EE 443 Review Notes for Lectures 1 through 13
(Fall 2019)

Lecture 1

1. Telecommunications purpose is to carry digitized signals around the World
2. Common wavelengths in OFC networks: 650 nm & 850 nm for plastic fiber, 850 nm & 1300 nm for multimode fiber, and 1310 nm & 1550 nm for single-mode fiber (long-haul)
3. Advantages of OFC – Very high information capacity; low attenuation per unit distance; high electrical isolation; fiber is smaller and lighter than copper wire; long lifetime; resistant to water & many chemicals
4. Disadvantages of OFC – More expensive to install; fiber is more fragile than copper wire; difficult to splice; more difficult to add network nodes after primary installation

Lecture 2

1. Applications for optical fibers: Communication/Data Storage; Broadcast/CATV/Cable TV; Networking; Industrial/Commercial; Military; Medical; Lighting and Imaging
2. Data networking topologies: Bus, Mesh, full mesh, ring, star & tree
3. Packet-Switched Network – Message is sent in packets and smart routers send these packets on to final destinations. Many paths are available to each router which selects the best path available. At the destination, the packets are assembled into applications. This is distributed communications.
4. Circuit-Switched Network – Wires and switches are connected to form a dedicated connection to each communication. Example is the Public Switched Telephone Network (PSTN)
5. Backbone or Core Networks are almost entirely optical fiber networks which carry massive amounts of data
6. Major users of OFC networks are Ethernet, Fibre Channel and SONET/SDH

Lecture 3
1. Optical fibers have a core region surrounded by a cladding layer, with a jacket layer (or layers) for protection.
2. Silica dominates optical fibers for telecommunication applications.
3. Silica optical fiber attenuation versus wavelength favors 1300 nm and 1550 nm for lowest attenuation per unit length.
4. Rayleigh scattering dominates fiber losses below the IR absorption limit.
5. OH absorption peaks must be accounted for in the use of optical fibers (especially around 1400 nm).
6. Optical fiber attenuation is characterized with attenuation coefficient $\alpha$ with the equation $P(z) = P(0) \cdot \exp(-\alpha \cdot z)$.
7. The absorption coefficient $\alpha$ exists in two forms: the Napierian $\alpha_p$ and the decadal $\alpha$, namely we have $\alpha \text{ [dB/km]} = 4.343 \cdot \alpha_p \text{ [1/km]}$.
8. The attenuation along a fiber is given by the Lambert-Beer law and is calculated from $P(z) = P(0) \cdot \exp(-\alpha z)$.
9. Power referenced to 1 milliwatt is stated in dBm (it is ten times the base-10 logarithm of the ratio of the power stated to 1 milliwatt).
10. **Optics Review**: Light is an electromagnetic wave that carries energy and momentum; travels in vacuum at constant speed of $c = 3 \times 10^8$ meters/second.
11. Snell’s law is $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$.
12. Law of reflection: On a planar surface the incident angle equals the reflection angle.
13. In the core of an optical fiber we desire to have total internal reflection to contain the optical signal.

**Lecture 4**

1. Silica is silicon dioxide and can exist in many forms or structures.
2. The index of refraction $n$ of silica is weakly dependent upon wavelength (common values range from $n = 1.4$ to $1.6$).
3. The equation governs wave travel along a transmission line with a superposition of waves of the form $A_{\text{magnitude}} \times \exp(j(kz - \omega t))$ where $k$ is the wave number ($2\pi/\lambda$) and $\omega$ is the radian frequency.
4. Waves have a phase velocity \( v_{\text{phase}} = \frac{\omega}{k} \) and the energy of the wave travels at the group velocity \( v_{\text{group}} = \frac{d\omega}{dk} \)

5. Modes exist in transmission lines and in general each mode travels at a different group velocity

6. There are two primary categories of optical fibers: multi-mode fibers and single-mode fibers – the single-mode fiber uses a very small diameter core whereas the multi-mode fiber has a larger core diameter

7. Optical fibers can be either step index (constant core \( n \)) or graded index (core \( n \) is shaped)

8. The index of refraction of the core is always greater than the cladding index of refraction

9. Single-mode fiber is best for long-haul applications such as for WAN, data center and submarine cable links; multi-mode fiber is best for shorter distance applications such as LAN and MAN networks

10. The numerical aperture \( NA \) of a fiber is \( NA = \sqrt{n_1^2 - n_2^2} \)

11. The acceptance angle \( \theta_{ac} \) is related to the \( NA \) by \( NA = n \cdot \sin(\theta_{ac}) \)

12. Linearly polarized modes exist in optical fibers for multi-mode fiber, but not of single-mode fiber

**Lecture 5**

1. The V-number was introduced and a way to evaluate if at least one mode is supported, and if more modes are supported (depends upon core radius \( a \)), then how many modes are estimated \( V = \frac{(2\pi a / \lambda)}{\sqrt{n_1^2 - n_2^2}} \times NA \)

2. An optical fiber has a cutoff wavelength that depends upon the V-number and is given by \( \lambda_c = \frac{(2\pi a / V)}{\sqrt{n_1^2 - n_2^2}} \times \sqrt{n_1^2 - n_2^2} \)

3. The mode-field diameter increases as wavelength increases

4. Digital bit rate \( B_T \) (with no overlapping adjacent pulses) is limited to the reciprocal of twice the bit period length \( \tau \), \( B_T < \frac{1}{2\tau} \)
5. The digital bit rate and the maximum bandwidth ($BW$) of the channel is dependent upon whether the data coding is return-to-zero (RZ) or non-return-to-zero (NRZ); $B_{\text{f}}(\text{max}) = 2 \times BW$ if NRZ and $B_{\text{f}}(\text{max}) = BW$ if RZ

6. Bandwidth times the length of the link is a useful metric for comparing the capacity different optical fiber links

7. Dispersion causes pulse spreading and attenuation of digital signals traveling down a dispersive fiber

8. Types of dispersion: (a) Modal dispersion (limited to multi-mode fibers), (b) chromatic dispersion (related to term material dispersion), and polarization mode dispersion

9. Modal dispersion is where the signal is spread in time because the propagation velocity of the optical signal is not the same for all modes

10. InterSymbol Interference (ISI) is the phenomena where adjacent pulses spread into each other making it more difficult to unambiguously interpret the signal without error

**Lecture 6**

1. Dispersion in optical fibers lead to digital pulse spreading and attenuation – called InterSymbol Interference (ISI)

2. Chromatic dispersion (also called material dispersion) of an optical medium is the phenomenon that the phase velocity and group velocity of light propagating in an optical fiber depend upon the optical frequency; that dependency results mostly from the interaction of light with electrons of the medium

3. Dispersion is usually stated in units of ps/nm/km

4. Waveguide dispersion is usually small in single-mode fiber as compared with chromatic dispersion

5. Polarization mode dispersion (PMD) is a form of modal dispersion where two different polarizations of light in a waveguide, which normally travel at the same speed, travel at different speeds due to random imperfections and asymmetries in the fiber core

6. Mode coupling (or mode mixing) occurs in multi-mode fiber when energy form one mode is transferred to other modes propagating in the fiber – this
tends to reduce the overall effect of dispersion in a fiber over longer distances
7. Mode coupling results from (a) fiber structural imperfections, (b) fiber diameter variations, index of refraction variations, microbending, fiber splices and connectors
8. Dispersion-engineered fibers can be designed to shift, flatten and compensate dispersion coefficients ($D$)
9. All optical fiber sources (LEDs and lasers) exhibit linewidth spread from the operation of the source – this linewidth spread has a similar effect as intrinsic fiber dispersion on the optical signal
10. Plastic fibers, compared to silica fibers, have much higher attenuation, larger in diameter & primarily useful at shorter wavelengths
11. Submarine Optical Fiber Cables (SOFC) are used in tele-communications (especially for Internet connection) for island-to-island, island-to-continent and continent-to-continent connection
12. Record: The Maera SOFC connection was completed in February 2018 which ran from Virginia Beach, VA to Bilbao, Spain, covering 4,100 miles with a 160-terabit/second data rate
13. As of February 2019, there were 378 SOFC connections in operation
14. Special ships are used to put down SOFC connections
15. SOFC require special construction to give them great tensile strength and protection for harsh environmental conditions

Lecture 7

1. Photons travel at the speed of light ($3 \times 10^8$ meters/second) and the energy of a photon is $E = hf$ and $E = |p|c$  [$h$ is Planck’s constant]
2. Atoms have discrete energy levels (think of Bohr model of atom) for which electrons make transitions either absorbing energy or emitting energy via photons, that is, $E_{nm} = E_n - E_m$
3. Absorption in an atom (or material) is the absorption of a photon which correspondingly raising the energy of an electron
4. There are two categories of emission: spontaneous (purely random) and stimulated (i.e., a passing photon stimulates the atom to emit another photon (with the same energy or frequency, same direction, same phase and same polarization
5. The Einstein coefficients are mathematical quantities which are a measure of the probability of absorption or emission of light by an atom or molecule. The Einstein A coefficient is related to the rate of spontaneous emission of light, and the Einstein B coefficients are related to the absorption and stimulated emission of light.

6. Population inversion \((N_2 > N_1)\) is required for laser operation.

7. With a two-level atomic system population inversion is not possible.

8. It requires three-level, four-level or higher, with an intermediate metastable level present, to achieve population inversion.

9. An optical cavity, with aligned reflecting mirrors at the ends, forms a Fabry-Pérot cavity.

10. Stimulated emission provides the gain or amplification in a laser cavity which must overcome the losses (from absorption and scattering in both the medium and at the mirrors).

11. Lasers are not perfectly monochromatic because of thermal motion, collisions and atomic vibrations being present gives rise to linewidth broadening.

12. Standing waves in cavities set up longitudinal modes which potentially can be involved in laser operation.

13. The frequencies of these standing waves in a cavity of length \(L\) is \(f = (mc^2/2nL)\) where \(m\) is an integer and \(n\) is the index of refraction. The mode spacing is given by \(\Delta \lambda = (\lambda^2/2nL)\).

14. The gain curve of the filled laser cavity is established by the stimulated emission transition energy with broadening included.

15. The longitudinal modes under the gain curve, where the gain exceeds the losses, sets the laser oscillating frequencies (often several adjacent frequencies can be present).

**Lecture 8**

1. Atoms have discrete energy levels (for outer electrons) but solids have energy bands where electrons and holes reside.

2. Electrons in conduction band from thermal generation or from donor atoms in lattice.

3. Holes in valence band from thermal generation or from acceptor atoms in lattice.

4. Electrons and holes viewed as wave packets in motion (can’t localize...
these charge carriers) with separate effective masses ($m^*$)
5. Semiconductors have forbidden bandgaps which dominate their physical properties
6. Holes have positive charge and electrons have negative charge which under low doping conditions can be treated as classical particles (but don’t look too closely at the “particle”)

Lecture 9

1. Bandgaps play a dominating role in semiconductors
2. Intrinsic semiconductors (undoped) have equal numbers of electrons and holes
3. Electrons are mobile in the conduction band and holes in the valence band
4. Concentrations are controlled by introducing impurity atoms (donors provide electrons and acceptors provide holes)
5. Each electron or hole state have both energy level and crystal momentum
6. Formation of pn junction: a depletion layer creates a potential barrier
7. In the depletion layer immobile donors are positive and immobile acceptors are negative
8. Donor dominated material is n-type and acceptor dominated material is p-type
9. Minority carriers exist along with the majority carriers following the law of mass action: $pn = n_i^2$
10. Spontaneous emission from electron-hole recombination with wavelength $\lambda = (1.24/E_G)$
11. Semiconductors can be either direct bandgap or indirect bandgap
12. Crystal momentum $k$ is quantized into discrete values as phonons
13. In indirect bandgap recombination both a photon (mainly energy) and a phonon (mainly momentum) must be emitted for the recombination to occur
14. Thus, minority carrier lifetime is generally much longer that for direct bandgap recombination because it is harder to balance both energy and momentum simultaneously
Lecture 10

1. Direct bandgap semiconductors are best for LEDs and lasers
2. Compound semiconductors allow for many direct bandgap options
3. Different compound semiconductors allow for bandgap and refractive index choice, but under the restriction of matching lattice spacings
4. Heterojunction is the interface between layers or regions of different crystalline semiconductors (with different bandgaps)
5. Double heterojunctions allow for quantum wells where electrons and holes can reside in greater concentrations
6. MBE and MOCVD are used to grow heterostructures
7. Rate equations for both electrons and photons were presented (refer to Lecture 10, slides 21 through 24)
8. A static analysis using the rate equations show that the light output is proportional the diode current beyond the laser threshold current
9. Differential external quantum efficiency is the slope of the $P-I$ characteristic
10. Stripe lasers have significant diffraction of their optical beam output
11. Stripe lasers use both gain-guiding and index-guiding for confinement in their laser cavity
12. Double heterostructures are used in many semiconductor lasers
13. Distributed feedback lasers use Bragg reflectors (periodic modulation of index of refraction)
14. Both standard and quarter-wave shifted distributed structures are used in distributed feedback (DFB) lasers

Lecture 11

1. Bragg gratings (aka distributed Bragg reflectors) can be used to make distributed feedback lasers (i.e., DFB lasers).
2. The Bragg grating is best positioned immediately above the laser’s active region (but not within the active region)
3. Multiple-quantum well structures can be used to confine photons (and electrons or holes)
4. VCSELs are “vertical cavity surface emitting lasers” which use Bragg reflectors positioned perpendicular to the laser beam direction to form the laser cavity
5. An anti-reflection coating is a quarter-wave layer to produce a dual reflection leading to the destructive interference of the two reflected waves
6. Optical lenses are used to focus a diverging laser beam to direct the laser’s output into the core of an optical fiber
7. Erbium-doped fiber amplifiers are used to amplify signals carried in the core of the optical fiber
8. Erbium exists as an ion within the optical fiber, thus forming a three-level laser medium
9. We started the new topic: optical detectors
10. The simplest optical detector is photoconductivity
11. The depletion region of a photodiode contains an electric field within the depletion region which immediately separates the electron and hole upon being created by the absorption of a photon in the depletion region
12. As light penetrates a material its intensity decays exponentially as the light travels deeper (characterized by absorption coefficient $\alpha_0$)
13. The absorption coefficient is a function of wavelength, with the band edge (or long-wave cutoff point) wavelength being $\lambda_C = (hc/E_G)$

Lecture 12

1. Photodiodes can be illuminated from the front side or back side
2. The PIN photodiode has an intrinsic (or low doped) region between the n-type and the p-type regions and increases the depletion region volume (by widening the depletion region of width W)
3. All photodiodes are operated in the reverse bias mode
4. There are three factors that affect the photodiode’s response time – (a) drift time of the carriers within the depletion region, (b) diffusion time of
carriers generated outside the depletion region, but within several diffusion lengths, and (c) junction capacitance resulting in an RC time constant with external resistances in a receiver

5. Carriers move in semiconductors under the influence of an electric field because these carriers are electrically charged – (a) at low electric fields by mobility $\mu$, and (b) at high electric fields at their saturated velocity ($v_{\text{sat}}$)

6. Most often photodiodes are bandwidth limited via their response time by drift time in the depletion region (i.e., maximum bandwidth is

$$BW_{\text{max}} = \frac{v_{\text{drift}}}{2\pi W}$$

This is essentially a “gain-bandwidth product” figure of merit

7. The best pulse response from a photodiode is when $W >> 1/\alpha$ ($\alpha$ is the absorption coefficient of the semiconductor) and the capacitance is small

8. Photodiodes are always designed to avoid being $RC$ time constant limited in response time

Lecture 13

1. Avalanche carrier multiplication arises from impact ionization of energetic carriers hitting the lattice (these carriers gain high energy from the strong electric field within the depletion region)

2. The multiplication factor $M$ is defined as the ratio of the multiplied photocurrent divided by the primary unmultiplied photocurrent

3. Avalanche photodiodes are doped so that only part of their depletion layer exceeds the critical electric field $E_c$ where avalanche multiplication occurs

4. The ionization coefficients model the strength of the multiplication; coefficients are different for different semiconductors and increase in magnitude with increasing electric field within the depletion region

5. Avalanche multiplication is an inherently noisy process

6. High electric fields at junction edges lead to excessive leakage current (like dark current) and lower breakdown voltages – guard-band rings are used at junction edges to reduce edge degradation

7. The major advantage of the avalanche photodiode (APD) is the inherent gain from carrier multiplication leading to superior performance over PIN photodiodes for recovering low-level optical signals
8. APDs have faster response times than pn-junction and PIN photodiodes.
9. However, APDs are more difficult to fabricate, possess higher noise, require higher reverse voltages, lower reliability and output a nonlinear current versus optical power input.

Midterm Given October 11, 2019

EE 443 Review Notes for Lectures 14 through 21
(Fall 2019)

Lecture 14

1. Thermal motion of charge carriers at equilibrium has a net zero thermal velocity, but the average carrier velocity \( v_{th} \) is of the order of \( 10^7 \) cm/sec with a randomizing mean time between collisions \( \tau_c = 10^{-13} \) seconds.
2. An applied electric field \( E \) gives a net drift velocity \( v_{drift} \) to the charge carriers, thus, an electric field establishes a drift current (where the force on the charge carriers is directly proportional to \( E \)).
3. The electron drift current density \( J = qnv_{drift} \).
4. Mobility \( \mu \) quantifies carrier drift from the applied electric field \( E \), where \( \mu = (q\tau_c/2m^*) \) and the drift velocity magnitude is equal to \( \mu E \).
5. For high electric fields, exceeding the critical electric field \( E_c \), the carrier velocity saturates at a nearly constant value \( v_{sat} \).
6. Diffusion current is the result of a non-uniform concentration of mobile charge carriers.
7. Fick’s first law:
   \[ J = -D \frac{dC}{dx} \]
8. Drift and diffusion currents add together in semiconductor materials for both electrons and holes.
9. Noise – we consider primarily white additive Gaussian noise (which follow a Gaussian probability distribution function characterized by a mean value and a standard deviation).
10. Thermal noise results from the thermal agitation of charged carriers; for resistor R, the mean-squared thermal noise voltage and mean-squared thermal noise current are given by

\[ <v_n^2> = 4kTR\Delta f \]
\[ <i_n^2> = \frac{4kT\Delta f}{R} \]

11. Thermal noise power is given by

\[ P_n = kT\Delta f \]; independent of value of R

12. Shot noise (a Poisson process) results from discrete charge carriers randomly crossing a region (like a depletion region) or potential barrier and have a mean-squared shot noise current of

\[ <i_n^2> = 2qI_{DC}\Delta f \]

13. Avalanche multiplication noise results from random collisions of highly energized charged carriers with the crystal lattice – very noisy and can only be empirically modelled

14. The signal-to-noise ratio (SNR) is defined as the ratio of the signal power to the total noise power at a specific node or point

15. The photodiode SNR is given by

\[ \frac{S}{N} = \frac{i_p^2}{2q(I_p + I_d)\Delta f} \]

Lecture 15

1. Model of noise in a two-port network can be accomplished by placing a voltage noise source and current noise source, with correlation coefficient \( \gamma \), at the input port of the network.

2. The signal-to-noise (SNR) for a photodiode with

\[ \frac{S}{N} = \frac{i_p^2}{2q(I_p + I_d)\Delta f + \frac{4kT\Delta f}{R_L}} \]

3. The noise factor (F) is defined as

\[ F = \frac{(S_{in} / N_{in})}{(S_{out} / N_{out})} = 1 + \frac{N_{amp}}{G \cdot N_{in}} \]
and the noise figure (NF) is calculated from $10 \log_{10} (F)$.

4. The signal-to-noise ratio of a photodiode with the amplifier’s noise is

$$\frac{S}{N} = \frac{I_p^2}{2q(I_p + I_d)\Delta f + \frac{4kT\Delta f}{R_L} + <\dot{i}_{amp}^2>} = \frac{I_p^2}{2q(I_p + I_d)\Delta f + \frac{4kT\Delta f}{R_L} F}$$

5. The noise equivalent power (NEP) is defined as

$$\text{NEP} = \frac{P_{\text{min}}}{\sqrt{\Delta f}} = \sqrt{\frac{4kT}{R_L}}$$

6. Bandwidth and noise tradeoff in a photoreceiver – increasing one generally decreases the other.

7. The bandwidth of a photodiode with biasing network is determined by the total capacitance and equivalent resistance at the front-end node.

8. An important figure of merit is the gain-bandwidth product of a network – it is best visualized on a log-log plot of gain versus frequency – the unity gain-bandwidth frequency is denoted by $f_T$.

9. Photoreceivers can be categorized into three bins: low-impedance front-end, high-impedance front-end, and transimpedance front-end.

10. Low-impedance photoreceiver – improves bandwidth but higher thermal noise is larger so this photoreceiver is not so good for long-haul OPC systems.

11. High-impedance photoreceiver – lowers bandwidth but increases noise performance leading to a reduction of dynamic range that can result in receiver saturation.

12. Transimpedance photoreceiver – overcomes some of the limitations of the high-impedance photoreceiver by using negative feedback resulting in higher bandwidth.

13. Closing the loop with feedback increase bandwidth where

$$B = \frac{1}{2\pi R_f C_T}$$

14. The feedback resistance $R_f$ can’t be made large enough to significantly lower the noise because higher values of $R_f$ lead to stability problems.
15. The transimpedance photoreceiver is generally preferred when all parameters are considered.

16. Field-effect transistors are generally used for preamplification in optical photoreceivers – high input impedance, voltage-controlled device, unipolar (no minority carriers), and lower noise smaller and simpler to fabricate than bipolar junction transistors (BJT).

17. MOSFET, silicon junction FET, GaAs MESFET and HEMT (MODFET) are all high-input impedance devices.

Lecture 16

1. The requirements of an OFC link include transmission distance, data rate and bit-error rate (BER).
2. Primary elements of the OFC link include source, fiber transmission link and photodetector (photodiode and amplifier).
3. Our two primary parameters of interest were (1) link power budget and (2) rise-time budget (to be sure we meet the data rate needed).
4. All OFC systems should have a link power margin (typically 6 to 8 dB) to allow for temperature variations, component aging and future component replacement or interchange.
5. The optical power-loss model included the source, fiber flylead connect, connectors, fiber sections (with splices as required), fiber flylead to receiver and photodiode (with amplifier).
6. Slide 15 summarized data on photodiodes receiver sensitivity versus data rate for several commonly used photodiodes (e.g., PIN vs APD).
7. One way to present a link-loss budget for an OFC link is to plot the power level versus distance of the link; showing source output power, step losses for connectors and splices, sloped loss of fiber itself, system margin and minimum detector sensitivity.
8. Another way to present a link-loss budget is with a spreadsheet table (which summarizes the loss increments on the plot).
9. The rise-time budget includes four rise time components: the transmitter rise time, the group velocity (material) dispersion rise time, the modal dispersion (multimode fiber only) rise time and the receiver (photodiode) rise time.
10. The system rise time is calculated by taking the root-mean-square of the sum of the four rise times.
\[
t_{\text{system}} = \sqrt{\sum_{i=1}^{4} t_i^2} ; \quad i = 1, 2, 3, 4
\]

11. The transmitter rise time depends upon the diode’s response time and the drive circuitry around it.

12. The receiver rise time is dominated by the behavior of an RC network with 10%-to-90% rise time \( \tau \) (nanoseconds) related to the receiver’s bandwidth \( B_{\text{rcvr}} \) in MHz by

\[
\tau = \frac{350}{B_{\text{rcvr}}}
\]

13. The group velocity (material) dispersion rise time can be estimated from the dispersion coefficient \( D \), the fiber length \( L \) and the spectral width \( \sigma_{\lambda} \),

\[
t_{\text{mat}} = |D| L \sigma_{\lambda}
\]

14. The modal dispersion rise time is estimated assuming a Gaussian pulse temporal response with a standard deviation (spread) \( \sigma \) where the full-width half-maximum rise time is

\[
t_{\text{FWHM}} = t_{\text{mod}} = 2\sigma \sqrt{2 \log_e (2)} = 2.35\sigma
\]

15. Examples of transmission distance versus data rate for both 800 nm and 1550 nm wavelengths were presented to illustrate the attenuation dominated region versus the dispersion dominated region of operation (obviously, at higher data rates).

**Lecture 17**

1. Pulse Code Modulation (PCM) is used to represent analog data as a sequence of binary (1s and 0s) digital signal (a string of bits).
2. A bit is the basic data unit in digital communications and the bit rate is the basic data rate.
3. Symbols are made up of combinations of bits for format signals for transmission.
4. The symbol rate is the number of symbols per second (also called the signal rate, or baud rate).
5. The bit rate \( R_b \) is the reciprocal of the bit period \( T_b \) \( (R_b = 1/T_b) \).
6. The symbol rate \( R_s \) is the reciprocal of the symbol period \( T_s \) \( (R_s = 1/T_s) \).
7. The bit rate may be written as $R_b = R_s \times \log_2 (n)$ where $n$ is the number of bits per symbol.

8. Signal-to-noise ratio (SNR) measures the signal power to noise power ratio.

9. Energy per bit $E_b$ to noise spectral density $N_0$ is related to the SNR by

$$\text{SNR} = \left( \frac{R_b}{B} \right) \left( \frac{E_b}{N_0} \right)$$

where $R_b$ is the bit rate and $B$ is the total bandwidth.

10. $E_b/N_0$ can be thought of as a normalized SNR. ($E_b = P_{\text{signal}} \times T_s$, where $T_s$ is the symbol period).

11. Baseband signaling can be categorized into four categories: Non-Return-to-Zero (NRZ), Return-to-Zero (RZ), Phase-encoded and Multi-level.

12. Desirable properties of a line code include:
   a. Self-synchronization
   b. Low bit error probability
   c. Suitable power spectral density
   d. Adequate transmission bandwidth
   e. Error detection capability

13. Primary examples of line codes presented were
   a. Unipolar RZ and unipolar NRZ
   b. Polar RZ and polar NRZ
   c. Bipolar NRZ and bipolar RZ (aka duo-binary)
   d. Bipolar RZ (3-level) or RZ-AMI
   e. Manchester (bi-phase or split-phase)

14. Manchester is the IEEE 802.3 standard (Ethernet) and has a transition at the center of every bit period (a “one” is $+A$ in the first-half of the period and is $-A$ in the second-half; a “zero” is $-A$ in the first-half of the period and $+A$ in the second-half).

15. Manchester coding is easy to synchronize, has no DC component but needs twice the bandwidth of NRZ coding.

16. The spectral density $S(f)$ of signal $s(t)$ is the Fourier transform

$$S(f) = \int_{-\infty}^{\infty} s(t) e^{-j2\pi ft} dt$$

and $s(t)$ can be regained by taking the inverse Fourier transform.
17. The power spectral density (PSD) of the signal describes the power spectral density – it is commonly expressed in watts per hertz (W/Hz).

18. The power spectral density of signal $s(t)$ is equal to $|S(f)|^2$.

19. The power spectral density can be obtained by taking the Fourier transform of the autocorrelation function of $s(t)$.

**Lecture 18**

1. Many factors can give rise to splice and connector loss: end gaps, non-concentric alignment, NA mismatch, core mismatch, non-coaxiality, poor finish or dirt on end of fiber strands.
2. Two types of fiber splicing are used: fusion splicing and mechanical splicing.
3. Fusion splicing is welding of two fibers together with careful alignment and use of an electric arc for heating.
4. Fusion splicing equipment is available for field and laboratory use.
5. Mechanical splicing commonly uses a V-groove for alignment of the fibers and then a lid is tightly fastened to mechanically grip the fibers.
6. Cleaving the ends of the fiber is a critical step in obtaining a good splice.
7. Evaluation of splice quality: Use optical time domain reflectometry. This is a measurement technique analogous to radar – a narrow light pulse is launched down the fiber and a sensitive detector then measures the reflected signal of the fiber under test.
8. In OTDR, connectors show typically show a reflection spike followed by a step down equal to the loss of the connector and splices show only a step down equal to the loss (no reflected pulse).
9. Many OFC connectors are available – connectors are for convenience and quick connect/disconnect and consist of a ferrule, a connector body, and a latching or coupling mechanism to hold the connection over time without failure.
10. The most common types of connectors are the FC, ST, SC, LC and the MTP connectors. While many others exist, these have been the most widely used.
11. Some connectors use fibers with an angled physical contact (APC) for mating to its companion connector.

**Lecture 19**
1. Optical nodes require components such as multiplexers, demultiplexers, optical add/drop multiplexers, reconfigurable optical add/drop multiplexers, and cross-connect switches.
2. Opto-electronic integrated circuits (OEIC) use planar and strip waveguide structures to carry optical signals.
3. Splitters are constructed using Y-junction path splitters and combiners are the inverse operation of splitters.
4. Splitters are a critical part of passive optical networks (called PONs).
5. Optical couplers are of two types: (1) core interaction type and (2) surface interaction type.
6. Couplers are made with n input ports and m output ports.
7. Couplers work by light scattering allowing for optical energy to bleed from one fiber core to an adjacent fiber core.
8. Couplers can be operated as switches, 3-dB splitters and fractional splitters where the splitting ratio controls the sampling of the main signal.
9. Key coupler parameters include the insertion loss, excess loss and the crosstalk loss (all usually expressed in decibels).
10. Electro-Optical effects (E-O effects) covered in Lecture 19 were the Pockels effect (a linear change in the index of refraction with an applied electric field) and the Kerr effect (a quadratic change in the index of refraction with an applied electric field).
11. Applications for E-O devices include scanning devices, phase modulators, polarization shifters, intensity modulators (Mach-Zehnder interferometers) and switches.
12. Electrodes are used on E-O materials in both longitudinal & transverse configurations to allow the internal electric field to be set by an applied voltage.
13. A Pockets cell phase modulator allows for a phase shift $\varphi = \varphi_0 - \pi(V/V_\pi)$ where $V$ is the externally applied voltage and $V_\pi$ is the half-wave voltage.
14. A commonly used E-O material is lithium niobate ($\text{LiNbO}_3$) and is capable of being modulated very rapidly (up to frequencies approaching 100 GHz).
15. Splitting an optical signal into two branches and applying the E-O effect to one of the branches, and thereafter recombining the two branches allows for a Mach-Zehnder interferometer to be formed.
An E-O prism can be made using a wedge-shaped structure with electrodes attached to the ends allows for a voltage-controlled bend angle of refracted light. This can be used to make an optical multiplexer of demultiplexer.

**Lecture 20**

1. Eye diagrams are used for the assessment of data handling ability of a digital transmission system, especially in optical fiber links.
2. Key parameters for eye diagrams: eye-opening height, eye time jitter, rise times and fall times, zero-crossings, overshoot and undershoot of waveforms and estimating best time to sample bit.
3. Bit error ratio testing makes use of pseudo-random bit patterns (PRBS) that are generated using algorithms to create bit sequences that represent actual data patterns used in the optical link and are reproducible.
4. Eye diagrams are displayed on fast, digital storage oscilloscopes.
5. A bit error ratio (BER) test instrument generates the desired PRBS sequence and sends repetitive copies on the bit pattern through the system under test (SUT), and then upon receiving the data streams from the system, compares the sent bit stream to the received bit stream (Slide 11).
6. Eye diagram degrade as the signal travels along the optical link (Slide 13).
7. Degradation of the eye is from three causes: (1) additive white Gaussian noise adding to the signal waveform, (2) inter-symbol interference (ISI) resulting in the overlapping of bits (Slide 16), and (3) fiber attenuation of the signal over long spans in the fiber link (Slide 17).
8. The results of bit error ratio tests are usually presented in the format of a plot of the bit error ratio (or ratio or probability) versus the signal-to-noise ratio (SNR) or the $E_b/N_0$ parameter. These are equivalent when properly interpreted.
9. A useful analysis of bit error ratio is carried out by combining additive white Gaussian noise (AWGN) to both the upper & lower bit signal levels where the noise broadens these levels relative to a decision level. Bit errors occur when the noise changes a one or zero level, so it crosses over the decision level.
10. Slides 21 through 34 presented a mathematical analysis of the calculation of the bit error probability (we used error function and complementary error functions to do this).
Lecture 21

2. This lecture covers wavelength division multiplexing.
3. Wavelength-division multiplexing (WDM) is a technology which multiplexes multiple optical carrier signals onto a single optical fiber by using different wavelengths.
4. Coarse WDM provides up to 18 (but practically only 16) channels across the multiple transmission windows of silica fibers. Wavelength spacing is 20 nm for CWDM.
5. Dense WDM (DWDM) refers originally to optical signals multiplexed within the 1550 nm band so as to leverage the capabilities (and cost) of erbium-doped fiber amplifiers (EDFAs).

<table>
<thead>
<tr>
<th>Name</th>
<th>Optical Band</th>
<th>Wavelength Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>(Original)-Band</td>
<td>1260 nm to 1360 nm</td>
<td>Original Band; PON upstream</td>
</tr>
<tr>
<td>E</td>
<td>(Extended)-Band</td>
<td>1360 nm to 1460 nm</td>
<td>Water peak band</td>
</tr>
<tr>
<td>S</td>
<td>(Short)-Band</td>
<td>1460 nm to 1530 nm</td>
<td>PON downstream</td>
</tr>
<tr>
<td>C</td>
<td>(Conventional)-Band</td>
<td>1530 nm to 1565 nm</td>
<td>Lowest attenuation; original DWDM band; compatible with fiber amplifiers and CATV</td>
</tr>
<tr>
<td>L</td>
<td>(Long)-Band</td>
<td>1565 nm to 1625 nm</td>
<td>Low attenuation; expanded DWDM band</td>
</tr>
<tr>
<td>U</td>
<td>(Ultralong)-Band</td>
<td>1625 nm to 1675 nm</td>
<td>Reserved for future use</td>
</tr>
</tbody>
</table>

7. Benefits of CWDM:
   1. Passive equipment that uses no electrical power
   2. Much lower cost per channel than DWDM
   3. Scalability to grow fiber capacity with little increased cost
   4. Allows uncooled lasers to be used
5. Ease of use compared to DWDM

Drawbacks of CWDM:

1. 16 channels may not be enough
2. Passive equipment that has no management capabilities
3. Costs significantly more per channel than BWDM
4. Fiber loss often excludes wavelengths below 1470 nm

8. The functionality of DWDM (Dense Wavelength Division Multiplexing) resembles that of CWDM. Currently, DWDM is limited to wavelengths between 1530 nm and 1625 nm, corresponding to the C and L bands. DWDM is more expensive compared to CWDM because more sophisticated transceivers must be used.

9. Number of channels in DWDM systems

Currently four specific frequency grids are defined to support dense wavelength division multiplexing applications:

(i) 12.5 GHz spacing (0.1 nm spacing)
(ii) 25 GHz spacing (0.2 nm spacing)
(iii) 50 GHz spacing (0.4 nm spacing)
(iv) 100 GHz spacing (0.8 nm spacing)

10. The arrayed waveguide grating is better than the fiber Bragg grating because (1) it handles a much wider range of wavelengths, and (2) can be fabricated in a much smaller size.

11. Advantages of DWDM

• Every wavelength is independent of others
• Optical amplifier acts on all wavelengths, providing cost savings over a single amplifier per fiber
• The capability to support up to 160 wavelengths means that over 1 Tb/s of traffic can be used (1 Tb = 10^{12} bits)
• Each wavelength can be a different traffic type such as SONET, gigabit, Ethernet or IP, and can operate at different speeds
• Easier network expansion – just add a new wavelength rather than adding a new fiber strand (low incremental cost)
• Allows for very long fiber links at very high data rates
• A key advantage to DWDM is that it's protocol- and bit-rate-independent

12. Disadvantages of DWDM
• Vendor inter-operability issues
  • DWDM systems can be extremely difficult to troubleshoot, manage and provision
• DWDM solutions are quite expensive
• Active solutions require a lot of set-up and maintenance expense
• Greater dependence on stable optical sources \( (e.g., \text{cooled and stabilized lasers}) \)
• Complicated transmitters and receivers
• Wide-band channel means high CAPEX and OPEX
• The wavelength domain involved in the network design and management, increases the difficulty for implementation