S_A(\omega) = \frac{P_0 T_b}{4}\mathrm{sinc}^2(\omega T_b/4)\sin^2(\omega T_b/2)$.
- No power at the carrier frequency $[S_A(\omega = 0) = 0]$.

RZ-Duobinary Format

- This format is a variant of the RZ-AMI format.
- Phase is changed only when an odd number of 0 bits occur between two successive 1 bits.
- Its use reduces intersymbol interference, a phenomenon that leads to errors at the receiver.
- This format requires considerable electronic processing of the NRZ data at the transmitter.
- Optical spectrum of the RZ-duobinary format is similar to that of the RZ-AMI format.

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Back
Close

AP-RZ Format

- A variant of the RZ format is known as alternate-phase RZ.
- Phase of two neighboring bits is alternated between two values that differ by a value other than π.
- Phase alternation by $\pi/2$ is often used in practice.
- Spectrum for the AP-RZ format is quite different from that of the CSRZ format.
- It contains more spectral peaks because peaks are separated by only $B/2$, rather than B.
- Experimental results show that the AP-RZ format can provide a better system performance compared with other formats.

Single-Sideband Format

- Signal bandwidth of any modulation format can be reduced by 50% by adopting a single-sideband scheme.
- Only one sideband, located on either side of the carrier frequency, is transmitted.
- This is possible because the signal spectrum is symmetric around the carrier frequency.
- Both the upper and lower sidebands contain the entire information content of the signal.
- Generation of an optical bit stream with a single sideband is not a simple task.

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▶
Back
Close

Single-Modulator Schemes

- Double-modulator configuration used for the RZ format suffers from a synchronization problem.
- It turns out that an RZ pulse train can be generated using a single modulator driven by a differentially encoded NRZ signal.
- Voltage level changes between its two values whenever next bit is a "1" bit.
- Modulator is biased at the peak of its transmission $(V_b = V_\pi)$.

$$T_m(V_1) = \sin^2\left(\frac{\pi}{2V_\pi}[2V_1(t) - V_\pi]\right) = \cos^2[\pi V_1(t)/V_\pi].$$

- An optical pulse is produced whenever electrical signal changes from low to high or high to low.

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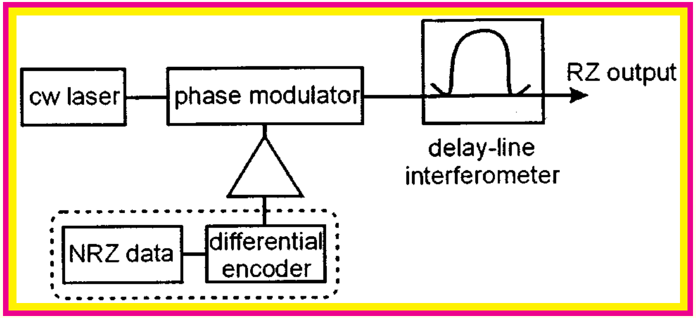
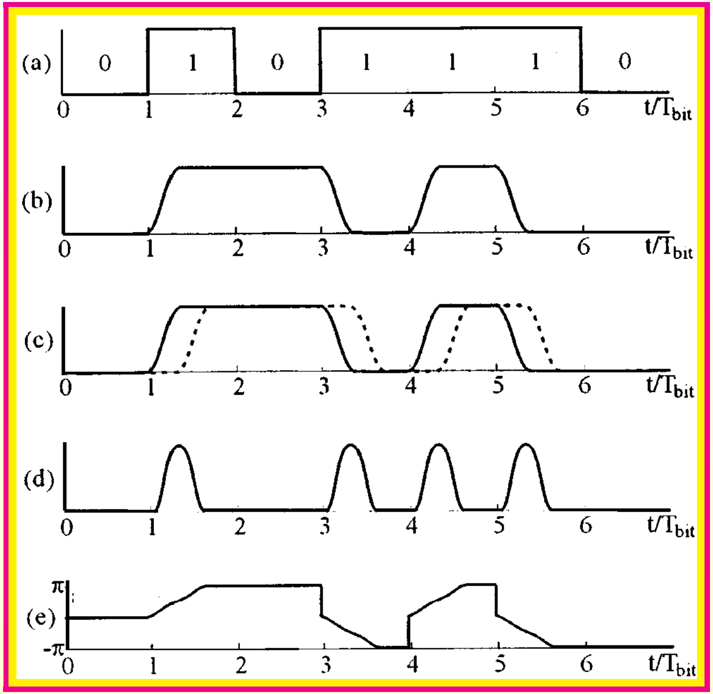
Back
Close

Single-Modulator Schemes



- Another scheme in which a single phase modulator produces an RZ signal from a differentially encoded NRZ bit stream.
- A π phase shift is produced whenever the voltage is nonzero.
- Phase-encoded optical signal is split into two equal parts inside a MZ interferometer.
- It is delayed in one branch by a fraction of bit slot.

Single-Modulator Schemes



NRZ data

Differential encoding

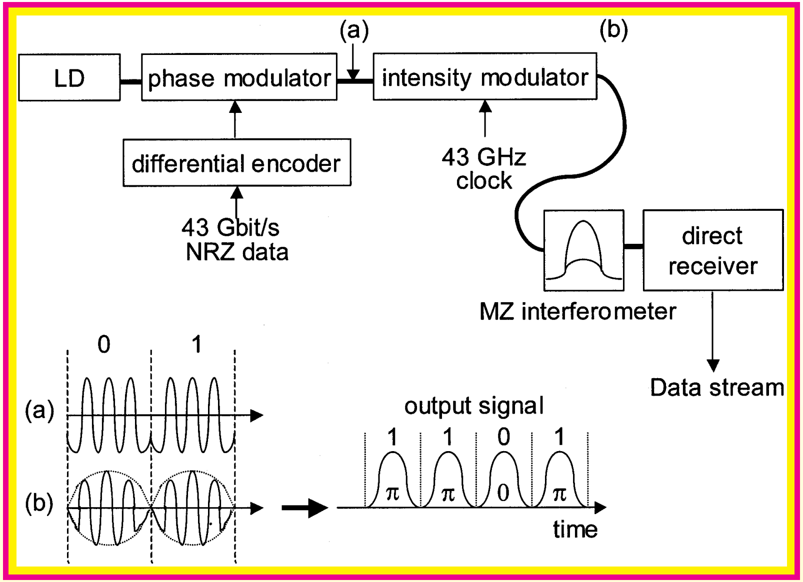
Phase profiles in two arms

Final RZ bit stream

Phase variation across it

Phase changes by π for every 1 bit (RZ-AMI format).

DPSK Transmitters



- Two modulators used at the transmitter end; second modulator acts as a pulse carver.
- A Mach–Zehnder interferometer employed at receiver to convert phase information into current variations.

Back
Close

DPSK Receivers

- Length difference between two arms of the MZ interferometer is corresponds to a delay of exactly one bit slot.
- One-bit delay allows us to reconstruct the original bit stream using a direct-detection scheme.
- MZ interferometer acts as an optical filter as follows:

$$\begin{pmatrix} \tilde{A}_b \\ \tilde{A}_c \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \begin{pmatrix} e^{i\omega T_b} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \begin{pmatrix} \tilde{A}(\omega) \\ 0 \end{pmatrix}.$$

- After Fourier transforming, power falling at the photodetector $P(t) = \frac{1}{4}|A(t) \pm A(t - T_b)|^2$.
- Choice of sign depends on whether the bar or cross port is used.
- Current at the receiver $I_d(t) = R_d P(t) \frac{1}{2}[1 \pm \cos(\Delta\phi)]$, where $\Delta\phi(t) = \phi(t) - \phi(t - T_b)$.

Transmitter Design

- Design of optical transmitters requires attention to many details.
- Applications related to computer-data and access networks have low cost as a major design objective.
- They employ low-power transmitters based on LEDs or VCSELs and do not require internal cooling.
- For metropolitan networks, low cost remains important but bit rates are higher (typically 2.5 Gb/s).
- Such networks use directly modulated semiconductor lasers.
- Submarine and terrestrial long-haul systems operate at high speeds and employ multiple WDM channels.
- Design requirements are most stringent for such systems.

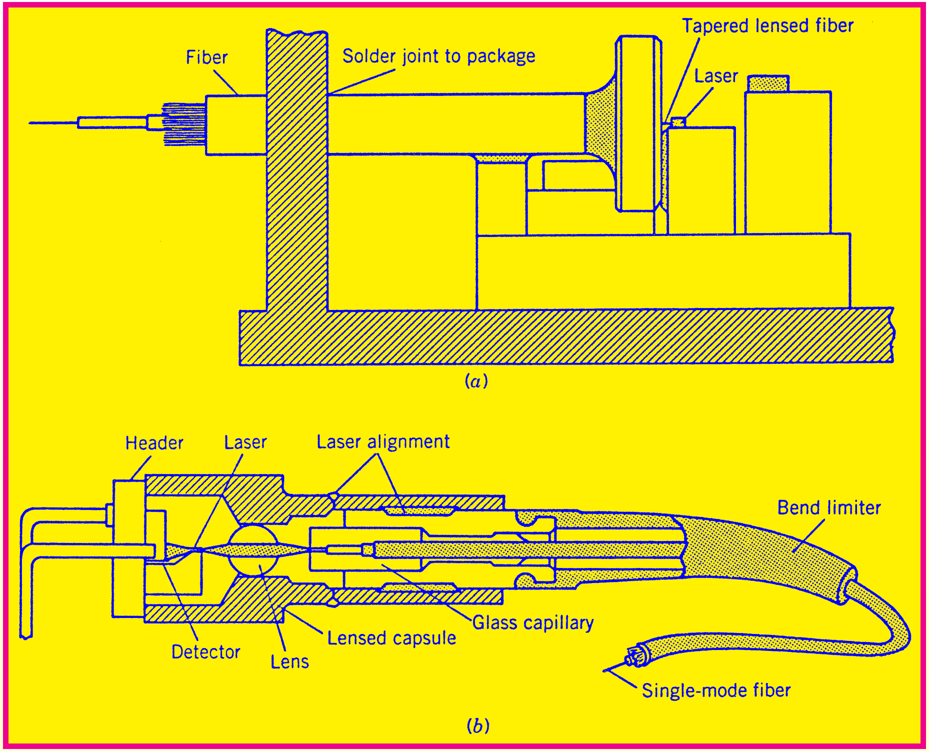
DFB-Laser Transmitters

- A distributed feedback (DFB) semiconductor laser is invariably used for stabilizing the channel wavelength.
- CW light from the DFB laser is coupled to a modulator as efficiently as possible.
- Modulator is often integrated with the laser.
- If that is not possible, an external $LiNbO_3$ modulator is employed.
- In both cases, optical bit stream generated needs to be launched into the fiber link without significant coupling losses.
- It is important to avoid and feedback into the transmitter.
- The output power needs to remain constant with aging.
- Several transmitter designs developed to meet these requirements.

Coupling Losses and Output Stability

- Coupling efficiency depends on optical source (LED versus laser) as well as on fiber (multimode versus single mode).
- Coupling inefficient when light from an LED is coupled into a single-mode fiber.
- Coupling efficiency for semiconductor lasers is 40 to 50% and can exceed 80% for VCSELs because of their circular spot size.
- A small piece of fiber (known as the pigtail) is included with every transmitter; coupling efficiency is maximized during packaging.
- A fiber connector is used to join the pigtail with the fiber cable.
- Two approaches are used for coupling light into fiber.

DFB-Laser Transmitters



Back
Close

Butt Coupling Issues

- Butt coupling provides only 10–20% efficiency if mode sizes are not matched.
- Typically, semiconductor lasers have an elliptical spot size of size 1 to 2 μm.
- Mode diameter of single-mode fibers exceeds 8 μm.
- Coupling efficiency can be improved by tapering the fiber.
- Fiber tip is aligned with the emitting region of the laser to maximize the coupling efficiency (typically 40%).
- Use of a lensed fiber can provide values close to 80% .

Lens Coupling Issues

- A sphere-shape lens is used to collimate laser light and focus it onto the fiber core.
- Coupling efficiency exceeds 70% for a confocal design.
- Alignment of the fiber core is less critical for the confocal design because spot size is magnified to match fiber's mode size.
- Mechanical stability of the package is ensured by soldering the fiber into a ferrule.
- Ferrule secured to the body by two sets of laser alignment welds.
- One set of welds establishes proper axial alignment, while the other set provides transverse alignment.
- A spot-size converter is sometimes used for maximizing the coupling efficiency (>80% possible).

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Back
Close

Optical Feedback Issues

- Semiconductor lasers are sensitive to optical feedback.
- Even a small amount of feedback ($<0.1\%$) can destabilize the laser through phenomena such as linewidth broadening, mode hopping, and intensity noise enhancement.
- Feedback reduced in practice with antireflection coatings.
- It can also be reduced by cutting the fiber tip at a slight angle so that reflected light does not hit the active region of laser.
- An optical isolator used for more demanding applications.
- A very compact isolator formed with a YIG sphere.
- A polarizer placed between the YIG sphere and fiber can also reduce the feedback by more than 30 dB.

Back
Close

Output Power Stability

- Each system is designed to operate with a certain amount of power.
- This power should be maintained during system lifetime.
- In practice, power level can change if coupling losses change because of mechanical motion of transmitter components.
- It can also change if the threshold current of laser itself increases because of aging-related degradations.
- To keep the power constant, most transmitters incorporate a mechanism that adjusts the current in a dynamic fashion.
- This is realized by a monitoring photodiode, which generates a control signal that is used to adjust the bias level.
- Rear facet of the laser is generally used for this purpose.

Wavelength Stability and Tunability

- Dense WDM systems operate with a channel spacing as small as 25 GHz (or 0.2 nm).
- Wavelength of each optical carrier should remains stable to within 1 GHz or so (within 10 pm).
- Use of DFB lasers helps because wavelength is set by a built-in grating internal to the laser structure.
- Wavelength is set by the grating period Λ through the Bragg condition $\lambda_B = 2\bar{n}\Lambda$.
- Stability of λ_B requires the mode index $\bar{n}$ to remain constant during system operation.

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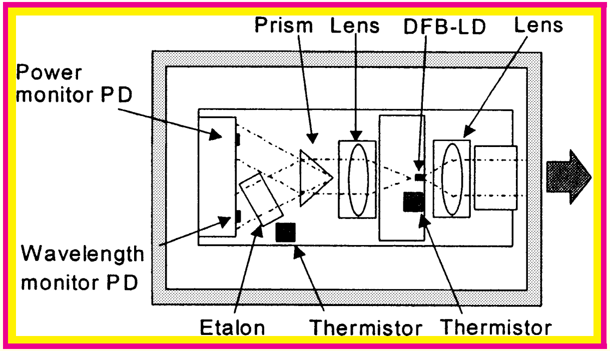
Back
Close

Wavelength Stability

- Near 1550 nm, wavelength can remain stable to within 10 pm only if changes in $\bar{n}$ are below 10^{-5}.
- Temperature variation of even 1°C can change $\bar{n}$ by an amount $> 10^{-5}$.
- one must control laser temperature to a fraction of 1°C.
- This is realized in practice by a thermoelectric cooler within the transmitter.
- Advanced transmitters employ a wavelength-monitoring scheme and control laser wavelength using a servo-loop mechanism.
- Several different schemes have been employed for this purpose.

Wavelength Monitoring



- Light from the back facet of the DFB laser is split into two branches using a prism.
- A Fabry–Perot étalon serves as a wavelength reference.
- It is designed such that one of its transmission peaks occurs precisely at the wavelength at which the laser is designed to operate.

Wavelength Monitoring

- Fabry–Perot étalon suffers from one problem.
- Variations in étalon temperature can affect its cavity length and its refractive index and shift its transmission peaks in an uncontrolled manner.
- A feedback loop solves this problem by monitoring étalon temperature and adjusting the feedback signal accordingly.
- Laser wavelength is kept constant by adjusting thermoelectric cooler current and changing laser temperature.
- With this approach, laser wavelength drifted by less than 1 pm even when laser module temperature varied from 5 to 70°C.
- Reliability tests indicate that wavelength drift should be less than 5 pm during a 25-year operating period.

Back
Close

Wavelength Tuning

- A large number of DFB lasers, each operating at a fixed wavelength on the ITU grid, is required for dense WDM systems.
- Maintenance of WDM transmitter with 100 or more channels is impractical because one must maintain a large inventory of individual DFB lasers.
- A solution is provided by tunable lasers whose wavelength can be tuned over a wide range electronically.
- Multisection DFB and distributed Bragg reflector (DBR) lasers have been developed to meet the conflicting requirements of stability and tunability.

Back
Close

Multisection Lasers

- A tunable DBR laser consists of active, phase-control, and Bragg sections. Each section can be biased independently.
- Current injected into the Bragg section changes Bragg wavelength through carrier-induced changes in the refractive index $\bar{n}$.
- Current injected into the phase-control section changes the phase of feedback through index changes in that section.
- Laser wavelength can be tuned almost continuously over the 10 to 15 nm by controlling currents in these sections.
- By 1998, such lasers exhibited a tuning range of 17 nm and output powers of up to 100 mW.
- Several new designs have been developed for tunable lasers.

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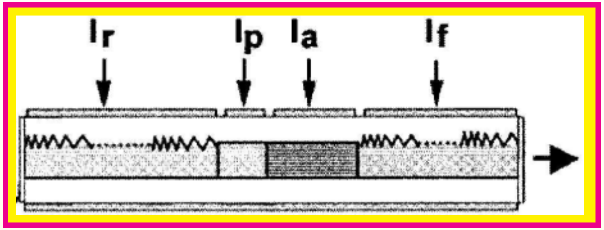
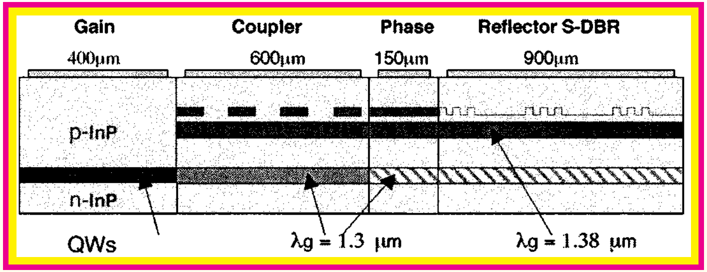
Back
Close

Sampled-grating DBR Lasers



- Sampled-grating DBR (SG-DBR) laser consists of four sections.
- Each section be controlled electronically by injecting currents.
- Two outer sections act as DBRs and are designed with a superstructure grating.
- Such lasers can be tuned over 100 nm with Vernier effect.
- Each SG-DBR section supports its own comb of wavelengths but spacing in each comb is not the same.
- The wavelength coinciding in the two combs becomes the output wavelength that can be tuned over a wide range.

Multisection Lasers

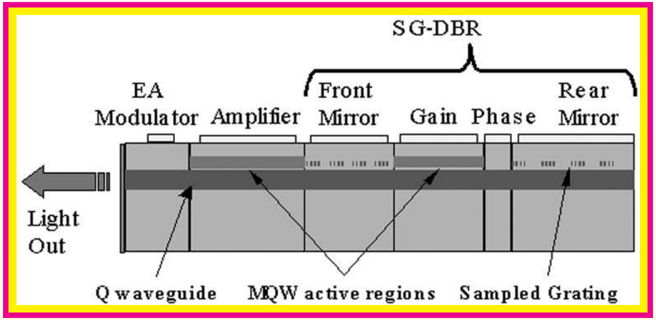


- In another design, a grating-assisted directional coupler is inserted between the active and phase-control sections.
- Coupler section has two vertically separated waveguides so that they form an asymmetric directional coupler.
- Grating can selectively transfer a single wavelength from the wavelength comb supported by the DBR section.
- Such lasers can provide a tuning range of more than 110 nm.

Monolithic Integration

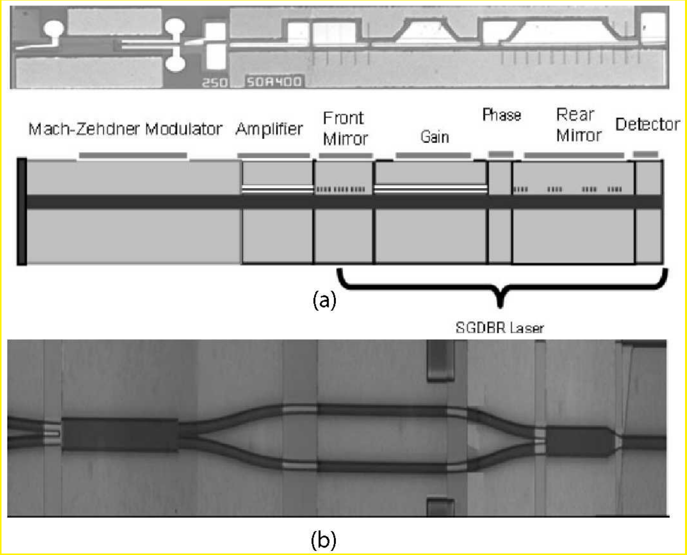
- Performance of high-speed transmitters can be improved by integrating monolithically the laser with driver electronics.
- Such monolithic transmitters are referred to as optoelectronic integrated circuits (OEICs).
- By 1995, 10-Gb/s laser transmitters were fabricated by integrating 1.55-μm DFB lasers with field-effect transistors.
- Concept of monolithic integration can be extended to build single-chip transmitters by adding more functionality on the same chip.
- Such devices are called photonic integrated circuits, as they integrate on the same chip multiple optical components.

Monolithic Integration of Modulator



- Performance can be improved by integrating an electro-absorption modulator with the DFB or DBR laser.
- By 2001, modulator-integrated transmitters were able to operate at a bit rate of 40 Gb/s.
- SG-DBR laser can be integrated with a modulator and a semiconductor optical amplifier (SOA), resulting in a six-section device.
- Use of a built-in optical amplifier permits power levels high enough that more than 10 mW of optical power can be coupled to a fiber.

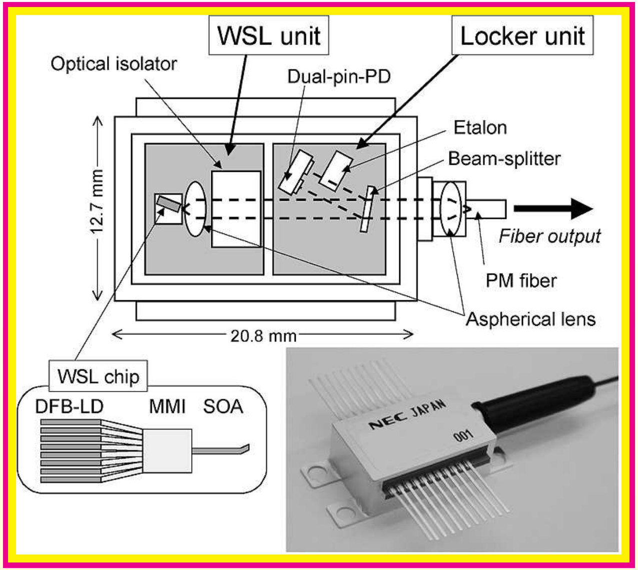
Monolithic Integration of Modulator



- Even a MZ modulator can be integrated with the laser if InP is used to make it.
- Device also incorporates a back-facet detector and a SOA.
- Whole device is only 3.4 mm long.

Back
Close

Wavelength-Selective Lasers (WSL)



- Multiple DFB lasers on the same chip provide an alternative solution to tunability.
- Package combines a WSL unit with a wavelength-locking unit that locks the laser wavelength using a Fabry–Perot étalon.

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▶
Back
Close

Wavelength-Selective Lasers (WSL)

- The WSL unit incorporates an array of eight DFB lasers whose output is sent to a single SOA through an MMI coupler.
- Each DFB laser can be tuned over a few nanometers by changing its temperature.
- This fine tuning permits setting of the transmitter wavelength precisely on the ITU grid.
- Wavelength can be changed by a much larger value by turning on individual DFB lasers selectively within the array.
- The combination of temperature tuning and multi-wavelength arrays produces transmitters that can operate anywhere within the S, C, and L bands.
- Entire transmitter can be fitted inside a standard butterfly package.

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Back
Close

Reliability and Packaging

- Optical transmitter should operate reliably over >10 years.
- Reliability requirements are more stringent for submarine systems.
- Since repairs are prohibitively expensive for them, all components are designed to last at least 25 years.
- Major reason for failure of transmitters is the optical source itself.
- Considerable testing performed to ensure a reasonable lifetime.
- It is common to quantify the lifetime by a parameter t_F known as *mean time to failure*.
- Typically, t_F should exceed 10^5 hours (about 11 years).

Back

Close

Reliability and Packaging

- Both LEDs and semiconductor lasers can stop operating suddenly (catastrophic degradation).
- They also exhibit a gradual mode of degradation in which device efficiency degrades with aging.
- Physically, gradual degradation is due to the onset of dark-line or dark-spot defects within the active region of the laser.
- Attempts are made to identify devices that are likely to fail.
- A common method is to operate the device at high temperatures and high current levels (accelerated aging).
- Changes in the operating current at a constant power provide a measure of device degradation.

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Back
Close

Transmitter Lifetime

- Degradation rate can be used to estimate the laser lifetime and the mean time to failure (MTTF).
- LEDs are normally more reliable than semiconductor lasers under the same operating conditions.
- MTTF for GaAs LEDs easily exceeds 10^6 hours and can be $>10^7$ hours at 25°C.
- MTTF for InGaAsP LEDs is even larger, approaching a value $\sim 10^9$ hours.
- By contrast, the MTTF for InGaAsP lasers is generally limited to 10^6 hours at 25°C.
- This value is large enough that semiconductor lasers can be used in undersea optical transmitters.

Back

Close