CONTENTS

PREFACE

This manual was prepared as an aid to instructors who have adopted my textbook, *Fiber Optic Communications*, for classroom use. It contains solutions to all problems in the first eleven chapters and solutions to a few problems in the twelfth chapter. Most solutions are not included for the twelfth (and final) chapter, as the problems there are open-ended design exercises with no unique answers.

In addition to problem solutions, this manual contains suggestions for teaching a fiber optics course using my textbook.

On occasion I post fiber-related materials on the Web. These change from time to time, but the plan is to have them always accessible from my home page. At the present time, I have a number of fiber demonstration (simulation) programs on that page. The address of my home page is:

www.fulton.asu.edu/~palais

I have tried to prepare a solutions manual and textbook as error-free as possible. Nonetheless, errors may be present and I would appreciate hearing about them so that corrections can be made in future printings.

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TEACHING A FIBER OPTICS COURSE

The book *Fiber Optic Communications* was written with several purposes in mind. Among them was to produce a textbook suitable for undergraduate electrical engineering students at the junior and senior level and also suitable for students of electronic technology. Adoptions of previous editions for both these purposes indicates a modicum of success in meeting the original goal. I think it will help instructors use the book appropriately by explaining just how I accomplished this result.

The book itself covers all major components of a fiber communications link and all significant communications and system theory for the design of complete systems. Thus, the book is comprehensive in its coverage. The biggest compromise in including such a wide variety of topics at a reasonable level and with reasonable depth in a moderately sized (and moderately priced) book was to exclude the many lengthy equation derivations found in some other texts. This reveals the key to using the book at different levels. The simplest level of presentation will follow the book closely and seldom derive the results given. Instead, emphasis will be placed on understanding and using the results for practical purposes. At the other extreme, for greater depth the instructor will supplement the text with derivations of the given results. In fact, this is what I do for my electrical engineering students at Arizona State University. These derivations are available in the literature referenced in the text. I can also provide help if you wish to contact me.

I am also led to believe that previous acceptance of the book occurred because of its clear and straightforward writing. Many students have expressed this thought to me.

Answers to all problems in the first eleven chapters appear at the end of the textbook. They are made available to the students so that they can check there own work. Numerous problems are provided to give the student a reasonable amount of practice at applying the principles contained in each chapter.

On the next few pages, I list sample semester schedules and discuss fiber laboratories.

TEACHING SCHEDULES

SCHEDULE 1: Electrical Engineering or Physics: Senior Level

This schedule is designed for a one-semester (16 week), three-credit hour, course for senior-level electrical-engineering or physics students.

WEEK	CHAPTER	SUBJECTS
1,2	1	Fiber Communications Systems
3	2	Optics Review
4,5	3	Lightwave Fundamentals
6,7	4	Integrated Optic Waveguides
8-11	5	Optical Fiber Waveguides
12-14	6	Optical Sources and Amplifiers
15-16	7	Light Detectors

This schedule allows for three hourly exams and a final exam, although individual instructors can modify the testing scheme as desired. The schedule assumes that derivations of many of the important equations are presented in class. A suggested example is the derivation of the mode equations for the dielectric slab waveguide.

This scheme presents an overview of fiber optics at the beginning of the semester and then discusses the details of the system components from the transmitting light source, to the fiber, to the receiving photodetector. This package of topics gives a comprehensive introduction to fiber communications.

SCHEDULE 2: Electronic Technology and Lower Level Electrical Engineering

This schedule is designed for a one-semester course suitable for students of electronic technology or possibly a second-year electrical engineering course. It assumes that the instructor will concentrate on applications of results rather than on their derivation.

WEEK	CHAPTER	SUBJECTS
1,2	1	Fiber Communications Systems
3	2	Optics Review
4	3	Lightwave Fundamentals
5	4	Integrated Optic Waveguides
6-8	5	Optical Fiber Waveguides
9-11	6	Optical Sources and Amplifiers
12-13	7	Light Detectors
14	8	Couplers and Connectors
15	9	Distribution Systems
16	10	Modulation

This scheme presents an overview of fiber optics at the beginning of the semester and then discusses the details of the system components from the transmitting light source, to the fiber, to the receiving photodetector. It then goes on to discuss splices and connectors, distribution systems for local-area networks, and various modulation schemes. Because derivations are excluded, instructors using this schedule can proceed further into the textbook than those using schedule 1.

SCHEDULE 3: **Advanced Course, First-Year Graduate Level Electrical Engineering and Physics**

This schedule is designed as a follow-on, advanced course, in fiber optics. It completes the textbook, specializing in special topics such as distribution systems for local-area networks, connectors and splices, modulation and coding formats, noise, and system design. Design includes signal-to-noise and bit-error rate calculations as well as system bandwidth calculations. I suggest that the instructor supplement the textbook material with the derivation of the field equations in a step-index fiber and a discussion of fiber-optic sensors.

WEEK	CHAPTER	SUBJECTS
1,2	8	Couplers and Connectors
3,4	9	Distribution Systems
5,6	10	Modulation
7-10	11	Noise and Detection
11,12	12	System Design
13,14		Fields in Fibers
15,16		Fiber Sensors

Material for development of the field equations in fibers and for fiber sensors appears in the literature and in a few advanced fiber books.

LABORATORIES

Fiber optics lends itself wonderfully well to laboratory work. Since different schools and different instructors have different resources and different budgets, no single set of detailed experiments can satisfy all requirements. This is not a laboratory manual, so the discussion of experiments will be brief. What I will do is describe the type of experiments you may wish to pursue.

Experiments can be designed to do several things. They can: (a) illustrate fundamentals, (b) teach practical measurement techniques, or (c) involve actual design. Most experiments are designed to do one or the other, but certain experiments combine more than one of these items. Instructors should decide which is most important for their own students.

I suggest doing as many experiments as possible with a visible light source. This makes experimentation easier, particularly when aligning optical systems. Since many fiber properties are independent of wavelength (such as numerical aperture and splice loss), a visible beam can be used even though infrared light is found in most practical fiber applications. A Helium-Neon laser is a convenient source of visible light.

SUGGESTED EXPERIMENTS

1. Lasers, Beam Patterns, and Power Measurements
2. Numerical Aperture
3. Refractive Index Profile Measurement
4. Fiber Splice Alignment Losses
5. Mechanical Splicing
6. Fusion Splicing
7. Fiber Attenuation
8. Fiber Bending Losses
9. OTDR Measurements
10. Light-Emitting Diodes
11. Photodetectors
12. Analog and Digital Link Design

I will supply a copy of the lab descriptions that we use at Arizona State University to those who are interested.

RESOURCES

The technique for building a fiber optics laboratory at a school involves a combination of the following procedures:

1. Find a space. This is often a battle with administrators involving limited space and heavy demand.
2. Obtain a budget from the school. Budgets may be tight (is there any other kind of budget?), but some financial commitment by the school is required.
3. Now that you have a place to work and a few dollars, determine what components, test equipment, mounting structures, and other hardware you can build, borrow from other labs, or otherwise scrounge.
4. Request donations of useable equipment from local industry or from commercial suppliers of optical equipment.

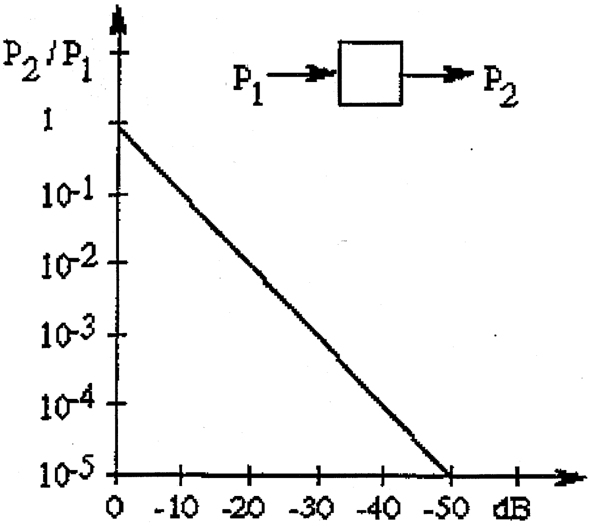
Unfortunately, the price of commercial fiber equipment is high for many items. For example, OTDRs and fusion splicers start near $10,000. On the other hand, light sources and detectors (operating at wavelengths near 850 nm) can be purchased for a few dollars.

CHAPTER 1

FIBER OPTIC COMMUNICATIONS SYSTEMS

1-1 $dB = 10 \log_{10} (P_2/P_1)$

Loss (dB)	Fractional Power (P_2/P_1)
0	1
-1	0.8
-3	0.5
-6	0.25
-10	0.1
-20	0.01
-30	0.001
-40	0.0001
-50	0.00001



1-2 $dB = 10 \log_{10} (P_2/P_1)$

$dB/10 = \log_{10} (P_2/P_1)$

$P_2/P_1 = 10^{dB/10}$

$P_2 = P_1 \times 10^{dB/10} = 0.001 \times 10^{dB/10}$

1-3 $P_1 = 2$ mW

$P_2 = P_1\, 10^{dB/10} = 2 \times 10^{-3} \times 10^{-11/10} = 0.159$ mW

1-4 $P_2 = P_1\, 10^{dB/10} = 10 \times 10^{-9}$

$P_1 = P_2\, 10^{-dB/10} = 10 \times 10^{-9} \times 10^{-(-50)/10}$

$P_1 = 10 \times 10^{-9} \times 10^{5} = 10^{6} \times 10^{-9} = 10^{-3}$ W $= 1$ mW

1-5 From the text, we find that RG-19/U weighs 1110 kg/km.

1 mile of cable x 1110 kg/km x 1.609 km/mile x 2.2 lbs/kg = 3929 lbs.

1-6 From the text, we find that RG-19/U has an attenuation of 22.6 dB/km at 100 MHz.

Using RG-19/U, the allowed loss is:

$$\text{Loss} = 10 \log_{10} \frac{P_1}{P_2} = 10 \log_{10} \frac{10^{-6}}{10^{-2}} = -40 \text{ dB}$$

Maximum coaxial cable length = 40/22.6 = 1.8 km

Using a fiber with loss, the maximum length of fiber is:

Length = 40/5 = 8 km

1-7 44.7×10^6 bps x 1 message/64,000 bps = 698 messages

1-8 With manually operated blinker lights, I would guess about 2 or 3 bps.

1-9 Conducting Cable

900 (pairs/cable) x 24 (messages/pair) = 21,600 messages

Fiber

144 (fibers/cable) x 672 (messages /fiber) = 96,768 messages

96,768 (fiber cable)/21,600 (copper cable) = 4.48

About 4.5 copper cables are needed to carry the same amount information as the single fiber cable.

At the DS-4 rate, each fiber carries 4032 messages. The comparative message rates are then: 144 x 4032/21600 = 26.88 or about a factor of 27.

1-10

$$A_{fiber} = \pi \left(\frac{D_{fiber}}{2}\right)^2 = \pi\left(\frac{12.7}{2}\right)^2 = 126.67 \text{ mm}^2$$

$$A_{copper} = \pi \left(\frac{D_{copper}}{2}\right)^2 = \pi \left(\frac{70}{2}\right)^2 = 3{,}848.48 \text{ mm}^2$$

$A_{copper} / A_{fiber} = 30$

1-11

Frequency (Hz)	Wavelength (m) $\lambda = c/f = 3 \times 10^8/f$	Region of EM Spectrum
10	3×10^7	Power
60	5×10^6	Power
10^3	3×10^5	Radio
2×10^4	1.5×10^4	Radio
10^6	3×10^2	Radio
10^9	0.3	Radio
10^{10}	0.03	Microwave
10^{14}	3×10^{-6}	Infrared

1-12 Visible wavelengths range from 0.4 μm to 0.7 μm.

When $\lambda = 0.4$ μm, $f = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/s}}{0.4 \times 10^{-6} \text{ m}} = 7.5 \times 10^{14}$ Hz

When $\lambda = 0.7$ μm, $f = \frac{3 \times 10^8 \text{ m/s}}{0.7 \times 10^{-6} \text{ m}} = 4.3 \times 10^{14}$ Hz

Bandwidth $= \Delta f = (7.5 - 4.3) \times 10^{14} = 3.2 \times 10^{14}$ Hz

1-13

$$W = hf = \frac{hc}{\lambda} = \frac{(6.625 \text{ x } 10^{-34} \text{ J} \cdot \text{ S})(3 \text{ x } 10^{8} \text{ m/s})}{\lambda}$$

$\lambda(\mu m)$	W(J)
0.6	$3.3 \text{ x } 10^{-19}$
0.82	$2.4 \text{ x } 10^{-19}$
1.3	$1.5 \text{ x } 10^{-19}$

A visible photon has more energy than an infrared photon.

1-14 $P = W/t = hfN = hNc/\lambda$, where N= number of photons/sec

$$P = 6.625x10^{-34}x10^{10}x3x10^{8} / 0.8x10^{-6} = 2.5x10^{-9}W$$

$I = 2.5 \text{ x } 10^{-9} \text{ W } (0.65 \text{ A/W}) = 1.6 \text{ nA}$

1-15

$$N = \frac{P\lambda}{hc} = \frac{(1 \text{ x } 10^{-9} \text{ W})(1.3 \text{ x } 10^{-6}\text{m})}{(6.625 \text{ x } 10^{-34} \text{ J} \cdot \text{ S})(3 \text{ x } 10^{8} \text{ m/s})} = 6.5 \text{ x } 10^{9} \text{ photons/second}$$

1-16

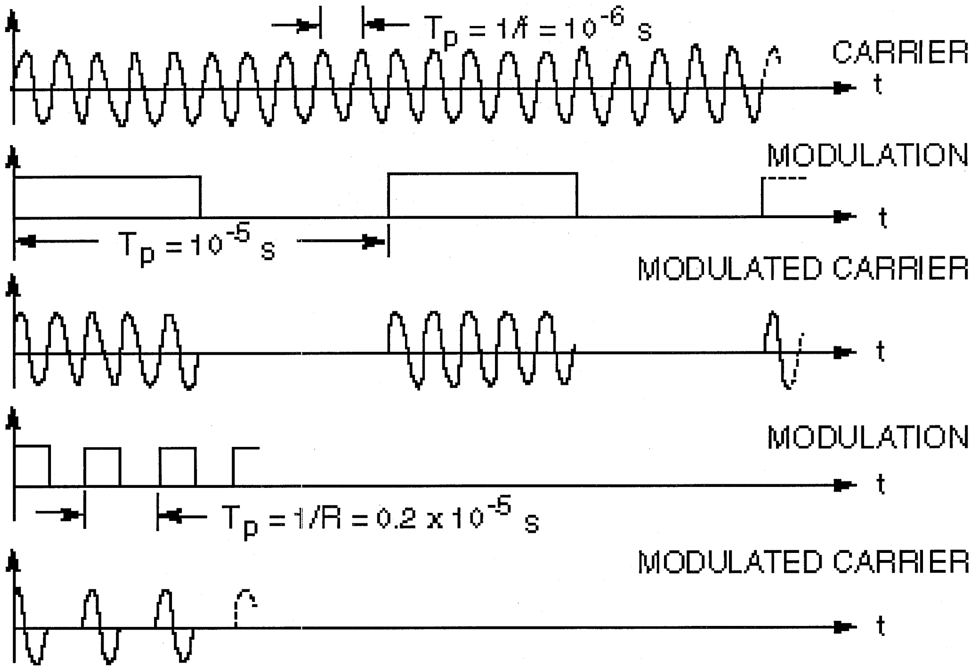
Carrier	Bit Rate (bps)
10 kHz	10^2
1 MHz	10^4
100 MHz	10^6
10 GHz	10^8
1 µm	$3 \text{ x } 10^{12}$

For the $\lambda = 1$ µm carrier

$$f = \frac{c}{\lambda} = \frac{3 \text{ x } 10^{8} \text{ m/s}}{1 \text{ x } 10^{-6} \text{ m}}$$

$$= 3 \text{ x } 10^{14} \text{ Hz}$$

1-17



1-18

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/s}}{1.06 \times 10^{-6} \text{ m}} = 2.83 \times 10^{14} \text{ Hz, BW} = 0.01f = 2.83 \times 10^{12} \text{ Hz}$$

Assume $\Delta f = 4000$ Hz for one voice channel. Then

2.83×10^{12} Hz x 1 channel/4000 Hz = 7×10^8 channels

1-19 Open-ended solution.

1-20 Assume there are 10 billion (10^{10}) homes each having one 4000 Hz channel, then 10^{10} (homes) x 4000 (Hz/home) = 4×10^{13} Hz is the required bandwidth. Using an optical beam of frequency

$f = 3 \times 10^{14}$ Hz

$$\frac{\Delta f}{f} = \frac{4 \times 10^{13}}{3 \times 10^{14}} = 0.133$$

The bandwidth 13.3% of the carrier frequency. This might be possible.

1-21

$$10^{10} \text{ messages} \left(\frac{6.4 \text{ x } 10^4 \text{ bps}}{\text{message}}\right) = 6.4 \text{ x } 10^{14} \text{ bps}$$

A single optical carrier at f $\simeq$ 3 x 10^{14} Hz could not be turned on and off this fast.

1-22 P = 100 nW = 100 x 10^{-9} W. Let N = number of photons

W = Nhf = Pt

N/t = P/hf = (P/hc) λ

(a) At 800 nm

$$N/t = \frac{10^{-7}\left(0.8 \text{ x } 10^{-6}\right)}{6.63 \text{ x } 10^{-34}\left(3 \text{ x } 10^{8}\right)} = 4 \text{ x } 10^{11} \text{ photons/second}$$

(b) At 1550 nm

N/t = 4 x 10^{11} (1.55/.8) = 7.8 x 10^{11} photons/second

(c) The longer wavelength requires more photons because the energy per photon is smaller at the longer wavelength.

1-23 P_R = -34 dBm

P_T = Transmitted power in dBm

L = -31 dB, system losses

$P_R = P_T + L$

$-34 = P_T - 31$

$P_T = -34 + 31 = -3$ dBm

P_T = 0.5 mW

1-24 T3 rate is R = 45 Mbps

The number of errors each second is:

$N_e = 10^{-9} (45 \times 10^6) = 45 \times 10^{-3}$ errors/s

In one minute, then

$N_e = 60 (45 \times 10^{-3}) = 2.7$ errors/minutes

1-25 $R = 2.3$ Gbps $= 2.3 \times 10^9$ bps

Total capacity of the 144 fibers is

$144 (2.3 \times 10^9) = 3.312 \times 10^{11}$ bps

Allowing 64,000 bps per voice message, yields

$$\frac{3.312 \times 10^{11}}{6.4 \times 10^4} = 0.5175 \times 10^7 = 5.175 \times 10^6 \text{ messages} = 5.175 \text{ million messages}$$

1-26 $P_r = -38$ dBm, $P_T = 4$ dBm

$L = 4 - (-38) = 42$ dBm

1-27 $P_1 = -60$ dBm $= 10 \log P_1(\text{mW})$

$P_1 = 10^{-6}$ mW $= 10^{-9}$ W

$P_2 = 60$ dBm $= 10 \log P_2(\text{mW})$

$P_2 = 10^6$ mW $= 10^3$ W

$P_2 - P_1 = 1000$ watts (approximately)

1-28 $L = -5 - 25 - 15 + 10 = 35$ dB

1-29 $f = c/\lambda = 3 \times 10^8/1.55 \times 10^{-6} = 1.93548 \times 10^{14}$

One hundredth of one percent is a data rate of:

$R = 10^{-4}(1.93548 \times 10^{14}) = 1.9354 \times 10^{10}$ bps $= 19.4$ Gbps

Use $R_{HDTV} = 20$ Mbps for each HDTV channel

$R/R_{HDTV} = 19.4 \times 10^9/20 \times 10^6 = 0.9677 \times 10^3 = 967$ video channels

1-30 Open-ended question.

1-31 OC-768 rate is 39,813.12 Mb/s

Number of voice channels is N:

$N=(39{,}813.12 \times 10^6)/(64 \times 10^3) = 622{,}080$

The actual number is less than this to accommodate overhead such as signaling and synchronization.

1-32 Photon energy W_p

$W_p = hf = hc/\lambda = 6.626 \times 10^{-34} \times 3 \times 10^8/\lambda$

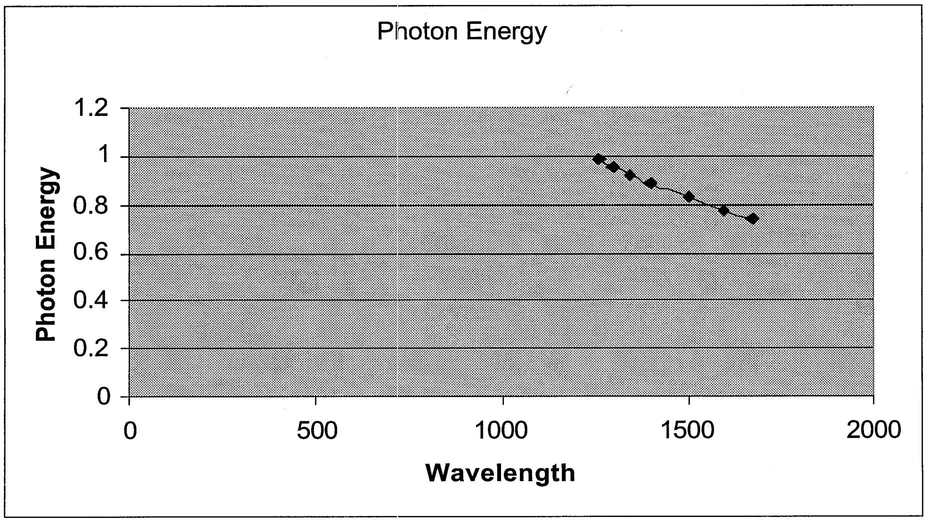
$W_p = 19.878 \times 10^{-26}/\lambda$ Joules

In eV

$W_p = 19.878 \times 10^{-26}/(1.6 \times 10^{-19}\,\lambda) = 1.2423 \times 10^{-6}/\lambda$

If the wavelength is in nm, the photon energy in eV becomes:

$W_p = 1242.3\,/\lambda$



1–33

Wavelength	Frequency	Energy
1.55 μm	1.935×10^{14} Hz	0.802 eV
1.55×10^{-3} mm	1.935×10^{11} kHz	1.282×10^{-19} J
1.55×10^{-6} m	1.935×10^{8} MHz	
1.55×10^{-9} km	1.935×10^{5} GHz	
	193.5 THz	

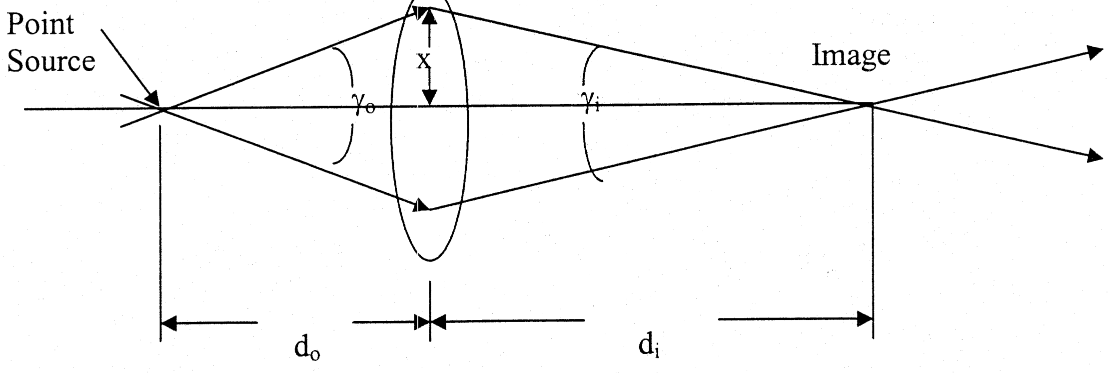
$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8}}{1.55 \times 10^{-6}} = 1.935 \times 10^{14}\ Hz$$

$$W_p = \frac{1242.3}{\lambda} = \frac{1242.3}{1550} = 0.802\ eV$$

CHAPTER 2

OPTICS REVIEW

2-1



$\tan(\gamma_o/2) = x/d_o$, $\tan(\gamma_i/2) = x/d_i$

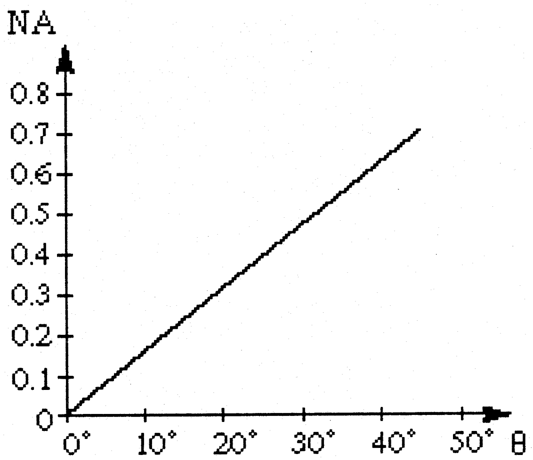
Thus, $$\frac{\tan\left(\frac{\gamma_i}{2}\right)}{\tan\left(\frac{\gamma_o}{2}\right)} = \frac{d_o}{d_i},\ \gamma_i = 2\tan^{-1}\left[\frac{d_o}{d_i}\tan\left(\frac{\gamma_o}{2}\right)\right]$$

Since $M = (d_o/d_i)^{-1}$, and $\tan\alpha = \alpha$ for small angles, then $\gamma_i / \gamma_o = 1/M$.

$\gamma_i = 8.32^\circ$ using the exact expression or $\gamma_i = 8^\circ$ using the approximate formula.

2-2 $NA = n_1 \sin\theta = \sin\theta$

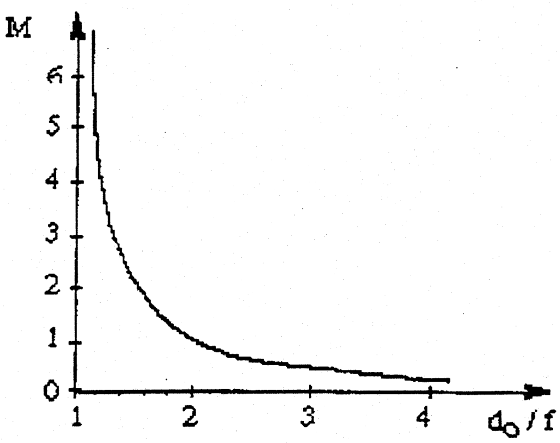
θ	NA
0°	0.0
10°	0.174
20°	0.342
30°	0.500
45°	0.707



2.3

$$d_i = \frac{fd_o}{d_o - f}\ ,\ M = \frac{d_i}{d_o} = \frac{1}{\frac{d_o}{f} - 1}$$

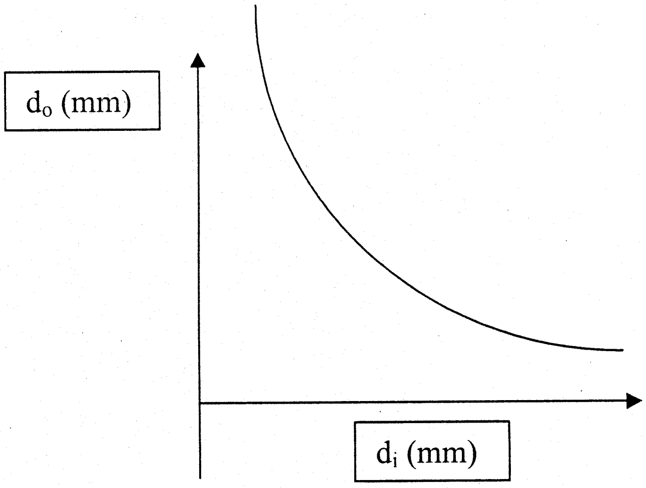
d_o/f	M
1	infinity
1.2	5
1.4	2.5
1.6	1.67
2.0	1.0
3.0	0.5
4.0	0.33



2.4 $f = 20$ mm, $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$,

$d_o = fd_i/(d_i - f) = 20\ d_i/(d_i - 20)$

d_i (mm)	d_o (mm)
20	infinity
25	100
30	60
60	30
80	26.7
	20



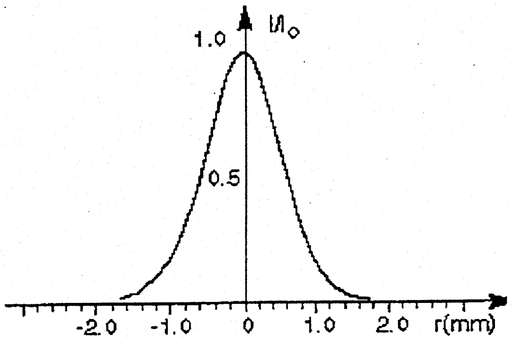
2.5 $f = 20$ mm, $D = 10$ mm, $\lambda = 0.8\ \mu m$, $d = 2.44\ \lambda f/D = 3.9\ \mu m$

2.6 $w = 1$mm, $\lambda = 0.8\ \mu m$, $f = 20$ mm

Focused spot size = $w_o = \lambda f / \pi w = 5.09\ \mu m$

2.7 $I/I_o = e^{-2r^2/w^2}$, $w = 1$ mm

r (mm)	I/I_o
0	1.0
0.2	0.923
0.4	0.726
0.6	0.486
0.8	0.278
1.0	0.135
1.5	0.011



2.8 $\lambda = 0.8\ \mu m$, $w = 1$ mm, $z_{moon} = 3.8 \times 10^8$ m

Divergence Angle = $\theta = 2\lambda/\pi w = 5.09 \times 10^{-4}$ r

Spot size on the moon = $w_{o,moon} = \theta\ z_{moon} / 2 = 96.7$ km

In miles, $w_{o,moon} =$ 96.7 km x (1 mi./1.609 km) = 60 miles

If R = 1 km,

$$w_o = \frac{\theta R}{2} = \frac{0.000509 \times 10^3}{2} = 0.255 \text{ m}$$

If R = 10 km,

$$w_o = \frac{\theta R}{2} = \frac{0.000509 \times 10^4}{2} = 2.55 \text{ m}$$

2.9 For glass $n \simeq 1.5$

(a) The velocity is:

$$v = \frac{c}{n} = \frac{3 \times 10^8}{1.5} = 2 \times 10^8 \text{ m/s}$$

The travel time is:

$t = 6 \times 10^6 / 2 \times 10^8 = 3 \times 10^{-2}$ seconds

$t = 30$ ms

(b) The satellite path is approximately

$d = 2 \times 22000 = 44{,}000$ miles

$d = 44000 \times 1609$ meters/mile

$d = 7.05 \times 10^7$ m

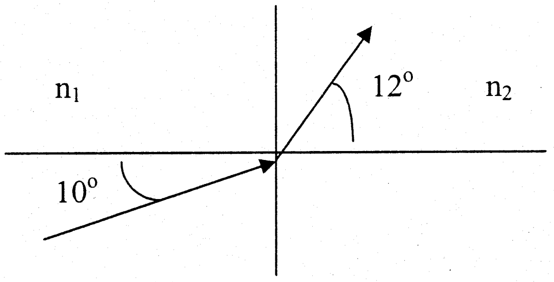
The travel time is:

$$t = \frac{7.08 \times 10^7}{3 \times 10^8} = 0.236 \text{ seconds} = 236 \text{ ms}$$

(c) The two-way satellite delay is about half a second. This is noticeable. The fiber delay is not noticeable.

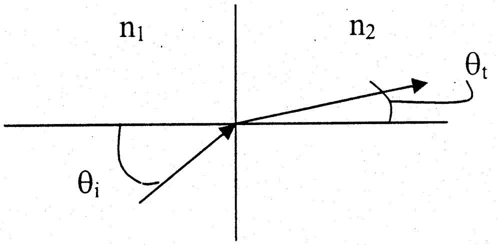
2-10

$$\frac{\sin \theta_t}{\sin \theta_i} = \frac{n_1}{n_2}$$

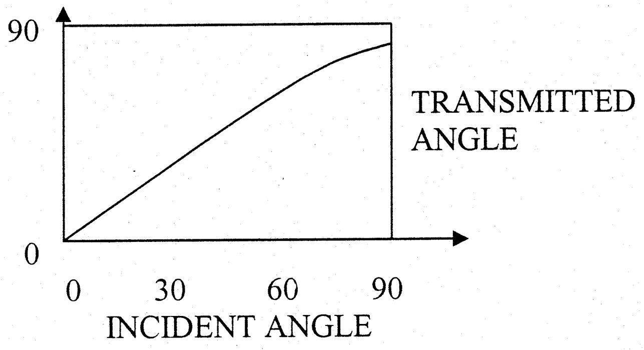


Since $\theta_t > \theta_i$, then $\sin \theta_t > \sin \theta_i$ and then we must have $n_1 > n_2$.

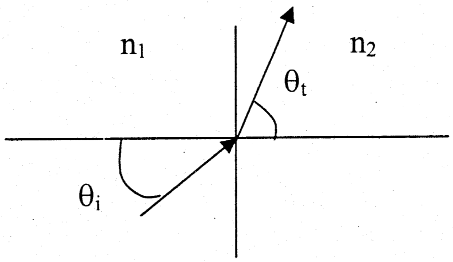
2-11 $\sin\theta_t = (n_1/n_2)\sin\theta_i = (1.46/1.48)\sin\theta_i = 0.986485\sin\theta_i$



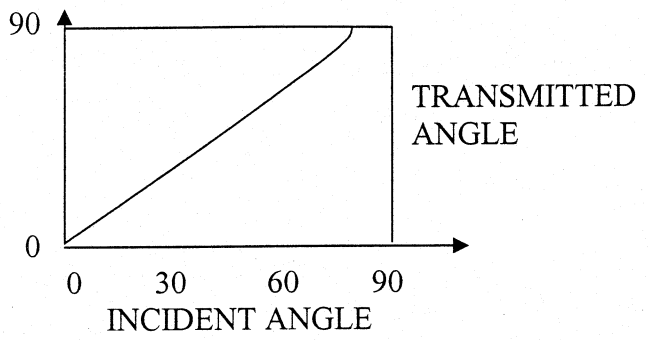
θ_i	θ_t
0	0
15	14.8
30	29.6
45	44.2
60	58.7
75	72.3
90	80.6



2-12 $\sin\theta_t = (n_1/n_2)\sin\theta_i = (1.48/1.46)\sin\theta_i = 1.01369\sin\theta_i$



θ_i	θ_t
0	0
15	15.2
30	30.5
45	45.2
60	61.4
75	78.3
80	86.7
80.57	90



2-13 $\lambda = \lambda_0 / n$

Fused silica: n = 1.46

Silicon: n = 3.5

All wavelengths in nm in the following table:

λ_0	λ (Silica)	λ (Silicon)
800	548	229
1300	890	371
1550	1062	443

The wavelength shortens when an optical beam enters a material from free space. The frequency remains the same. The photon energy (hf) remains the same.

2-14 Use a refractive index of 1.5. The wave velocity is;

$$v = \frac{c}{n} = \frac{3\times10^8}{1.5} = 2\times10^8\ m/s$$

The distance traveled in one second (and, thus, the fiber length) is:

$$d = vt = 2\times10^8 \times 1 = 2\times10^8\ m$$

2-15 $\frac{I}{I_0} = e^{-2r^2/w^2}$

$$0.5 = e^{-2r^2/w^2}$$

Solve for D=2r, with the result:

$$D = 2r = 2w\sqrt{\frac{\ln 2}{2}} = 1.177w$$