Lecturer: Prof. Dr. Moustafa Hussein   **Optical Communications**
G.T.A. Eng. Ahmed Fahmy

Sheet (0)

General in Communications

1] a. Write the relation between the frequency and wavelength of an emw propagating in free space.
   b. Designate the wavelengths of the waves having the frequencies:
   500 Hz, 50 kHz, 50 MHz, 5 GHz, 5 THz, 50 THz, 500 THz, 5 PHz, 50 PHz, 5 EHz,   500 EHz.
   c. Calculate the frequencies of the emws having the wavelengths:
   30 km, 300 m, 3 m, 3 dm, 3 cm, 3 mm, 0.3 mm, 30 μm, 3 μm, 0.3 μm, 30 nm, 0.3 nm, 30 pm.

2] An effective antenna must have a length at least λ/10 , where λ is the wavelength of the emw to be radiated by the antenna. Calculate the minimum length of the antenna to radiate:
   100 Hz, 1000 Hz, 10 kHz, 1 MHz, 10 MHz, 100 MHz, 200 MHz, 2 GHz.

3] In AM radio broadcasting, each station is allocated a frequency span of 10 kHz width. How many stations can broadcast simultaneously in the medium wave (MW) broadcasting range extending from 530 kHz to 1620 kHz ?

4] FM radio broadcasting operates in the frequency range 88 MHz - 108 MHz. If each FM station is allocated 200 kHz, how many FM stations could be accommodated ?

5] In telephone systems, single side band AM modulation is adopted, where each call is allocated a frequency band of 4 kHz. If the bandwidth of the communication channel (coaxial cable) counts up to12 MHz, what is the number of telephone calls that can be sent simultaneously (multiplexed) on this cable?

6] An optical fiber can carry up to 1 Tbps. Given that each call is allocated a frequency band of 4 kHz:
   a. calculate the bps of each call.
   b. calculate the no. of calls that can be transmitted through this fiber.

7] Two identical multimode fibers operating at a certain wavelength that causes only intermodal dispersion. Fiber I is a step index one carrying 60 telephone calls (64 kbps each). Fiber II is an optimum near parabolic graded index one carrying 10000 video signals (compressed) and can transmit a number of bits 1000 times that can be transmitted by fiber I. Estimate the bit rate of each compressed video signal.

8] Each television channel occupies a frequency bandwidth of 7 MHz. The VHF channels 1 to 4 are allocated the frequency range 41-69 MHz, while the VHF channels 5-12 occupy the frequency range 174-230 MHz. Designate the lower and upper frequency ends of each TV channels.
   a. If the picture carrier is 1.25 MHz far from the lower edge of the channel and the sound carrier is 0.25 MHz lower than the upper edge, designate the frequency of the picture and sound carriers of each of the channels 1-12.
   b. What are the lower and upper edges of the UHF channels 13-64 that start from 470 MHz?

   picture carrier   sound carrier
         ↓   ↓
   1.25 MHz   **5.5 MHz**   **0.25 MHz**
   ---------!------------!---!----!------
   181 MHz   **188 MHz**

Lecturer: Prof. Dr. Moustafa Hussein	Optical Communications
G.T.A. Eng. Ahmed Fahmy	

Sheet (1)

Optical Fiber Waveguides

1] A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.5 and a cladding refractive index of 1.47. Determine:

      a. the critical angle at the core-cladding interface;

      b. the NA for the fiber.

      c. the acceptance angle in air for the fiber.

$(78.5^{o} , 0.30 , 17.4^{o})$

2] An optical fiber has a numerical aperture of 0.20 and a cladding refractive index of 1.59. Determine:

      a. the acceptance angle for the fiber in water which has a refractive index of 1.33;

      b. the critical angle at the core-cladding interface.

$(8.6^{o} , 83.6^{o})$

3] The velocity of light in the core of a step index fiber is 2.01×10^{8} m/s, and the critical angle at the core-cladding interface is 80°. Determine the numerical aperture and the acceptance angle for the fiber in air, assuming it has a core diameter suitable for consideration by ray analysis. The velocity of light in vacuum is 2.998×10^{8} m/s.

$(0.26 , 15.07^{o})$

4] A step index fiber with a large core diameter compared with the wavelength of the transmitted light has an acceptance angle in air of 22° and a relative refractive index difference of 3%. Estimate the numerical aperture and the critical angle at the core-cladding interface for the fiber. $(0.37 , 75.9^{o})$

5] A step index fiber with a suitably large core diameter for ray theory consideration has core and cladding refractive indices of 1.44 and 1.42 respectively. Calculate the acceptance angle in air for skew rays which change direction by 150° at each reflection.

(67.5^{o})

6] The relative refractive index difference between the core axis and the cladding of a graded index fiber is 0.7% when the refractive index at the core axis is 1.45. Estimate the value of the numerical aperture.

(0.172)

7] A multimode graded index fiber has an acceptance angle in air of 8°. Estimate the relative refractive index difference between the core axis and the cladding when the refractive index at the core axis is 1.52.

(0.42%)

8] A typical relative refractive index difference for an optical fiber designed for long transmission is 1%. Estimate the NA and the solid acceptance angle in air for the fiber when the core index is 1.46. Further, calculate the critical angle at the core-cladding interface within the fiber. It may be assumed that the concepts of geometric optics hold for the fiber.

$(0.21 , 0.13 , 81.9^o)$

9] Skew rays are accepted into a large core diameter (compared to the wavelength of the transmitted light) step index fiber in air at a maximum axial angle of 42°. Within the fiber they change direction by 90° at each reflection. Determine the acceptance angle for meridional rays for the fiber in air.

(28.2^o)

10] An optical fiber in air has a NA of 0.4. Compare the acceptance angle for meridional rays with that for skew rays which change direction by 100° at each reflection.

$(\theta_a=23.6^o , \theta_{as}=38.5^o)$

11] A step index fiber has a solid acceptance angle in air of 0.115 radians and relative refractive index difference of 0.9%. Estimate the speed of light in the fiber core.

$(2.11x10^8$ m/s$)$

12] A multimode step index fiber with a core diameter of 80 μm and a relative index difference of 1.5% is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48, estimate: a. the normalized frequency for the fiber.
        b. the number of guided modes. $(75.8 , 2873)$

13] A graded index fiber has a core with a parabolic refractive index profile which has a diameter of 50 μm. The fiber has a numerical aperture of 0.2. Estimate the total number of guided modes propagating in the fiber when it is operating at a wavelength of 1 μm.

(247)

14] A graded index fiber with a parabolic refractive index profile core has a refractive index at the core axis of 1.5 and a relative index difference of 1%. Estimate the maximum possible core diameter which allows single-mode operation at a wavelength of 1.3 μm.

$(6.6 \mu$m$)$

15] Determine the cutoff wavelength for a step index fiber to exhibit single-mode operation when the core refractive index and radius are 1.46 and 4.5 μm, respectively, with the relative index difference being 0.25%. $(1.214 \mu$m$)$

16] A step index fiber has a numerical aperture of 0.16, a core refractive index of 1.45 and a core diameter of 60 μm. Determine the normalized frequency for the fiber when light at a wavelength of 0.9 μm is transmitted. Further, estimate the number of guided modes propagating in the fiber.

$(33.5 , 561)$

17] A multimode step index fiber has a relative refractive index difference of 1% and a core refractive index of 1.5. The number of modes propagating at a wavelength of 1.3 μm is 1100. Estimate the diameter of the fiber core.

$(92 \mu$m$)$

18] A graded index fiber with a parabolic index profile supports the propagation of 742 guided modes. The fiber has a numerical aperture in air of 0.3 and a core diameter of 70 μm. Determine the wavelength of the light propagating in the fiber. Further, estimate the maximum diameter of the fiber which gives single-mode operation at the same wavelength.

(1.2 μm , 4.4 μm)

19] A graded index fiber with a core axis refractive index of 1.5 has a characteristic index profile (α) of 1.9, a relative refractive index difference of 1.3% and a core diameter of 40 μm. Estimate the number of guided modes propagating in the fiber when the transmitted light has a wavelength of 1.55 μm, and determine the cutoff value of the normalized frequency for single-mode transmission in the fiber.

(94 , 3.45)

20] A single-mode step index fiber has a core diameter of 7 μm and a core refractive index of 1.49. Estimate the shortest wavelength of light which allows single-mode operation when the relative refractive index difference for the fiber is 1%.

(1.93 μm)

21] In problem [20], it is required to increase the fiber core diameter to 10 μm whilst maintaining single-mode operation at the same wavelength. Estimate the maximum possible relative refractive index difference for the fiber.

(0.49%)

22] A single-mode step index fiber which is designed for operation at a wavelength of 1.3 μm has a core and cladding refractive indices of 1.447 and 1.442 respectively.
a. When the core diameter is 7.2 μm, confirm that the fiber will permit single-mode transmission.
b. Estimate the range of wavelengths over which this will occur.

(λ_{min} = 1.131 μm)

23] A single-mode step index fiber has core and cladding indices of 1.498 and 1.495 respectively.
a. Determine the core diameter required for the fiber to permit its operation over the wavelength range 1.48 to 1.60 μm.
b. Calculate the new fiber core diameter to enable single-mode transmission at a wavelength of 1.30 μm.

(11.95 μm , 10.5 μm)

24] A single-mode fiber has a core refractive index of 1.47. Sketch a design characteristic of relative refractive index difference Δ against core radius for the fiber to operate at a wavelength of 1.30 μm. Determine whether the fiber remains single-mode at a transmission wavelength of 0.85 μm when its core radius is 4.5 μm.

ARAB ACADEMY FOR SCIENCE & TECHNOLOGY & MARITIME TRANSPORT
COLLEGE OF ENGINEERING & TECHNOLOGY
Electronics and Communications Department

Lecturer: Prof. Dr. Moustafa Hussein   Optical Communications
G.T.A. Eng. Ahmed Fahmy

Sheet (2)

Transmission Characteristics of Optical Fibers

1] When the mean optical power launched into an 8 km length of fiber is 120 μW, the mean optical power at the fiber output is 3 μW. Determine:
   a. the overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splices.
   b. the signal attenuation per kilometer for the fiber.
   c. the overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB.
   d. the numerical input/output power ratio in (c).

(16.0 dB , 2.0 dB.km^{-1} , 29 dB , 794.3)

2] The mean optical power launched into an optical fiber link is 1.5 mW and the fiber has an attenuation of 0.5 dB.km^{-1} . Determine the maximum possible link length without repeaters (assuming lossless connectors) when the minimum mean optical power level required at the detector is 2 μW.

(57.5 km)

3] The numerical input/output mean optical power ratio in a 1 km length of an optical fiber is found to be 2.5. Calculate the received mean optical power when a mean optical power of 1 mW is launched into a 5 km length of the fiber (assuming no joints or connectors).

(10.24 μW)

4] A 15 km optical fiber link uses fiber with a loss of 1.5 dB.km^{-1} . The fiber is jointed every kilometer with connectors that give an attenuation of 0.8 dB each. Determine the minimum mean optical power that must be launched into the fiber in order to maintain a mean optical power level of 0.3 μW at the detector.

(703 μW)

5] A multimode graded index fiber has a refractive index at the core axis of 1.46 with a cladding refractive index of 1.45. The critical radius of curvature which allows large bending losses to occur is 84 μm when the fiber is transmitting light of a particular wavelength. Determine the wavelength of the transmitted light.

(0.819 μm)

6] A single-mode step index fiber with a core refractive index of 1.49 has a critical bending radius of 2 mm when illuminated with light at a wavelength of 1.30 μm. If the cutoff wavelength for the fiber is 1.15 μm, calculate its relative refractive index difference.

.   (0.67%)

7] Two step index fibers exhibit the following parameters:
   a. A multimode fiber with a core refractive index of 1.50, a relative refractive index difference of 3% and an operating wavelength of 0.82 μm.
   b. An 8 μm core diameter single-mode fiber with a core refractive index of 1.50, a relative refractive index difference of 0.3% and an operating wavelength of 1.55 μm.
   Estimate the critical radius of curvature at which large bending losses occur in both cases.

   (9 μm , 34 mm)

8] A multimode graded index fiber exhibits total pulse broadening of 0.1 μs over a distance of 15 km. Estimate:
   a. the maximum possible bandwidth on the link assuming no intersymbol interference.
   b. the pulse dispersion per unit length.
   c. the bandwidth-length product.

   (5 MHz , 6.67 ns.km^{-1} , 75 MHz.km)

9] a. A multimode step index fiber gives a total pulse broadening of 95 ns over a 5 km length. Estimate the bandwidth-length product for the fiber when a RZ digital code is used.
   b. A single-mode step index fiber has a bandwidth-length product of 10 GHz.km. Estimate the rms pulse broadening over a 40 km digital optical link without repeaters consisting of the fiber, and using a RZ digital code.

   (26.32 MHz.km , 800 ps)

10] An 8 km optical fiber link without repeaters uses multimode graded index fiber which has a bandwidth-length product of 400 MHz.km. Assume RZ code and estimate:
   a. the total pulse broadening on the link.
   b. the rms pulse broadening on the link.

   (10.0 ns , 4 ns)

11] A glass fiber exhibits material dispersion given by $|\lambda^2(d^2n_1/d\lambda^2)|$ of 0.025. Determine the material dispersion parameter at a wavelength of 0.85 μm, and estimate the rms pulse broadening per kilometer for a good LED source with an rms spectral width of 20 nm at this wavelength.

   (98.1 ps.nm^{-1}.km^{-1} , 1.96 ns.km^{-1})

12] Estimate the rms pulse broadening per kilometer for the fiber in problem [11] when the optical source used is an injection laser with a relative spectral width σ_λ/λ of 0.0012 at a wavelength of 0.85 μm.

   (0.10 ns.km^{-1})

13] The material dispersion in an optical fiber is defined by $|d^2n_1/d\lambda^2|$ is 4.0x10^{-2} μm^{-2}. Estimate the pulse broadening per kilometer due to material dispersion within the fiber when it is illuminated with an LED source with a peak wavelength of 0.9 μm and an rms spectral width of 45 nm.

   (5.4 ns.km^{-1})

14] The material dispersion parameter for a glass fiber is 20 ps.nm^{-1}.km^{-1} at a wavelength of 1.5 μm. Estimate the pulse broadening due to material dispersion within the fiber when light is launched from an injection laser source with a peak wavelength of 1.5 μm and an rms spectral width of 2 nm into a 30 km length of the fiber.

   (1.2 ns)

15] A 6 km optical link consists of a multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate:
a. the delay difference between the slowest and fastest modes at the fiber output.
b. the rms pulse broadening due to intermodal dispersion on the link.
c. the maximum bit rate that may be obtained without substantial errors on the link assuming only intermodal dispersion.
d. the bandwidth-length product corresponding to (c).

(300 ns , 86.7 ns , 2.3 Mbit.s^{-1} , 13.84 MHz.km)

16] A multimode step index fiber has a numerical aperture of 0.2 and a core refractive index of 1.47. Estimate the bandwidth-length product for the fiber assuming only intermodal dispersion and a RZ code.

(15.3 MHz.km)

17] An 11 km optical fiber link consisting of optimum near parabolic profile graded index fiber exhibits rms intermodal pulse broadening of 346 ps over its length. If the fiber has a relative refractive index difference of 1.5%, estimate the core axis refractive index. Hence, determine the numerical aperture for the fiber.

(1.45 , 0.25)

18] Compare the rms pulse broadening per kilometer due to intermodal dispersion for the multimode step index fiber of problem [15] with the corresponding rms pulse broadening per kilometer for an optimum near parabolic profile graded index fiber with the same core axis refractive index and relative refractive index difference.

(14.4 ns.km^{-1} , 14.4 ps.km^{-1})

19] Estimate the bandwidth-length product for the step index fiber of problem [16] considering the rms pulse broadening due to intermodal dispersion within the fiber and comment on the result. Indicate the possible improvement in the bandwidth-length product when an optimum near parabolic profile graded index fiber with the same relative refractive index difference and core axis refractive index is used. In both cases, assume only intermodal dispersion within the fiber and assume the use of a RZ code.

(15.3 MHz.km ; improved to 16.52 GHz.km)

20] A multimode step index fiber has a numerical aperture of 0.3 and a core refractive index of 1.45. The material dispersion parameter for the fiber is 250 ps.nm^{-1}.km^{-1} which makes material dispersion the totally dominating <u>intramodal</u> (chromatic) dispersion mechanism. Estimate:
a. the total rms pulse broadening per kilometer when the fiber is used with an LED source of rms spectral width 50 nm.
b. the corresponding bandwidth-length product for the fiber.

(32.4 ns.km^{-1} , 6.2 MHz.km)

21] A multimode, optimum near parabolic profile graded index fiber has a material dispersion parameter of 30 ps.nm^{-1}.km^{-1} when used with a good LED source of rms spectral width 25 nm. The fiber has a numerical aperture of 0.4 and a core axis refractive index of 1.48. Estimate the total rms pulse broadening per kilometer within the fiber assuming waveguide dispersion to be negligible. Hence, estimate the bandwidth-length product for the fiber.

(774 ps.km^{-1} , 258 MHz.km)

22] A multimode step index fiber has a relative refractive index difference of 1% and a core refractive index of 1.46. The maximum optical bandwidth that may be obtained with a particular source on a 4.5 km link is 3.1 MHz.

a. Determine the rms pulse broadening per kilometer resulting from <u>intramodal (chromatic)</u> dispersion mechanisms.

b. Assuming waveguide dispersion may be ignored, estimate the rms spectral width of the source used, if the material dispersion parameter for the fiber at the operating wavelength is 90 ps.nm^{-1}.km^{-1}.

(2.82 ns.km^{-1} , 31.57 nm)

ARAB ACADEMY FOR SCIENCE & TECHNOLOGY & MARITIME TRANSPORT
COLLEGE OF ENGINEERING & TECHNOLOGY
Electronics and Communications Department

Lecturer: Prof. Dr. Moustafa Hussein   **Optical Communications**
G.T.A. Eng. Ahmed Fahmy

Sheet (3)

Directional Coupler and Optical Fiber Connection

1] Prove that, for a lossless coupler
$$L_{THP} = -10 \log(1 - 10^{-L_{TAP}/10})$$

2] A coupler has an excess loss of 1 dB and a splitting ratio of 1:1. How much of the input power reaches the two output terminals?

$$(P_2 = P_3 = 0.397 \, P_1)$$

3] Fill in the spaces in the shown table

Coupler Description	L_{TAP} (dB)	L_{THP} (dB)	Splitting Ratio
3 dB	3	3	1:1
6 dB	6	1.25	3:1
10 dB	10	0.46	9:1
12 dB	12	0.28	15:1

Note: a 10 dB coupler is one that has 1 10 dB tap loss.

4] An ideal 4-port directional coupler has a 4:1 splitting ratio.
   a) What fraction of the input power goes to each of the ports?
   b) Compute the throughput loss, the tap loss, the directionality and the excess loss.

5] Repeat problem [4] for the splitting ratios: 3:1 and 1:1.

6] A four port directional coupler has a 4:1 splitting ratio and an excess loss of 2 dB. The coupler's directionality is 40 dB.
   a) What fraction of the input power goes to each of the ports?
   b) Compute the throughput loss and the tap loss.

7] Repeat problem [6] for the splitting ratios   3:1 and 1:1.

8] Repeat problem [6] for a directionality of 30 dB. Compare results with that obtained in [6].

9] A four port directional coupler has 60 μW optical power launched into port 1. The measured output powers at ports 2, 3 and 4 are 26.0, 27.5 and 0.004 μW, respectively. Determine the excess loss, the tap loss, throughput loss, directionality (cross-talk) and the splitting ratio of this coupler.

10] The measured optical powers from ports 2 and 3 of a four port directional coupler are 52.0 and 47.0 μW, respectively. If the excess loss specified for the device is 0.7 dB. Calculate the amount of power that is launched into port 1 in order to obtain these output power level. Hence, determine the throughput and tap losses and the directionality of this coupler as well as the splitting ratio.

When the specified cross talk of the coupler is -45 dB, calculate the output optical power that would be measured at port 2 when the above input power level is maintained.

11] An optical fiber has a core refractive index of 1.5. Two lengths of the fiber with smooth and perpendicular (to the core axes) end faces are butted together. Assuming the fiber axes are perfectly aligned, calculate the optical loss in decibels at the joint (due to Fresnel reflection) when there is a small air gap between the fiber end faces.

(0.36 dB)

12] A silica multimode step index fiber has a core refractive index of 1.46. Determine the optical loss in decibels due to Fresnel reflection at a fiber joint with:

a. a small air gap.

b. an index matching epoxy which has a refractive index of 1.40.

It may be assumed that the fiber axes and end faces are perfectly aligned at the joint.

(0.31 dB , 3.8×10^{-3} dB)

13] The Fresnel reflection at a butt joint with an air gap in a multimode step index fiber is 0.46 dB. Determine the refractive index of the fiber core.

(1.59)

ARAB ACADEMY FOR SCIENCE & TECHNOLOGY & MARITIME TRANSPORT
COLLEGE OF ENGINEERING & TECHNOLOGY
Electronics and Communications Department

Lecturer: Prof. Dr. Moustafa Hussein   Optical Communications
G.T.A. Eng. Ahmed Fahmy

Sheet (4)

Light Sources and Photodiodes

1] A ruby laser contains a crystal length 4 cm with a refractive index of 1.78. The peak emission wavelength from the device is 0.55 μm. Determine the number of longitudinal modes and their frequency separation.

2] The longitudinal modes of a gallium arsenide injection laser emitting at a wavelength of 0.87 μm are separated in frequency by 278 GHz. Determine the length of the optical cavity and the number of longitudinal modes emitted. The refractive index of gallium arsenide is 3.6.

3] When 3×10^{11} photons each with wavelength of 0.85 μm are incident on a photodiode, on average 1.2×10^{11} electrons are collected at the terminals of the device. Determine the quantum efficiency and the responsivity of the photodiode at 0.85 μm.

4] When 10^{11} photons per second each with an energy 1.28×10^{-19} J are incident on an ideal photodiode, calculate:
a) The wavelength of the incident radiation.
b) The output photocurrent.

5] A photodiode has a quantum efficiency of 0.65% when photons of energy 1.5×10^{-19} J are incident upon it.
a) At what wavelength is the photodiode operating?
b) Calculate the incident optical power required to obtain a photocurrent of 2.5 μA when the photodiode is operating as described above.

6] A p-i-n photodiode on average generates one electron-hole pair per 3 incident photons at a wavelength of 0.8 μm. Assuming the electrons are collected, calculate:
a) The quantum efficiency of the device.
b) The mean output photocurrent when the received optical power is 10^{-7} W.

7] A p-n photodiode has a quantum efficiency of 50% at a wavelength of 0.9 μm, calculate:
a) Its responsivity at 0.9 μm.
b) The received optical power if the mean photocurrent is 1 μA.
c) The corresponding number of received photons at this wavelength.
d) The corresponding number of generated electrons at this wavelength.

8] When 800 photons per second are incident on a p-i-n photodiode at a wavelength of 1.3 μm, they generate on average 550 electrons per second which are collected. Calculate the responsivity of the device.

ARAB ACADEMY FOR SCIENCE & TECHNOLOGY & MARITIME TRANSPORT
COLLEGE OF ENGINEERING & TECHNOLOGY
Electronics and Communications Department

Lecturer: Prof. Dr. Moustafa Hussein	Optical Communications
G.T.A. Eng. Ahmed Fahmy	

Sheet (5)

Optical Fiber Systems

1] An optical fiber link of length 4 km comprises a fiber cable with an attenuation of 5 dB.km^{-1}. The splice losses for the link are estimated at 2 dB.km^{-1}, and the connector losses at the source and detector are 3.5 and 2.5 dB respectively. Ignoring the effects of dispersion on the link, determine the total channel loss. (34 dB)

2] The following parameters are established for a long-haul single-mode optical fiber system operating at a wavelength of 1.3 μm.

Mean power launched from the laser transmitter	- 3 dBm
Cabled fiber loss	0.4 dB.km^{-1}
Splice loss	0.1 dB.km^{-1}
Connector losses at the transmitter and receiver	1 dB each
Mean power required at the APD receiver:	
when operating at 35 Mbit/s (BER 10^{-9})	- 55 dBm
when operating at 400 Mbit/s (BER 10^{-9})	- 44 dBm
Required safety margin	7 dB

Estimate:
a. the maximum possible link length without repeaters when operating at 35 Mbit/s (BER 10^{-9}). It may be assumed that there is no dispersion-equalization penalty at this bit rate.
b. the maximum possible link length without repeaters when operating at 400 Mbit/s (BER 10^{-9}) and assuming no dispersion-equalization penalty at this bit rate.
c. the reduction in the maximum possible link length without repeaters of (b) when there is a dispersion-equalization penalty of 1.5 dB. It may be assumed for the purposes of this estimate that the reduced link length has the 1.5 dB penalty.

(86 km , 64 km , 3 km)

3] Components are chosen for a digital optical fiber link of overall length 7 km and operating at a 20 Mbit.s^{-1} using an RZ code. It is decided that an LED emitting at 0.85 μm with graded index fiber to a p-i-n photodiode is suitable choice for the system components, giving no dispersion-equalization penalty. An LED which is capable of launching an average of 100 μW of optical power (including connector loss) into a 50 μm core diameter graded index fiber is chosen. The proposed fiber cable has an attenuation of 2.6 dB.km^{-1} and requires splicing every 1 km with a loss of 0.5 dB per splice. There is also connector loss at the receiver of 1.5 dB. The receiver requires mean incident power of - 41 dBm in order to give the necessary BER of 10^{-10}, and it is predicted that a safety margin of 6 dB will be required. Write down the optical power budget for the system and hence determine its viability.

(excess power margin = 2.3 dB)

4] A D-IM analog optical fiber link of length 2 km employs an LED which launches mean optical power of - 10 dBm into a multimode optical fiber. The fiber cable exhibits a loss of 3.5 dB.km^{-1} with splice losses calculated at 0.7 dB.km^{-1}. In addition, there is connector loss at the receiver of 1.6 dB. The p-i-n photodiode receiver has a sensitivity of - 25 dBm for an SNR of 50 dB and with a modulation index of 0.5. It is estimated that a safety margin of 4 dB is required. Assuming there is no dispersion-equalization penalty:
   a. perform an optical power budget for the system operating under the above conditions and ascertain its viability.
   b. Estimate any possible increase in link length which may be achieved using an injection laser source which launches mean optical power of 0 dBm into the fiber cable. In this case, the safety margin must be increased to 7 dB.
 (excess power margin = 1.0 dB, increase in length = 1.9 km and excess power margin = 0.0 dB)

5] An optical fiber system uses fiber cable which exhibits a loss of 7 dB.km^{-1}. Average splice losses for the system are 1.5 dB.km^{-1}, and connector losses at the source and detector are 4 dB each. After safety margins have been allowed, the total permitted channel loss is 37 dB. Assuming the link to be attenuation limited, determine the maximum possible transmission distance without a repeater.

(3.41 km)

6] A digital single-mode optical fiber system is designed for operation at a wavelength of 1.5 μm and a transmission rate of 560 Mbits.s^{-1} over a distance of 50 km without repeaters. The single mode injection laser is capable of launching a mean optical power of   - 13 dBm into the fiber cable which exhibits a loss of 0.25 dB.km^{-1}. In addition, average splice losses are 0.1 dB at 1 km intervals. The connector loss at the receiver is 0.5 dB and the receiver sensitivity is - 39 dBm. Finally, an extinction ratio penalty of 1 dB is predicted for the system. Perform an optical power budget for the system and determine the safety margin.

(7.6 dB)

7] An analog optical fiber system employs an LED which emits   3 dBm mean optical power into air. However, a coupling loss of 17.5 dB is encountered when launching into a fiber cable. The fiber cable which extends for 6 km without repeaters exhibits a loss of 5 dB.km^{-1} It is spliced every 1.5 km with an average loss of 1.1 dB per splice. In addition, there is a connector loss at the receiver of 0.8 dB. The PIN-FET receiver has a sensitivity of - 54 dBm at the operating bandwidth of the system. Assuming there is no dispersion-equalization penalty, perform an optical power budget for the system and establish a safety margin.

(5.4 dB)

8] A 500 Mbps optical fiber link of length L km employs an ILD of a rise time 0.12 ns which launches a mean optical power of 1 mW into a multimode optimum near parabolic graded index optical fiber. The fiber cable exhibits a loss of 0.2 dB/km and has splices at 1 km intervals with 0.2 dB loss in each. In addition, there is connector losses 1.5 dB and 0.8 dB at the source and detector respectively. The p-i-n photodiode receiver has a sensitivity of - 40 dBm and a built-in capacitance 1 pF. Assuming 2 dB dispersion equalization penalty and a 3.9 dB safety margin:
   1. Prove that the fiber link length must be 80 km.
   2. If it is required to increase the link length by 20 km, an EDFA (amplifier) must be used. Estimate its gain.
   3. For the new 100 km fiber, if the fiber has a chromatic dispersion 1 ps/km and an intermodal dispersion 2.5 ps/km, estimate the load resistance that must be connected to the photodiode.

9] A (80 km) and (40 Mbps) optical fiber link employs an ILD of a rise time (0.01 ns) which launches a mean optical power of (1 mW) into the fiber and p-i-n photodiode receiver of sensitivity of (-40 dBm) and a built-in capacitance (1 pF). The fiber is single-mode with (1 ps/km) chromatic dispersion and a material loss of (0.2 dB/km). The fiber also has splices at (1 km) intervals with (0.2 dB) loss in each. In addition, there is (2 dB) dispersion equalization penalty and the coupling losses are (1.5 dB) and (0.8 dB) at the source and detector, respectively. An EDFA is used to increase the link length by (20 km). **Keeping the same safety margin before and after using the EDFA**, estimate:

    1. Safety margin.
    2. EDFA gain.
    3. Load resistance.

10] A (1.25 Gbps) optical fiber link of length L km employs an ILD of a rise time (0.05 ns) which launches a mean optical power of (1 mW) into a multimode optimum near parabolic graded index optical fiber. The fiber cable exhibits a loss of (0.2 dB/km) and has splices at (1 km) intervals with (0.2 dB) loss in each. In addition, there is connector losses (1.5 dB) and (0.8 dB) at the source and detector respectively. The p-i-n photodiode receiver has a sensitivity of (- 40 dBm) and a built-in capacitance (0.1 pF). Assuming (2 dB) dispersion equalization penalty and a (3.9 dB) safety margin:

    1. Prove that the fiber link length must be (80 km).
    2. If it is required to increase the link length by (20 km), an EDFA (amplifier) must be used. Estimate its gain.
    3. For the new (100 km) fiber, if the fiber has a chromatic dispersion (0.5 ps/km) and an intermodal dispersion (1.0 ps/km), estimate the load resistance that must be connected to the photodiode.

OPTICAL COMMUNICATIONS

Contents:
1. **Historical Development.**
   - The general system.
   - Advantages and disadvantages.
2. **Optical Fiber Waveguides.**
   - Ray theory.
   - Mode theory.
   - Cylindrical fiber.
   - Single-mode and multimode fibers.
   - Step index and graded index fibers.
3. **Transmission Characteristics of Optical Fibers.**
   - Attenuation.
   - Dispersion.
4. **Optical Fibers and Cables.**
   - Fiber materials.
   - Fiber fabrication.
   - Optical fiber cables.
5. **Optical Fiber Connection.**
   - Fiber splices.
   - Fiber connectors.
   - Fiber couplers.
6. **Optical Sources.**
   - Laser.
   - Light emitting diode (LED).
7. **Optical Detectors.**
   - Photodiodes.
8. **Optical Fiber Communication System.**
9. **Applications and Future Developments.**
   - Public network applications.
   - Military applications.
   - Civil, consumer and industrial applications.
   - Optical sensor systems.
   - Computer applications.
   - Local area networks.

Experimental Projects:
1. Handling Fibers and Numerical Aperture Measurement.
2. Fiber Attenuation.
3. Single-Mode Fibers I.
4. Single-Mode Fibers II.
5. Coupling Fiber to Semiconductor Sources.
6. Connectors and Splices.
7. Components for Fiber Communication.
8. Optical Fiber Communication Link.

Reference:
Optical Fiber Communications: Principles and Practice, John M. Senior
Printice Hall Ltd., UK, 2nd ed., 1992

Useful Relations in Fiber Optics

Snell's Law	$\dfrac{\sin \phi_1}{\sin \phi_2} = \dfrac{n_2}{n_1}$	**Maximum Bit Rate** $\quad B_T = 0.2/\sigma$, σ is the rms pulse broadening.
Critical Angel, φ_c	$\sin \phi_c = \dfrac{n_2}{n_1}$	**Bandwidth for RZ code** $\quad BW = B_T$
Relative Refractive Index Difference	$\Delta = \dfrac{(n_1^2 - n_2^2)}{2n_1^2}$ $\cong \dfrac{(n_1 - n_2)}{n_1}$	**Bandwidth-Length Product** $\quad BW.L$
Acceptance Angle, θ_a	$n_o \sin \theta_a = (n_1^2 - n_2^2)^{1/2}$	**Material Dispersion Parameter** $\quad M = \dfrac{\lambda}{c}\left\lvert\dfrac{d^2 n_1}{d\lambda^2}\right\rvert$
Solid Acceptance Angle	$\cong \pi\,\theta_a^2 = \pi \sin^2\theta_a$	**rms pulse broadening due to mat. disp.** $\quad \sigma_m \cong (\Delta\lambda)\,L\,M$

Numerical Aperture, NA :		Intermodal Dispersion:
a. for meridional rays	$NA = n_o \sin \theta_a$	1. Step Index Fibers:
b. for skew rays	$NA = n_o \sin \theta_{as} \cos \gamma$	Delay difference between extreme meridional ray and the axial ray $\quad \delta T_s \cong \dfrac{Ln_1^2\Delta}{cn_2} \cong \dfrac{L(NA)^2}{2n_1 c}$
Normalized Frequency, V	$V = (2\pi/\lambda)\,a\,n_1\,\sqrt{2\Delta}$ $= a\,k\,(NA)$	rms pulse broadening due to intermodal dispersion $\quad \sigma_s \cong \dfrac{\delta T_s}{\sqrt{12}} \cong \dfrac{L\,n_1\,\Delta}{2\sqrt{3}\,c} \cong \dfrac{L(NA)^2}{4\sqrt{3}\,n_1\,c}$
Cutoff Value for Single Mode Operation	$V_c = 2.405(1 + 2/\alpha)^{1/2}$	2. Graded Index Fibers:
Cutoff Wavelength	$\lambda_c = \lambda\,(V/V_c)$	a. parabolic ($\alpha=2$) $\quad \delta T_g = \dfrac{Ln_1\Delta^2}{8c}$
Effective Refractive Index	$n_{eff} = \beta/k$	b. optimum α for minimum pulse broadening $\quad \alpha_{op} = 2 - 12\Delta/5$ $\quad \sigma_g = \dfrac{Ln_1\Delta^2}{20\sqrt{3}c}$
Number of Modes in Step Index Fibers	$M_s \cong V^2/2$	Total rms pulse broadening $\quad \sigma_T = (\sigma_{intramodal}^2 + \sigma_{intermodal}^2)^{1/2}$
Number of Modes in Graded Index Fibers of a grading index, α	$M_g \cong (\dfrac{\alpha}{\alpha+2})(\dfrac{V^2}{2})$	Fresnel Reflection Coefficient $\quad r = \left(\dfrac{n_1 - n}{n_1 + n}\right)^2$
Number of decibels (dB)	$10\log_{10}\dfrac{P_i}{P_o}$	Loss at a <u>single</u> interface $\quad Loss_{Fres} = -10\log_{10}(1 - r)$
Attenuation	$\alpha_{dB/km}\,.L_{km} = 10\log_{10}\dfrac{P_i}{P_o}$	Radiation Frequency in a Laser Cavity $\quad f = \dfrac{qc}{2nL}$
Critical Radius a. single-mode: R_{cs}	$\dfrac{20\lambda}{(n_1 - n_2)^{3/2}}(2.748 - 0.996\dfrac{\lambda}{\lambda_c})^{-3}$	
b. multimode: R_c	$\dfrac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{3/2}}$	