University of Pennsylvania
EMTM Program

Photonics

The Basics and Applications of
Modern Photonics, Fiber Optics Communications,
and Optical & Image Signal Processing

Winter 1998-1999

(See page 4 for initial assignment.)

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EXEN 625: Photonics

Abbreviated Course Syllabus

People:

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Course Objective and Description:

This course provides a blend of photonic fundamentals and applications to the fast moving technology involved in optical communication systems and devices. Photonics is becoming increasingly important as limitations of speed, size and bandwidth affect many electronic devices and systems. Here the fundamentals of waves and their interactions with structures and materials are combined with the application of these effects to lasers, other electro-optical devices, and optical systems and networks. The course covers optical wave properties; fiber and integrated optics with applications to optical communications; lasers and their operation and uses; selected optical devices; an introduction to optical signal processing; and selected reviews of emerging photonic technologies including optical networks and architectures. You will develop an overview of modern photonics, a understanding of optical communications systems, and a knowledge of photonics in technology.

Course Outline:

I. Role of Photonics and Fiber Optics
  A. Lasers and Their Uses
  B. Fiber Optics and Optical Communication Systems
  C. Integrated Optics
  D. Optical Signal Processing

II. Introduction to Lasers and Light
  A. Laser Light vs. Natural Light
  B. Overview of Laser Operation
  C. Types of Lasers
  D. Laser Beam Output

III. Basics of Optics (or Optics with a Little Math)
  A. Some Basics of Waves
  B. Optical Materials
  C. Reflection
  D. Refraction
  E. Diffraction
  F. Coherence

IV. Principles of Laser Operation (or Optics with a Little Physics)
  A. Overview
  B. Atomic System
  C. Laser Cavities and Output
  D. Laser Design
  E. Laser Types and Modifications and Their Applications (or Optics with a Few Pictures)

V. Fiber and Guided Wave Optics (or Optics with Mirrors)

VI. A. Optical Fibers
  B. Thin Film Integrated Optics

- C. Applications to Optical Communications and Optical Systems
- D. Class Project

VI. Optical Systems and Networks
- A. Devices
- B. Networks
- C. Architecture

VII. Applications of Holography and Optical Signal Processing

Photonics

Readings/Assignments/Projects/Grades

1. The course notes entitled *Photonics* (this document) is an abbreviated version of *Notes on Lasers and Light* which highlights the most important aspects of light, lasers, fiber optics, and optical communications and signal processing. It forms the outline for the course and integrates readings, course notes, assignments, mini-projects, and a final project. This is your key reference. You are responsible for the parts that are covered in class or assigned for reading.

2. Homework will be assigned from this document (see problems at the end). Assistance in solving these problems and review sessions will be given by Thomas Wu <xwu@ee.upenn.edu>, a Penn Ph.D. student in Electrical Engineering. Late homework is not accepted.

3. *Notes on Lasers and Light* covers in greater technical detail selected aspects of the properties of light and the operation of lasers. It provides a readily available source for selected technical and scientific aspects of the course for which you may want additional information.

4. *Fiber Optic Communications* by Joseph C. Palais is a general text covering the photonic landscape from optical basics to fiber optics fundamentals to systems aspects of fiber communications. Chapters 1 through 5 provide background material for the first part of the course while the remaining portion (especially chapters 6, 8, 9, 12) form the text for the second half of this course on fiber optics. The bibliography at the end (pg. 315) is useful for further reading.

5. The series of articles entitled *Designers Guide to Fiber Optics* provides a good, although dated, overview of fiber optics system design and will be coordinated with the text by Palais. A series of papers starting with the article, *Lightwave Communications: The Fifth Generation* by D. Emmanuel, provide an overview of fiber optical communication systems. Of particular interest are all-fiber systems and the use of non-linear optics and solitary waves in modern systems.

6. *Optical Communication Systems* by J. Gowar is dedicated to the details of the generation, transmission, and reception of photonic signals for communications. This book covers material from basic wave propagation to systems concepts. Several relevant chapters are included in the course material. *Fiber Optic Networks* by P. Green provides some of the useful systems and networks aspects of the course. Several chapters of this text are also included.

7. A variety of reprints from the recent literature are included in the course material and will be supplied as needed. Mini-projects will be taken from current discoveries in photonic technology.

8. You may be interested in Web-based information on recent advances in photonics. The PennWell Publishing site <http://www/lfw/com/> is a good place to start.

9. A demonstration laboratory will be included as time permits.

10. Grades will be weighted on the following items (all percentages are approximate):

All homework	15%
Two mini-projects	15%
Quiz (Session VI if given)	15%
Final Project (due start of next term)	35%
Final Project Presentation (Session VI)	10%
Class participation	10%

Reading and Review Problem Assignments

Session I

<u>Before Session I,</u> skim chapters 1 - 3 (pg. 1 - 78) of *Fiber Optic Communications*, and read the attached course notes *Photonics* for Session I (pg. 5-12). **After Session I,** skim the first half of the handout *Notes on Lasers and Light*, read the project description (end of this document), review the reading material listed above as needed, and do review problems (end of this document) for next session as assigned in class.

Session II

Read the second half of the handout *Notes on Lasers and Light*, the attached course notes *Photonics* for Session II and chapters 2 - 3 (pg. 36 - 78) of *Fiber Optic Communications*. Skim this document and look at the requirements for the final project. Do review problems for next session.

Session III

Read the reprinted material from the text *An Introduction to Lasers and their Applications*, the course notes *Photonics* for Session III. Do review problems for next session and finalize choice of teams and topic for your final photons project.

Session IV

Skim chapters 4 and 6 of *Fiber Optic Communication* and read chapter 5. Also read the first half of the handout *Designers Guide to Fiber Optics,* the course notes *Photonics* for Session IV. Do review problems for next session. You will be asked to identify the participants in your project and the general topic of your final project.

Session V

Skim chapters 7, 8, 9 and 12 of *Fiber Optic Communication*, read the second half of the handout *Designers Guide to Fiber Optics,* the course notes *Photonics* for Session V. Do review problems for next session. Be prepared to give a two minute summary of your final project to the class. After class, prepare for quiz at the beginning of Session VI.

Session VI

Skim chapters 9 and 12 of the text *Fiber Optic Communications* and review the material on optical Fouler transforms and optical signal processing in *Photonics*, review Fourier transforms and read the paper "The Use of Optical Fourier Transforms to Obtain Pleomorphism, Size and Chromatic Clumping in Nuclear Models," by C. P. Miles and D. L. Jaggard, *Anal. Quant. Cytology J. 3,* 149-156 (1981) or read alternative material assigned in class. Do review problems and have a draft of your photonics project ready. The final project is due at the start of the next term (approximately two weeks after our final classroom session). Be prepared with VU graphs for a five to ten minute talk that provides an overview of your final project. Prepare for the course quizz.

The photonics final project description, sample mini-projects, sample quizzes, lab description, and review problems are given on the last pages of this document.

Photonics

Dwight L. Jaggard

Session I

I. Role of Photonics in Emerging Technologies
   A. Lasers and Their Uses

   B. Fiber Optics and Optical Communication Systems

   C. Integrated Optics

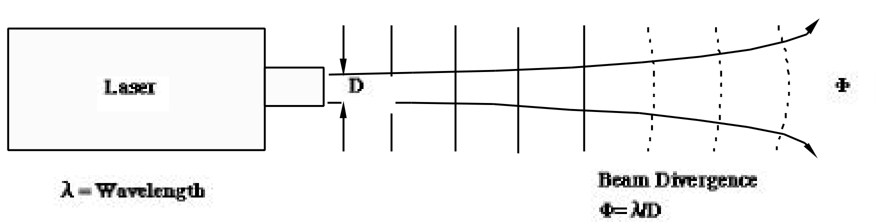
   D. Optical Signal Processing

II. Introduction to Lasers and Light
(See *Notes on Lasers and Light* by D. L. Jaggard)

   A. Laser Light vs. Natural Light
      1. Directionality

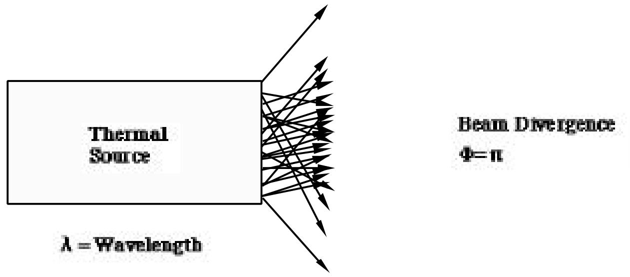
Laser:

Beamwidth ~ λ/D ~ 10^{-3} radians



Thermal:

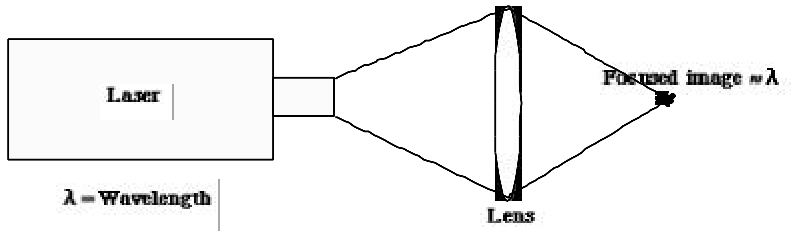
Beamwidth ~ π radians


Thermal
Source
λ = Wavelength
Beam Divergence
Φ= π

2. Focusing

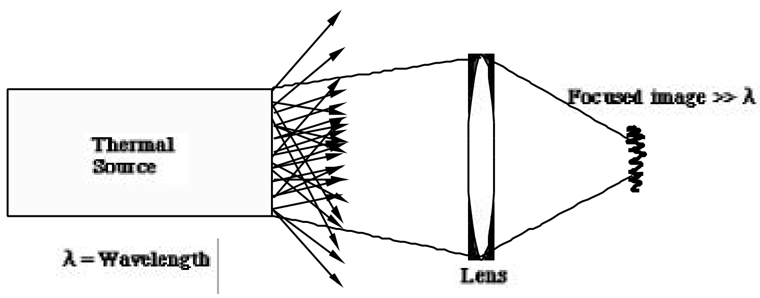
Laser:

Minimum spot size ~ λ



Thermal:

Minimum spot size >> λ



Wavelength:

$\lambda = \frac{c}{f}$ (in free space)

λ = wavelength (m)

c = speed of light = 3 x 10^8 (m/s)

f = frequency (Hz. or cps) = $\omega/2\pi$

3. Intensity

Laser is brighter than the sun!
Sun brightness ˜ 1.5 x 10^5 lumens/cm^2-str.
Laser brightness ˜ 10^8 lumens/cm^2-str.
On a per frequency basis, laser is ~ 10^6 more intense
(Safety)

Units:

Intensity

1 watt = 680 lumens

Angles

Planar Angle θ

$$\theta = \frac{\text{arc length of circle}}{\text{radius of circle}}$$

2π radians = all of a circle = 360°

Solid Angle Ω

$$\Omega = \frac{\text{area of sphere}}{\text{radius of sphere}}$$

4π steradians = all space

Length

1Å = 10^{-10} m
1 micron = 10^{-6} m
light travels 1 foot in one nanosecond (= 10^{-9} sec)

4. Monochromaticity

Laser:
Energy spread over λ of < 1Å = 10^{-10} m
Sun:
Energy spread over λ from 4,000 Å - 7,000 Å

Differential Wavelength/Differential Frequency:

$$\Delta\lambda = -\frac{c}{f^2} \quad \Delta f$$

$\Delta\lambda$ = change in wavelength
c = speed of light = 3 x 10^8 (m/s)
f = frequency
Δf = change in frequency

5. Coherence

Coherence:

A measure of the ability of a wave to interfere with a delayed or displaced version of itself.

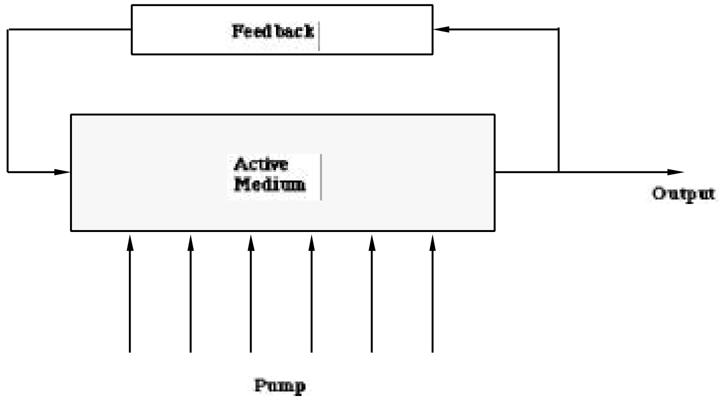
Laser:
Light can interfere with itself over significant distances (speckle)
Sun:
Light cannot interfere with itself easily

Coherence length l_c coherence time τ:

B. Overview of Laser Operation

1. Laser Architecture

Three components needed:
- Source of power (pump)
- Amplifier (active medium)
- Feedback (cavity or reflector)



LASER ARCHITECTURE

2. Typical He-Ne Laser

C. Types of Lasers
1. Gas

2. Solid

3. Liquid

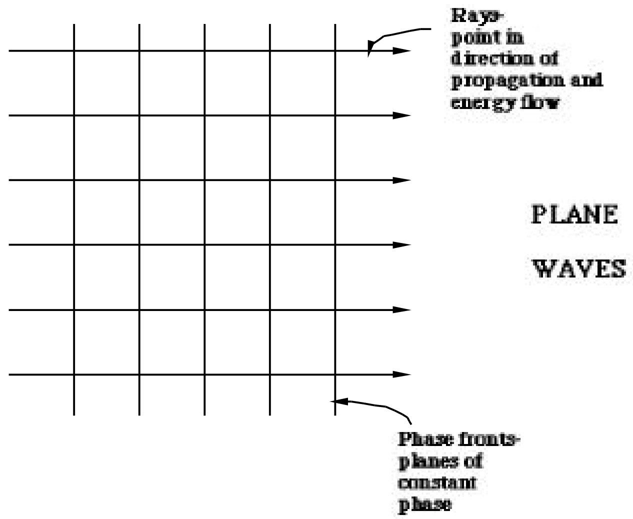
D. Laser Beam Output
1. Divergence-diffraction effect/beam waist

2. Cavities
Modes
Typical output

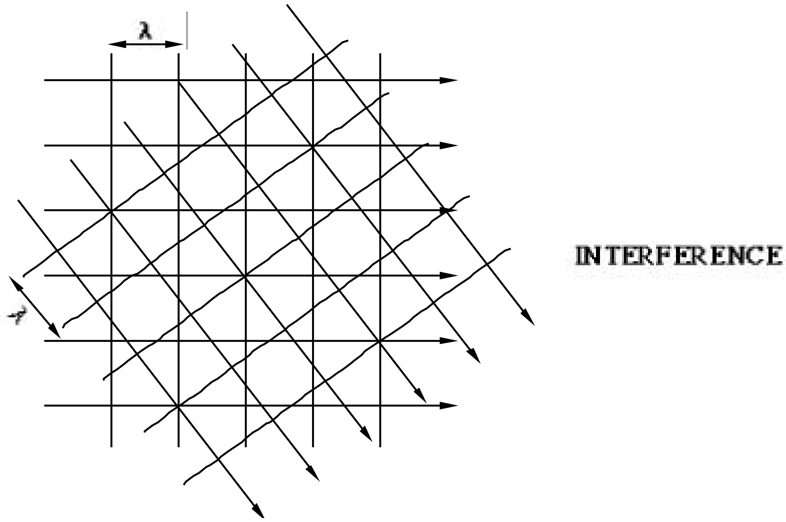
III. Basics of Optics (or Optics with a Little Math)

A. Some Basics of Waves

1. Rays and phase fronts


Rays-
point in
direction of
propagation and
energy flow
PLANE
WAVES
Phase fronts-
planes of
constant
phase

2. Interference



3. Form of waves

Electric field

$$\mathbf{E}(z,t) = A \cos[2\pi(ft - \frac{z}{\lambda} + \phi] \hat{\mathbf{e}}_1$$

Need four quantities to describe

Amplitude	A
Wavelength (or frequency)	$\lambda = c/f$ (in free space)
Phase	ϕ
Polarization	$\hat{\mathbf{e}}_1$ (unit vector)

4. Auxiliary relations

$$k = \text{wavenumber} = \frac{2\pi}{\lambda} = \frac{\omega}{c}$$

$$\omega = 2\pi f$$

$$f = \frac{c}{\lambda} \quad \text{(in free space)}$$

5. Electric and Magnetic Fields and Intensity

$$\mathbf{H}(z,t) = B\cos[2\pi(ft - \frac{z}{\lambda} + \phi] \hat{\mathbf{e}}_2$$

Intensity ~ $|\mathbf{E}|^2$

B. Optical Materials

1. Refractive index

Index of Refraction:

$$n = \frac{\text{velocity in free space}}{\text{velocity in material}}$$

If n varies with frequency or wavelength, the material is said to be *dispersive*.

$n > 1$ (usually)

2. Dispersion

For most materials, n decreases with decreasing frequency or increasing wavelength

This change in velocity can be used to manipulate wavefronts and waves and is the principal used for the operation of the lens and the prism

C. Reflection

1. Some Simple Rules

Simple Rule #1:

The angle of incidence equals the angle of reflection.

Simple Rule #2:

At normal incidence, the *field* reflection coefficient is given by

$$\rho = -\frac{n_2 - n_1}{n_2 + n_1} \quad .$$

and the *intensity* reflection coefficient (or *reflectance*) is given by

$$R = \left| \frac{n_2 - n_1}{n_2 + n_1} \right|^2 .$$

2. Refraction

Refraction is the bending of light rays by an interface between two materials of differing refractive indices due to the difference in the phase velocity in each case.

3. More Simple Rules and Refraction

Simple Rule #3:

The *critical angle* θ_c for waves at oblique incidence is given by

$$\sin \theta_c = \frac{n_2}{n_1}$$

for $n_2 < n_1$.

Simple Rule #4:

The *Brewster angle* θ_b for waves at oblique incidence is given by

$$\tan \theta_b = \frac{n_2}{n_1}$$

for both $n_2 < n_1$ and $n_2 > n_1$.

Simple Rule #5:

Snell's law of refraction is given by

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad .$$

Session II

4. Reflection at Any Angle

In general, the power reflection coefficients $R_{||}$ and $R_{\perp}$ for parallel and perpendicular polarization can be found and written in a simple format. The result is

Rule #6:

$$R_{||} = \frac{\tan^2[\theta_1 - \theta_2]}{\tan^2[\theta_1 + \theta_2]}$$

$$R_{\perp} = \frac{\sin^2[\theta_1 - \theta_2]}{\sin^2[\theta_1 + \theta_2]}$$

where the angles θ_1 and θ_2 are the angle and incidence and the angle of refraction, respectively, related by **Simple Rule #5**.

[Note that $R_{||}$ (above) is the same as R_p (of the text), likewise for $R_{\perp}$ and R_s.]

5. Applications:

a. Total internal reflection–prisms and fibers

b. Lens-beam expander

c. Mirrors

d. Polarizers (Brewster angle mirrors)

D. Diffraction

1. *Diffraction is the spatial spreading of light due to propagation or scattering by an object*. Since the distribution of light far from a source is proportional to the Fourier transform of the source distribution, we see that small (measured in wavelengths) sources have a large amount of spreading while large (measured in wavelengths) sources have a small amount of spreading. Diffraction is an attribute of all sources of waves and is responsible for the spreading in free space of microwave beams, optical beams and acoustics. Mathematically, this is given by the relation

   Beamwidth ~ λ/D (λ = wavelength of wave, D = diameter of beam) as stated previously.

2. A comparison of *diffraction* and *refraction* for typical optical waves is useful. Since for most optical materials the index of refraction decreases with increasing wavelength, by Snell's law it is clear that for *refraction*, higher frequency (e.g., blue) light is usually bent more than for lower frequency (e.g., red) light. However, for *diffraction*, larger wavelength (e.g., red) light is bent more by scattering from a grating or edge than smaller wavelength (e.g., blue) light. That is, diffraction and refraction (from normally dispersive materials) have opposite behavior with variations in wavelength or frequency.

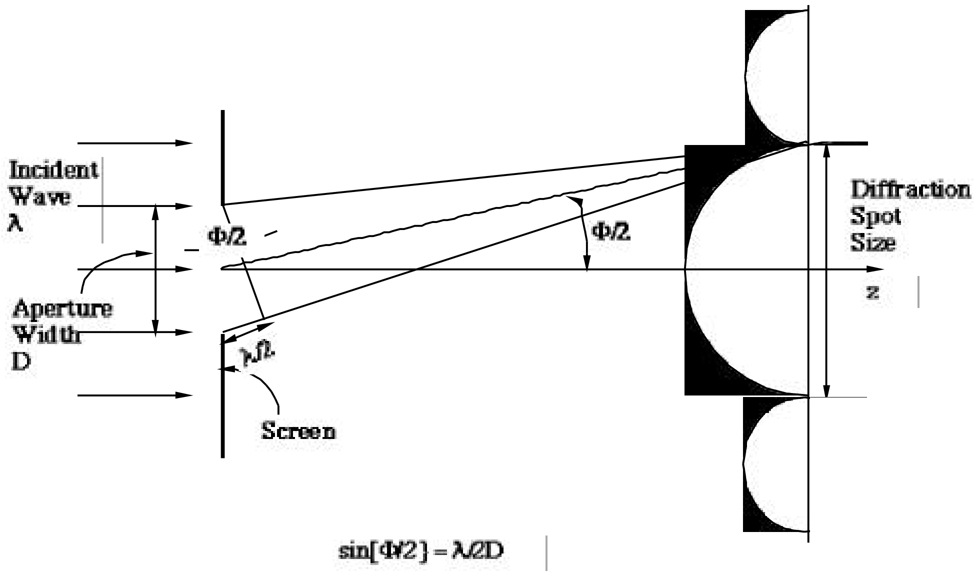
3. Ray Picture of Diffraction

   If two rays are considered which emanate from the edge of an aperture of width D illuminated by a plane wave of wavelength λ, they destructively interfere at a half spot size on each side of the optic axis (see next page). Simple trigonometry demonstrates that

$$\sin[\Phi/2] = \frac{\lambda/2}{D}$$

   where Φ is the beamwidth (in radians). For small angels, this leads directly to our previously stated relation

$$\Phi \sim \lambda/D.$$



Note:

Nulls occur when destructive interference appears from to rays which are 180° (= π radians) out of phase.

4. Physical or Wave Optic Viewpoint

An alternative viewpoint, which we shall investigate later in dealing with optical signal processing, shows that the far-field pattern is the Fourier transform of the source distribution. Below is given a summary of this result. Details are given in the last section of these notes.

The diffracted optical field $\psi(x,y,z)$ is given in terms of integration or summation over the aperture (in the $z = 0^+$ plane) of the aperture field $\psi^0(x',y',0)$ (see next page). This is known as *Huygen's principle.* Here k ($=2\pi/\lambda$) is the wavenumber of the incident wave and θ is the angle of the observer with respect to the z axis.

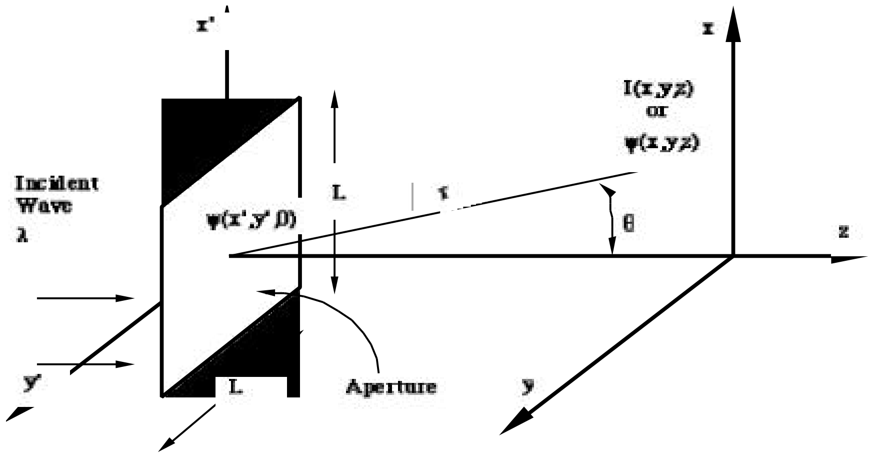
$$\psi(x,y,z) = \frac{k}{2\pi i r} \cos\theta \int_{-}\int_{-} \psi^0(x',y',0) \exp[-i \frac{k}{r}(xx' + yy')] \, dx' \, dy'$$

In the *far-field* this expression becomes

$$\psi(x,y,z) = C\, F[\psi^0(x',y',0)]\Big|_{f_x = x/\lambda r\,,\ f_y = y/\lambda r}$$

where

$$C = \frac{k}{2\pi i} \quad \cos\theta \ \frac{e^{ikr}}{r}$$



Note:

Intensity = $I(x,y,z) = |\psi(x,y,z)|^2$

Spot Size $\Delta x = \dfrac{2\lambda r}{L}$

Beamwidth $\Delta\theta = \dfrac{2\lambda}{L}$

Example: Find the far-field pattern for a two dimensional square aperture of side L as shown above.

Solution:

$$\psi^0(x',y',0) = \mathrm{rect}[x'/L]$$

$$\psi(x,y,z) = C\, F[\psi^0(x',y',0)]\Big|_{f_x = x/\lambda r\,,\ f_y = y/\lambda r}$$

$$= C\, |L|^2\, \mathrm{sinc}[Lf_x]\, \mathrm{sinc}[Lf_y]\Big|_{f_x = x/\lambda r\,,\ f_y = y/\lambda r}$$

$$= C\, |L|^2\, \mathrm{sinc}[Lx/\lambda r]\, \mathrm{sinc}[Ly/\lambda r]$$

Clearly the first zero along the x axis in the far-field is at $Lx/\lambda r = 1$ or $\Delta x = \frac{2\lambda r}{L}$ is the width of the main diffraction spot. This rigorously confirms the previous results up to a numerical factor.

5. Resolution and Diffraction

Diffraction is the limiting effect to the ultimate resolution of optical instruments and systems. *Resolution* is a measure of the ability of a system to distinguish between signals which are closely spaced in wavelength.

The *resolving power* R_p of an optical instrument or system is defined by

$$R_p = \frac{\lambda}{\Delta\lambda} \quad .$$

Derivations for a number of devices are carried out in the detailed notes, here we summarize these results.

DEVICE	PARAMETERS	RESOLVING POWER	TYPICAL RESOLUTION
Prism	Beamwidth B Dispersion $dn/d\lambda$	$B\, dn/d\lambda$	10,000
Grating	Beamwidth B Spacing d	B/d	100,000
Interferometer	Finesse $\mathcal{F}$ Cavity length L Wavelength λ	$2\mathcal{F}L/\lambda$	10,000,000

E. Coherence

1. *Coherence* is the ability of light to interfere with a delayed or displaced version of itself. Interference with a delayed version produces a measure of longitudinal coherence and yields a measure of coherence time t_c and its associated longitudinal coherence length $l_c = ct_c$. Interference with a displaced version produces a measure of transverse coherence and yields a measure of the coherence area and the transverse coherence length l_t. Together, one can envision a coherence volume composed of the coherence length l_c and a cross-sectional area given by $l_t \times l_t$.

2. Longitudinal Coherence

Optically, one uses the Michelson interferometer the measure the degree of longitudinal coherence. This is described in the handout "Notes on Lasers and Light." Mathematically, it is the autocorrelation function which measures the degree to which a wave is like a delayed or time-shifted version of itself. The self coherence function $\Gamma(\tau)$ as a function of time delay τ is defined as the autocorrelation of the light wave field u(t).

$$\Gamma(\tau) = ?\ u(t + \tau)\, u^*(t)\, dt$$

A normalized version, the coherence function $\gamma(\tau)$ has an envelope which is called the fringe visibility V. Here,

$$\gamma(\tau) = \frac{\Gamma(\tau)}{\Gamma(0)} \quad .$$

The width of the visibility V is called the coherence length. Rigorously, one defines the longitudinal coherence time as

$$t_c \equiv\ ?\ |\gamma(\tau)|^2\, d\tau \quad .$$

From the fundamental properties of autocorrelations and Fourier transforms, the definition above and from numerous examples, one finds

$$t_c \sim \frac{1}{\Delta\nu}$$

where $\Delta\nu$ is the spectral width of the light wave field. This yield the longitudinal coherence length as

$$l_c = c\, t_c = \frac{c}{\Delta\nu} \quad .$$

3. Transverse Coherence

Transverse coherence is measured by examining the maximum separation distance two pinholes can be placed in a beam and still demonstrate interference. It can be shown that the transverse coherence length l_t is approximated by

$$l_t \sim \frac{\lambda}{\Delta\theta}$$

for a source of angular dimension $\Delta\theta$ from the observer and of wavelength λ. This is due to the interference from different portions of a source as seen from the observer. Clearly, a point source (e.g., a distant light) has a large coherence length. The coherence area is given by

$$A_t \sim l_t{}^2 \sim \frac{\lambda^2}{\Delta\Omega}$$

where $\Delta\Omega$ is the solid angle subtended by the source at the observer.

longitudinal coherence length $l_c = ct_c$. Interference with a displaced version produces a measure of transverse coherence and yields a measure of the coherence area and the transverse coherence length l_t. Together, one can envision a coherence volume composed of the coherence length l_c and a cross-sectional area given by $l_t \times l_t$.

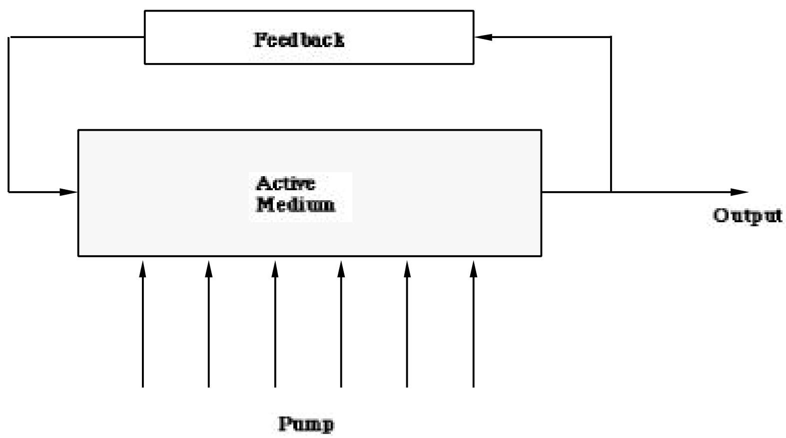
Session III

III. Principles of Laser Operation (or Optics with a Little Physics)

A. Overview

Remember that lasers need three components in order to operate:

- ❍ Feedback (cavity)
- ❍ Active medium or amplifier(atomic system)
- ❍ Pump (e.g., electrical discharge, optical, electrical current)



LASER ARCHITECTURE

One needs to know the operational characteristics of these three components or sub-systems to understand laser operation and output properties.

B. Atomic System

1. Energy levels

Each atomic element has discrete energy levels as shown below.

This atomic systems can absorb or emit light when the atom makes a transition from one level to another. The frequency of emission or absorption is related to the difference in energy levels by :

$$\Delta E = E_1 - E_o = hf$$

where

$h = 6.6 \times 10^{-34}$ (MKS units) = Plank's constant

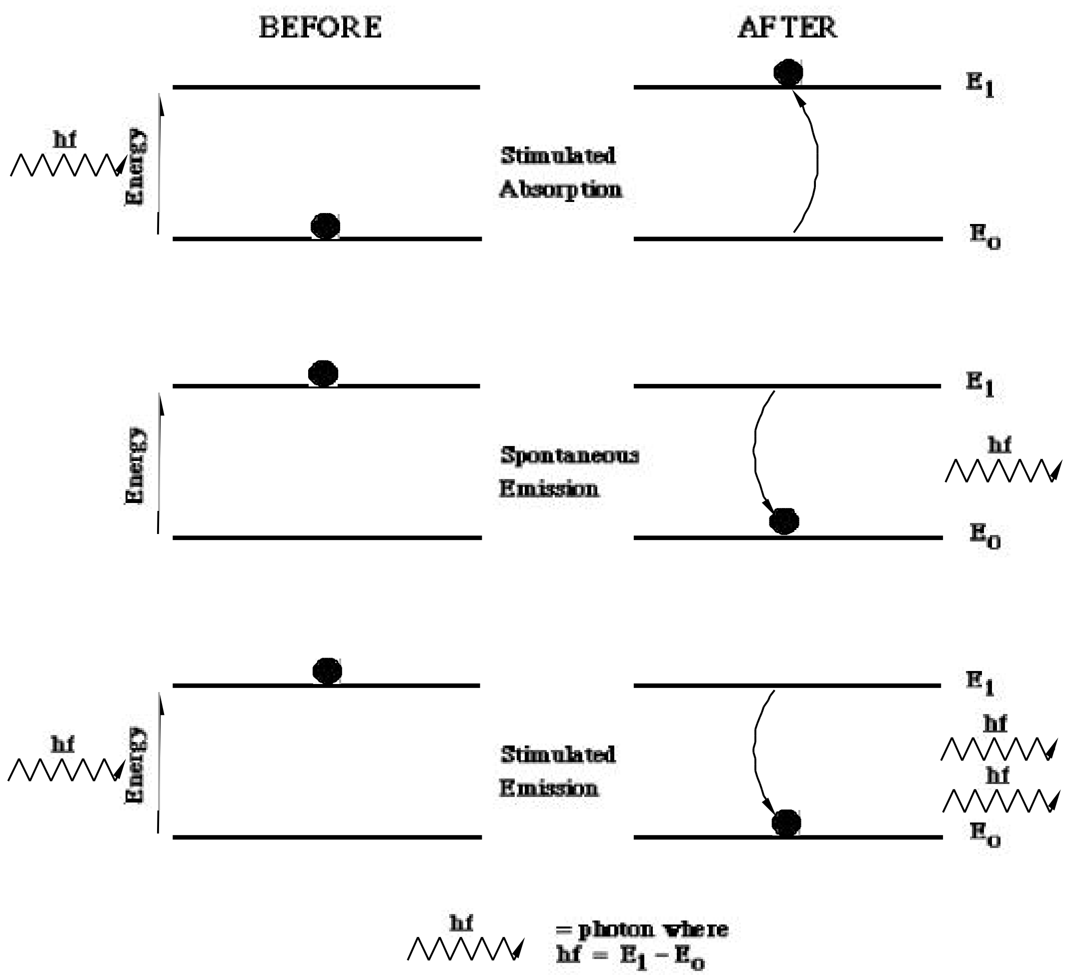
f = frequency (Hz)

The probability of a given transition is measured by the transition lifetime τ. If τ is large, a transition is said to be *forbidden*. The upper level of forbidden transitions are called *metastable states.* Typically $\tau \sim 10^{-6}$ s for allowed transitions.

Selection rules (from quantum mechanics) can be used to determine if transitions are allowed or forbidden. Transition lifetimes can also be calculated.

2. Absorption and Emission

Three types of processes shown below are possible for two-level atomic systems. In the first, an incoming photon excites the atomic system from a lower energy state into a higher energy state. This is called *stimulated absorption.* In the second, an atomic system spontaneously goes to a lower energy state through the emission of a photon. This is called *spontaneous emission* or *fluorescence*. In the third, an incoming photon produces a second coherent photon by reducing the energy state of the system. This is called *stimulated emission* and is responsible for laser action. In each case, the relation $hf = E_1 - E_o$ links the difference in energy with the frequency of the relevant photon.



3. Einstein Relations

$W_{10}^{spont} = A_{10} N_1$ = rate of spontaneous emission from level 1 to level 0

where

N_1 = # atoms in level 1

A_{10} = coefficient of spontaneous emission

$W_{01}^{stim} = B_{01} N_0 \rho$ = rate of stimulated absorption from level 0 to level 1

where

N_0 = # atoms in level 0

B_{01} = coefficient of stimulated absorption from level 0 to level 1

ρ = energy density per unit frequency of of incoming photons

$W_{10}^{stim} = B_{10} N_1 \rho$ = rate of stimulated absorption from level 1 to level 0

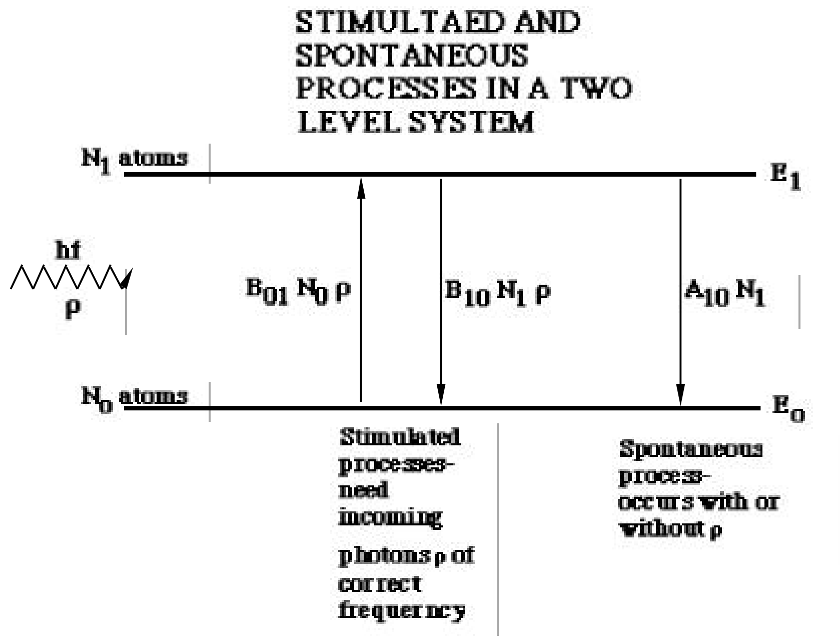
where

N_1 = # atoms in level 1

B_{10} = coefficient of stimulated absorption from level 1 to level 0

ρ = energy density per unit frequency of of incoming photons

4. Simulated and Spontaneous Processes



In thermal equilibrium, the populations of the two energy levels are given by the Boltzman distribution

$$\frac{N_1}{N_o} = \frac{\#\text{ atoms in level 1}}{\#\text{ atoms in level 0}} = e^{-hf/kT}$$

where

$hf = E_1 - E_o$

k = Boltzman's constant = 1.380×10^{-23} (MKS units)

T = temperature (in degrees Kelvin)

5. Relation of Gain to Population

Since an active or gain medium (i.e., the amplifier) is the atomic system, a wave which travels through the system needs to extract energy from the atoms. Thus, the intensity increases as

$$I(z) = I_o \, e^{\gamma z}$$

where γ is the gain constant.

It can be shown that this constant is proportional to the population difference between the two atomic levels and given by the relation

$$\gamma = \frac{(\tilde{N}_1 - \tilde{N}_o)\, hfn}{c} \quad g(f)$$

where

$g(f)$ is the *line-shape function*
(power spectral density of absorption or emission line)

$\tilde{N}_1$ = N_1 per unit vol.

$\tilde{N}_o$ = N_o per unit vol.

n = refractive index of atomic system

f = resonant frequency of system = $(E_1 - E_o)/h$

c = speed of light

❍ γ is positive, and therefore there is gain, only if there is a *population inversion* given by the condition $N_1 > N_o$.

C. Pumps

1. Population Inversion

Any method that can produce a population inversion is called a *pump*. For any energy level *i*, the Boltzman distribution giving the number density in the i^{th} level divided by the number density in the ground state is given by

$$\frac{N_i}{N_o} = \frac{\#\text{ in level } i}{\#\text{ lowest (ground) state}} = e^{-(E_i - E_o)/kT} < 1 \quad .$$

Therefore, N_i is less than N_o under equilibrium conditions.

Typical methods include:

❍ Electrical discharge

❍ Optical

- ❍ Electrical current
- ❍ Chemical reaction
- ❍ Mechanical (i.e., gas dynamic)

Most pumps are either two or three level configurations (see *Notes on Lasers and Light*).

2. Line Shape and Line Width

Experimentally is has been found out that emission and absorption take place over a range of frequencies, Δf, rather than at a single discrete frequency. The means the energy levels are "smeared." The lineshape function g(f) describes the frequency dependence of the emission or absorption, properly normalized so that its integral over all frequencies is unity.

3. Types of broadening

- ❍ Lifetime
- ❍ Collision
- ❍ Doppler

The atomic system, due to one or more of these broadening mechanisms, as a characteristic linewidth on the order of $10^2 - 10^{10}$ Hz.

D. Laser Cavities, Output and Design

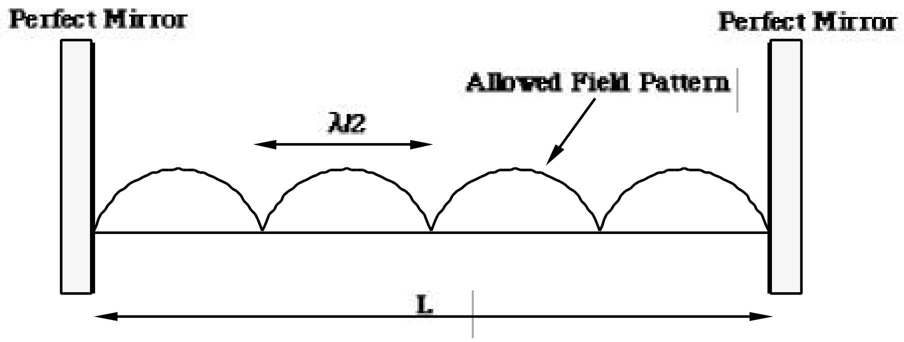
1. Ideal Cavity

An ideal cavity is one formed by plane parallel mirrors. The field arranges itself so that an integral number of half wavelengths fit the in the cavity of length L. This means,

$$L = m\frac{\lambda}{2} \qquad (m = 0, 1, 2, 3, \ldots)$$

where λ is the wavelength in the gain medium (= λ_o/n).

IDEAL CAVITY



This means that the longitudinal mode spacing in frequency is given by

$$\Delta f = \frac{c}{2nL}$$

and the transmission coefficient is unity at these discrete frequencies.

2. Laser Cavities

Clearly, an ideal cavity will not let any light out for use. Therefore, one causes one or both mirrors to become partially reflecting so that the optical field can leak out in a usable laser cavity. As seen from our analysis of the Fabry-Perot cavity, this causes the output transmission to take on a characteristic frequency or line width, Δf_l.

The cavity finesse $\mathcal{F}$ is defined to be

$$\mathcal{F} = \frac{\text{line spacing}}{\text{line width}} = \frac{\Delta f}{\Delta f_l} \quad .$$

From the Fabry-Perot analysis this was found to be related to the (intensity) reflection coefficient R of the mirrors by

$$\mathcal{F} = \frac{\pi\sqrt{R}}{1 - R} \quad .$$

3. Lasing Condition

The condition for lasing or oscillation is that the round-trip journey of a wave replicates the wave. This self-consistent condition can be seen by examining a laser cavity of length L, with (intensity) mirror reflectances of R_1 and R_2 filled with a gain medium of gain constant γ.

Clearly this equation yields the self-consistency condition for lasing. When combined with our previous result for oscillation we find the two necessary conditions for lasing.

Lasing Conditions:

$$L = m\frac{\lambda}{2} \qquad (m = 0, 1, 2, 3, \ldots)$$

(Cavity condition)

$$1 = R_1 R_2 e^{2(\gamma-\alpha)L}$$

(Self-consistency condition)

4. Cavity Stability

The mirrors of a cavity are slightly curved to prevent a beam from walking out of the cavity after several bounces. This leads us to the stability condition for cavities.

Stability Condition:

$$0 < g_1 g_2 < 1$$

where

$$g_1 = 1 - L/R_1$$

$$g_2 = 1 - L/R_2$$

Note:

- ❍ If the configuration is confocal, the beam spot size at the mirrors is minimum
- ❍ One typically wants a large spot size to minimize beam divergence
  This requires near-planar mirror (which are hard to adjust)

V. Laser Types and Modifications and Their Applications (or Optics with a Few Pictures)
(See VU graphs)

A. He-Ne Laser

B. Noble Gas Laser

C. CO_2 Laser

D. Dye Lasers

E. Semi-Conductor Lasers

F. Integrated Optical Lasers

Session IV

VI. Fiber and Guided Wave Optics (or Optics with Mirrors)

A. Optical fibers

(For details, see "Designer's Guide to Fiber Optics," chapters two and three of the book *Optical Communication Systems* and additional handouts on fiber optics.)

1. Basic Principals of Operation

a. Ray Picture

In the *ray picture*, we treat light as traveling along straight ray paths.

Reminders:

Index of Refraction:

$$n = \frac{\text{velocity in free space}}{\text{velocity in material}}$$

If n varies with frequency or wavelength, the material is said to be *dispersive.*

$n > 1$ (usually)

Critical Angle:

The *critical angle* θ_c for waves at oblique incidence is given by

$$\sin \theta_c = \frac{n_2}{n_1}$$

for $n_2 < n_1$.

Typically, the cladding (n_2) and core (n_1) refractive indices are within a few percent of each other which limits the critical angle to rays near grazing. For example, if $n_2 = 1.46$ and $n_1 = 1.48$, $\theta_c = 80.6^o$.

Note that rays which travel down the center of the guide travel a shorter path than those which travel down the fiber making the maximum number of bounces.

Example:

For an axial distance L along the fiber, the straight ray will take a time $[n_1 L/c]$ to traverse the fiber length while the most oblique ray will take the time $[n_1 L/c \sin \theta_c = n_1^2 \quad L/n_2 c]$. The time difference is given by

$$\Delta T = \frac{n_1}{n_2}\frac{L}{c} \quad \Delta n$$

where $\Delta n = n_1 - n_2$.

b. Modal Picture

An alternative picture of wave propagation in fibers is the *modal picture* in which the wavelike characteristics of light are used. A *mode* is simply a spatial distribution of an optical field (e.g., the electric field) or optical intensity. In fibers and waveguides, the modes represent the transverse distribution of an optical field or optical intensity. The price one pays is in the use of industrial strength mathematics.

Several important results are obtained from the modal picture.

- The optical field has an exponentially decaying portion outside the core

- Each mode can be thought of as the sum of two rays traveling with a given angle with respect to the fiber axis

- Normalized frequency V is given by

$$V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}$$

  where d is the core diameter and λ is the wavelength.

- Only a single mode (an axial ray) can propagate for $V < 2.405$ in step-index fibers.

- The approximate number of propagating modes is given by

$$N = V^2/2$$

  for step-index fibers.

2. Dispersion

Dispersion is the spreading of pulses as they traverse a length of optical fiber. This can be due to the propagating of different modes (or equivalently different rays) or can be due to dispersive material.

a. Modal dispersion

From our previous discussion, rays which travel at different angles or modes which travel with different velocities lead to *modal dispersion* or *multipath time dispersion* given by

$$\left.\frac{\Delta T}{L}\right|_{\text{modal}} = \frac{n_1}{n_2}\,\frac{\Delta n}{c}$$

where $\Delta n = n_1 - n_2$.

For unclad step-index glass fibers this leads to (n_2 = 1.00 and n_1 = 1.50)

$$\frac{\Delta T}{L}\bigg|_{modal} = 2.5 \times 10^{-9} \text{ s/m} = 2.5\ \mu\text{s/km}$$

while for clad step-index fibers this leads to (n_2 = 1.46 and n_1 = 1.48)

$$\frac{\Delta T}{L}\bigg|_{modal} = 6.76 \times 10^{-11} \text{ s/m} = 67.6 \text{ ns/km}$$

which is much less than the unclad case.

b. Material dispersion

As discussed previously, the variation of refractive index with wavelength or frequency leads to *material dispersion* to the various travel velocities of differing frequencies within a pulse. This effect is typically much smaller than modal dispersion and can be quantified. The mathematics is somewhat more complicated than that given previously for modal dispersion but leads to the simple expression

$$\frac{\Delta T}{L}\bigg|_{material} = \left|\frac{\Delta\lambda}{\lambda}\ \frac{1}{c}\ \lambda^2\ \frac{d^2n}{d\lambda^2}\right|$$

Typical values for GaAs light-emitting diode sources ($\Delta\lambda/\lambda = 0.035$) is

$$\frac{\Delta T}{L}\bigg|_{material} = 2.5 \text{ ns/km}$$

while for laser sources which have a narrower spectral output ($\Delta\lambda/\lambda = 0.0035$) one finds

$$\frac{\Delta T}{L}\bigg|_{material} = 0.25 \text{ ns/km}$$

in silica ($\lambda^2\ \frac{d^2n}{d\lambda^2} = 0.021$).

In any case, these values are seen to be from somewhat less to a lot less than the modal dispersion values found above. This means that ultimately, material dispersion will provide the fundamental limit to dispersion and that this will be dependent upon the type of source used.

c. Waveguide dispersion

Rays associated with different frequencies and modes travel at slightly different angles. Alternatively, different frequency modes “see” different refractive indices depending on the amount of the mode outside the guiding or core region. This leads to waveguide dispersion which is present even if both modal and material dispersion could be eliminated. This dispersion becomes apparent when wavedivision multiplexing (WDM) is used to increase the capacity of a fiber optic system. It can be decreased by making the index of the cladding approach the index of the core.

d. Dispersion effects and its reduction

Dispersion limits the bit rate B or bandwidth Δf of pulses which can be transmitted. To first order we find (using Fourier transforms to make it rigorous)

$$B \sim 2\Delta f \sim \frac{1}{\Delta T} \quad .$$

Often, the quantity $\Delta f\, L$ will be quoted as the *bandwidth-distance product* of the fiber.

To reduce modal dispersion:

- ❍ Clad fiber with refractive index close to that of the core
- ❍ Make the fiber single mode by causing $V < 2.405$ so that modal dispersion is eliminated
- ❍ Use graded-index fibers to minimize ray path differences (this works for meridional rays but not for skew rays)

To reduce material dispersion:

- ❍ Use material with small variation of refractive index
- ❍ Use spectrally narrow sources
- ❍ Operate source at or near the point of inflection in the $n(\lambda)$ vs. λ curve ("wavelength of zero material dispersion")

As an alternative, one can use solitary wave fibers in which the effects of material dispersion are offset by nonlinearities.

d. Multiple dispersion effects

Multiple dispersion effects are most often found (unless the fiber is operated single mode). In this case, the time delays add as the root of the sum of the squares so that for modal and material dispersion (assuming one can neglect waveguide dispersion), one finds the total delay $\Delta T\big|_{total}$ represented by

$$\frac{\Delta T}{L}\Big|_{total} = \sqrt{\left[\frac{\Delta T}{L}\Big|_{modal}\right]^2 + \left[\frac{\Delta T}{L}\Big|_{material}\right]^2}$$

3. Attenuation Losses

Loss can come through absorption, scattering or fiber bending

a. Absorption

Absorption losses in glasses can come from three factors:

- ❍ intrinsic absorption of the basic material
- ❍ impurity absorption
- ❍ atomic defect absorption

i. Intrinsic absorption

This is due to charge transfer bands in the ultraviolet and vibration or multiphonon bands in the near infrared. For most glasses, the ultraviolet bands are a greater problem. Typically, absorption from this source is less than 1 dB/km.

ii. Impurity absorption

Metal ions (e.g., Fe, Cu, V and Cr) are typical sources of impurity absorption. In addition, OH radicals provide attenuation at the rate of approximately 1 dB/km/ppm.

iii. Atomic defect

Atomic defect absorption is induced by a stimulus (e.g., thermal history or intense radiation).

b. Scattering

Scattering losses in fibers can come about through Rayleigh scattering (the blue sky effect) and radiation losses.

i. Rayleigh scattering

Materials scatter light due to frozen in thermal fluctuations which will provide a fundamental limit the attenuation when all other sources are eliminated. These fluctuations scatter propagating light back toward the source or out of the fiber. The loss is proportional to λ^{-4} and so can be minimized by using larger wavelength (i.e., smaller frequencies) in which the fluctuations are no longer "seen" by the light wave.

ii. Radiation losses

For cladding of finite thickness, some of the exponentially decaying portion of the mode will be absorbed by the jacket. This is especially true for modes in which the there is considerable power near the periphery of the core. This can be decreased by increasing the cladding and keeping the cladding low loss.

c. Bending losses

If the fiber is bent, rays which would usually be captured due to total internal reflection can now escape the fiber. Therefore, tight turns should be avoided.

Session V

4. Other Elementary Aspects of System Losses

There are many sources of loss in any fiber system as one proceeds from the source to the fiber and on to the receiver. Loss is given as a ratio of output to input powers or often given in decibels (dB). The latter allows losses to be added up by adding the total dB loss. To find the loss in dB, use the following relation:

$$\text{Loss or Gain (dB)} = 10 \log_{10} (\text{output power/input power})$$

This means that –3 dB indicates a loss of half the power.

a. Numerical Aperture

The *numerical aperture* (NA) defines the acceptance cone half-angle α of the fiber. From Snell's law and the critical angle expression it is expressed as

Numerical Aperture:

$$NA = \sin \alpha = \sqrt{n_1^2 - n_2^2} = \sqrt{2n\,\Delta n}$$

for step index fibers where $\Delta n = n_1 - n_2$ and $n = (n_1 + n_2)/2$

b. Packing Fraction

(~–1.1 dB)

c. Reflection

Fresnel reflection produces a loss in dB of

$$10 \log_{10} \left\{ 1 - \left[\frac{n_1 - 1}{n_1 + 1} \right]^2 \right\} \quad (\sim -0.2 \text{ dB})$$

d. Area mismatch

If the area of the source is larger than the fiber area, there is no method which can be used to recover the light (e.g., a lens will not work).

e. Profile of sources

Not all of the light leaving the source makes is captured by the fiber due to the numerical aperture. For Lambertian sources where the intensity profile is given by $I(\theta) = I_o \cos\theta$, θ being the angle from the source normal, the total power P_o is given by integrating over all forward directions. However, only the amount of power P from $\theta = 0$ to $\theta = \alpha$ can be captured by the fiber. Thus, the loss is given by

$$\frac{P}{P_o} = NA^2 = 2n\,\Delta n$$

for a step-index fiber.

As before, this can be placed in dB to yield a loss of

$$10 \log_{10} 2n\,\Delta n \quad (\sim -12 \text{ dB}).$$

4. Sources

Sources should be high power, to overcome attenuation, and spectrally narrow to avoid dispersion.

a. Spectral width
b. LED and Lasers

5. Receivers

a. PIN Photodiodes
b. Avalanche Photodiodes
c. Receiver losses

6. Systems Considerations

a. Coupling
b. Multiplexing
c. Modulation
d. More system losses

7. Cables and Splicing

a. Bundles
b. Connection losses

8. Use as Light Transporters and Imaging Bundles

B. Thin Film Integrated Optics

C. Applications to Optical Communications

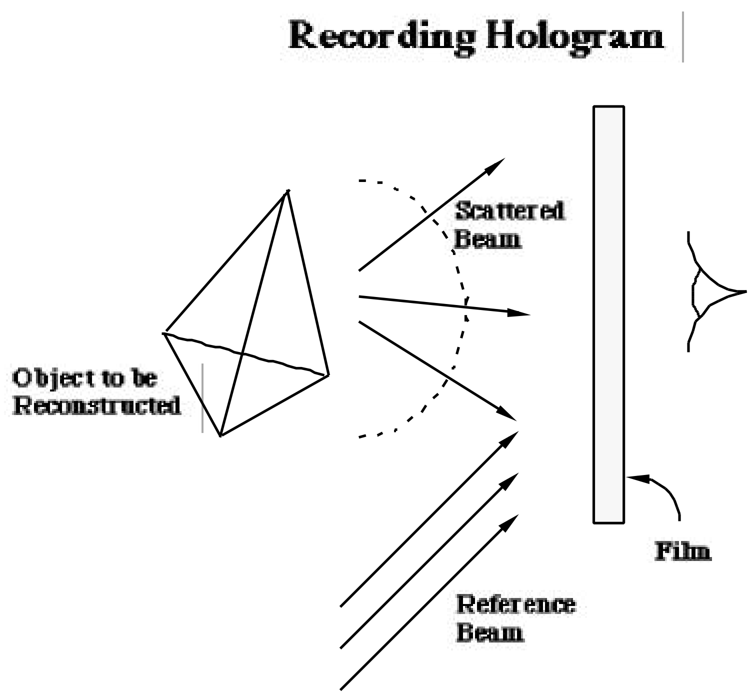
D. Design Project

VII. Holography and Optical Signal Processing

(See chapter from *Introduction to Fourier Optics* by J. Goodman)

A. Recording a Hologram

Illuminate the object of interest and record the scattered light wave S and the reference light wave R on film. The film transmittance t is proportional to the intensity of the incident light which is equal to the absolute value squared of the sum of R and S.



Calculations give us the following results (R and S are complex and given by an amplitude and phase) for the film transmittance t after illumination and developing.

Scattered light wave = S

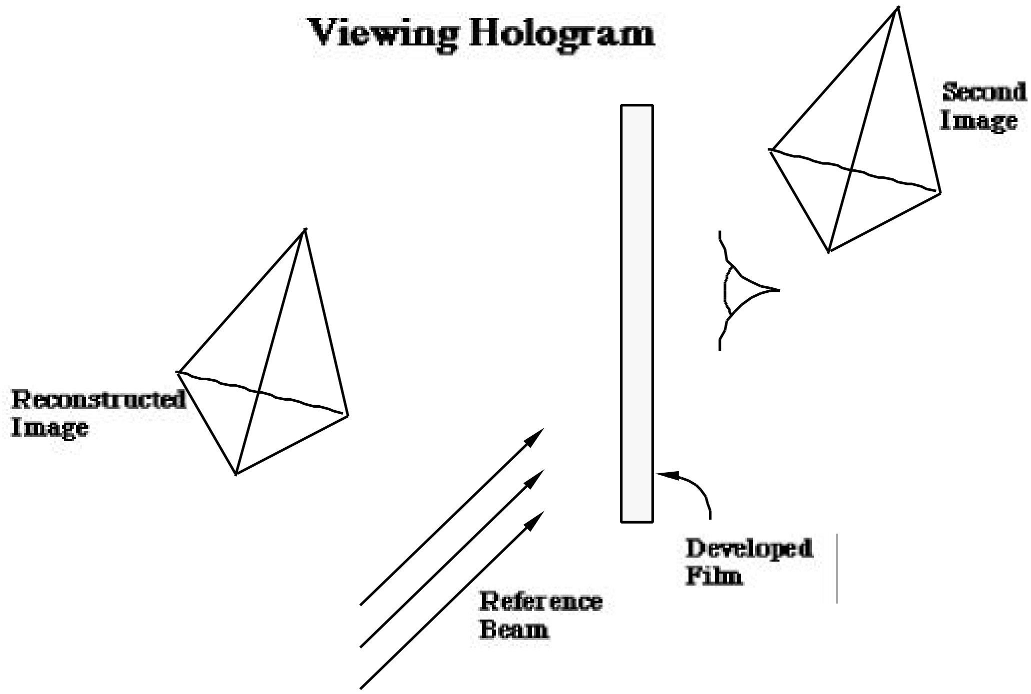
Reference light wave = R

Intensity of $(S + R) = |S + R|^2 = S\,S^* + R\,R^* + S\,R^* + S^*\,R$

Transmittance of film = t ~ Intensity = $S S^* + R R^* + S R^* + S^* R$

B. Viewing a Hologram

After the film is developed, the same reference beam that was used originally to illuminate the unexposed film is used again to illuminate the developed film. The light which is emitted from this film is the product of the transmittance *t* and the reference light wave *R*.



To reconstruct the image, illuminate the developed hologram with the original reference beam. The light wave available is the product of *R* and *t*.

Light wave from film = $R\,t = R(S\,S^* + R\,R^* + S\,R^* + S^*\,R)$

$$= R\,|S|^2 + R\,|R|^2 + S\,|R|^2 + S^*\,R^2$$

The first term is very small since $|S| << |R|$. The second term is a constant with respect the image. It represents the light which travels straight through the developed film due to the reference beam and carries no information regarding the original object. The third term is the reconstructed image. It is proportional to the original object field *S* times a constant which only changes the overall intensity of this wave field. Therefore, the exact (up to a multiplicative constant) original wave field is reproduced by the film. This is the desired holographic image. This gives the viewer the illusion of seeing the original object. The fourth term is a second (unwanted) image created on the viewer side of the film.

C. Applications
1. Nondestructive evaluation and testing
2. Imaging

Session VI

VIII. Fourier Transforms

A. Introduction to Fourier Transforms (F.T.'s)
1. Why Fourier Transforms?
2. Applications

B. Fourier Transforms Fundamentals
1. System requirements
2. Signal requirements
3. Basic Idea
   a. Physical notion - how to invent a Fourier transform
   b. Fourier transform pair

$$\mathsf{F}[g(t)] = G(\omega) = \int_{-} g(t)\exp(-i\omega t)\,dt$$

$$\mathsf{F}^{-1}[G(\omega)] = g(t) = \int_{-} G(\omega)\exp(i\omega t)\,\frac{d\omega}{2\pi}$$

OR

$$\mathsf{F}[g(t)] = G(f) = \int_{-} g(t)\exp(-i2\pi ft)\,dt$$

$$\mathsf{F}^{-1}[G(f)] = g(t) = \int_{-} G(f)\exp(i2\pi ft)\,df$$

(Note: $f = \omega/2\pi$ = cyclic frequency
$\omega = 2\pi f$ = radian frequency.)

5. Handy Formulae:

a. DeMoivre's Theorem

$$z^n = \rho^n(\cos n\phi + i \sin n\phi) = \rho^n e^{in\phi}$$

b. Euler's Identities

$$e^{\pm i\phi} = \cos \phi \pm i \sin \phi$$

$$\cos \phi = \frac{1}{2} [e^{+i\phi} + e^{-i\phi}]$$

$$\sin \phi = \frac{1}{2i} [e^{+i\phi} - e^{-i\phi}]$$

5. Delta Function

a. Def:

$$\int_{-} \delta(t)\ dt = 1$$

and

$$\delta(t) = 0 \text{ for } t \ ?\ 0$$

b. Properties

i) $\int_{-} g(t)\ \delta(t - a)\ dt = g(a)$

ii) $\delta(at) = |a|^{-1}\ \delta(t)$

iii) $\int_{-} g(t)\ \delta'(t)\ dt = -\ g'(0)$

iv) $\delta(t) = \delta(-t)$ [even function]

v) $\delta'(t) = -\ \delta'(-t)$ [odd function]

e. A Useful Relation

$$\int_{-} e^{i\omega t}\, d\omega = 2\pi\, \delta(t)$$

$$\int_{-} e^{-i\omega t}\, dt = 2\pi\, \delta(\omega)$$

Replace ω by $2\pi f$ to get:

$\delta(t) \leftrightarrow 1$

$1 \leftrightarrow \delta(f)$

d. Candidates

Gaussian function

Rectangle or pulse function

Tiangle function

Lorentizian

e. Comb function

$$\text{comb}(t/T) = \sum_{n=-} \delta(t/T - n) \quad = |T| \sum_{n=-} \delta(t - nT)$$

C. Fourier Transform Properties I

1. Linearity

$$\mathsf{F}[a\, g(t) + b\, h(t)] = a\, G(f) + b\, H(f)$$

2. Scaling

$$\mathsf{F}[g(at)] = \frac{1}{|a|}\, G(f/a)$$

3. Shifting

$$\mathsf{F}[g(t-a)] = G(f)\, e^{-i2\pi f a}$$

4. Modulation

$\mathcal{F}[g(t)\, e^{+i2\pi f_o t}] = G(f-f_o)$

5. Convolution and Products

$\mathcal{F}[g(t) \ast h(t)] = G(f)\, H(f)$

where $g(t) \ast h(t) \equiv \int_{-}^{} g(t')\, h(t-t')\, dt'$

Note: The inverse holds as well,

$\mathcal{F}[g(t)\, h(t)] = G(f) \ast H(f)$

6. Cross Correlation and Autocorrelation

$\mathcal{F}[g(t) \star h(t)] = G(f)\, H^*(f)$

where $g(t) \star h(t) \equiv R_{gh} \equiv \int_{-}^{} g(t')\, h^*(t'-t)\, dt'$ = cross correlation

If g(t) = h(t), autocorrelation results,

$\mathcal{F}[g(t) \star g(t)] = G(f)\, G^*(f) = |G(f)|^2$ = power spectral density

where $g(t) \star g(t) \equiv R_{gg} \equiv \int_{-}^{} g(t')\, g^*(t'-t)\, dt'$ = autocorrelation

7. Differentiation

$$\mathcal{F}\left[\frac{d^n g(t)}{dt^n}\right] = (i2\pi f)^n\, G(f)$$

8. Power Series

$$\mathcal{F}[(-it)^n\, g(t)] = \left[\frac{d^n G(f)}{df^n}\right]$$

9. Applications

10. Content, Variation and Wiggliness

Consider an aperiodic function g(t). The *content*, *variation* and *wiggliness* of this function are given by the following relations:

$$\textit{content} = \int_{-} \left| g(t) \right| dt$$

$$\textit{variation} = \int_{-} \left| \frac{dg(t)}{dt} \right| dt$$

$$\textit{wiggliness} = \int_{-} \left| \frac{d^2 g(t)}{dt^2} \right| dt$$

It can be shown that if G(f) is the F.T. of g(t),

$$|G(f)| \leq \begin{array}{l} \text{content} \\ \text{variation}/|(2\pi f)| \\ \text{wiggliness}/|2\pi f|^2 \end{array}$$

D. Fourier Transform Properties II

1. Parseval's Theorem

$$\int_{-\infty}^{\infty} |g(t)|^2 \, dt = \int_{-\infty}^{\infty} |G(f)|^2 \, df$$

2. F.T.'s of Periodic Functions

Def:

If g(t+T) = g(t) for all t, then g(t) is a <u>periodic function</u> with period T.

For g(t) periodic, we write it in terms of its Fourier series as

$$g(t) = \sum_{n=-\infty}^{\infty} G_n \, e^{in2\pi f_o t}$$

where $f_o = \frac{1}{T}$ (the fundamental frequency) and

$$G_n = \frac{1}{T} \int_0^T g(t) \, e^{-in2\pi f_o t} \, dt$$

Its F.T. is given as

$$\mathcal{F}[g(t)] = \sum_n G_n \, \delta(f - nf_o)$$

3. Moments

$$n^{th} \text{ moment of } g(t) = \int_{-\infty}^{\infty} t^n \, g(t) \, dt = \left[\frac{d^n G(0)}{df^n}\right] \frac{1}{(-i)^n}$$

4. Uncertainty Relations

5. Some Useful F.T. Pairs

g(t) $\hat{U}$ **G(f)**
$A \;\hat{U}\; A\,\delta(f)$
$A\,\delta(t) \;\hat{U}\; A$
$\mathrm{rect}(t/T) \;\hat{U}\; \lvert T\rvert\,\mathrm{sinc}(Tf)$
$A\cos(2\pi f_o t) \;\hat{U}\; \frac{A}{2}\,[\delta(f - f_o) + \delta(f + f_o)]$
$A\sin(2\pi f_o t) \;\hat{U}\; \frac{A}{2i}\,[\delta(f - f_o) - \delta(f + f_o)]$
$\Lambda(t/T) \;\hat{U}\; \lvert T\rvert\,\mathrm{sinc}^2(Tf)$
$\mathrm{comb}(t/T) \;\hat{U}\; \lvert T\rvert\,\mathrm{comb}(Tf)$
$e^{-\alpha t^2} \;\hat{U}\; \sqrt{\frac{\pi}{\alpha}}\; e^{-\pi^2 f^2/\alpha}$
$e^{-\alpha\lvert t\rvert} \;\hat{U}\; \frac{2\alpha}{\alpha^2 + [2\pi f]^2}$

E. Fourier Series
1. Periodic functions
2. Intuitive meaning of series
3. Coefficients
4. Relation between Fourier series and Fourier transforms

F. Whittaker-Shannon Sampling Theorem

> A bandlimited signal with no spectral frequency components above a maximum frequency f_M (Hz) is uniquely specified by its (exact) values at uniform intervals less than $\frac{1}{2f_M}$ apart. The sampling rate (in sec.) $\frac{1}{2f_M}$ is known as the *Nyquist rate.*

1. Reasonableness

2. Proof

3. Imperfect sampling and inaccuracies
   a. Finite sample width
   b. Finite number of samples
   c. Discretization errors

IX. Two Dimensional Fourier Transforms and Optical Signal Processing

A. Two Dimensional Spatial Functions

1. Concept of Spatial Frequency

In the time domain, t and f are called *conjugate variables* and are shown as,

t Û f

Likewise, in the spatial domain x and f_x are the conjugate variables. Here,

x Û f_x (where f_x is the spatial frequency in cycles per meter)

This can be extended to two dimensions so that,

x,y Û f_x,f_y

2. Two Dimensional Fourier Transforms

If g(x,y) is a two-dimensional function with *spatial coordinates* x and y,

$$\mathcal{F}[g(x,y)] = G(f_x,f_y) = \int_{-}\int_{-} g(x,y) \exp[-i2\pi(f_x x + f_y y)]\, dx\, dy$$

$$\mathcal{F}^{-1}[G(f_x,f_y)] = g(x,y) = \int_{-}\int_{-} G(f_x,f_y) \exp[i2\pi(f_x x + f_y y)]\, df_x\, df_y$$

where f_x and f_y are *spatial frequencies* along x and y. (*Spatial frequency* is the number of variations or cycles per unit length.)

If g(x,y) = g(x) g(y), g(x,y) is *separable* and one can take two one-dimensional Fourier transforms.

For example,

rect(x/X) rect(y/Y) Û |X| |Y| sinc(Xf_x) sinc(Yf_y).

B. Circular Symmetry $\{(x,y,)$ Û (r,θ) and (f_x,f_y) Û $(\rho,\phi)\}$

This produces the Fourier-Bessel pair for θ and ϕ independence

$$F[g(r)] = G(\rho) = 2\pi \int_0 r\, g(r)\, J_0(2\pi r\rho)\, dr$$

$$F^{-1}[G(\rho)] = g(r) = 2\pi \int_0 \rho\, G(\rho)\, J_0(2\pi r\rho)\, d\rho$$

Example: Circular apertures

$$\text{circ}(r) \;\text{Û}\; \frac{J_1(2\pi\rho)}{\rho} = \text{jinc}(\rho)$$

Likewise, scaling and other theorems hold so that,

$$\text{circ}(r/a) \;\text{Û}\; a^2 \frac{J_1(2\pi a\rho)}{a\rho} = a^2\, \text{jinc}(a\rho)$$

C. Two-Dimensional Sampling

1. Methods of Sampling and Sampling Rate
2. Space-Bandwidth Product and Information Content

D. Fourier Transforms (F.T.'s) and Optics

1. Diffraction

The diffracted optical field $\psi(x,y,z)$ is given in terms of integration or summation over the aperture (in the $z = 0^+$ plane) of the aperture field $\psi^0(x',y',0)$. This is known as *Huygen's principle.* Here $k\ (=2\pi/\lambda)$ is the wavenumber of the incident wave and θ is the angle of the observer with respect to the z axis.

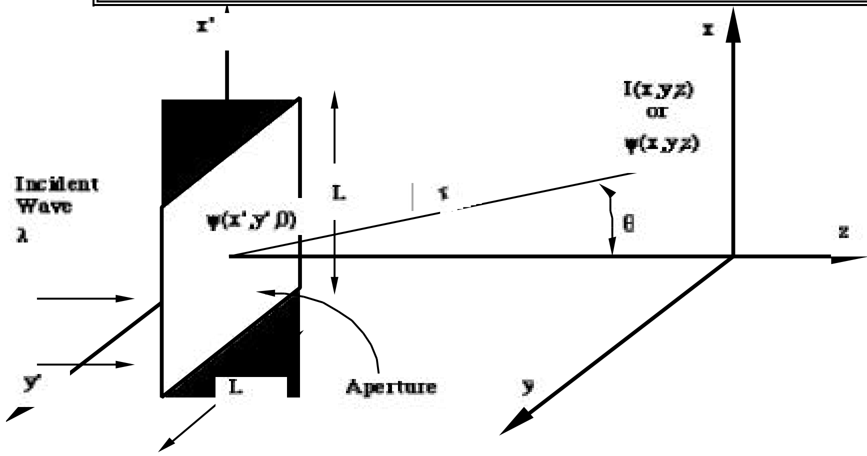
$$\psi(x,y,z) = \frac{k}{2\pi i} \cos\theta \int_{-} \int_{-} \psi^0(x',y',0) \exp[-i \frac{k}{r} (xx' + yy')]\, dx'\, dy'$$

In the *far-field* this expression becomes

$$\psi(x,y,z) = C\, F[\psi^0(x',y',0)] \Big|_{f_x = x/\lambda r,\ f_y = y/\lambda r}$$

where

$$C = \frac{k}{2\pi i} \cos\theta \frac{e^{ikr}}{r}$$



Note:

Intensity = $I(x,y,z) = |\psi(x,y,z)|^2$

Spot Size $\Delta x = \frac{2\lambda r}{L}$

Beamwidth $\Delta\theta = \frac{2\lambda}{L}$

Example: Find the far-field pattern for a two dimensional square aperture of side L as shown above.

Solution:

$$\psi^0(x',y',0) = \text{rect}[x'/L]\ \text{rect}[y'/L]$$

$$\psi(x,y,z) = C\ F[\psi^0(x',y',0)] \Big|_{f_x = x/\lambda r,\ f_y = y/\lambda r}$$

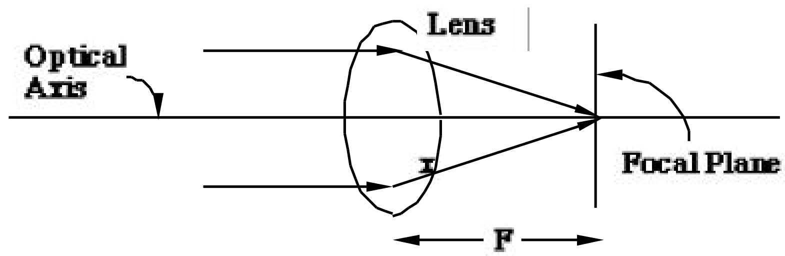
$$= C\ |L|^2\ \text{sinc}[Lf_x]\ \text{sinc}[Lf_y] \Big|_{f_x = x/\lambda r,\ f_y = y/\lambda r}$$

$$= C\ |L|^2\ \text{sinc}[Lx/\lambda r]\ \text{sinc}[Ly/\lambda r]$$

Clearly the first zero along the x axis in the far-field is at $Lx/\lambda r = 1$ or $\Delta x = \frac{2\lambda r}{L}$ is the width of the main diffraction spot. This rigorously confirms the previous results up to a numerical factor.

2. Lenses

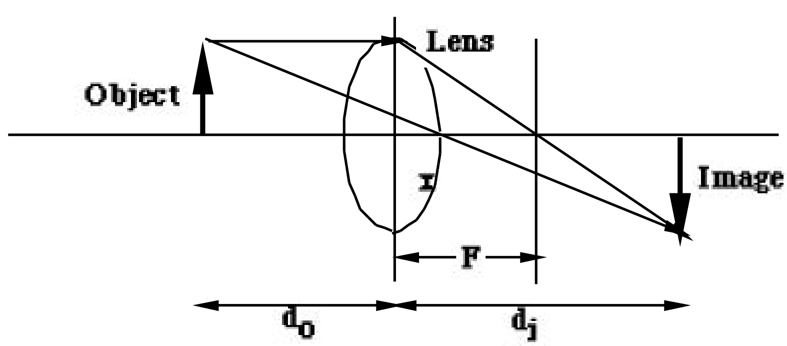
Lenses generally have two purposes, imaging and taking the (two-dimensional) Fourier transform. They are characterized by their *focal length F* which is the distance from a lens to its minimum spot size when illuminated by a plane wave source.

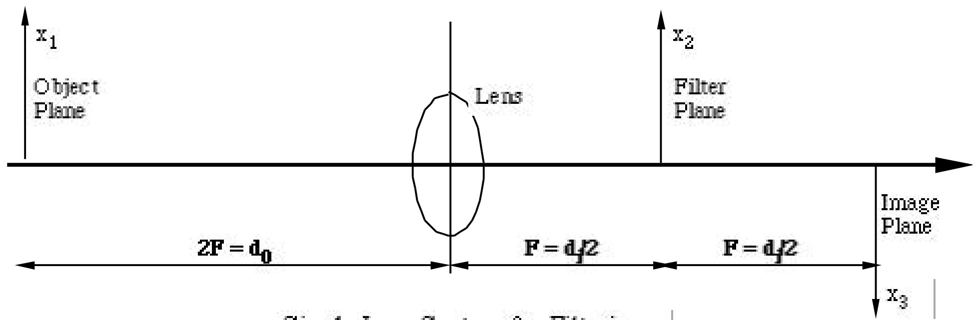


Imaging Law

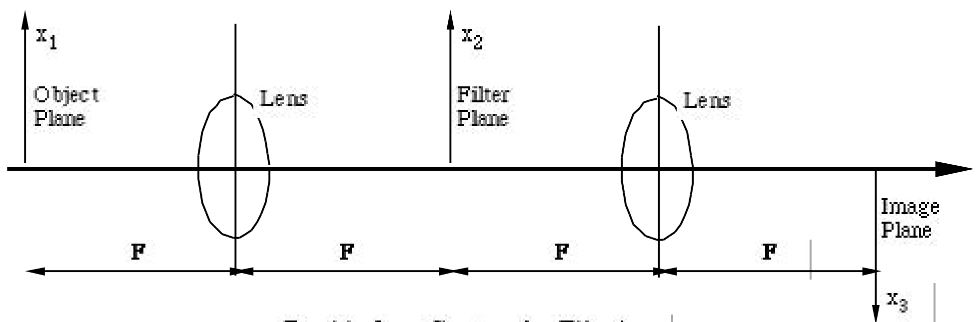
For imaging, the object distance d_o, the image distance d_i and the focal length of the lens F are related by

$$\frac{1}{d_i} + \frac{1}{d_o} = \frac{1}{F}$$





Single Lens System for Filtering



Double Lens System for Filtering

<u>F.T. Law</u>

A lens brings the far-field region to the back focal plane of the lens. Therefore, one can write at the focal plane of a lens (replace r with *F* in the previous result for aperture diffraction)

$$\psi(x,y,F) = C\,\mathcal{F}[\psi^0(x',y',0)]\Big|_{f_x = x/\lambda F,\ f_y = y/\lambda F}$$

where

$$C = \frac{k}{2\pi i} \quad \cos\theta \ \frac{e^{ikr}}{r}$$

for an incident field $\psi^0(x',y',0)$ before the lens. This means that two-dimensional transparencies placed in front of a lens will have their optical two-dimensional Fourier transform appear one focal length behind the lens when the transparency is illuminated by coherent (e.g., laser) light.

The $f^{\#}$ of a lens is a measure of how "powerful" it is, that is it is a measure of how much it can bend the rays of incident light.

$$f^{\#} = \frac{F}{D} \gtrsim \quad 1$$

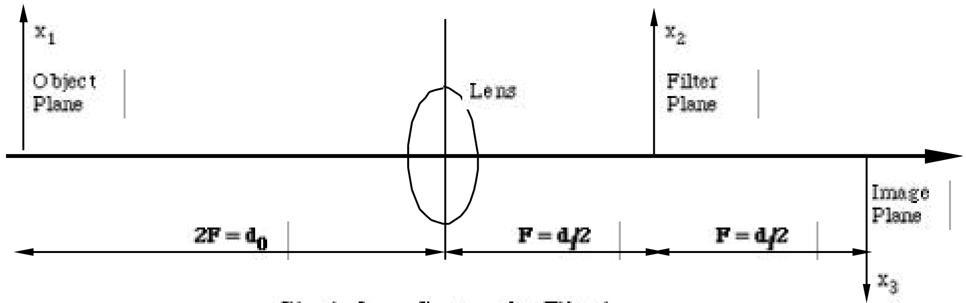
where

F = focal length of lens
D = diameter of lens

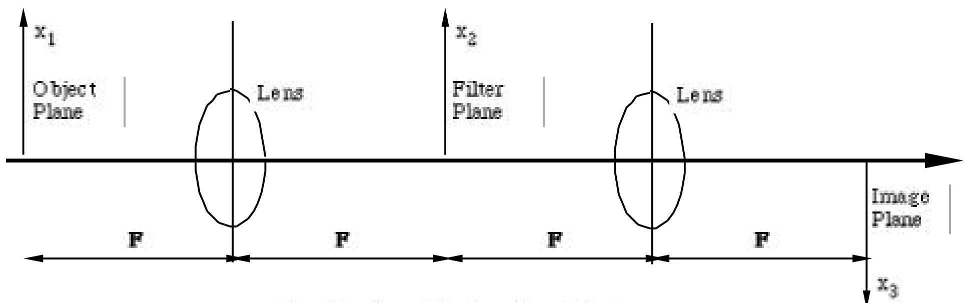
[Note: If f# is small, lens is "powerful" but distortions may occur due to lack of depth of field.]

3. Filtering

These two fundamental properties of lenses, their ability to both image and perform an optical Fourier transform, can be combined to give access to the Fourier plane of an object, and therefore allow filtering to take place, and to simultaneously image so that the image is a filtered version of the object. Both high- and low-pass operations can be easily obtained by using an aperture or a stop, respectively, in the Fourier plane. A one-lens or a two-lens configuration can be used.



Single Lens System for Filtering



Double Lens System for Filtering

[See handouts on optical Fourier transforms, from *The Atlas of Optical Transforms*, for examples of spatial filtering using optics.]

E. Coherent and Incoherent Imaging

For imaging configurations, a lens can be thought of as a linear system with an impulse response. Since high spatial frequencies propagate at large angles to the optical axis, not all spatial frequencies in an object or transparency will be passed by a lens of finite diameter. Therefore, the impulse response of a lens will tend to smear an image of a given object. In the spatial frequency domain we can easily represent this by the transfer function of the system. This transfer function $H(f_x,f_y)$ or (f_x,f_y) differs for coherent and incoherent systems, respectively. They are shown next and are simple functions of the scaled pupil function P(x,y) of the aperture.

Coherent System Transfer Function

$$H(f_x,f_y) = P(-\lambda d_i f_x, -\lambda d_i f_y)$$

where P(x,y) is the *pupil function* of the aperture. It is defined by the simple equation

$$P(x,y) = \begin{cases} 1 & \text{x,y in the aperture or lens} \\ 0 & \text{x,y outside the aperture or lens} \end{cases}$$

Therefore, for a lens of radius *a*, $P(x,y) = \mathrm{circ}(\sqrt{x^2 + y^2}\,/a) = \mathrm{circ}(r/a)$. The impulse response, $h(x,y) = \mathcal{F}^{-1}\{H(f_x,f_y)\}$, provides the resolution limit of this system.

Incoherent System Transfer Function

$$(f_x,f_y) = H(f_x,f_y) \star H(f_x,f_y) = P(-\lambda d_i f_x, -\lambda d_i f_y) \star P(-\lambda d_i f_x, -\lambda d_i f_y)$$

One immediately notices the following differences between coherent and incoherent systems:

- In both coherent and incoherent systems, one has a cutoff frequency due to the finite diameter of a lens
- In coherent systems, the cutoff frequency is lower than for the incoherent counterpart and the response below cutoff is flat
- In incoherent systems, the response below the cutoff frequency is not flat but the cutoff frequency is twice as large as for the coherent case
- Other factors, such as speckle, may be of importance. This leads one to consider the benefits of incoherent or partially coherent imaging.

Example:

Examine the resolution of an optical system which is illuminated by a He-Ne laser (λ = 0.6328 μm). The object is a bar pattern and the image is observed 1 meter from the lens. Here the bar pattern transparency t(x,y) is a series of stripes 1 mm wide on 2 mm centers, each 10 cm in height.

a. Find the (minimum) radius *a* of the lens so that the imaged bar pattern is just resolved along x.

b. Give a rough sketch of this just resolved image.

Solution:

The bar pattern is given by

$$t(x,y) = [\mathrm{rect}(x/10^{-3}) \ast \mathrm{comb}(x/2 \times 10^{-3})]\ \mathrm{rect}(y/0.1)$$

The impulse response $h(x_i,y_i)$ of the lens of radius *a* for coherent illumination (He-Ne laser) is the *jinc* function found by the relations

$$h(x_i,y_i) = \mathcal{F}\{P(\lambda d_i x, \lambda d_i y)\}\Big|_{\substack{f_x = x_i \\ f_y = y_i}}$$

$h(x_i,y_i)$ =

{

Error!}2 EQ \F(J1(2par/ldi),ar/ldi)

along the image coordinates (x_i,y_i).

Therefore, the width of the main peak is given by

$$\frac{a\,\Delta x_i}{\lambda d_i} = 1.22$$

or

$$\Delta x_i = \frac{(1.22)\,(0.6328 \times 10^{-6})}{a}$$

For resolution, one requires that the width of the *jinc* function be about the width of the bar so that $\Delta x_i = 10^{-3}$. This implies $a = 10^{-3}$. Therefore, a 1 mm radius lens would just resolve this bar pattern along x.

F. Optical Signal Processing

1. Sample Configurations

2. Fine Sorting–The Matched Filter

Here one uses a particular filter to find objects which have a specified shape or texture. For example, this may be used in character recognition.

It can be shown that the correct filter to use for a desired signal g(x,y), given a noise spectral density $S_n(f_x,f_y)$, is $\{G^*(f_x,f_y)/S_n(f_x,f_y)\}$.

3. Gross Sorting–Diffraction Pattern Sampling

Here one uses Fourier domain sampling to provide clues suitable for gross sorting of images. This technique is useful when objects are to be classified into several bins according to general characteristics rather than detailed characteristics. For example, this may be used for classification of radar imagery into urban and rural areas. Some method of sampling the Fourier domain, such as a ring-wedge detector, deals with only a small amount of the total information available.

[See reprint, C. P. Miles and D. L. Jaggard, "The Use of Optical Fourier Transforms to Obtain Pleomorphism, Size and Chromatic Clumping in Nuclear Models," *Anal. Quant. Cytology J. 3*, 149-156 (1981).]

Photonics

Review Problems

These are problems selected to provide a review of the lecture material. Specific assessments will be given at the end of each class.

Due Session II

0. a. Come to class and give a brief presentation and lead a brief discussion on some aspect of the use of optical communications or lasers in your industry. This is not to be exhaustive but you should plan on two or three minutes for your presentation and questions.
   b. Find an article describing a "new invention" in optics. Read and be prepared to give a summary.

1. Problem 1-3 (pg. 33) from the text *Fiber Optic Communications.*

2. Problem 1-12 (pg. 34) from the text *Fiber Optic Communications.*

3. Problem 1-20 (pg. 34) from the text *Fiber Optic Communications.*

4. We spent time discussing the amplitude, phase and frequency of optical signals. What use is polarization (i.e., the orientation of the electric field) in optical communications? (See chapter 3 of your text if you need further discussion of polarization.)

5. The moon is one-quarter million miles away. What is the diameter of an expanded argon-ion laser ($\lambda = 0.5145\ \mu m$) beam for a divergence of 1 μrad? What is the surface area on the moon illuminated by such a laser beam originating from earth?

6. How could one use a stack of plates (e.g., microscope slides) to polarize a beam of light which is initially unpolarized? Show your configuration. How many plates would you need?

7. Calculate the Brewster angle and the critical angle for a GaAs-air interface. The refractive index of GaAs (gallium-arsenide) is 3.655.

8. Problem 1-23 (pg. 35) from the text *Fiber Optic Communications.*

9. Problem 1-25 (pg. 35) from the text *Fiber Optic Communications.*

10. a. Problem 3-6 (pg. 76) from the text *Fiber Optic Communications.*
    b. Problem 3-7 (pg. 76) from the text *Fiber Optic Communications.*

Due Session III

11. What is the longitudinal coherence length of a source (He-Ne) with wavelength 0.6328 μm and a wavelength spread of 10^{-13} μm.

12. As we learned, a laser needs a feedback mechanism, an amplifying or active medium and a pump in order to operate. In desktop sized or larger lasers, the feedback mechanism is often a resonant cavity constructed formed by a pair of dielectric mirrors which determine the spectral output of the laser.

    Suppose one wanted to build a very small laser using integrated circuit technology in which a p-n junction forms the active medium which is pumped by a current source. The problem remains of constructing an appropriate resonant cavity.

    Consider a small laser which is to become integrated into a system such that its output is channeled directly into a thin-film waveguide or transmission line. In this case, the laser region and the guiding region are to be deposited (or diffused) onto the same substrate and it is difficult to deposit a mirror in such a configuration. Describe the construction of a resonant cavity for such a laser if the this laser is to be integrated into a thin-film waveguide. In this case, layers of material can be deposited with different refractive indices and their composition can be varied along the longitudinal axis of the laser or across it. Lasers of this type can be replicated and closely spaced such that they form a laser array on a chip of considerable power. Sketch your solution and be prepared to discuss it in class.

13. A thin slit of width 1 mm is illuminated by a plane wave of a He-Ne laser. At a distance of 5 m what is the width of the main diffraction peak?

14. Consider the design of a cavity which will be used as a spectrum analyzer with a line or mode spacing of 10^9 Hz and a linewidth of 10^6 Hz. What should be the length and the mirror reflectances of this cavity?

15. The cavity of an Ar-Ion laser is 0.5 m long.

    a. Suppose the active gas used in these lasers has a spectral width of 1.5 GHz ($=1.5 \times 10^9$ Hz). How many cavity modes can oscillate or lase? What is the approximate longitudinal coherence length of this laser?

    b. Explain how one could increase the coherence length of the laser output by introducing a second short cavity of length D inside the laser cavity.

16. Problem 2-9 (pg. 51-52) from the text *Fiber Optic Communications.*

17. Group Mini-Project due (see pg. 62).

Due Session IV

18. Problem 3-1 (pg. 76) from the text *Fiber Optic Communications.*

19. Problem 3-2 (pg. 76) from the text *Fiber Optic Communications.*

20. Problem 3-3 (pg. 76) from the text *Fiber Optic Communications.*

21. Problem 3-4 (pg. 76) from the text *Fiber Optic Communications.*

22. Using the *Designer's Guide to Fiber Optics* handout, design a fiber optic link suitable for maximum distance between repeaters using the products given in the tables. Choose source, fiber and receiver. Note frequency of operation and take into account all losses of the system. List and calculate, or estimate, all losses. Provide the total loss from source to receiver for a 10 km link.

23. Repeat the previous problem for a system which is to have the largest bandwidth over 10 km without regard to attenuation. Find the maximum bit rate for this optical link.

24. The products given in the Designer's Guide to Fiber Optics are somewhat dated. Based on your reading of other information (e.g., see Optical *Communication Systems*, or your text *Fiber Optic Communication*), what would be a more realistic estimate for the total loss from to source to receiver for problem 22. based on recent technology and a more realistic estimate for the maximum bit rate for problem 23. based on recent technology?

    Be prepared to discuss the results of the above three problems in class.

25. Understand the operation of a distributed feedback (DFB) laser.

26. Read the article *Lightwave Communications: The Fifth Generation* by E. Desurvire and other material on soliton fiber transmission and erbium doped fibers in your course material. Be prepared to discuss this paper in class.
    In particular, consider the following issues:
    - i. What are the five generations of lightwave communications?
    - ii. What defines the "fifth generation?"
    - iii. What are the major elements of the lightwave communication system of the future?
    - iv. What is the role of basic science to this technology?
    - v. How long did it take to go from the basic science to a prototype? How much longer will it take to place this system in operation?
    - vi. How can redundancy be put into these communications systems if used for transatlantic links?
    - vii. What policy issues are at stake?
    - viii. What sociological issues need to be addressed?
    - ix. What is the economic benefit of such systems?
    - x. What is the effective dispersion of such systems and how does it compare with conventional fiber optic communications systems?

27. Sketch a design for a fiber sensor. That is, design a system where a fiber is used to measure some quantity of interest such as pressure, temperature, or magnetic field.

28. **Work in groups to consider <u>one</u> of the following problems.**
Be prepared to discuss your solutions and lead the class in a discussion of your ideas. Develop appropriate sketches of implementation and consider limitations, both scientific and practical.

Problem No. 1

It is desired to find imperfections in continuously moving sections of cloth as it is being manufactured. How would you use optics to perform an automatic examination? (Of particular interest are missing threads and double threads.)

Problem No. 2

US paper currency can be easily counterfeited using recently developed color copiers and computerized methods of scanning and printing. How could one prevent such counterfeiting at a relatively low cost? (It is desired that the methods used are relatively inexpensive and do not greatly alter the appearance of the money.)

Problem No. 3

A robotic vision system is desired to obtain accurate images in a manufacturing environment. Suggest methods by which a single sensor can be automatically focused on a desired object (similar to the automatic focusing systems in modern cameras). How can one get stereoscopic images? What advantages might this provide for a robotics vision system?

29. **Prepare a brief overview of your photonics final project.**
Use a few ($\leq$ 4) VU graphs and handouts as desired. (This presentation will form part of your photonics project grade since this will be your only oral presentation on this material. You will have 4 minutes for presentation and 1 minute for questions.)

30. Problem 5-9 (pg. 138) from the text *Fiber Optic Communications.*

31. Problems 5-20 and 5-21 (pg. 139) from the text *Fiber Optic Communications.*

32. Problem 5-25 (pg. 139) from the text *Fiber Optic Communications.*

33. Estimate the total cost for placing a single trans-Atlantic optical fiber from New York to London. Include material and installation costs and itemize. Note the type of fiber and estimate the bit rate for this link assuming an appropriate source. (After making your estimate, if you have access to the actual cost, include that as well.)

Due Session V

34. During our session next Program weekend, we will discuss the use of Fourier transforms for optical signal processing. Read section VIII of the course notes *Photonics* and do the following problems in preparation for class.

a. Sketch the function g(x) = rect(x/L) and find and sketch its Fourier transform $G(f_x)$. [Remember, rect(x) = 1/2 for |x| < 1/2, and rect(x) = 0 for |x| > 1/2.]

b. Consider now the two-dimensional problem g(x,y) = rect(x/a) rect (y/b). Find its two-dimensional Fourier transform $G(f_x,f_y)$.

c. Suppose a He-Ne laser (λ = 0.6328 μm) plane wave illuminates a square aperture of size 3mm x 3mm. A distance 5m away its diffraction pattern (that is the intensity which is proportional to the Fourier transform of the field, absolute value squared) is viewed on the wall. What is the width of the main lobe of the diffraction pattern, from null to null, observed on the wall? What is the intensity of the first (largest) sidelobe relative to the main lobe maximum value? What is the expression for the intensity as a function of coordinates x and y? (Hint: use the Fourier transform relation for optics given in the notes.)

d. Two square apertures of size 3mm x 3mm are placed a distance 6mm apart along the x' axis in the plane z = 0. Find an expression for the far field a mplitude ψ(x,y,z) (i.e., the Fourier transform). Make a sketch of the far field as a function of [x/λz] given that y = 0. That is, sketch ψ(x,0,z) as a function of x, showing the important quantities such as zero crossings. (Hint: use the Fourier transform relation for optics given in the notes and remember the shift theorem and the Euler identities.)

35. A bandlimited signal g(x,y) is recorded in a degraded way by a laser printer. The recording is f(x,y) is given by:

$$f(x,y) = \sum_{n:m=-8}^{8} g(n,m)\ e^{-\pi^2[(x-np)^2 + (y-mp)^2]/\alpha^2}$$

where α and p are known (real and positive) numbers.

Given the function f(x,y), can one recover g(x,y)? If so how and note limitations. If not, why not? Assume that the maximum spatial frequency of the image is 200 lines per millimeter along both the x and y axis. Use plots and equations and explain your method of reconstruction.

Due Session VI

36. A two dimensional square microwave antenna array is designed for operation in the far field (i.e., Fraunhofer zone). The array consists of one hundred twenty one (121) 0.1 cm square apertures with center-to-center spacing of 10 cm on a regular 11 × 11 grid. Each aperture is

driven by a time-harmonic source with constant amplitude and phase across each aperture opening.

a. For a source at 10 GHz (= 1×10^{10} Hz), sketch the approximate far-zone radiation power or intensity pattern along one of the principal axes. Indicate all important widths, zero crossings and heights. What is the beamwidth between nulls? What is the ratio of highest sidelobe level to the main beamwidth level?

b. Using the geometry stated in the first paragraph with all elem ents driven in phase, what is the highest frequency that can be generated by the source for this array such that only one mainlobe appears in the entire half-plane in front of the array?

37. Describe an optical diffraction pattern sampling system for continuously monitoring the quality of cloth as it is manufactured. The challenge is in detecting missing lines of thread and double lines of thread in otherwise normal material. Sketch the optical source and optical sensing system showing all relative locations and dimensions. Indicate the method for determining the presence or absence of defects and be sure to indicate the sensor geometry and appropriate diffraction pattern dimensions and sensor dimensions. Explain how your system works using the necessary analytical and qualitative descriptors.

38. Describe an optical diffraction pattern sampling system for the monitoring of SAR (synthetic aperture radar) imagery. The images are contained on rolls of 35 mm film and are radar pictures of terrain from the Middle East. The maximum resolution of the film is approximately 200 lines per millimeter. It is desired to automatically indicate regions of:

    i) Unoccupied sandy areas
    ii) Inhabited rural areas
    iii) Cities
    iv) Farm land
    v) Roads

39. Photonics final project due.

Sample Group Mini-Project – I

After considering the article on "tacky lasers," please prepare the following group (approximately five people per group) presentation for our next meeting. Elect one member of the group to be the representative (see item 4. below).

Consider the following items.

1. What differentiates the tacky laser from what is already available?
   What are the fundamental limitations on its operation and usefulness?
   How can you get additional information if needed[†]?

2. Find the best new application for the tacky laser assuming that within two years the laser will be reliable (lifetime of several thousand hours), can be excited using current (rather than by light), and can operate at room temperature. Remember the comments of your classmates raised in our class discussion last weekend and this.

3. For this application, estimate the time and cost of bringing the new service or product to the market place. What is the advantage of your service or product as compared to what is available? What is the market? How long will it take to break even? What are the potential risks? What assumptions have you made?

4. Prepare several overhead transparencies for a presentation to the rest of the class who will act as a source of venture capital (be sure to bring along your check books!) and will ask questions. <u>Be able to explain your entire idea (technical, market, financing) in five minutes or less.</u> Submit a copy of the transparencies to me before your talk and include all names of participants on the title page.

5. A short group report is optional and may be submitted only if material is needed in addition to the presentation for a basic understanding of your concept.

[†] See R. E. Slusher, "Semiconductor Microlasers and Their Applications," *Optics & Photonics News*, pp. 8 - 17 (February 1993).

Sample Group Mini-Project – II

In your group, consider the solution to the problem of counterfeit documents (e.g., money, stamps, stock or bond certificates, transcripts).

Decide:

1. What problem are you solving? Are you considering currency or general documents?

2. Identify the key issues.

3. Find the constraints (e.g., technical, practical, financial, public acceptance).

3. What solutions can you quickly generate to address the key issues? Consider both high-tech and low-tech solutions.

4. Can you find one or two high-potential candidate solutions? What are their strengths and weaknesses?

Sample Group Mini-Project – III

You have read a paper describing the fifth generation of optical communications systems. What is the sixth generation? Are we in it now? If so, what are its characteristics? If not, what technological or business breakthroughs are needed?

Decide:

1. What is the role of nonlinear optics in sixth generation systems?
2. What role, if any, do all-glass systems play a role in sixth generation systems?
3. What is the timetable for you definition of a sixth generation system>
4. What are the non-technical issues to be decided?

Laboratory Demonstration

1. Beam Expander and Collimated Beam

How is the beam expander constructed?
How can the focal length of the smaller lens (objective) be determined?
How can one check if the beam is really collimated?
Is the laser beam polarized?
How does the expanded beam change the spreading or beam diffraction?

2. Total Internal Reflection and Critical Angle

What are some applications of total internal reflection?
Is total internal reflection polarization sensitive?
What happens if a fingerprint is applied on a reflecting surface of the prism?
How could this effect be used as a sensor?

3. Brewster Angle

Is the Brewster angle polarization sensitive?
If the Brewster angle is measured to be 57.2° what is the refractive index of a glass slide?
Would you expect the Brewster angle of a glass slide to be 39.2° ? Why?
Does reflection always tend to polarize unpolarized light?

4. Diffraction Patterns and Optical Fourier Transforms

When the small square aperture is placed in the collimated beam, what intensity pattern do you expect? Why? What about a circular aperture?
Using a ruler and the intensity diffraction pattern, how can you find the wavelength of the source?
What happens to the laser beam when the pinhole is removed?
What is the purpose of the pinhole? How does it work?

5. Optical Fibers and Fiber Coupling

Why is the light guided by the glass fibers?
Why does light appear outside of the fiber at the conical transition region?
Why can you see the light inside the fiber?
Why does coupling occur when a drop of water is applied to the fiber junction?

6. Light Scattering

Is the white light initially polarized?
Is the scattered light polarized? Why or why not?
Is high or low frequency light scattered more efficiently by the milk particles?
Is high or low frequency light left in the beam?
Should one use small or large wavelength light to avoid small particle scattering

in optical fibers?

Guidelines for Oral Presentations

In this class, oral presentations will often represent the work of a group and will be restricted in time to allow all groups to present their ideas. Most often, overhead transparencies (i.e., VU graphs) will be a useful aid. Slides, video clips and demonstrations may also be helpful.

From seeing and hearing a number of presentations, I make the suggestions below.

1. Make an outline of your most important ideas before putting together your presentation. Be sure you and your audience both know the main point of your talk at the beginning and end of your presentation.

2. Stay within the time restriction. Distill your ideas to their clearest representation. Have your audience wanting more information – not less.

3. An excellent rule-of-thumb is to limit the number of VU graphs to one per minute *or less*. Start with a title slide, next provide an outline or overview if you have fifteen slides or more, and end with conclusions. Keep your main presentation to the main points. In most presentations, there is no need to be exhaustive or to represent all of the things that you tried but did not work. Back-up slides can provide technical or financial details and be used to answer questions.

4. For presentations of less than ten minutes, it is most effective to have a single presenter represent a group. Chose your best communicator to present the material and have all members of the group available to answer questions.

5. VU graphs should have large print, lots of open space, and not more than five bullets per page. *Do not* use pages from a technical report reproduced on transparencies. These are unreadable. For overheads use black lettering on a light background for most readable slides. For slides or electronic presentations, light lettering on a dark background is easier to read.

6. For technical or financial material, a picture or graph is often the most useful and efficient format for summarizing data or presenting completely new ideas. Tables with a lot of data are often confusing. Color is often useful to convey additional information. Keep your viewgraphs “clean.”

7. Start your talk with something that connects to the background of your audience. Remember to sequentially “talk with” a number of people in your audience, completing each idea before making eye contact with the next person. Eyes that dart or scan the audience convey a lack of trustworthiness.

8. Practice your talk and invite feedback from a friendly group before your presentation. Don't end sentences with an upward pitch of your voice. This makes your sentences appears to be tentative and undermines your credibility.

9. Control annoying habits such as pacing, jingling change in your pocket, playing with jewelry or hair. Know where to place your hands when you speak. Avoid most mechanical pointers. Have the overhead projector on only when presenting material from that slide or overhead. For other discussion, turn off the projector.

Photonics Final Project Guidelines
Due: Beginning of Next EMTM Term

Your final project paper should discuss the technical aspects and applications of an area of photonics discussed in class (e.g., lasers, optical fibers, thin-film optical devices, optical communications systems, optical signal processing) or another area of recent or emerging importance in photonics of your own choosing. The report should also discuss previous and competitive technologies, and the potential use of the technology you choose. It is this combination of technical and business aspects that make the most successful final project. You may also include market or potential market aspects of your choice.

The following list is representative of appropriate topics:

1. Use of solitary wave fibers in optical communications
2. Principals and applications of fiber sensors
3. Methods of optical pattern recognition
4. Principals of operation and applications of integrated optical lasers
5. Synthetic aperture radar (SAR) and its (optical or other) signal processing
6. Comparison of satellite and fiber communications for long-distance communication and data transfer
7. Optical neural networks and/or computers
8. Integrated optical devices for signal processing or communications
9. Robotic vision: automated optical inspection of circuit boards or other manufactured parts
10. Industrial uses of holography for nondestructive evaluation and testing
11. Open optical links for line-of sight communication
12. Infrared imaging devices
13. Medical/dental photonics
14. Electro-optical devices and systems

15. All glass optical fiber networks: their configuration, operation and performance

A typical final project report will most likely include discussions of the following:

1. Previous technology and its limitations

2. Brief trajectory of the photonic technology covered in your report

3. Comparison of reported technology with competing technologies and their limitations, advantages or trade-offs

4. Scientific basis for photonic technology, scientific breakthroughs and fundamental scientific limitations

5. Quantitative technical analysis of photonic device or system† (This may include a sketch or block diagram, and a discussion of operation and analysis.)

6. Applications and future use

7. Market and business considerations

A suitable starting place for many photonic technologies would be *Scientific American* which periodically covers these topics in an excellent non-mathematical manner or an individual in your organization who works in the area. Likewise, *Laser Focus World* and similar trade journals are useful. Additional technical information can often be found in recent textbooks (usually easier to read) and review or other articles in journals (usually more challenging to read) such as *Proceedings of the IEEE, Journal of the Optical Society of America, Applied Optics, IEEE Proceedings on Lightwave Technology* or other references found in the Moore School Library. The IEEE Press often publishes excellent collections of papers on photonics. Please include an appropriate bibliography of all material used for your report. Call me at (215) 898-8241 if you have trouble locating background material or e-mail <jaggard@seas.upenn.edu>. Thomas Wu <xwu@ee.upenn.edu> will also be able to help.

† This is a major portion of your paper and should be specific and include a sample calculation of device or system characteristics. Lengthy analyses, if needed, can be placed in an appendix with all relevant results placed in the body of the report. Summarize findings with appropriate graphs, charts or tables.

The report should be the focused work of an individual or (preferably) a two person team. If the work is done by a team, please submit a single integrated report. Limit the scope of your topic such that the report of an individual does not exceed 15-20 pages and a team report does not exceed 30-40 pages. (Here, *less* is *more*!)

A few hints from past experience may be in order.

1. Keep the scope of your report limited.

2. Be sure to identify what is *your* contribution and what portions are the contributions of others. Notations in the text should identify where each reference is used. If figures and tables are taken from other work, be sure to identify them through a reference.

3. Keep an appropriate balance between technical and business aspects of the project.

4. A typical paper outline might look like this:

   Title Page
      Title
      Name(s)

   Executive Summary

   I. Introduction and History

   II. General Scientific/Technical Background and Basis of Operation

   III. Applications

   IV. Competing Technologies and Market Considerations

   V. Conclusions

   Bibliography