PME557
Engineering Optics

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National Tsinghua University
Department of Power Mechanical Engineering

Class Information

- Time: Lecture M 1:20-3:10 (Eng Bldg 1 211)
  Lab Th 1:10-2:10 PM (TBA)
- Instructor: Wei-Chih Wang

  office: Delta 319

  course website: http://depts.washington.edu/mictech/optics/me557.index.html
- Suggested Textbooks:

  - Optical Methods of Engineering Analysis, Gary Cloud, Cambridge University Press.
  - Handbook on Experimental Mechanics, Albert S. Kobayashi, society of experimental mechanics.
  - Applied Electromagnetism, Liang Chi Shen, Weber&Schmidt Dubury
  - Fundamentals of Photonics, B. Saleh, John Wiley& Sons.
  - Optoelectronics and Photonics: Principles and Practices, S. O. Kasap, Prentice Hall.
  - Fiber optic Sensors, E. Udd, John Wiley& Sons
  - Selected papers in photonics, optical sensors, optical MEMS devices and integrated optical devices.

Class information

- Grading

  Homework and Lab assignments 80% (3 assignments and 3 lab reports)

  Final Project 20%

- Final Project:

  - Choose topics related to simpleo free space optics design, fiberopic sensors, waveguide sensors or geometric Moiré, Moiré interferometer, photoelasticity for mechanical sensing or simple optical design.

  - Details of the project will be announced in mid quarter

  - Four people can work as a team on a project, but each person needs to turn in his/her own final report.

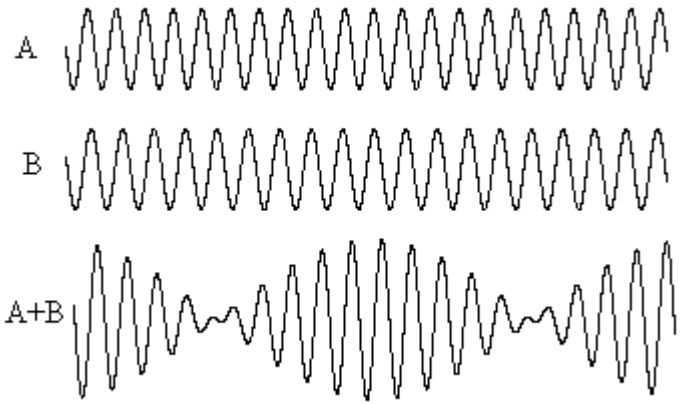
  - Oral presentation will be held in the end of the quarter on your final project along with a final report.

Objectives

The main goal of this course is to introduce the characteristics of light that can be used to accomplish a variety of engineering tasks especially in mechanical analysis.

Manipulate phase modulation for mechanical measurement:

monitoring changes in interference pattern due to a mechanical modulation



$$\sin A+\sin B = 2\sin(A+B)/2 \cdot \cos(A-B)/2$$

Let $A = k_1x+\omega_1t+\phi_1 \quad k_1 = 2\pi n_1/\lambda$

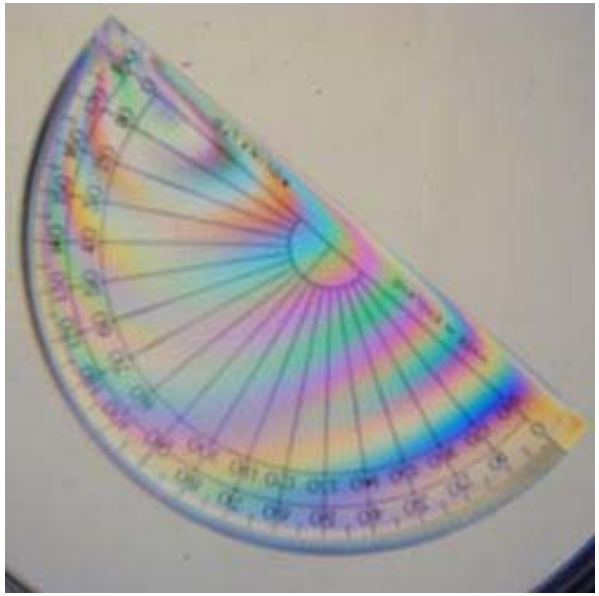
$B = k_2x+\omega_2t+\phi_2 \quad k_2 = 2\pi n_2/\lambda$

Course Outline

GOALS: To develop student understanding of

Week 1 Ray-Optics Approach (Snell's law, Geometric optics, thin lens, matrix method) and Light sources and photodetectors
Week 2 Electromagnetic-Wave Approach (wave equation, polarization, diffraction, interference, grating)
Week 3 Electromagnetic-Wave Approach (wave equation, polarization, diffraction, interference, diffraction grating, waveplate, Jones matrix)
Week 3 Geometric Moiré: In-plane displacement measurement
Week 4 Geometric Moiré: out of plane displacement measurement
Week 5 Moire Interferometry: Interference and Diffraction, Grating fabrication
Week 6 Moiré Interferometry: Holographic Interferometry
Week 7 Photoelasticity
Week 8 Photoelasticity
Week 9 Fiberoptic and polymer waveguide sensors
Week 10 Final project presentation

Photoelasticity



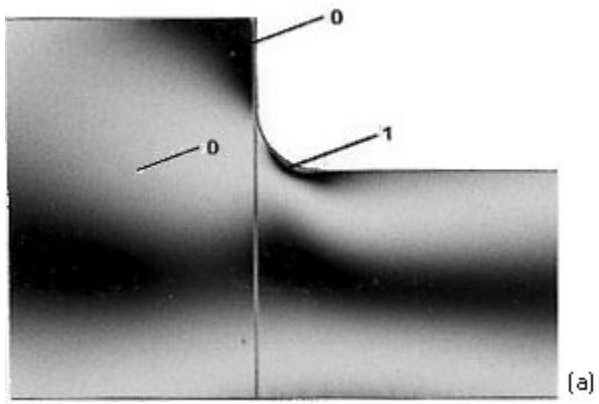
Department of Materials Science and Metallurgy
University of Cambridge

The effect that an isotropic material can become birefringent (anisotropic), when placed under stress is called photoelasticity.

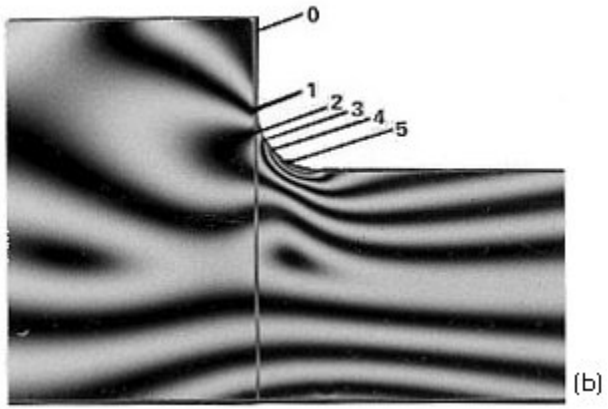
Under compression → negative uniaxial crystal.
Under tension → positive uniaxial crystal.

Induced birefringence is proportional to the stress.
can be used to study stress patterns in complex objects (e.g. bridges) by building a transparent scale model of the device.

Photoelasticity effect



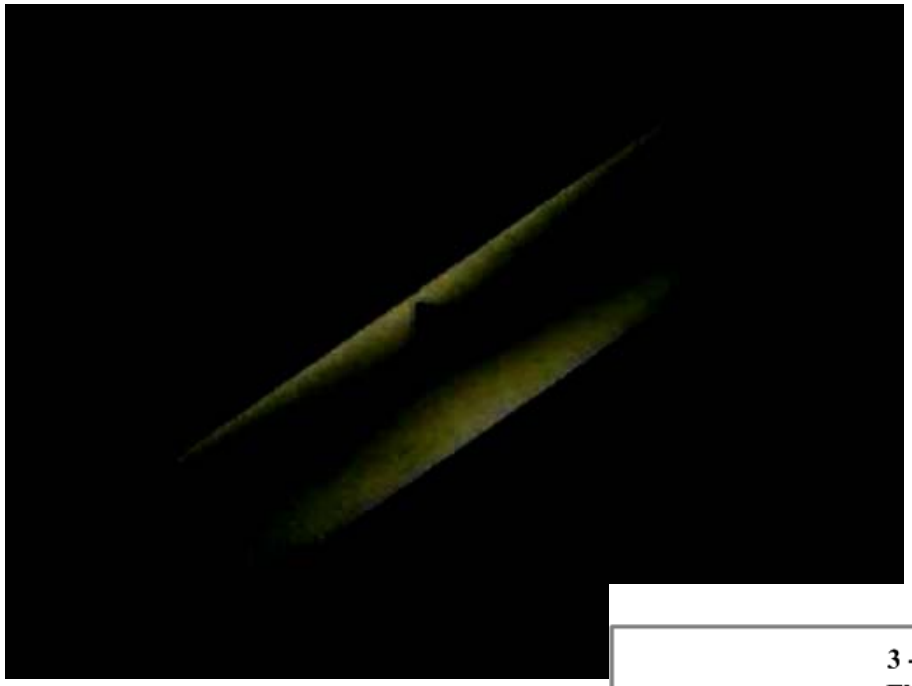
Low load

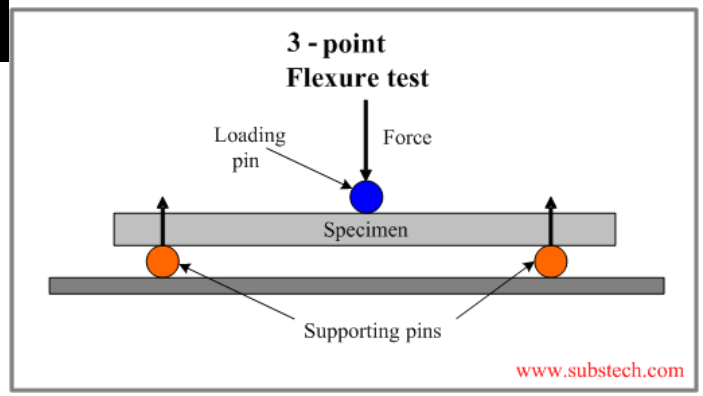


High load

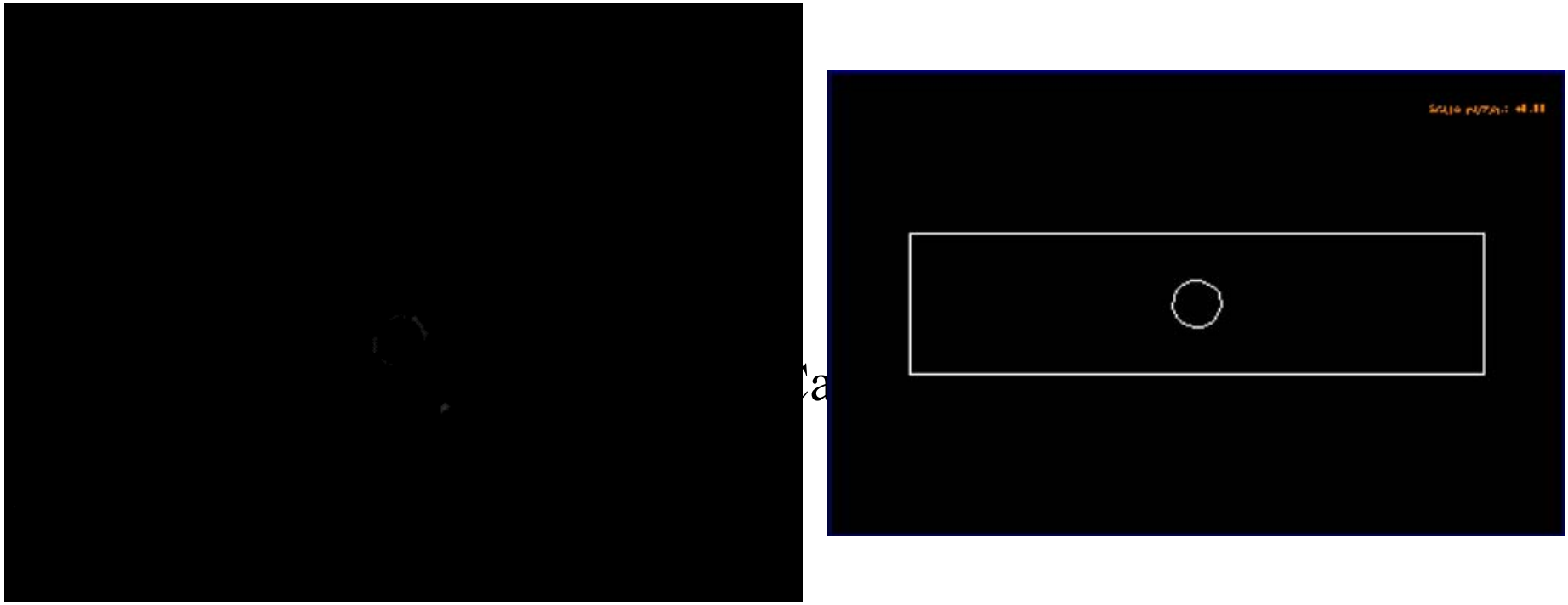
University of Maryland

As the load is increased and new fringes appear, the earlier fringes are pushed toward the areas of lower stress. With further loading, additional fringes are generated in the highly stressed regions and move toward regions of zero or low stress until the maximum load is reached. The fringes can be assigned ordinal numbers (first, second, third, etc.)





Annealed bar undergoing 3-point bending under a circular polariscope



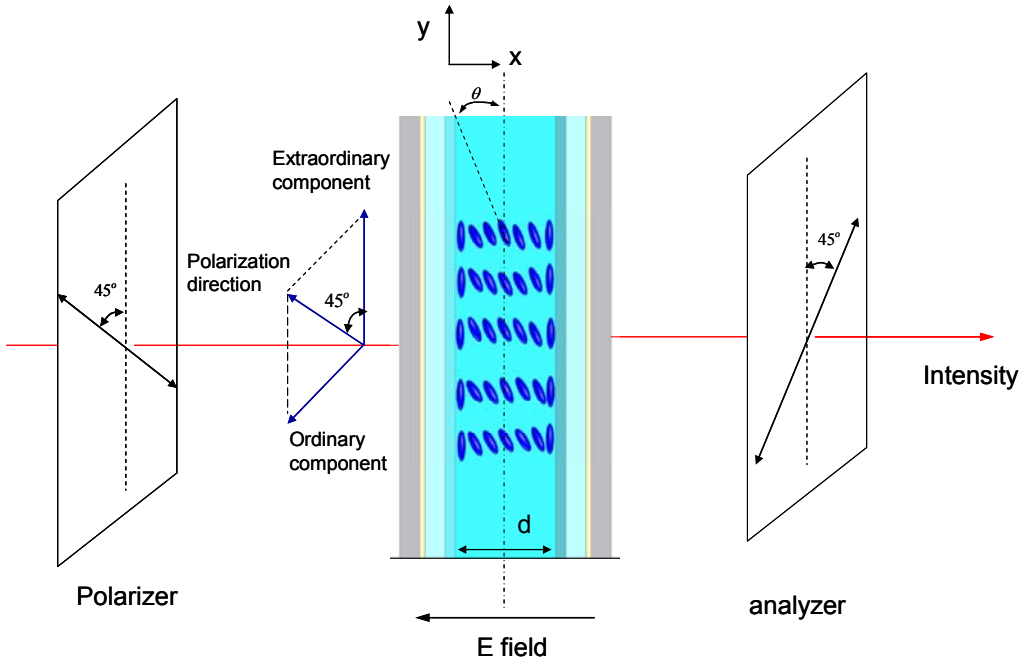
Annealed bar undergoing 3-point bending under a circular polariscope

$$T = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} \exp(-j\Delta\phi) & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & \frac{1}{2} \end{pmatrix} = \frac{1}{4}(e^{(-j\Delta\phi)} - 1) \begin{pmatrix} 1 & -1 \\ 1 & -1 \end{pmatrix}$$

$$I = I_o |T|^2 = I_o \sin^2(\tfrac{\Delta\phi}{2})$$

$$= \frac{I_0}{2}(1 - \cos\Delta\phi)$$

$\Delta\phi$ phase difference between the ordinary and extraordinary components



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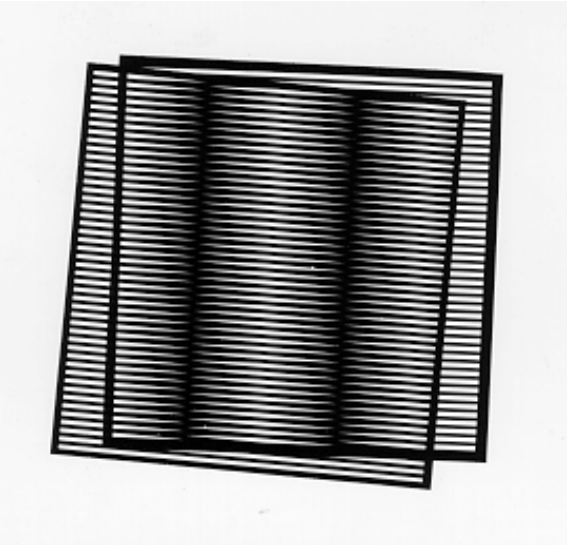
Moiré effect is the mechanical interference of light by superimposed network of lines.

The pattern of broad dark lines that is observed is called a moiré pattern.

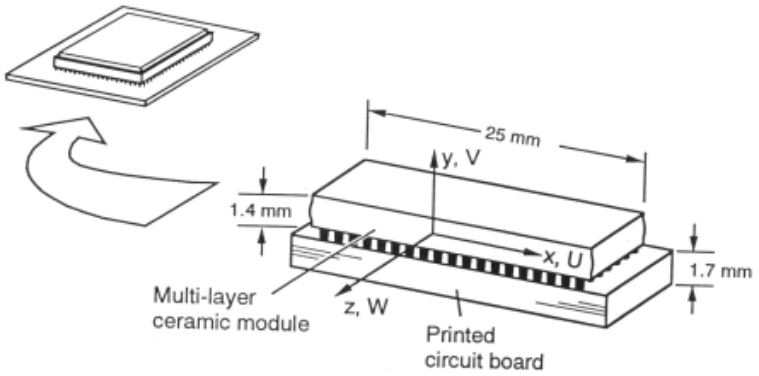


Superimposed Gratings

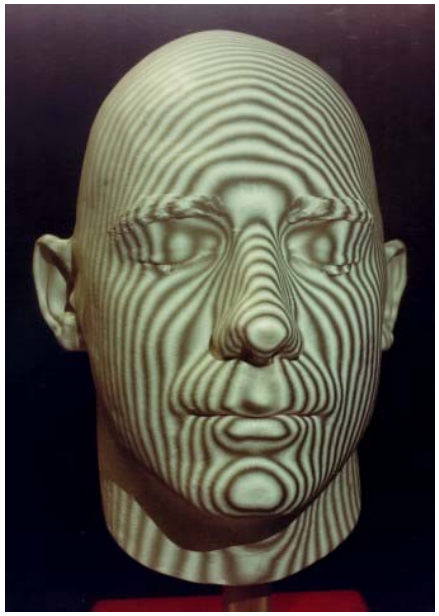
In most basic form, Moiré methods are used to measure

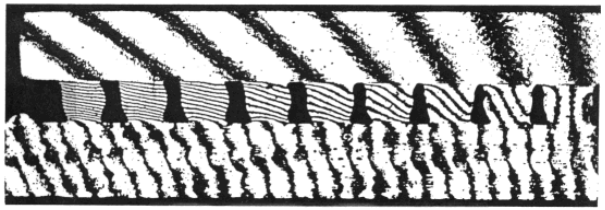
Displacement fields; either

- in plane displacement



- out of plane



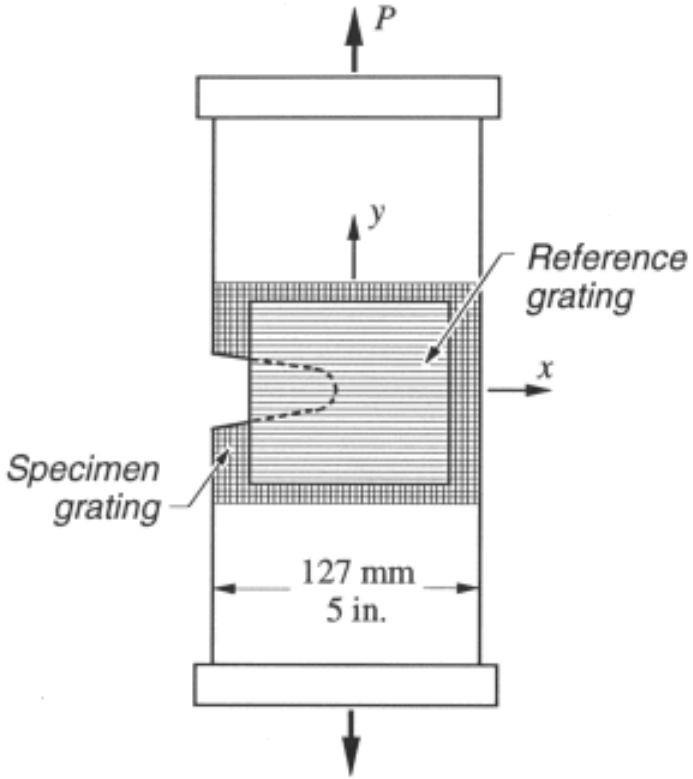


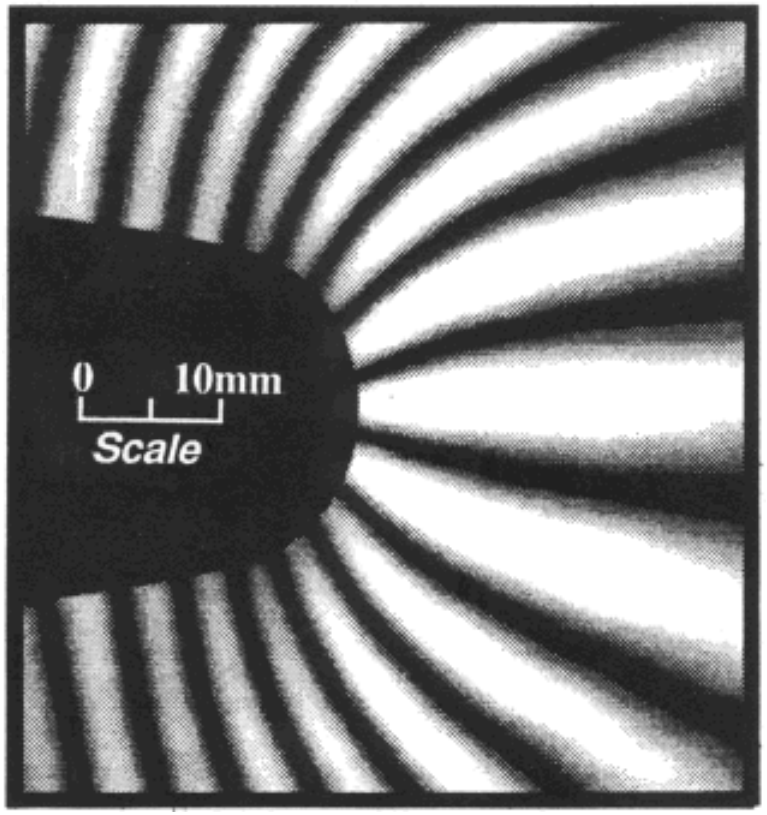
U (or u_x) displacement field of a ceramic ball grid array package assembly, subjected to an isothermal loading of ΔT = -60°C (cooling the specimen from 82°C to room temperature).

Univ. of Maryland

Moiré Fringes Superimposed on Model Head

Geometric Moiré





V (or u_y) displacement field of a deeply notched tensile specimen. The contour interval is 50 μm per fringe.

In-Plane

Geometric moiré

Sensitivity (No. of fringes per unit displacement)	Less than 100 lines/mm
Contour Interval (displacement/fringe order)	Greater than 10 micrometers
Field of View	Large

Moiré Interferometery

Sensitivity (No. of fringes per unit displacement)	2.4 lines/micrometer
Contour Interval (displacement/fringe order)	.417 micrometers
Field of View	Small (typically 5mm to 50mm)

Microscopic Moiré Interferometry

Sensitivity (No. of fringes per unit displacement)	4.8 lines/micrometer
Contour Interval (displacement/fringe order)	208 to 20.8 nanometers
Field of View	Microscopic (typically 50 micromters to 1 mm)

Out of Plane

Shadow Moiré/Projection Moiré

Sensitivity (No. of fringes per unit displacement)	less than 100 lines/mm
Contour Interval (displacement/fringe order)	greater than 10 micrometers
Field of View	Large (up to 100 mm)

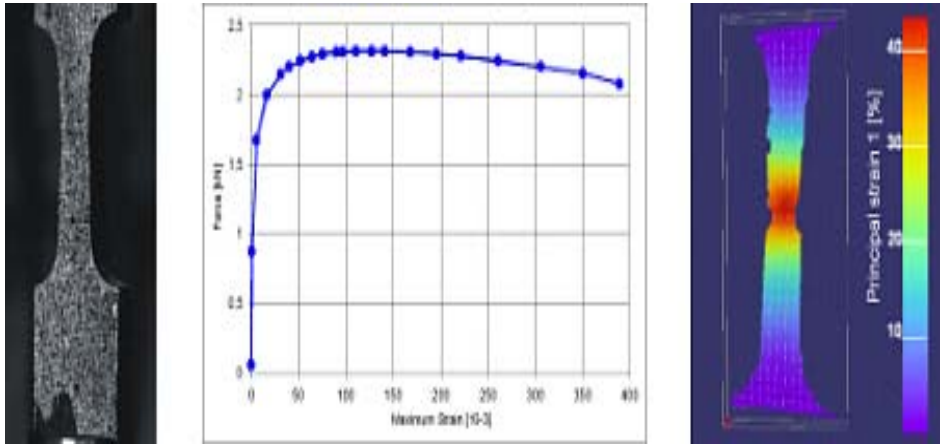
INFRARED FIZEAU INTERFEROMETRY

Sensitivity (No. of fringes per unit displacement)	200 to 400 lines/mm
Contour Interval (displacement/fringe order)	2.5 to 5 micrometers
Field of View	Medium (5 to 45 mm)

Digital Image Correlation

Material properties

DIC offers characterization of material parameters far into the range of plastic deformation. Its powerful data analysis tools allow the determination of the location and amplitude of maximum strain, which are important functions in material testing.



Live image (left), maximum principal strain (middle), principal strain (right)

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Fiberoptic Sensors

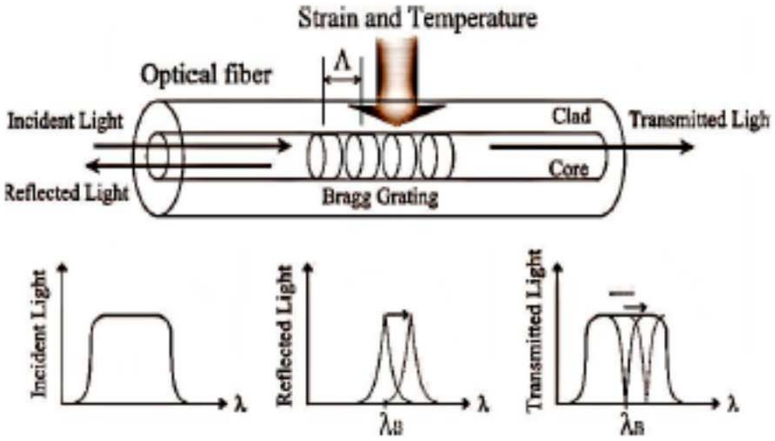


Figure 3. Fiber Bragg grating.

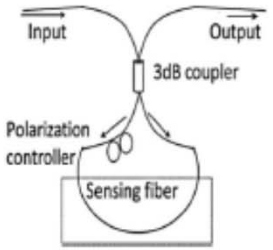


Figure 11. Schematic of the sensor based on a Sagnac interferometer.

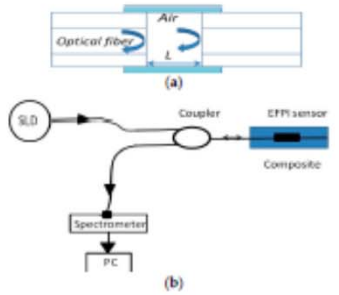


Figure 9. (a) One of the typical EFPI sensor design; and (b) schematic experimental arrangement for the EPFI sensor [70].

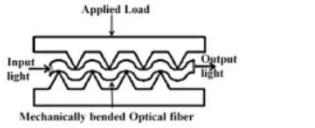


Figure 14. Micro bend sensor concept [40].

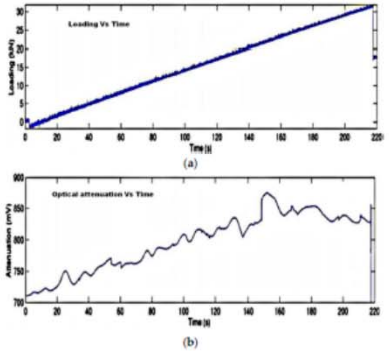


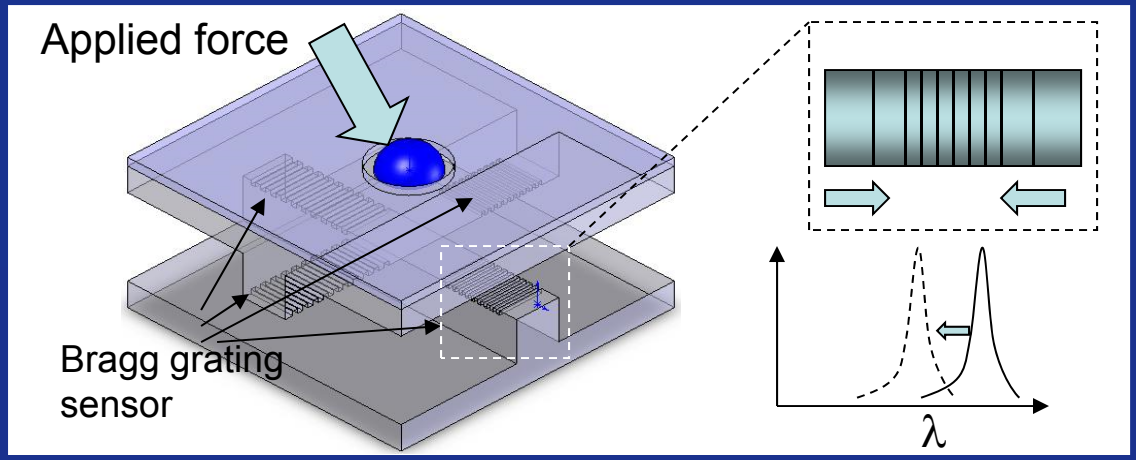
Figure 15. The temporal profiles corresponding to loading (a) and optical signal attenuation (b) [40].

M. Ramakrishnan, Sensor, 2016

Bragg grating sensor (NIH R21)

MICRO TECH LAB

Strain at the locations of the gratings is determined by monitoring the shifts in wavelength of reflected signal from the perturbed gratings. Shear pressure can be derived based on relative changes in these optical strain gages



Concept of Detecting

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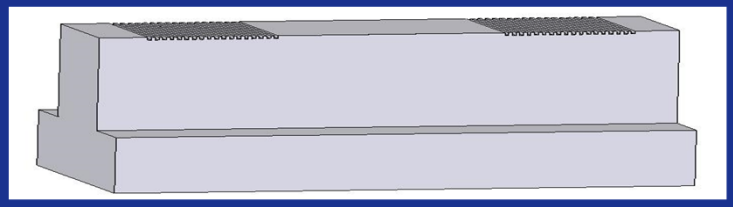
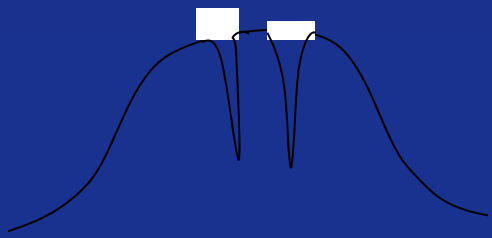
Waveguide

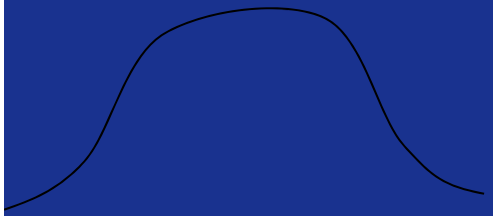
Gratings

Output

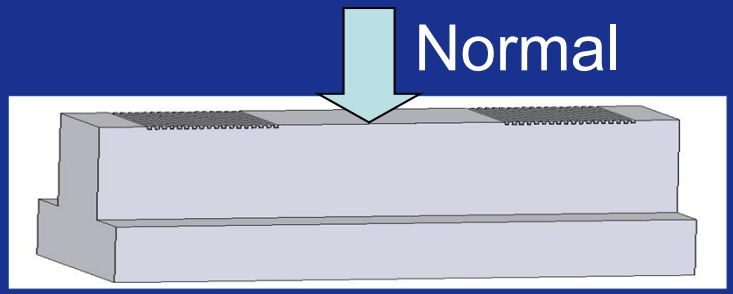


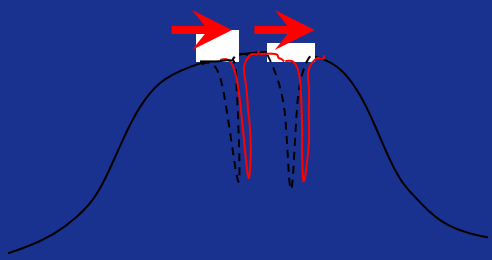


Input

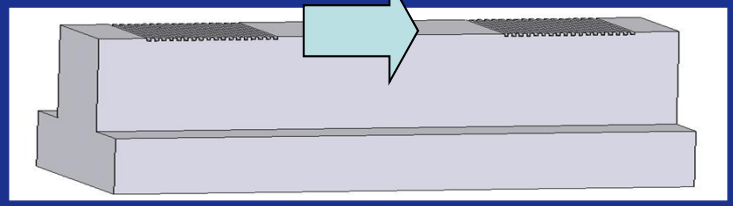


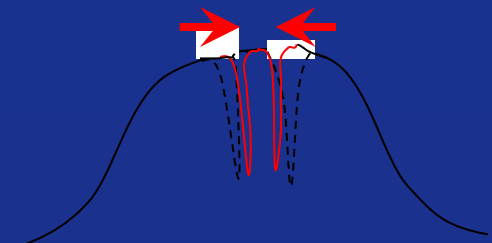
Normal





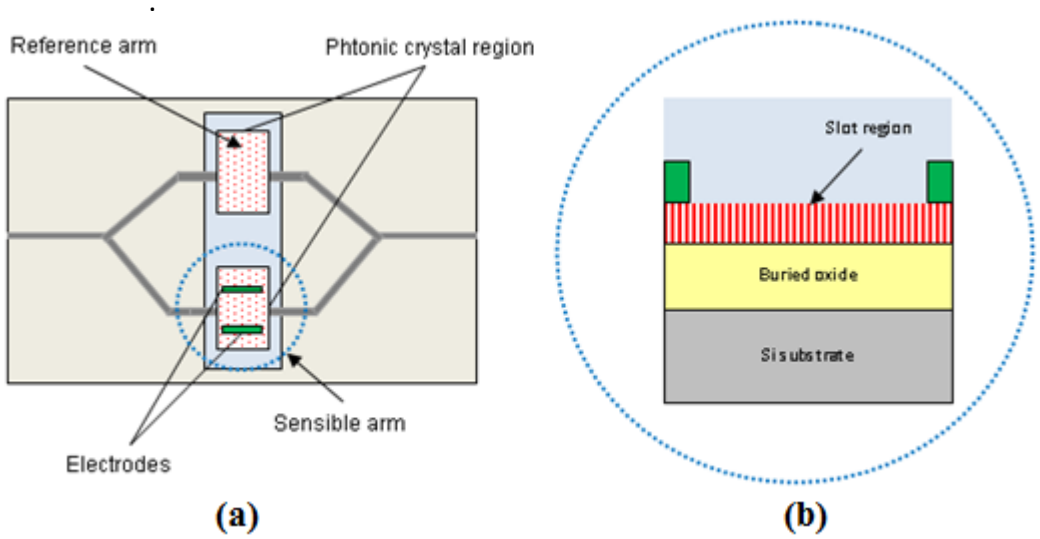
Shear

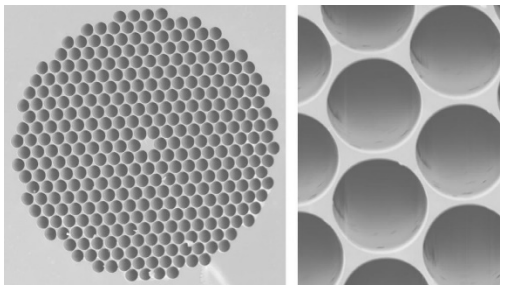




$\lambda_B = 2\Lambda n_{eff}$

Periodic Structure Sensors





MZI with slot Photonic Crystal waveguide (a) and cross-sectional view (b). A, Troia

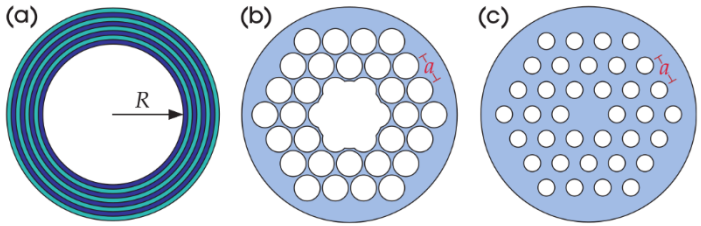


Figure 1: Three examples of photonic-crystal fibers. (a) Bragg fiber, with a one-dimensionally periodic cladding of concentric layers. (b) Two-dimensionally periodic structure (a triangular lattice of air holes, or "holey fiber"), confining light in a hollow core by a band gap. (c) Holey fiber that confines light in a solid core by index guiding.

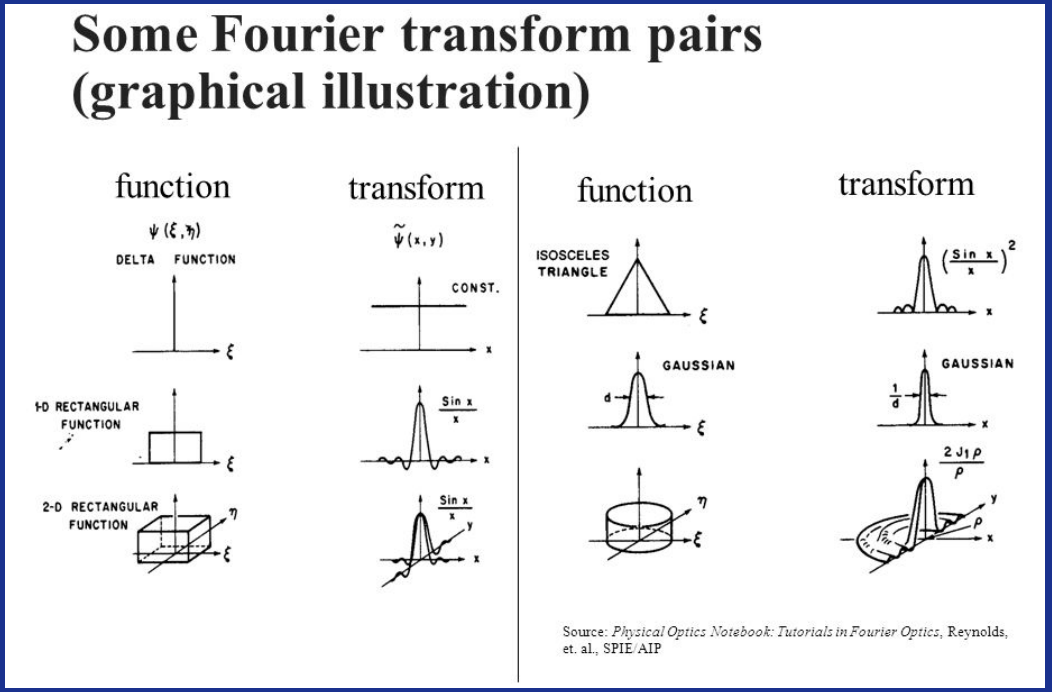
SEM micrographs of a photonic-crystal fiber produced at US Naval Research Laboratory. (left) The diameter of the solid core at the center of the fiber is 5 μm, while (right) the diameter of the holes is 4 μm

Technology based on low-loss periodic dielectric materials.

Fourier Optics

Study of classical **optics** using **Fourier** transforms, in which the wave is regarded as a superposition of plane waves that are not related to any identifiable sources; instead they are the natural modes of the propagation medium itself.

- Spatial transformation



Everything is possible!

- Cloaking
- Super lens (n=1)
- Lossless
- Zero refractive index
- UFO?

Stealth?

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Alien Technology?
Material for making Potter's invisible cloak?
Coated absorbing material?

What's a Metamaterial?

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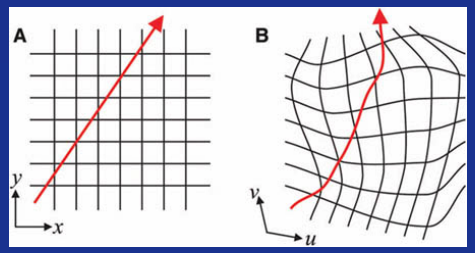
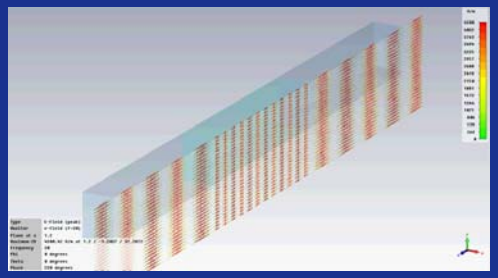
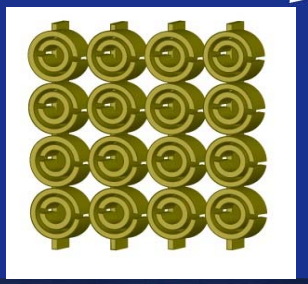
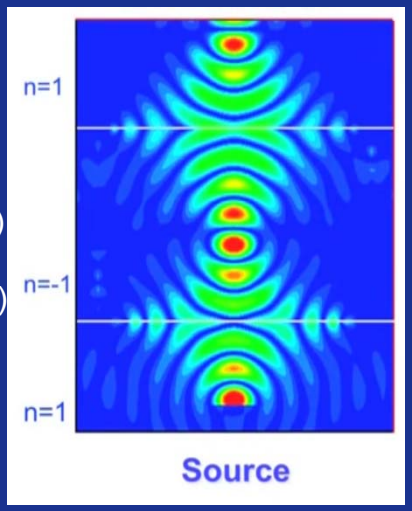
- Meta-?
  - Alloy?
  - Concrete?

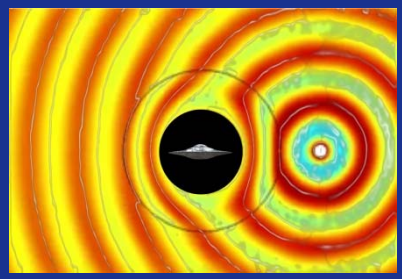






- Artificially engineered materials
  - V.G.Veselago (1968) Theory
  - J.B.Pendry (1996, 1998) –ε (thin wires)
  - J.B.Pendry (1999) –μ (split-ring resonator)
  - D.R.Smith (2000) LHM (combo)



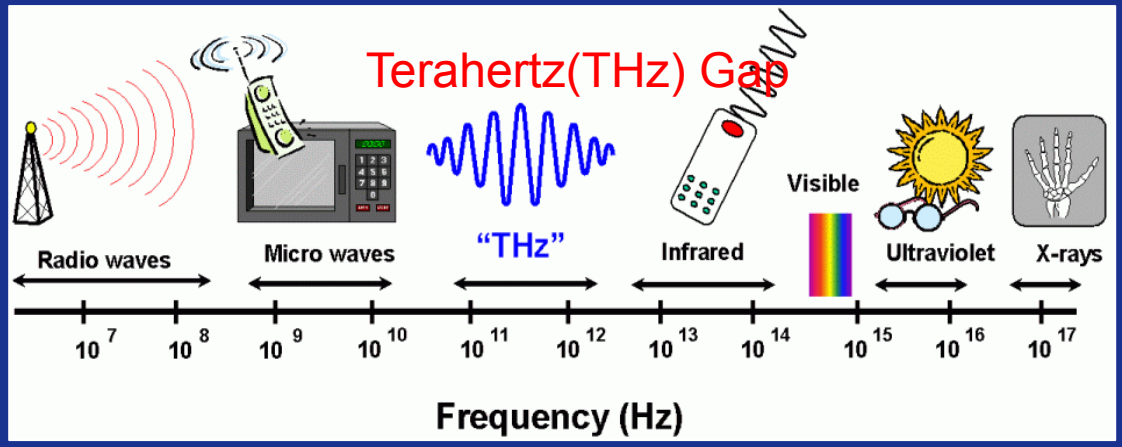


- Applications
  - Wave manipulation: -n, cloaking, superlens, transformation optics

Orwin Hess. Optics: arewell to Flatland
Nature 455, 299 (2008).

- How to categorize it?

What is TeraHertz?



- **THz radiation (EM wave)**
  - THz wave (0.1 THz to 10THz, 30μm to 3mm)
  - Non-ionizing & non-destructive (frequency is low)
  - Penetrate most of dielectric material (fabric, plastic or tissue)
  - Several absorption lines for water
  - Rotational & vibrational frequencies of most molecules

THz Applications

- **Nondestructive detection (NDT)**
  - THz image system
    - Explosive detection
    - Concealed weapons detection
    - Moisture content
    - Composite, structural defect, Coating thickness
- **Spectrum measurement**
  - THz finger print
  - Chemical analysis
  - Skin cancer detection
  - Molecular rotation, protein folding

L-3 Communications Security & Detection Systems, Inc.

Picometrix's T-Ray 2000®

Picometrix's T-Ray 4000®

Constraints:

Short working distance -low power
Resolution limited by pixel No. of bolometer based camera
mechanical stage for beam steering

Demonstration of free space and intrinsic sensors

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- Give them some tubing and some optical transparent material and have the create something or make something in class.

Let's make something

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- I want you to use something you think you have right now and make it into something optical

Software for ray and wave optics

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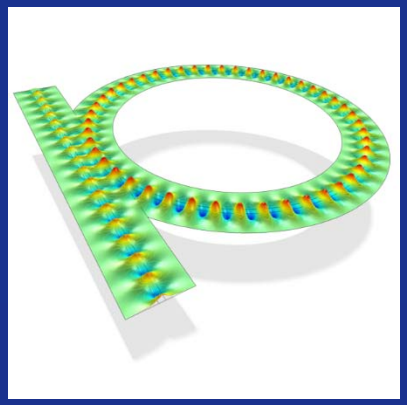
- Ray: COMSOL ray optics module, QIOPTIQ, OSLO trace pro, Zemax
- Wave: COMSOL, Rsoft, Optiwave (mostly FEM, FTDT)



COMSOL

Example of an optical waveguide, a wave propagates around a ring and interferes with a wave propagating in a straight waveguide

Our way

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- Solidworks + Ray Optics (Why?)
  - RP our design!
  - Edible Optics !

What's my way of teaching the class?

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- Experiential learning- learning through reflection on doing
- Tactile learning!
- How many people remember stuff you learn from Physics class?
- How many people actually apply what you learn from your class to your everyday life outside school?

Experimental Learning

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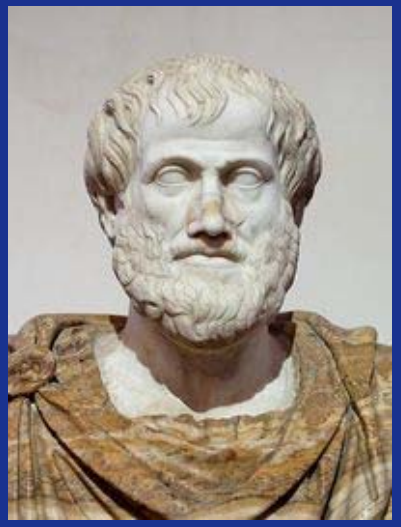
The general concept of learning through experience is ancient. Around 350 BCE, Aristotle wrote in the *Nichomachean Ethics* "for the things we have to learn before we can do them, we learn by doing them".[5] But as an articulated educational approach, experiential learning is of much more recent vintage. Beginning in the 1970s, David A. Kolb helped to develop the modern theory of experiential learning, drawing heavily on the work of John Dewey, Kurt Lewin, and Jean Piaget.[6]

wikipedia

Experimental Learning

MICRO TECH LAB



"For the things we have to learn before we can do them, we learn by doing them."

— Aristotle, The Nicomachean Ethics

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The test of all knowledge is experiment.
Experiment is the sole judge of scientific "truth"….
There are *theoretical* physicists who imagine, deduce, and guess at new laws, but do not experiment; and then there are *experimental* physicists who experiment, imagine, deduce and guess.

- Richard Feynman, *Feynman lectures on Physics*

What is Light?

MICRO TECH LAB

All the fifty years of conscious brooding have brought me no closer to the answer o the question, “what are light quanta?” Of course today every rascal thinks he knows the answer, but he is deluding himself.

- Albert Einstein, 1951

Early days, a light beam was thought to consist of particles. Later, the phenomena of interference and diffraction were demonstrated which could be explained only by assuming a wave model of light. Much later, it was shown that phenomena such as photoelectric effect and Compton effect could be explained on if we assume a particle model of light.

* Ajoy Ghatak, Optics, Macgraw Hill, 2010

* The photoelectric effect is the observation that many metals emit electrons when light shines upon them. Electrons emitted in this manner can be called photoelectrons. The phenomenon is commonly studied in electronic physics, as well as in fields of chemistry, such as quantum chemistry or electrochemistry (Wikipedia).
* *Compton scattering is the inelastic scattering of a photon by a charged particle, usually an electron. It results in a decrease in energy (increase in wavelength) of the photon (which may be an X ray or gamma ray photon), called the Compton effect. (Wikipedia)

Particle Model

- Newton- argued that the geometric nature of the laws of reflection and refraction could only be explained if light was made of particles, which he referred to as corpuscles, as waves do not tend to travel in straight lines.

Corpuscular model-

Most important experimental facts which led to the early belief in the corpuscular model of light were:

1. Rectilinear propagation of light which results in the formation of sharp shadows
2. 2. light could propagates in vacuum

- Assume light travel in straight lines
- Snell- law of reflection and refraction (x component of the momentum)

Corpuscular Model

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The corpuscular model is the simplest model of light. According to the theory, a luminous body emits stream of particles in all direction. Issac Newton, in this book Opticks also wrote," Are not the ray of light every small bodies emitted from shinning substance?"

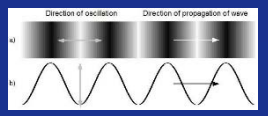
Based on this, light is assumed to be consisted of very small particles so that when two light beams overlap, a collision between the two particles rarely occurs. Using this model, one can explain the laws of reflection and refraction.

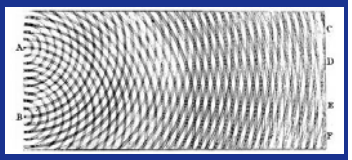
-reflection law follows considering the elastic reflection of a particle by plane surface.

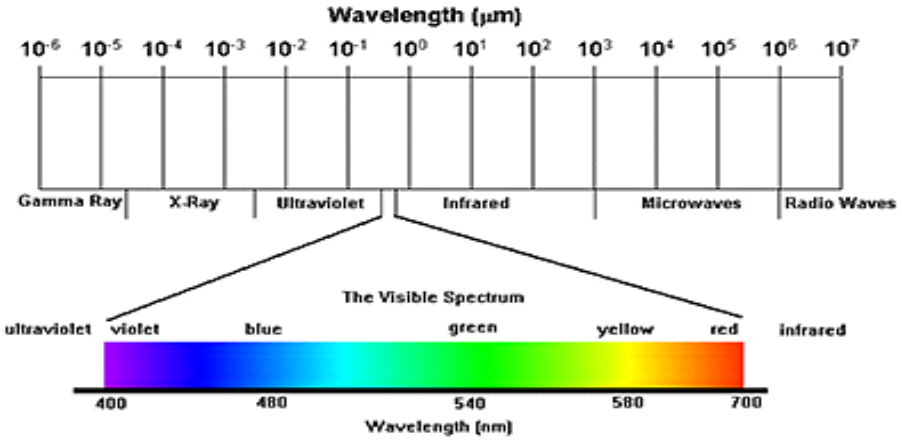
- Refraction law assume that the motion is confined to the xy plane. The trajectory of particle is determined by conservation of x component momentum

Wave Model

- Grimaldi- observe diffraction of white light through small aperture quote, ”light is a fluid that exhibits wave-like motion.” (1665)
- Huygen- propose first wave model explaining reflection and refraction(1678)
- Young- perform first interference experiment could only be explained by wave. (1801)
- Malus- observed polarization of light. (1802)
- Fresnel- gives satisfactory explanation of refraction and equation for calculating diffraction from various types of aperture (1816)
- Oersted- discover of current (1820)
- Faraday- magnetic field induces electromotive force (1830)
- Maxwell- Maxwell equation, wave equation, speed of EM wave (1830)
- Hertz- carried out experiment which produce and detect EM wave of frequencies smaller than those of light and law of reflection which can create a standing wave.







The electromagnetic spectrum can be divided into several wavelength (frequency) regions, among which only a narrow band from about 400 to 700 nm is visible to the human eyes. Note that there is no sharp boundary between these regions. The boundaries shown in the above figures are approximate and there are overlaps between two adjacent regions.

•**Radio Waves**: 10 cm to 10 km wavelength.
•**Microwaves**: 1 mm to 1 m wavelength. The microwaves are further divided into different frequency (wavelength) bands: **(1 GHz = 10^9 Hz)**

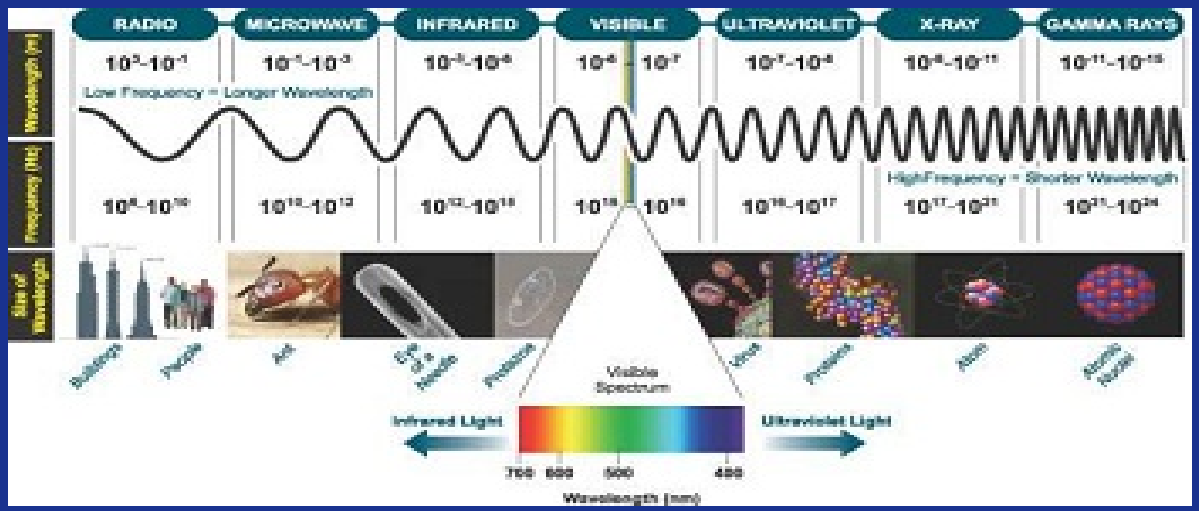
- **P band**: 0.3 - 1 GHz (30 - 100 cm)
- **L band**: 1 - 2 GHz (15 - 30 cm)
- **S band**: 2 - 4 GHz (7.5 - 15 cm)
- **C band**: 4 - 8 GHz (3.8 - 7.5 cm)
- **X band**: 8 - 12.5 GHz (2.4 - 3.8 cm)
- **Ku band**: 12.5 - 18 GHz (1.7 - 2.4 cm)
- **K band**: 18 - 26.5 GHz (1.1 - 1.7 cm)
- **Ka band**: 26.5 - 40 GHz (0.75 - 1.1 cm)

•**Visible Light**: This narrow band of electromagnetic radiation extends from about 400 nm (violet) to about 700 nm (red). The various color components of the visible spectrum fall roughly within the following wavelength regions:

- **Red**: 610 - 700 nm
- **Orange**: 590 - 610 nm
- **Yellow**: 570 - 590 nm
- **Green**: 500 - 570 nm
- **Blue**: 450 - 500 nm
- **Indigo**: 430 - 450 nm
- **Violet**: 400 - 430 nm

•**Ultraviolet**: 3 to 400 nm
•X-Rays:
•10^{-8} to 10^{-11} m
•**Gamma Rays**: 10^{-11} m (10 pm) or lower

What is Light



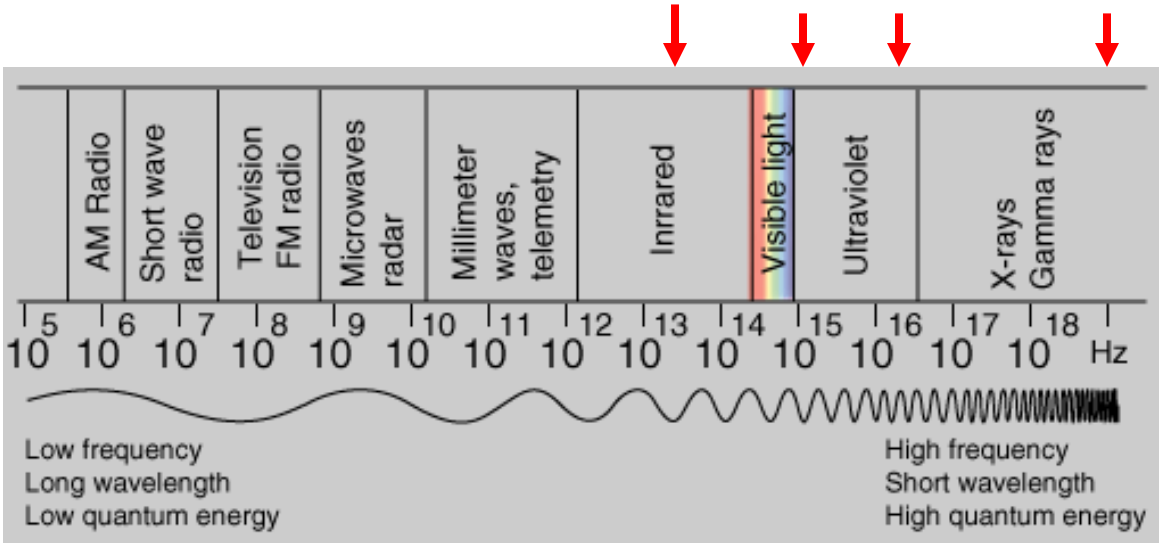
- Light is part of the electromagnetic spectrum
- Visible light is not inherently different from the other parts of the electromagnetic spectrum with the exception that the human eye can detect visible waves
- A stream of photons which are massless particles each travelling with wavelike properties at the speed of light

Visible light is a narrow part of the electromagnetic spectrum and in a vacuum all electromagnetic radiation travels at the speed of light:

$$c_o = 299,792,458 \pm 1.2 \text{ m/s}$$

Speed of light $\approx 3 \times 10^8$ m/s.

Electromagnetic Spectrum



Light is just one portion of the various electromagnetic waves. The electromagnetic spectrum covers an extremely broad range, from radio waves with wavelengths of a meter or more, down to x-rays with wavelengths of less than a billionth of a meter. Optical radiation lies between radio waves and x-rays on the spectrum, exhibiting a unique mix of ray, wave, and quantum properties.

Ultraviolet Light

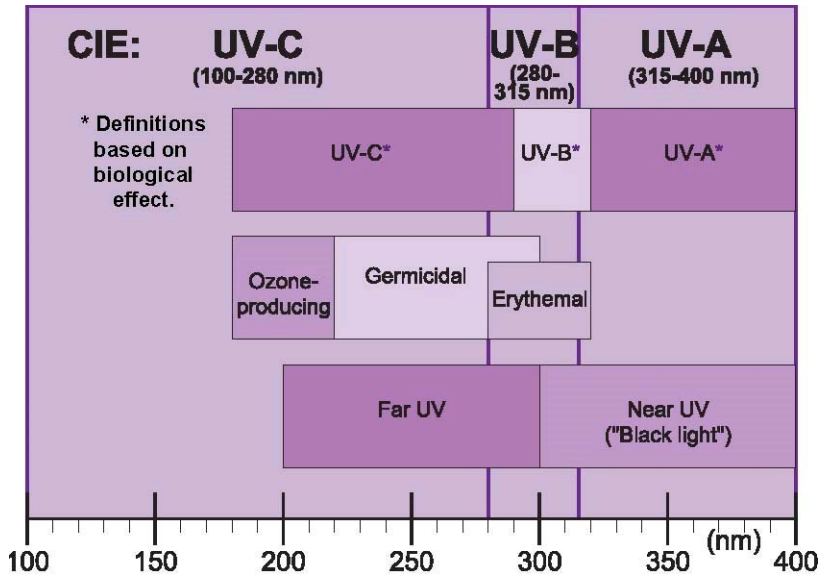


Fig. 1.2 Common ultraviolet band designations.

Short wavelength UV light exhibits more quantum properties than its visible and infrared counterparts. Ultraviolet light is arbitrarily broken down into three bands, according to its anecdotal effects.

UV-A is the least harmful and most commonly found type of UV light, because it has the least energy. UV-A light is often called black light, and is used for its relative harmlessness and its ability to cause fluorescent materials to emit visible light - thus appearing to glow in the dark. Most phototherapy and tanning booths use UV-A lamps.

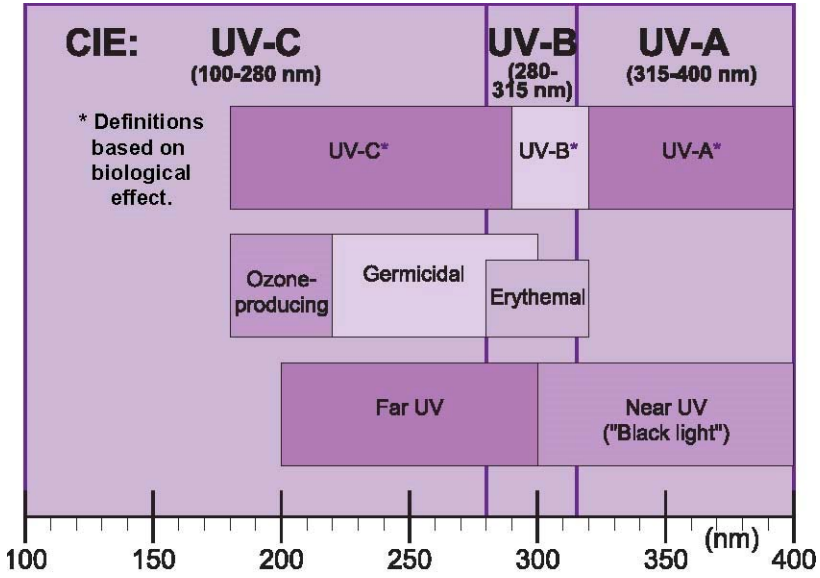
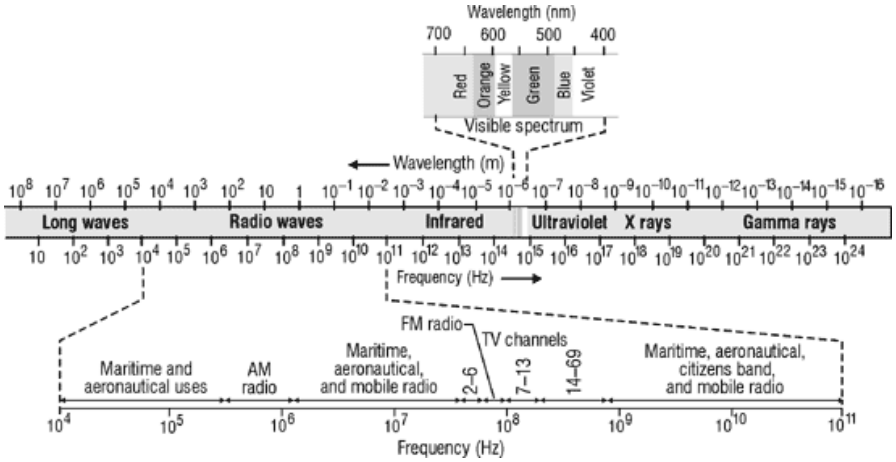


Fig. 1.2 Common ultraviolet band designations.

UV-B is typically the most destructive form of UV light, because it has enough energy to damage biological tissues, yet not quite enough to be completely absorbed by the atmosphere. UV-B is known to cause skin cancer. Since most of the extraterrestrial UV-B light is blocked by the atmosphere, a small change in the ozone layer could dramatically increase the danger of skin cancer.

Short wavelength UV-C is almost completely absorbed in air within a few hundred meters. When UV-C photons collide with oxygen atoms, the energy exchange causes the formation of ozone. UV-C is almost never observed in nature, since it is absorbed so quickly. Germicidal UV-C lamps are often used to purify air and water, because of their ability to kill bacteria.

Electromagnetic spectrum



At x-ray and shorter wavelengths, electromagnetic radiation tends to be quite particle like in its behavior, whereas toward the long wavelength end of the spectrum the behavior is mostly wavelike. The visible portion occupies an intermediate position, exhibiting both wave and particle properties in varying degrees.

Like all electromagnetic waves, light waves can interfere with each other, become directionally polarized, and bend slightly when passing an edge. These properties allow light to be filtered by wavelength or amplified coherently as in a laser.

What is light?

We see light as color and brightness

It's actually electromagnetic radiation:

Partly electric, partly magnetic

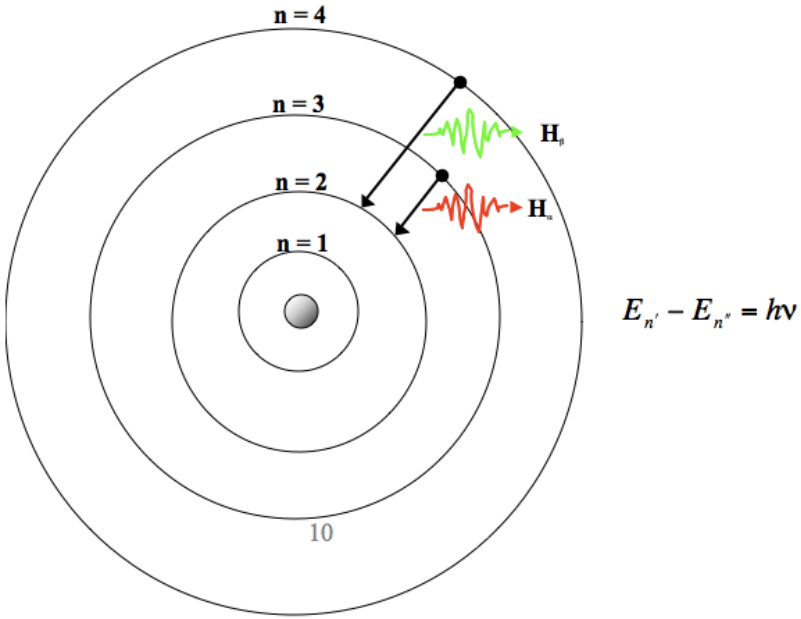
Flows in straight line (radiates)

Where does light come from?

- The Sun and stars.
- But how do they make light?
- It all starts with ATOMS
- A nucleus surrounded by electrons that orbit.
- Like the planets in the solar system, electrons stay in the same orbit, unless…

Where does light come from(2)

- Electrons get kicked into a different orbit
- This doesn't happen very often in solar systems, but it does in atoms
- If you add energy to an atom (heat it up), the electrons will jump to bigger orbits.
- When atom cools, electrons jump back to original orbits.
- As they jump back, they emit light, a form of energy

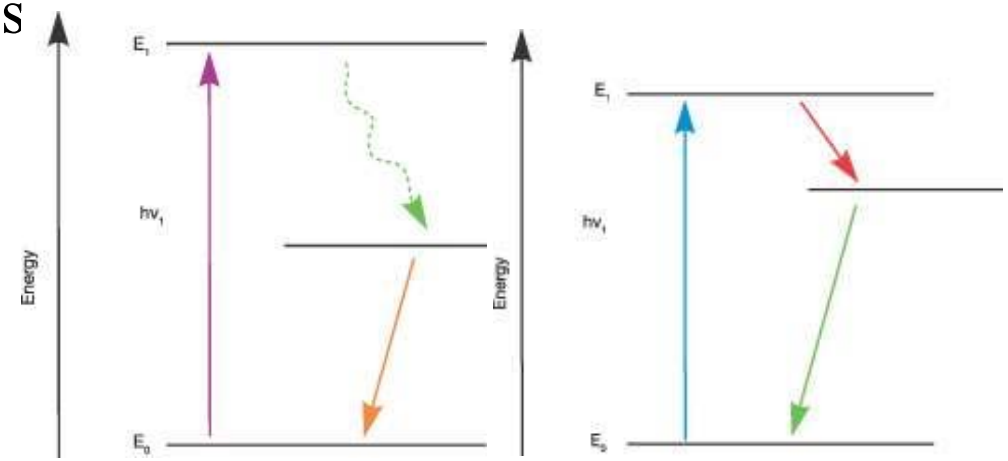


Color of light

- Each electron that jumps back emits one photon of light
- What color is this light?
- Depends on how big the jump between orbits was
- The bigger the jump, the higher the energy.
- The energy determines color; a blue photon has more energy than a red
- Shine all the colors together, you get white light!

What is Light?

Matter is composed of atoms, ions or molecules and it is light's interaction with matter which gives rise to the various phenomena which can help us understand the nature of matter. The atoms, ions or molecules have defined energy levels usually associated with energy levels that electrons in the matter can hold. Light can be generated by the matter or a photon of light can interact with the energy levels in a number of ways.



Examples of Light absorption of a photon to raise atom or molecule to higher energy levels and emitting a photon and instead relaxes to the lower energy state

Photons

According to quantum physics, the energy of an electromagnetic wave is quantized, i.e. it can only exist in discrete amount. The basic unit of energy for an electromagnetic wave is called a **photon**. The energy *E* of a photon is proportional to the wave frequency *f*,

$E = h \times f$

where the constant of proportionality h is the **Planck's Constant**,

$h = 6.626 \times 10^{-34}$ J s.

Light as particle

- A photon is like a particle, but it has no mass
- Think of a photon as a grain of sand.
- We see so many photons at the same time it's like seeing all the sand on a beach; we don't notice the single grains
- When light hits film in a film camera, it acts like photons.

Light as a wave

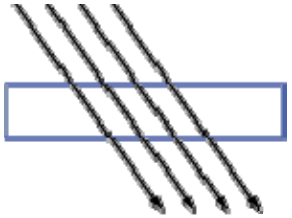
- But sometimes light acts like a wave
- A wave has a wavelength, a speed and a frequency.
- We'll learn more about wave behavior when we talk about polarization
- All light travels same speed (in vacuum)
- The energy goes up as frequency goes up
- Color depends on frequency
- Wavelength gets shorter as frequency goes up

Speed of light

- Light travels at 3x 10^8 meters/second
- It takes 8 minutes for a light wave (or a photon) to travel from the sun to the earth.
- We see the moon because it reflects the sun's light
- It takes 1 second for light reflected off the moon to reach the earth.

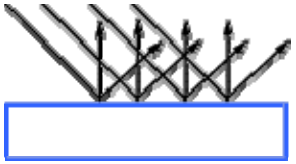
Light and matter

- When light hits something (air, glass, a green wall, a black dress), it may be:
- Transmitted (if the thing is transparent)
- Reflected or scattered (off mirror or raindrops)
- Absorbed (off a black velvet dress)
- Often it's some combination. Take a simple piece of paper: you can see some light through, white reflects, black print absorbs.



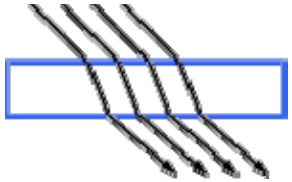
The waves can **pass through** the object

The waves can be **reflected** off the object.



The waves can be **scattered** off the object.

The waves can be **absorbed** by the object.



The waves can be **refracted** through the object.

W.Wang

Reflection and color

- Remember, white light contains all colors (a rainbow or prism separates them so we can see this)
- Why does a green wall look green in the sunshine?
- Why does it look different when it's in the shade?
- Well, in the dark, it's black. No light reflects off it.
- A green wall reflects only green light; it absorbs all the other colors.

Absorption and color

- Why is a black car hotter than a white car in the summer?
- Remember light is energy. Heat is another form of energy.
- A white car reflects all wavelengths of light.
- A black car absorbs all wavelengths of light, absorbing the energy and turning it to heat.

Light transmission

- Transparent materials transmit light, like windows.
- Remember all light has same speed in vacuum?

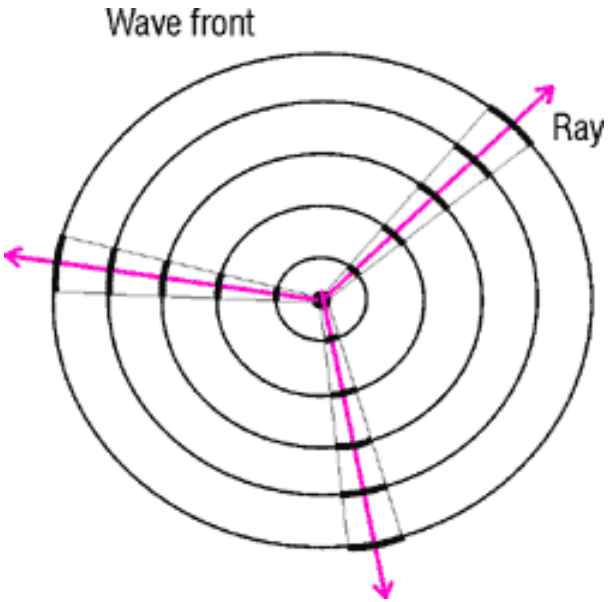
  $C = \lambda f = 3 \times 10^8 \ (m/s)$

- Different frequencies have different speeds in transparent materials – that causes a prism to separate the colors. $V(\lambda) = C/n(\lambda)$
- Colored glass or plastic only transmits the color that it is; it absorbs or reflects the other colors.

Light rays and light waves

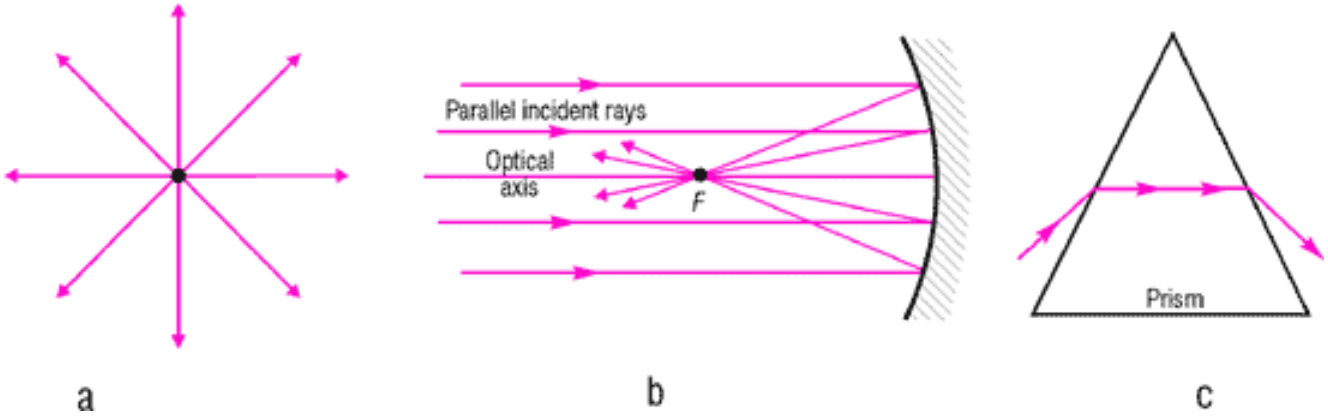
We can classify optical phenomena into one of three categories: **ray optics**, **wave optics**, and **quantum optics**.

Wave from the bubble



Light rays and wavefronts

Geometric construct of a light ray we can illustrate propagation, reflection, and refraction of light



Light as a particle

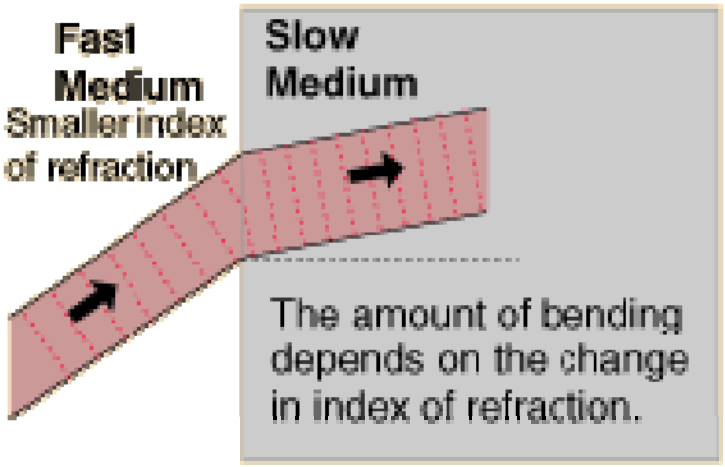
Typical light rays in (a) *propagation*, (b) *reflection, and* (c) *refraction*

Geometric optics is also called ray optics. Light travels in the form of rays. Ray optics only concern with the location and direction of light rays.

Geometric optics completely ignore the finiteness of the wavelength

Index of Refraction

In a material medium the effective speed of light is slower and is usually stated in terms of the index of refraction of the medium. The index of refraction is defined as the speed of light in vacuum divided by the speed of light in the medium.



HyperPhysics

$$n = \frac{C_o}{C}$$

The indices of refraction of some common substances

Vacuum	1.000	Ethyl alcohol	1.362
Air	1.000277	Glycerine	1.473
Water	4/3	Ice	1.31
Carbon disulfide	1.63	Polystyrene	1.59
Methylene iodide	1.74	Crown glass	1.50-1.62
Diamond	2.417	Flint glass	1.57-1.75

The values given are approximate and do not account for the small variation of index with light wavelength which is called dispersion (n = function of wavelength).

We define a **ray** as the path along which light energy is transmitted from one point to another in an optical system. The basic laws of geometrical optics are the law of reflection and the law of refraction.

Law of reflection: $|\theta_r| = |\theta_i|$
Snell's law, or **the law of refraction**: $n_i \sin\theta_i = n_t \sin\theta_t$.

If not being reflected or refracted, a light ray travels in a straight line.

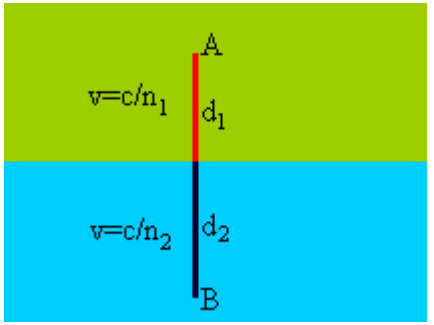
The **optical path length** of a ray traveling from point A to point B is defined as c times the time it takes the ray to travel from A to B.

Assume a ray travels a distance d_1 in a medium with index of refraction n_1 and a distance d_2 in a medium with index of refraction n_2.

The speed of light in a medium with index of refraction n is c/n. The travel time from A to B therefore is

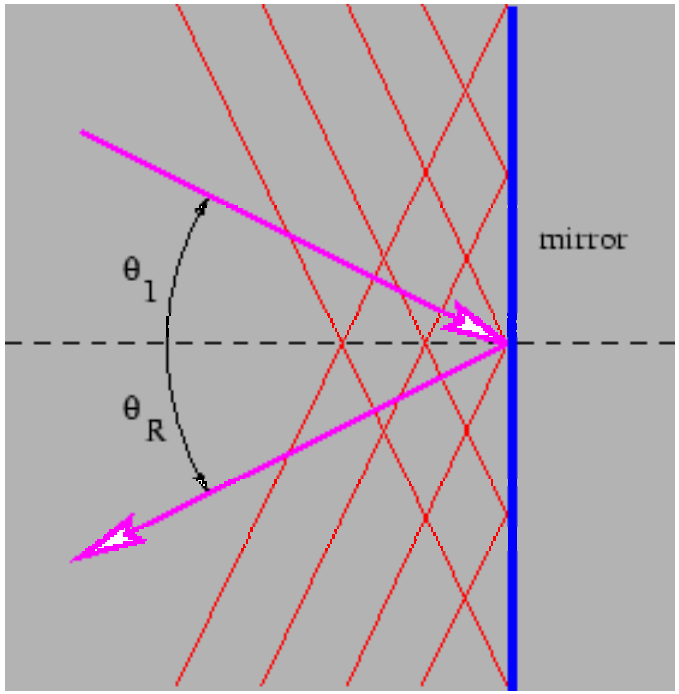
$$t = n_1 d_1/c + n_2 d_2/c.$$

The **optical path length** is OPL = $n_1 d_1 + n_2 d_2$.

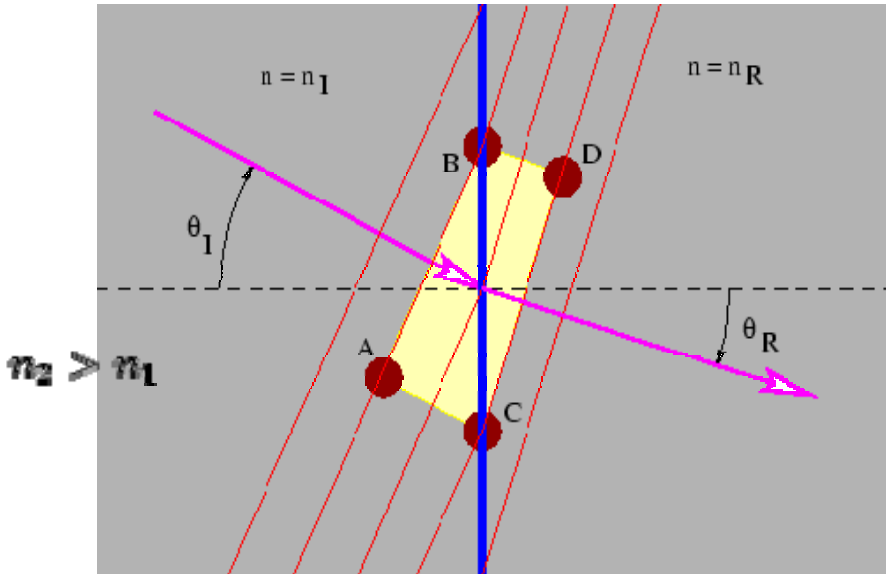


Most of what we need to know about geometrical optics can be summarized in two rules:

1) the laws of reflection
2) The law of refraction.



wave vector and wave front of a wave being reflected from a plane mirror



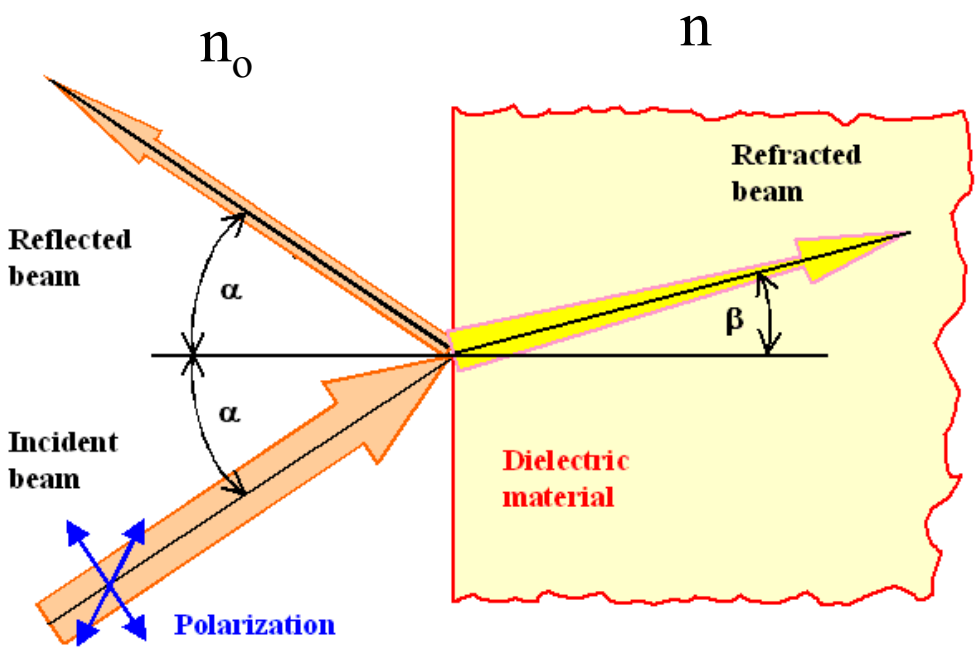
refraction of a wave from an interface between two dielectric media

Fermat's Principle:

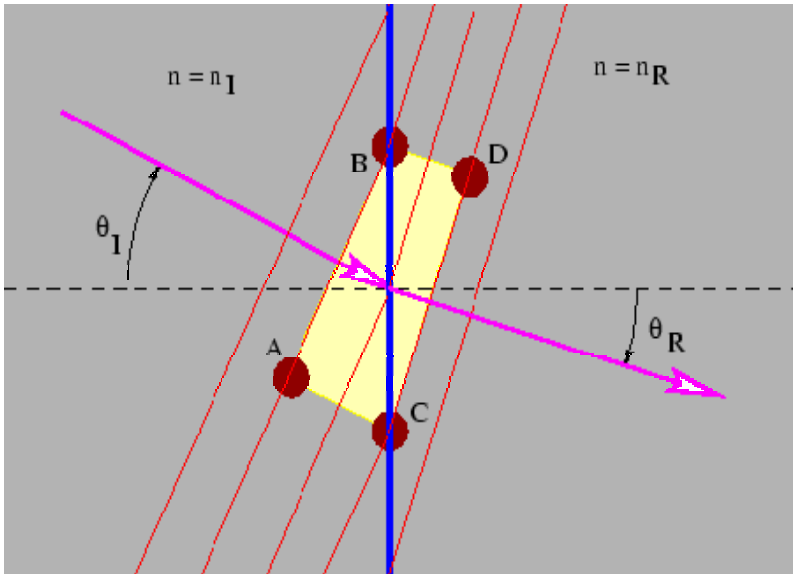
An alternate approach to geometric optics is fermat's principle. The path of a ray of light between two points is the path that minimizes the travel time.

In Fermat's Principle the optical path length between points A and B can be calculated in either direction, A to B or B to A, the result is the same. This leads to the principle of geometrical reversibility.

Law of Refraction



Snell's Law: $n_o \sin\alpha = n \sin\beta$



Since $n_R > n_I$, the speed of light in the right-hand medium is less than in the left-hand medium. The frequency of the wave packet doesn't change as it passes through the interface, so the wavelength of the light on the right side is less than the wavelength on the left side.

The side AC is equal to the side BC times $\sin\theta_I$. However, AC is also equal to $2\lambda_I$, or twice the wavelength of the wave to the left of the interface. Similar reasoning shows that $2\lambda_R$, twice the wavelength to the right of the interface, equals BC times $\sin\theta_P$. Since the interval BC is common to both triangles, we easily see that

$$\frac{\lambda_I}{\lambda_R} = \frac{\sin\theta_I}{\sin\theta_R}$$

Since $\lambda_R = Cf$ *and* $\lambda_I = Cf$ $\Rightarrow$ $n_I \sin\theta_I = n_R \sin\theta_R$

Light reflecting off of a polished or mirrored surface obeys the law of reflection: the angle between the incident ray and the normal to the surface is equal to the angle between the reflected ray and the normal.

Precision optical systems use first surface mirrors that are aluminized on the outer surface to avoid refraction, absorption, and scatter from light passing through the transparent substrate found in second surface mirrors.
When light obeys the law of reflection, it is termed a *specular* reflection. Most hard polished (shiny) surfaces are primarily specular in nature. Even transparent glass specularly reflects a portion of incoming light.

Diffuse reflection is typical of particulate substances like powders. If you shine a light on baking flour, for example, you will not see a directionally shiny component. The powder will appear uniformly bright from every direction.
Many reflections are a combination of both diffuse and specular components. One manifestation of this is a *spread* reflection, which has a dominant directional component that is partially diffused by surface irregularities

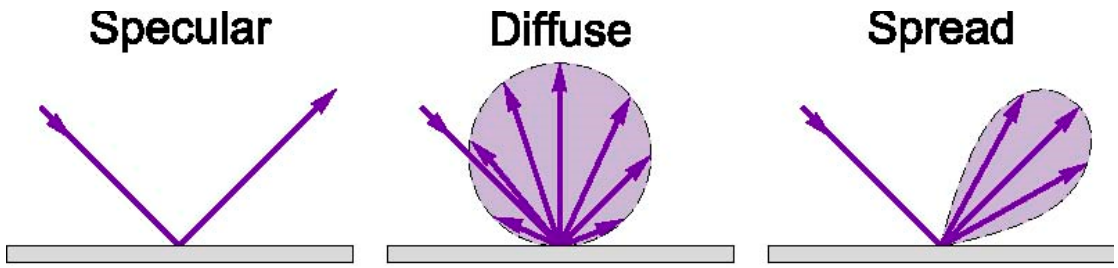
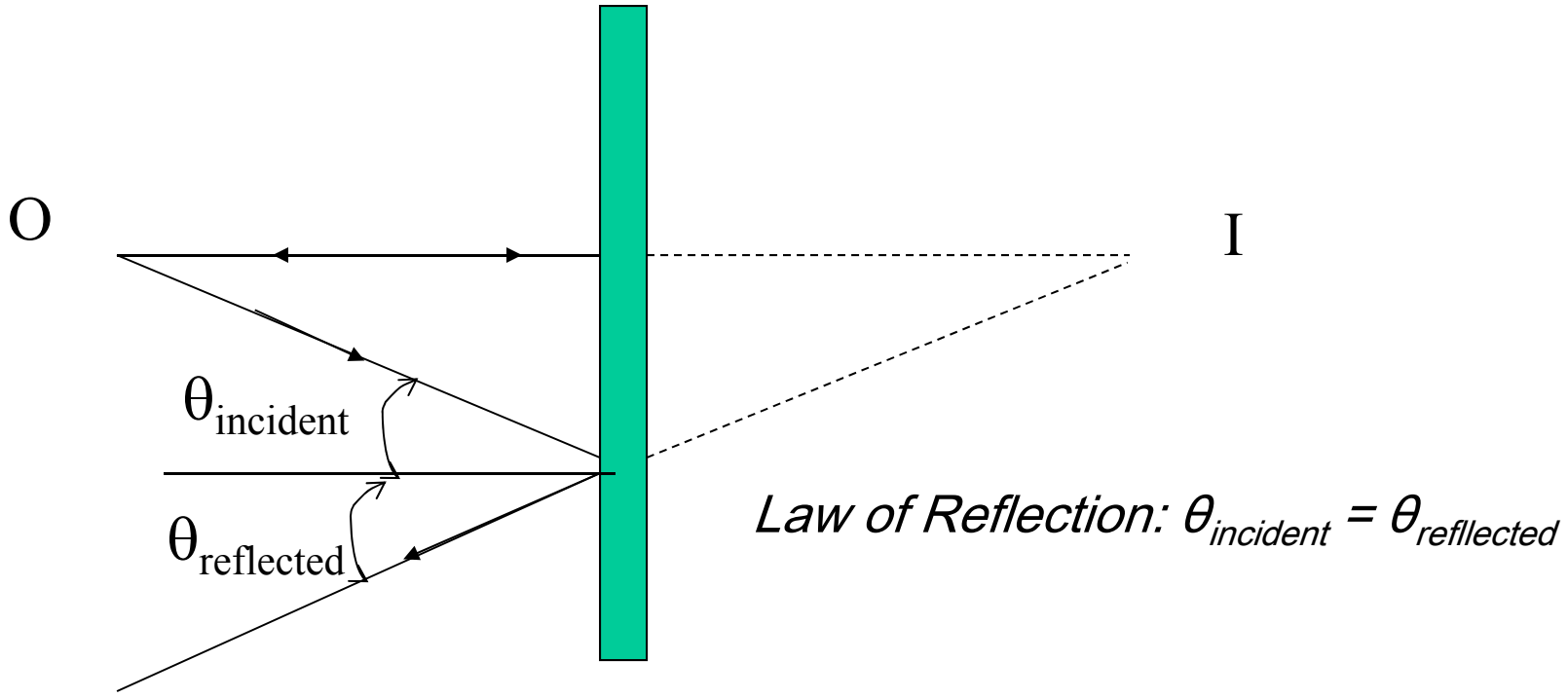


Fig. 3.2 Specular, diffuse, and spread reflection from a surface.

Reflection



The angles of incidence, $\theta_{incident}$, and reflection, $\theta_{reflected}$, are defined to be the angles between the incoming and outgoing wave vectors respectively and the line normal to the mirror. The law of reflection states that $\theta_{incident} = \theta_{refllected}$. This is a consequence of the need for the incoming and outgoing wave fronts to be in phase with each other all along the mirror surface. This plus the equality of the incoming and outgoing wavelengths is sufficient to insure the above result.

Reflection

$AA' = AB/\tan(\theta_I)$
$AB = \lambda_I$

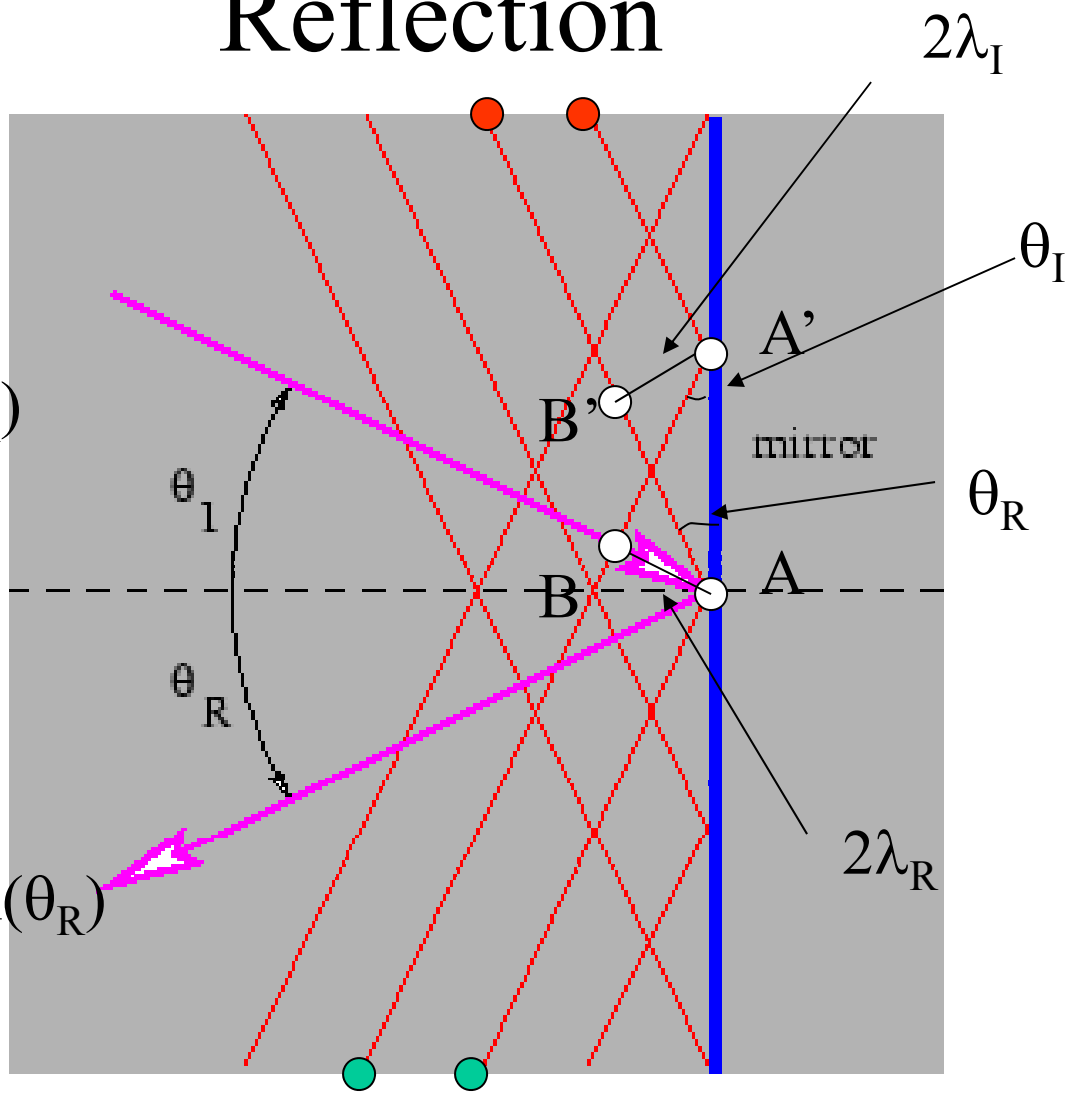
$AA' = A'B'/\tan(\theta_R)$
$A'B' = \lambda_R$

Since $\lambda_I = \lambda_R$
Then

$\lambda_I \tan(\theta_I) = \lambda_R \tan(\theta_R)$

So

$\theta_I = \theta_R$



Plane Mirror

Reflection

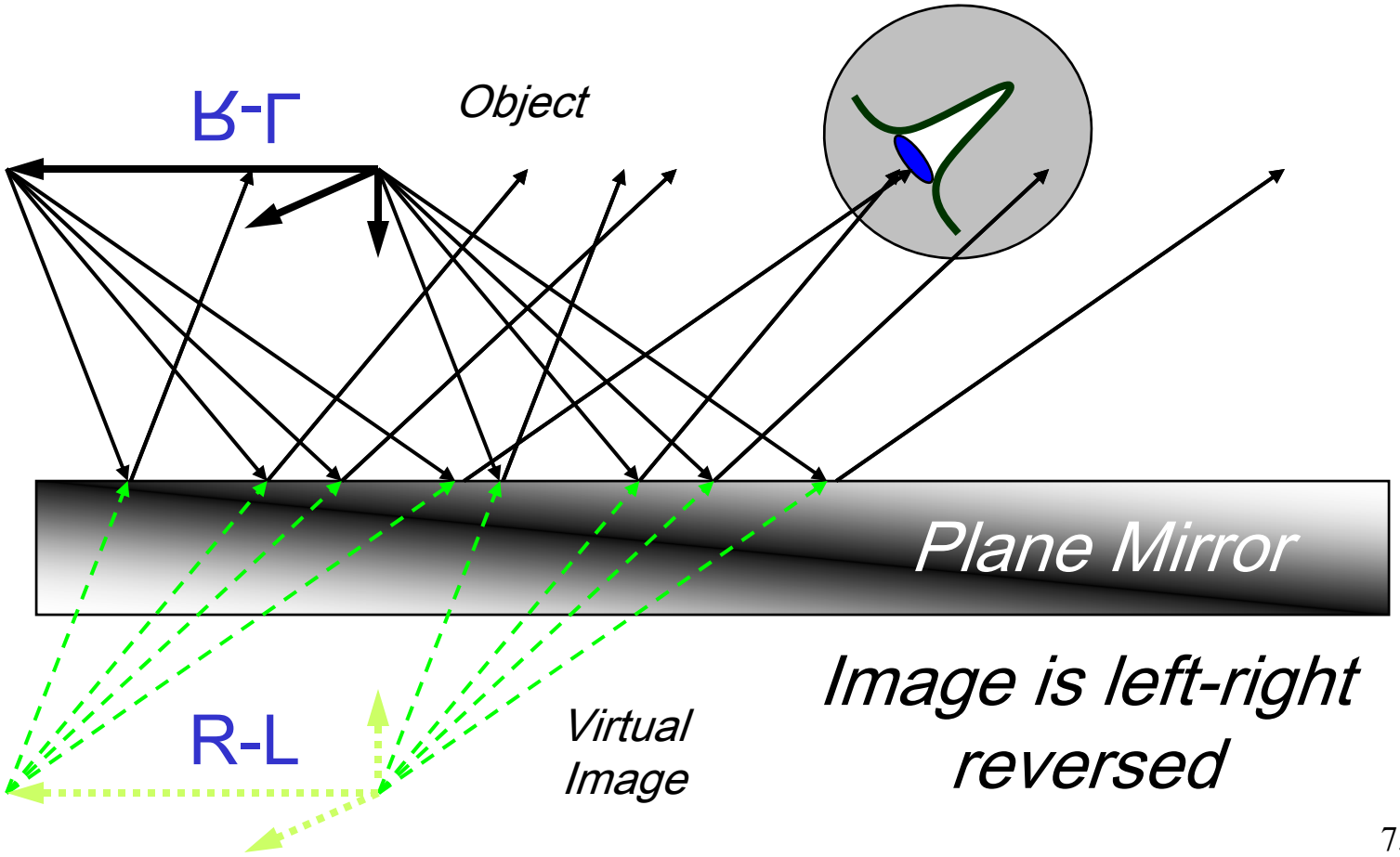
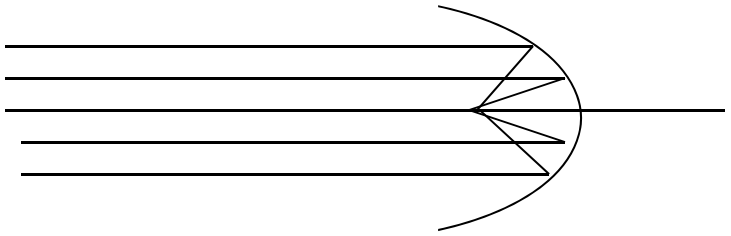


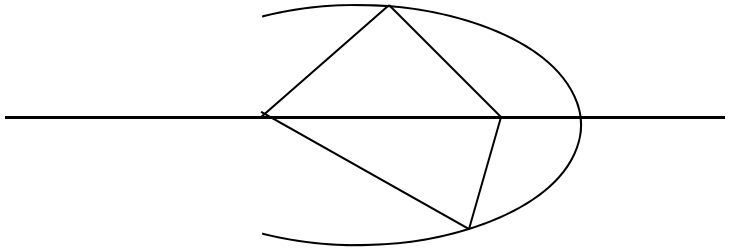
Image is left-right reversed

Curve Mirrors

Paraboloidal mirrors: main purpose focusing all incident rays parallel to its axis to a single point. Using in telescope for light collecting element or reflector in flashlights.



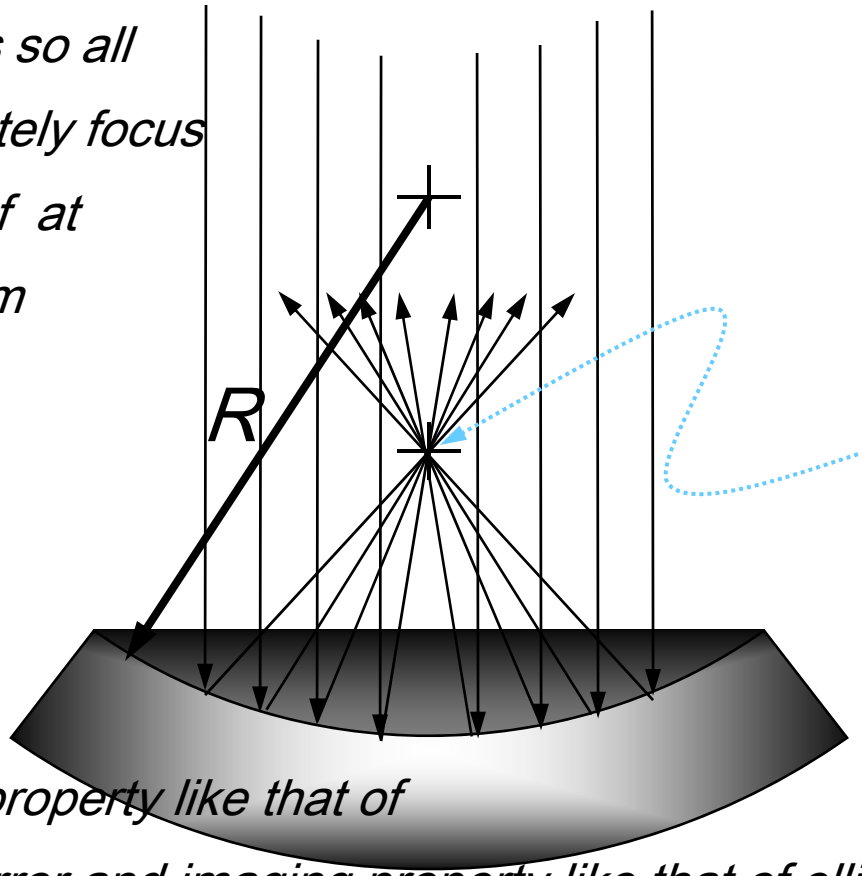
Elliptical mirrors: reflects all rays emitted from one of its two foci. The distances traveled by the light from two foci along any of the paths are all equal.



Geometric Optics

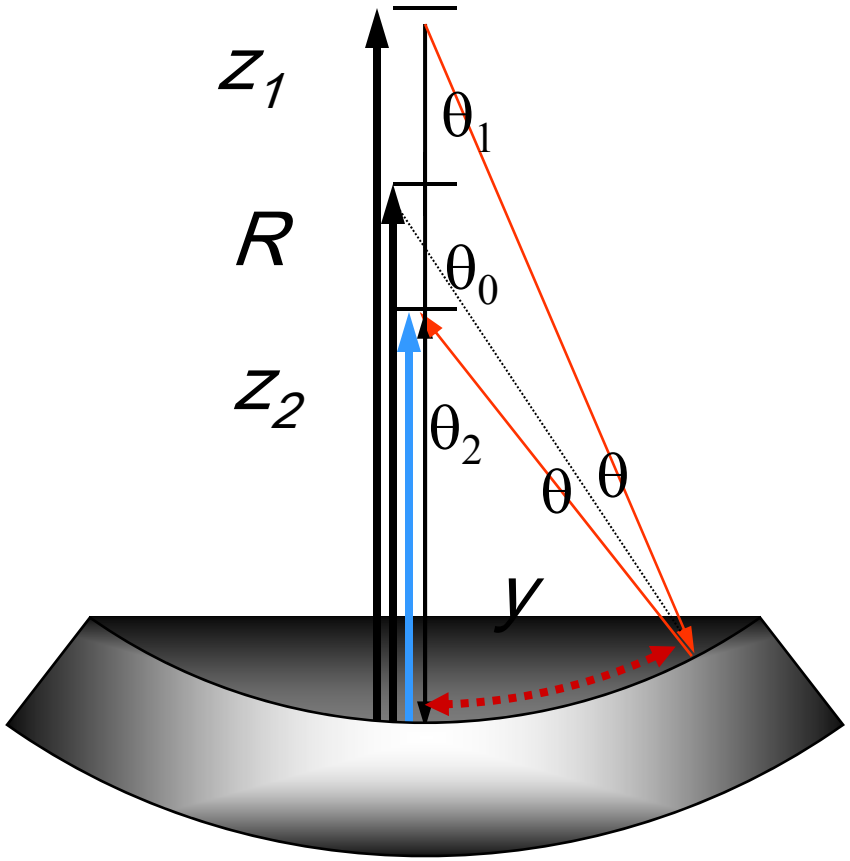
Assume parallel rays
Close to the axis so all
Rays approximately focus
to a single point f at
distance R/2 from
mirror center.

Concave Spherical Mirror



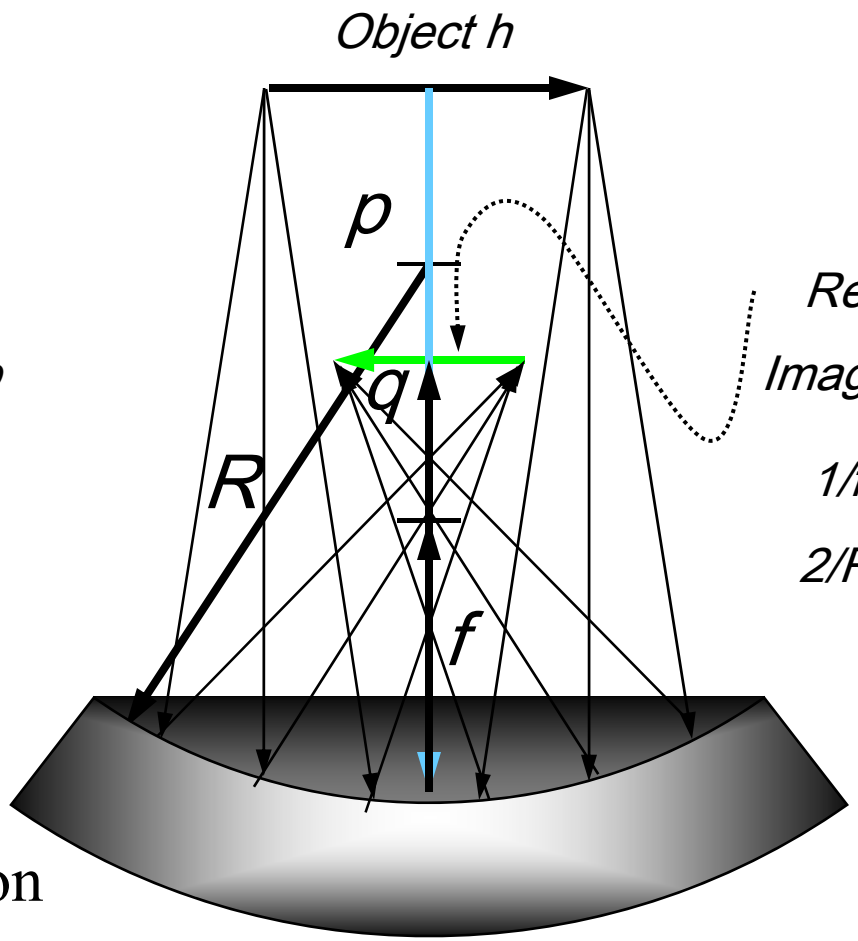
Using paraxial
Approximation,
Spherical mirror
Has a focusing property like that of
Paraboloidial mirror and imaging property like that of elliptical mirror.

Concave Spherical Mirror



Concave Spherical Mirror

Reflection



Magnification

$M = h'/h = -q/p$

Real

Image h'

$1/f = 1/p + 1/q$

$2/R = 1/p + 1/q$

p= object length

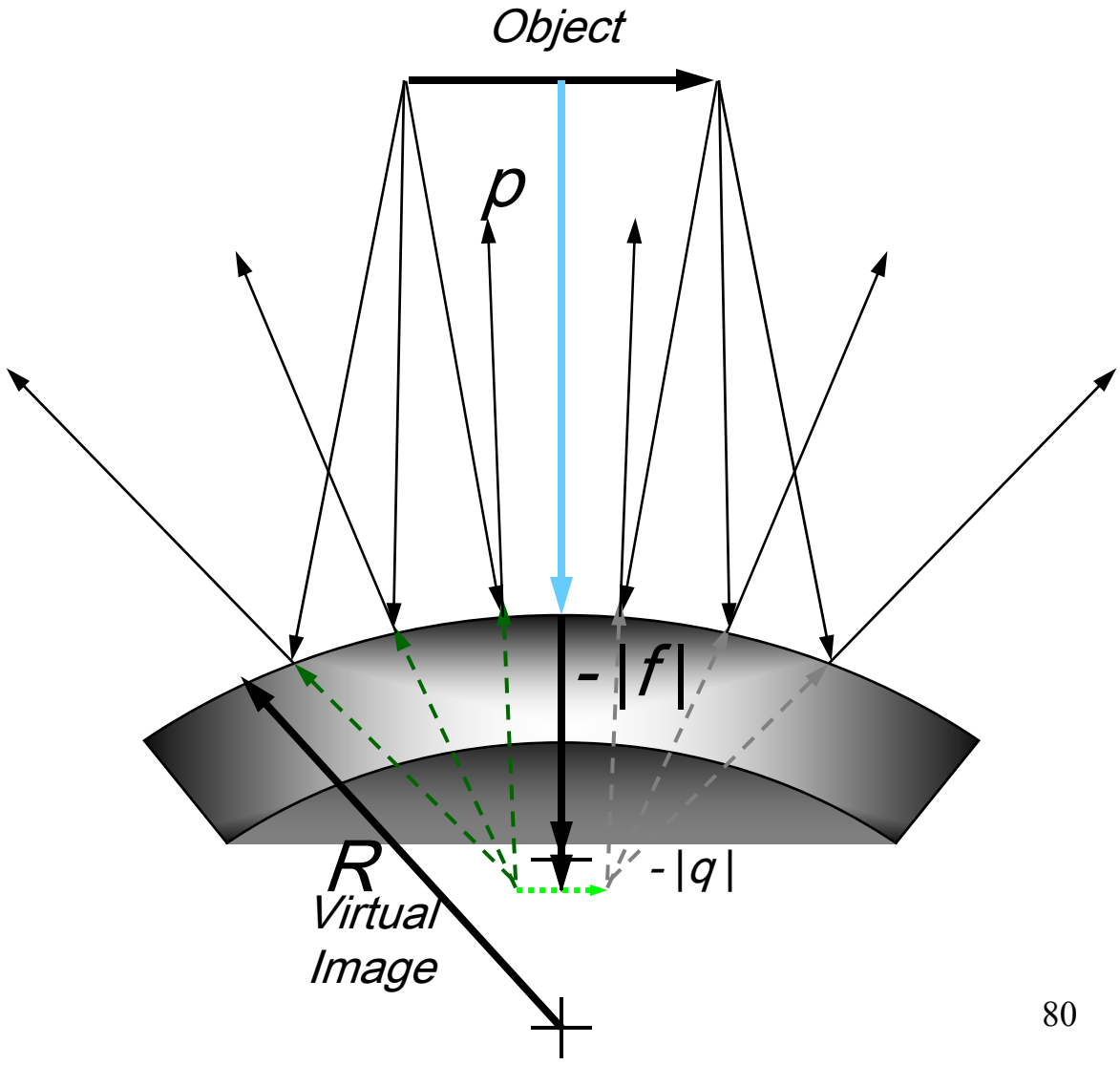
q = image position

Convex Spherical Mirror

$$1/f = 1/p + 1/q$$

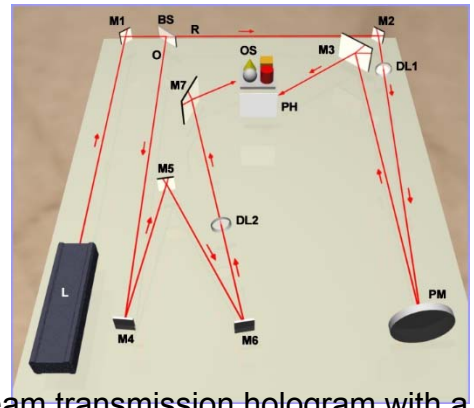
$$-1/|f| = 1/p - 1/|q|$$

$$M = h'/h = |q|/p$$

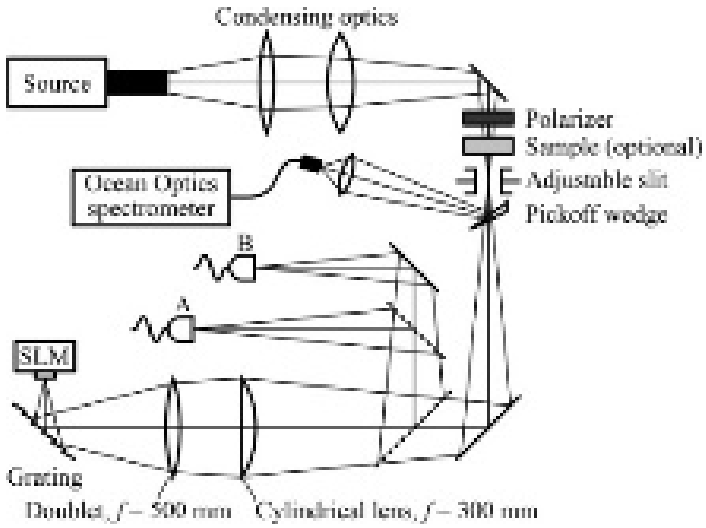


Why Mirrors

- Reflected light preserves many or most of the detailed physical characteristics of the original light
- Most mirrors are designed for visible light; however, mirrors designed for other wavelengths of electromagnetic radiation are also used
- Curved mirrors produce magnified or diminished images or focus light or simply distort the reflected image.
- Allow long working distance in a limited space.
- Allow light to change direction
- Allow Beam splitting
- Minimized dispersion effect



multi-beam transmission hologram with a single object beam



Multiple-output multivariate optical computing for spectrum recognition

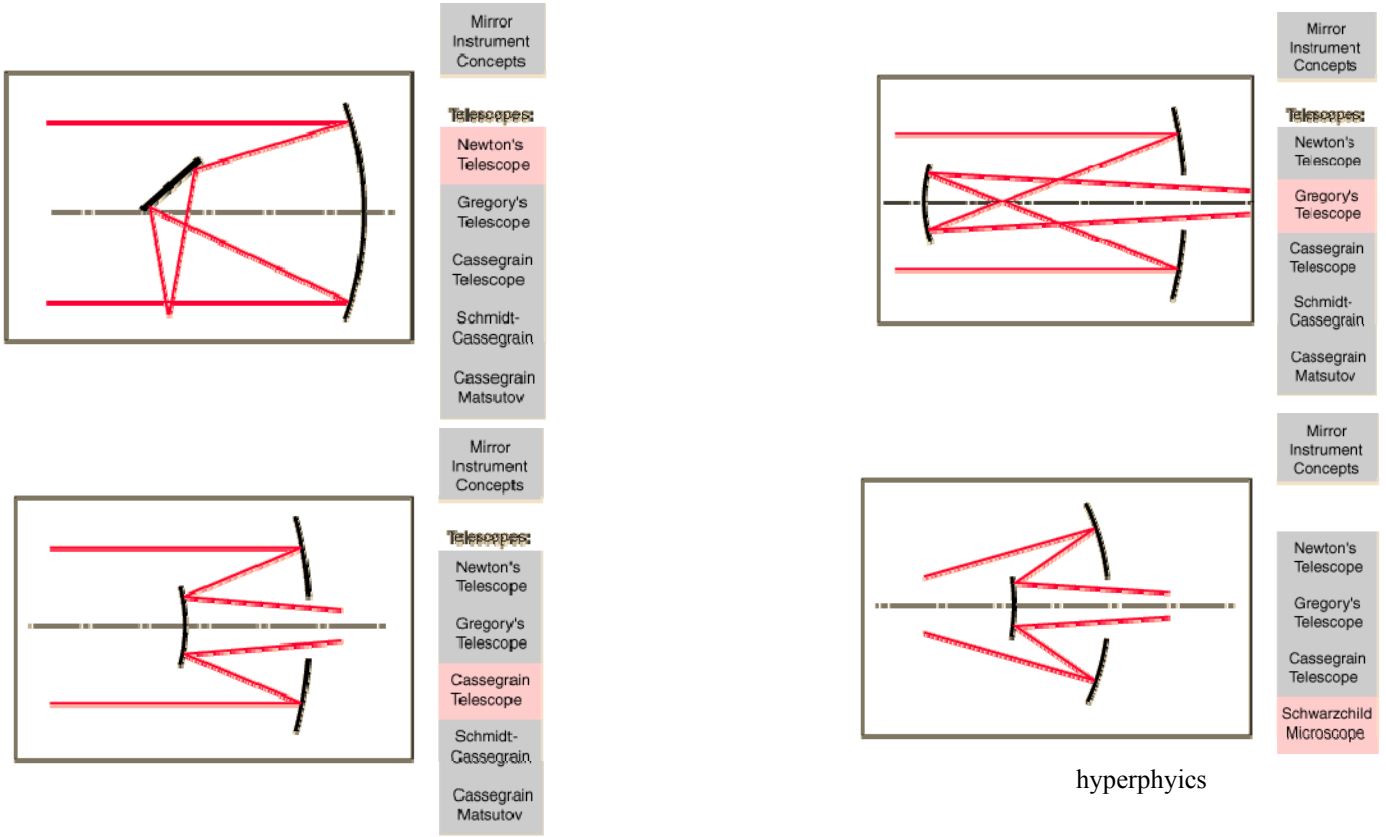
Application

- Laser cavity end mirrors
- Hot and cold mirrors,
- Thin-film beamsplitters
- Coatings on modern mirrorshades
- Telescope and Camera lenses

Mirror Systems for Telescope Applications

Instruments which use only mirrors to form images are called catoptric systems, while those which use both lenses and mirrors are called catadioptric systems (dioptric systems being those with lenses only).

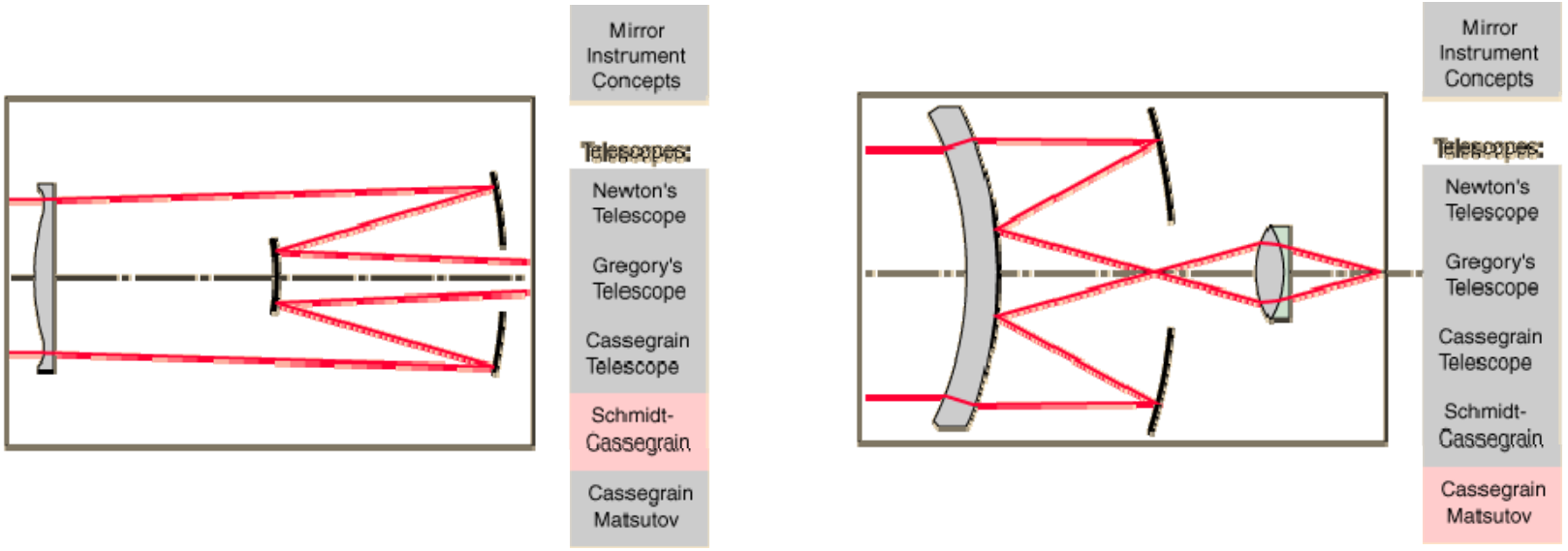
Catoptric Systems



hyperphyics

Catoptric systems are those which use only mirrors for image formation. They constrast with catadioptric systems which use both mirrors and lenses and with pure dioptric systems which use only lenses.

Catadioptric Systems

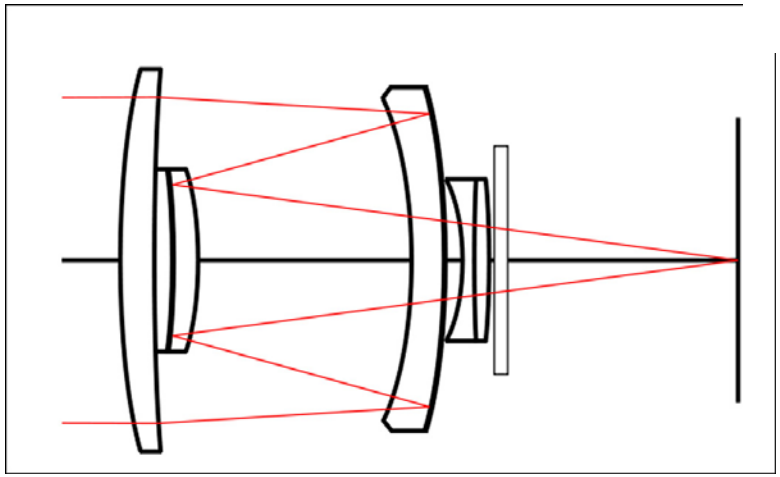


hyperphyics

Catadioptric systems are those which make use of both lenses and mirrors for image formation. This constrasts with catoptric systems which use only mirrors and dioptric systems which use only lenses. (i.e. Nikon 500mm mirror lens)

Mirror Lens (Reflex Lens)

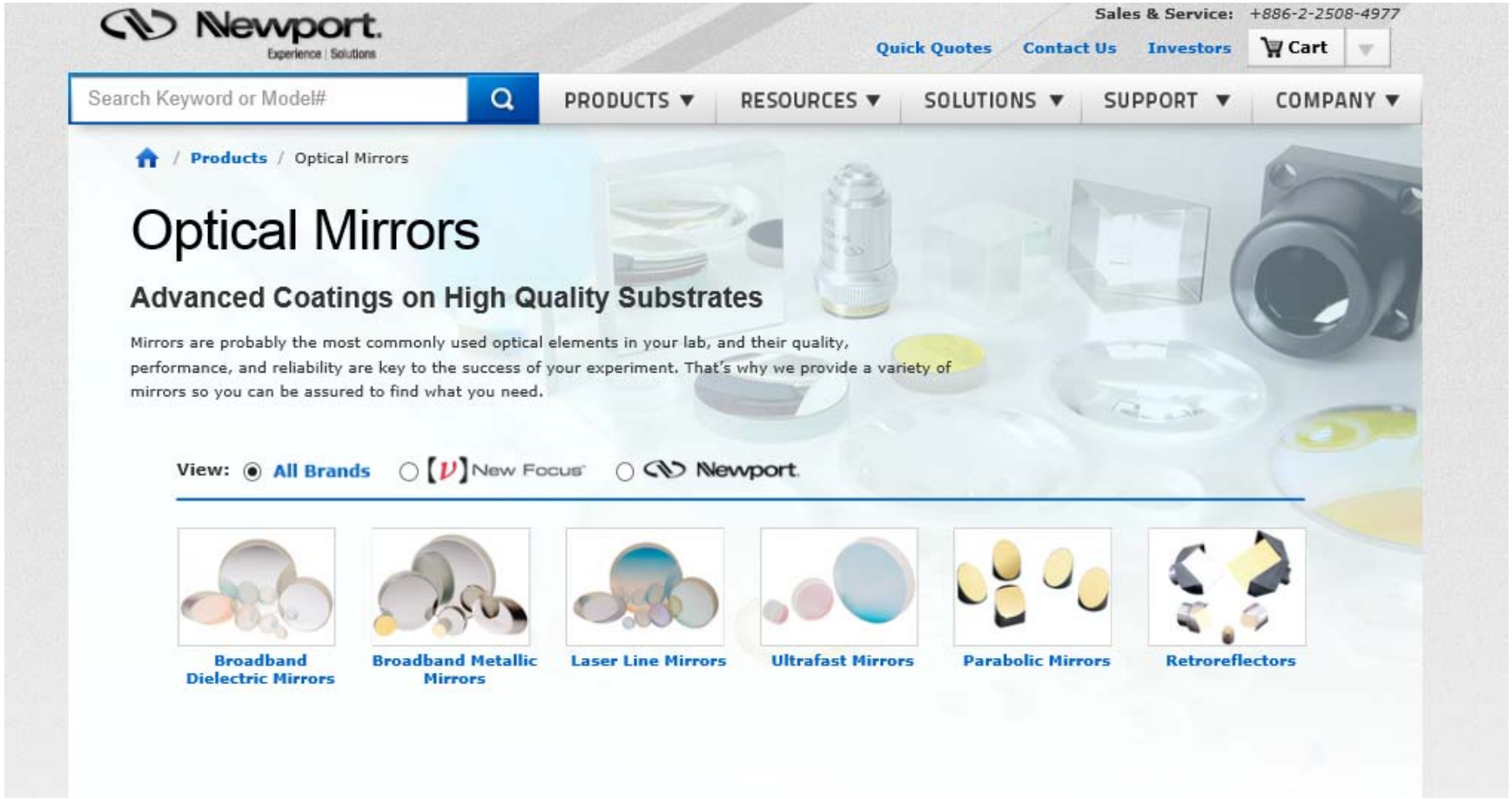
- Reduce Lens length
- Simpler lens design



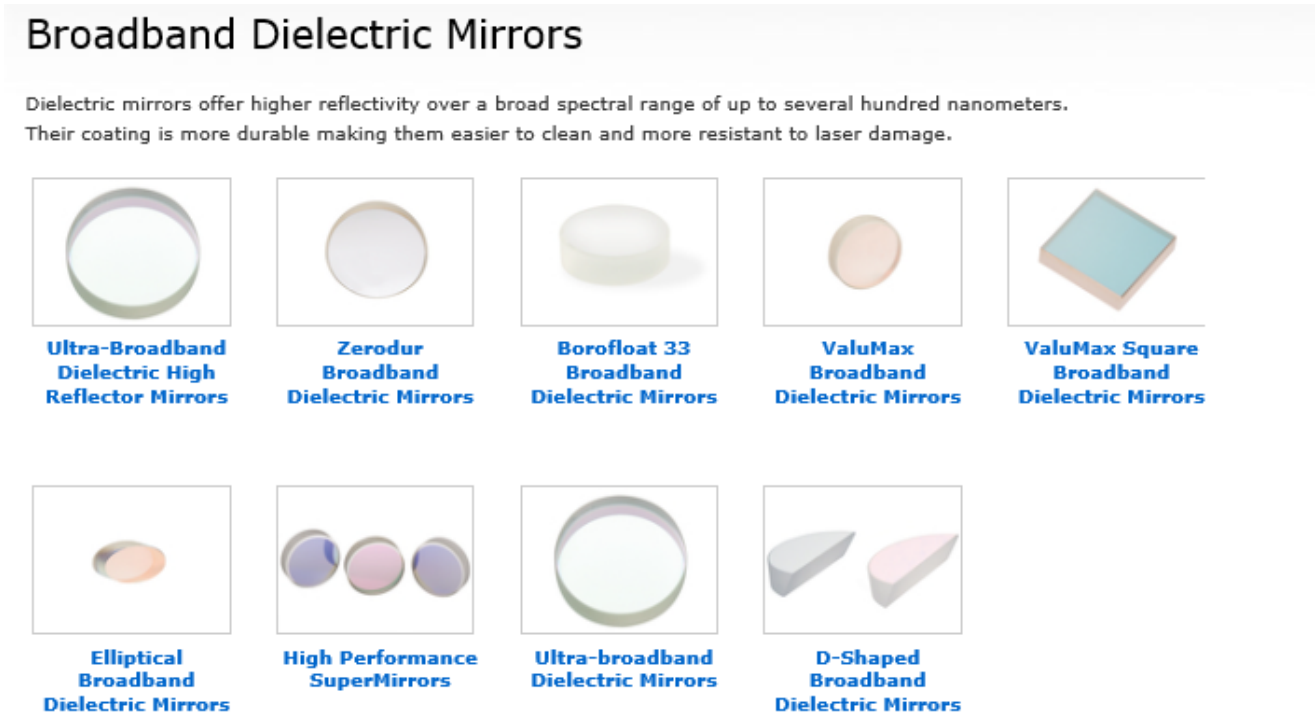
Nikon 500mm

Tokina 300mm

Different Types of Mirrors



Dielectric Mirrors

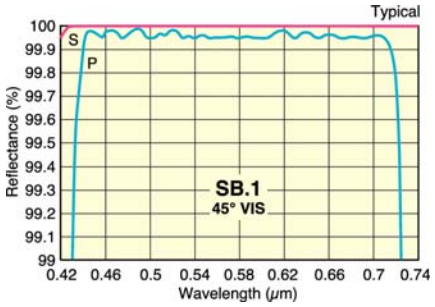


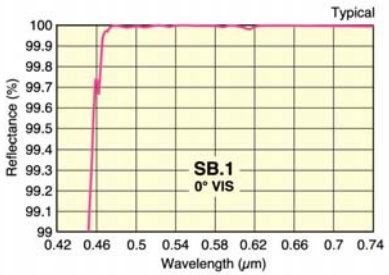
A dielectric mirror, also known as a Bragg mirror, is a type of mirror composed of multiple thin layers of dielectric material, typically deposited on a substrate of glass or some other optical material. By careful choice of the type and thickness of the dielectric layers, one can design an optical coating with specified reflectivity at different wavelengths of light. Dielectric mirrors are also used to produce ultra-high reflectivity mirrors: values of 99.999% or better over a narrow range of wavelengths can be produced using special techniques. Alternatively, they can be made to reflect a broad spectrum of light, such as the entire visible range or the spectrum of the Ti-sapphire laser. Mirrors of this type are very common in optics experiments, due to improved techniques that allow inexpensive manufacture of high-quality mirrors. Examples of their applications **include laser cavity end mirrors, hot and cold mirrors, thin-film beamsplitters, and the coatings on modern mirrorshades.**

Example of a dielectric mirror

Newport Broadband SuperMirror, 25.4mm, Ref>99.9%, 0-45 Deg AOI, 485-700nm

Model	10CM00SB.1
Wavelength Region	VIS
Wavelength Range	485-700 nm
Mirror Shape	Round
Substrate Size	Ø25.4 mm
Material	UV Grade Fused Silica
Coating Type	Broadband IBS Coating
Surface Quality	20-10 scratch-dig
Surface Flatness	λ/10 at 632.8 nm
Coating Code	SB.1
Angle of Incidence	0-15°
Clear Aperture	≥central 50% of diameter
Reflectivity	R_s, R_p>99.9% @ 485-700 nm
Thickness	6.35 mm
Thickness Tolerance	±0.38 mm
Diameter Tolerance	+0/-0.1 mm
Chamfers	±0.25 mm
Chamfers Angle/Tolerance	45° ± 15°
Diameter	25.4 mm
Cleaning	Cleaning techniques specifically developed for ultra high performance optics may be used by qualified personnel

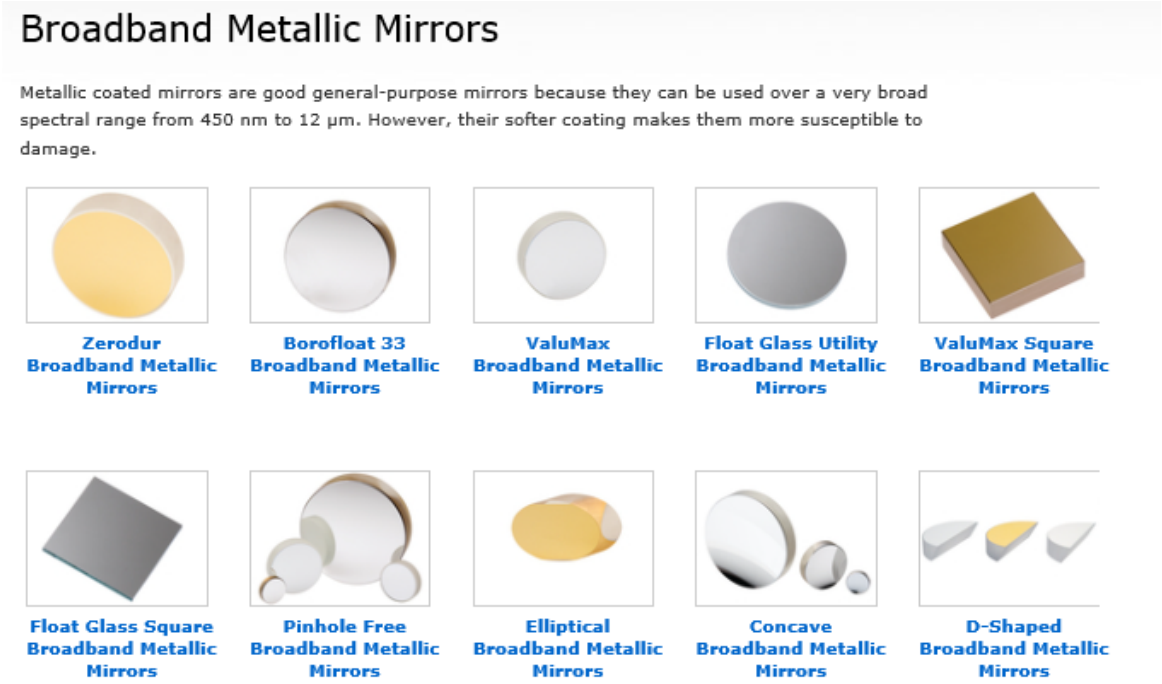




The 10CM00SB.1 is a Broadband Super Mirror, 25.4 mm in diameter, 6.35mm thick, and coated to have a reflectivity of > 99.9%, 0-45 °, from 485 to 700 nm.

Broadband SuperMirrorsTM are extremely high performance dielectric mirrors. They are produced with ion beam sputtered (IBS) coatings on superpolished fused silica substrates to achieve very low scatter and absorption. These mirrors have reflectivity greater than 99.9%, independent of polarization, at any angle of incidence from 0–45°.

Metallic Mirror



Mirror made of very thinly coated metal deposition made of aluminum coating (reflectivity of 87% to 93%) or silver mirror coating (reflectivity of 95% to 98%) and gold coating (` 95%) in visible band is used. Most commonly used mirrors.

Example of a metallic mirror

Newport General Purpose Silver Coated Mirror, 1.0 in., 450 - 12,000 nm

Model	5103
Wavelength Region	Broadband
Diameter	1.00 in. (25.4 mm)
Mirror Shape	Round
Material	Borofloat® 33
Wavelength Range	450-12000 nm
Surface Quality	25-10 scratch-dig
Surface Flatness	λ/10 at 632.8 nm
Clear Aperture	≥central 80% of diameter
Damage Threshold	30 kW/cm^2 (cw), 0.5 J/cm^2 (10-ns pulse)
Thickness	0.32 in. (8.0 mm)

The 5103 General Purpose Silver Coated Mirror can be used over a broad spectral range with better than **95% reflectivity from 450 nm to beyond 12 µm**. It's proprietary silver-based coating makes this 1.0 inch (25.4 mm) diameter mirror highly reflective from 0° to 45° and virtually **insensitive to polarization**. Protective dielectric coatings make it resistant to tarnish and oxidation. Plus it has minimal phase distortion, so it is useful for ultrafast-pulsed applications with Ti:Sapphire and other lasers.

Laser Mirrors

Laser Line Mirrors

Our laser line mirrors are highly efficient reflectors optimized for a narrow wavelength range.

Zerodur Laser Line Dielectric Mirrors

Borofloat 33 Laser Line Dielectric Mirrors

Elliptical ND:YAG Laser Line Dielectric Mirrors

Long Lived Deep UV Excimer Mirrors

High Energy ND:YAG Laser Mirrors

High Energy Excimer Laser Mirrors

Example of a Laser mirror

Newport Femtosec Optimized Silver Mirror, 0-45° AOI, 25.4 mm, 600-1100 nm

Model	5103
Wavelength Region	Broadband
Diameter	1.00 in. (25.4 mm)
Mirror Shape	Round
Material	Borofloat® 33
Wavelength Range	450-12000 nm
Surface Quality	25-10 scratch-dig
Surface Flatness	λ/10 at 632.8 nm
Clear Aperture	≥central 80% of diameter
Damage Threshold	30 kW/cm^2 (cw), 0.5 J/cm^2 (10-ns pulse)
Thickness	0.32 in. (8.0 mm)

The 10B20EAG.1 Femtosecond Optimized Silver Mirror is 25.4 mm in diameter, 6.35 mm thick, and broadband optimized for 540 - 1100 nm. **This ultrafast mirror is designed for zero to 45 degrees angle of incidence for S and P polarization**. The absolute value of GDD (Group Delay Dispersion) is an astounding less than 5 fs from 550 to 1050 nm. Ideal for use with ultrashort pulse lasers, this high reflectance beamsteering mirror gives R>99% 600-1000 nm at 0 deg AOI, Rp>98.5% 580-1000 nm at 45 deg AOI and Rs>99% 540-1000 nm. Careful thin film coating design and advanced coating processes result in a mirror with maximum reflectivity and bandwidth with minimum effect on pulse dispersion.

W.Wang

Group Delay Dispersion

The group delay dispersion (also sometimes called *second-order dispersion*) of an optical element is the derivative of the group delay with respect to the angular frequency, or the second derivative of the change in spectral phase:

$$D_2(\omega) = \frac{\partial T_g}{\partial \omega} = \frac{\partial^2 \varphi}{\partial \omega^2}$$

It is usually specified in fs^2 or ps^2. Positive (negative) values correspond to normal (anomalous) chromatic dispersion. For example, the group delay dispersion of a 1-mm thick silica plate is +35 fs^2 at 800 nm (normal dispersion) or −26 fs^2 at 1500 nm (anomalous dispersion). Another example is given in Figure 1.

If an optical element has only second order dispersion, i.e., a frequency-independent D_2 value, its effect on an optical pulse or signal can be described as a change of the spectral phase:

$$\Delta\varphi(\omega) = \frac{D_2}{2}(\omega - \omega_0)^2$$

where ω_0 is the angular frequency at the center of the spectrum.

Note that the group delay dispersion (GDD) always refers to some optical element or to some given length of a medium (e.g. an optical fiber). The GDD per unit length (in units of s^2/m) is the *group velocity dispersion* (GVD).

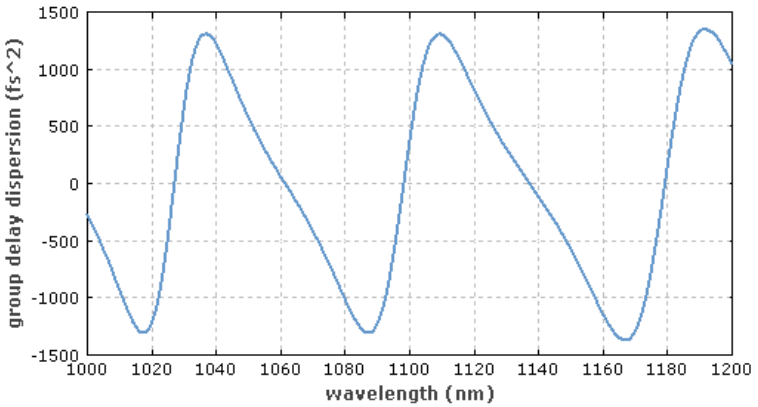


Figure 1: Wavelength-dependent group delay dispersion of a Gires–Tournois interferometer made of a 5-μm thick silica layer on a high reflector.

Other Types of Mirrors

- Other types of reflecting device are also called "mirrors".
- **Acoustic mirrors** are passive devices used to reflect and perhaps to focus sound waves. Acoustic mirrors were used for selective detection of sound waves, especially during World War II. They were used for detection of enemy aircraft, prior to the development of radar. Acoustic mirrors are used for remote probing of the atmosphere; they can be used to form a narrow diffraction-limited beam.[51] They can also be used for underwater imaging.
- **Active mirrors** are mirrors that amplify the light they reflect. They are used to make disk lasers.[52] The amplification is typically over a narrow range of wavelengths, and requires an external source of power.
- **Atomic mirrors** are devices which reflect matter waves. Usually, atomic mirrors work at grazing incidence. Such mirrors can be used for atomic interferometry and atomic holography. It has been proposed that they can be used for non-destructive imaging systems with nanometer resolution.[53]
- **Cold mirrors** are dielectric mirrors that reflect the entire visible light spectrum, while efficiently transmitting infrared wavelengths. These are the converse of hot mirrors.
- **Corner reflectors** use three flat mirrors to reflect light back towards its source, they may also be implemented with prisms that reflect using total internal reflection that have no mirror surfaces. They are used for emergency location, and even laser ranging to the Moon.
- **Hot mirrors** reflect infrared light while allowing visible light to pass. These can be used to separate useful light from unneeded infrared to reduce heating of components in an optical device. They can also be used as dichroic beamsplitters. (Hot mirrors are the converse of cold mirrors.)
- **Metallic reflectors** are used to reflect infrared light (such as in space heaters or microwaves).
- **Non-reversing mirrors** are mirrors that provide a non-reversed image of their subjects.
- **X-ray mirrors** produce specular reflection of X-rays. All known types work only at angles near grazing incidence, and only a small fraction of the rays are reflected.[54] See also X-ray optics.

Acoustic Mirror

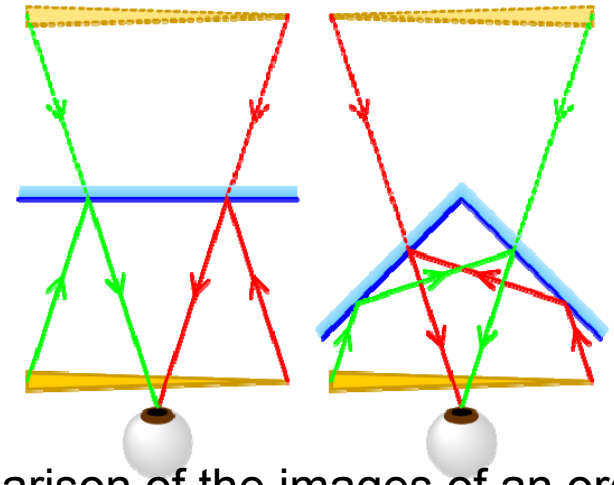
- WWI rconnasant acoustic mirror built as early warning system for aircraft attacks
- The British built an impressive system of acoustic mirrors for coastline defense along the English Channel before World War II. These mirrors consisted of large structures built of concrete. There were several different shapes as the British experimented with the best design, but each shape reflected sound waves and focused them in a particular area where a microphone or human listener could be located.

Photo by flickr user tobyct used under Creative Commons License

Google map

Non- reversing Mirror

A non-reversing mirror (sometimes marketed as a true mirror) is a mirror that presents its subject as it would be seen from the mirror. A non-reversing mirror can be made by connecting two regular mirrors at their edges at a 90 degree angle. If the join is positioned so that it is vertical, an observer looking into the angle will see a non-reversed image. This can be seen in public toilets when there are mirrors on two walls which are at right angles. Looking towards the corner, such an image is visible. The problem with this type of non-reversing mirror is that there is a big line down the middle interrupting the image. However, if first surface mirrors are used, and care is taken to set the angle to exactly 90 degrees, the join can be made invisible. (wkipedia)



Comparison of the images of an ordinary mirror (left) and the first type of non-reversing mirror (right)

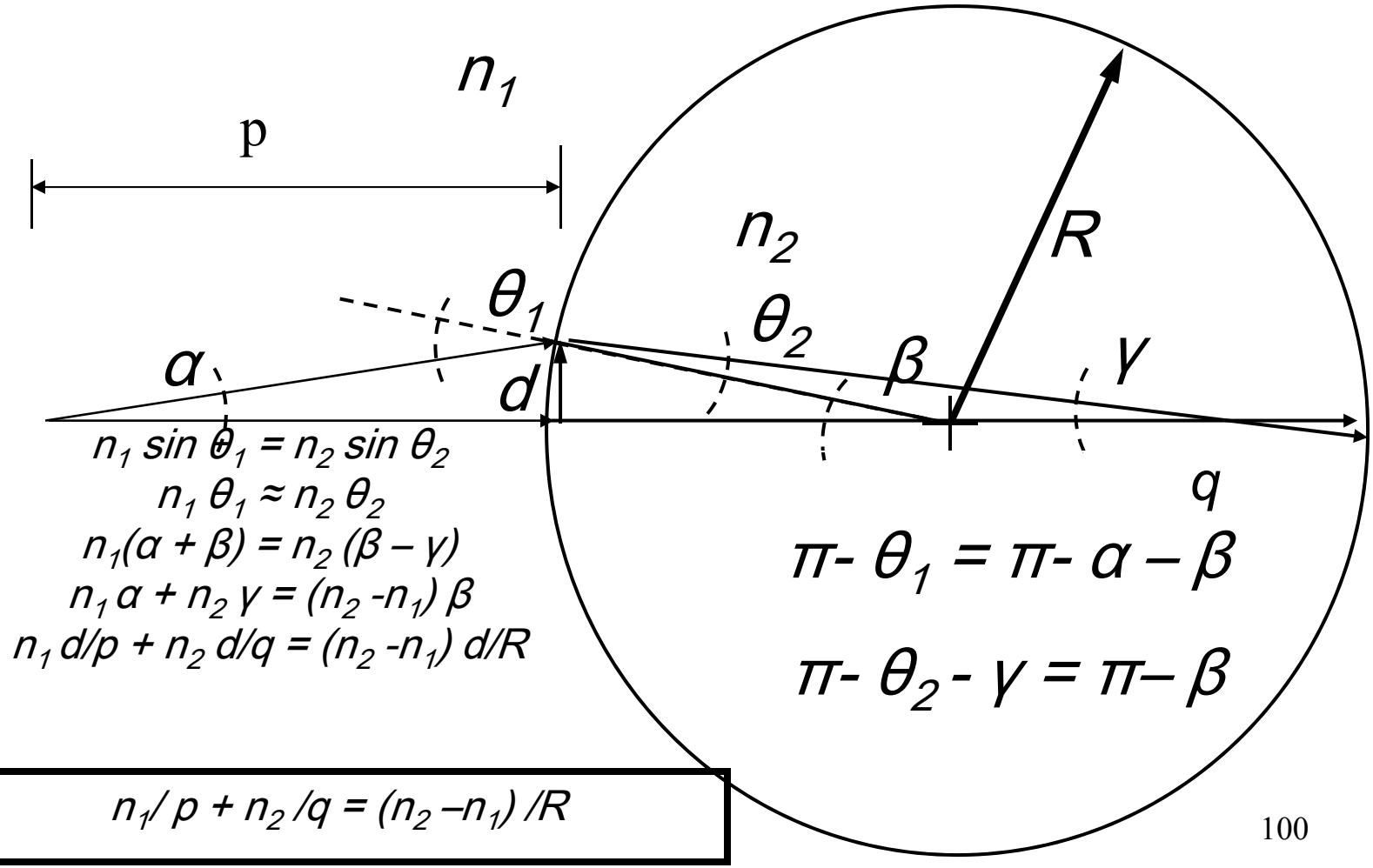
ordinary mirror (left) and two perpendicular mirrors forming the first type of non-reversing mirror (right)

Design project 1

- Design a mirror system to focus, diverge or collimate an incident beam or create some interesting magic tricks or illusion or something you can think of that using ray tracing technique.
- Show all calculation and design.

Spherical Boundary and Lenses

Refraction *Spherical Surface*



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

$n_1\,\theta_1 \approx n_2\,\theta_2$

$n_1(\alpha + \beta) = n_2(\beta - \gamma)$

$n_1\,\alpha + n_2\,\gamma = (n_2 - n_1)\,\beta$

$n_1\,d/p + n_2\,d/q = (n_2 - n_1)\,d/R$

$\pi - \theta_1 = \pi - \alpha - \beta$

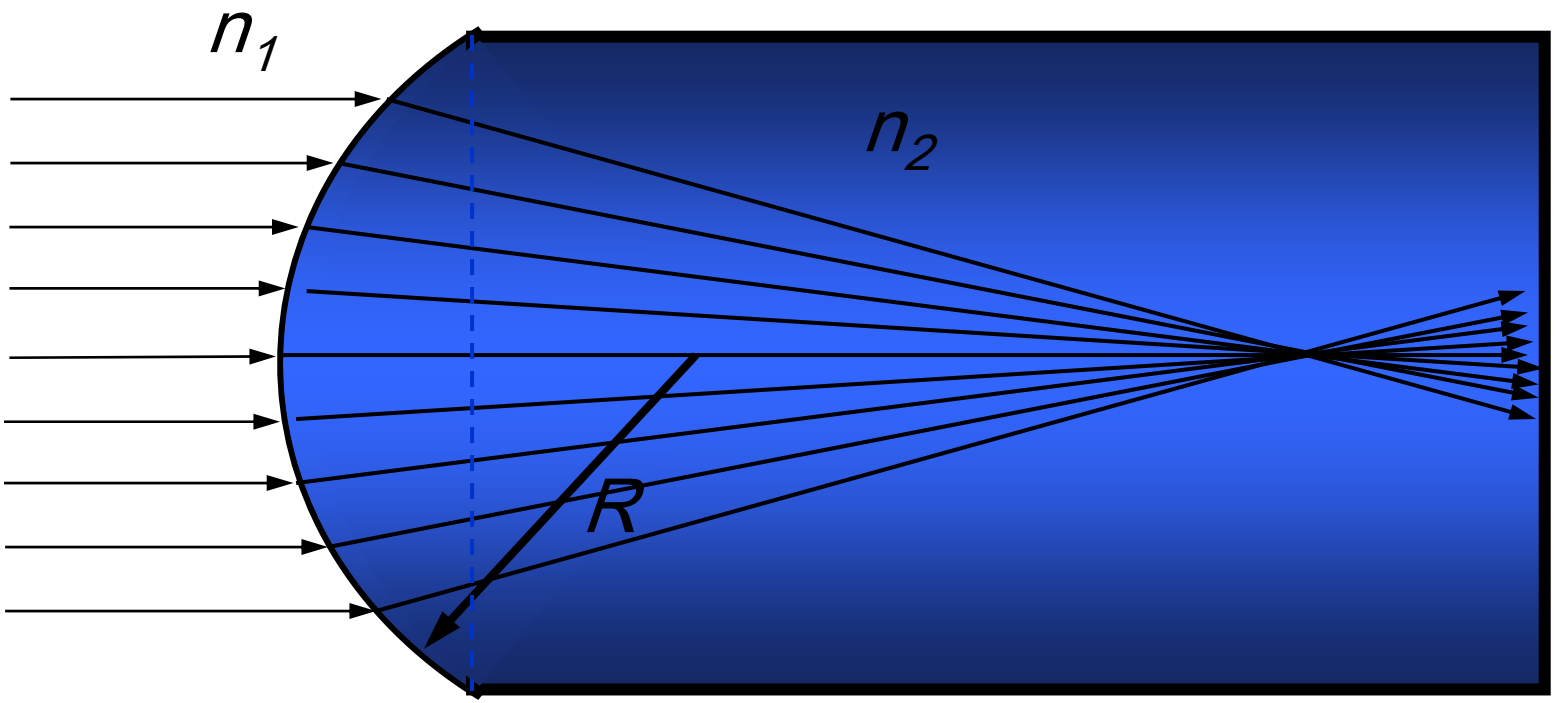
$\pi - \theta_2 - \gamma = \pi - \beta$

$$n_1/p + n_2/q = (n_2 - n_1)/R$$

Lens bounded by spherical surface and flat surface

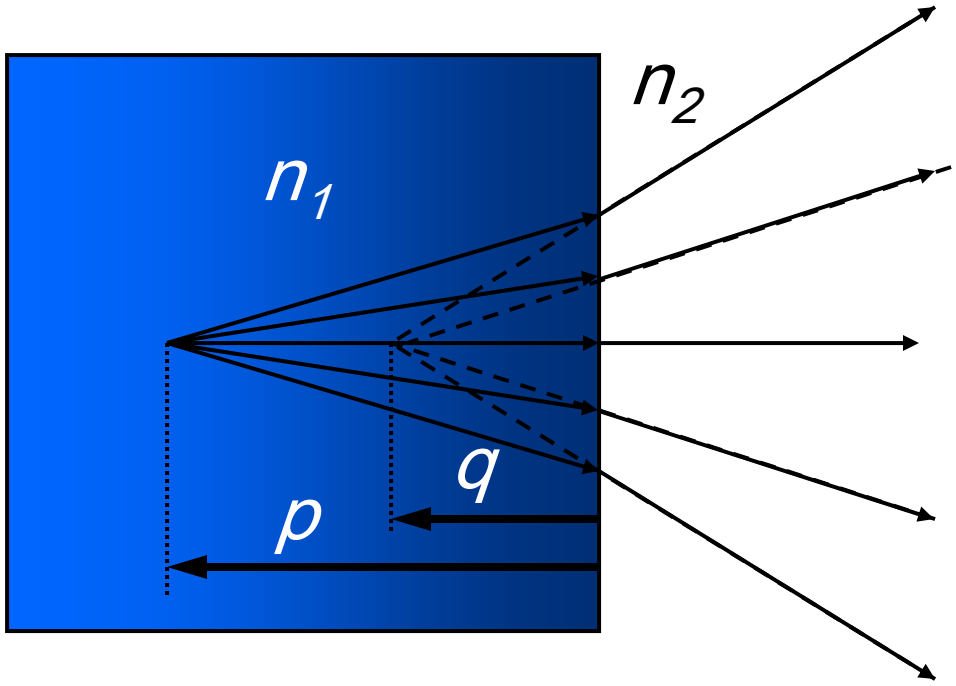
Refraction

Spherical Surface



$$n_1/p + n_2/q = (n_2 - n_1)/R$$

Flat Refracting Surface



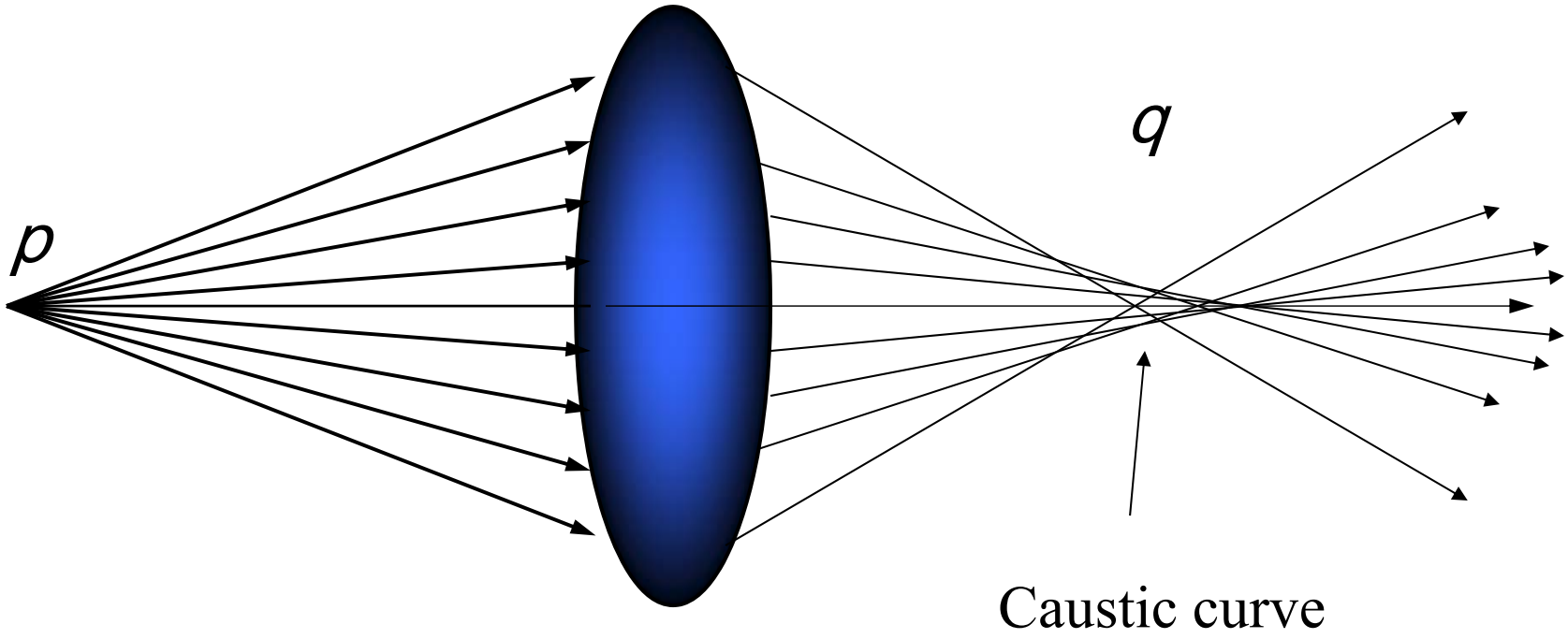
$n_1/p + n_2/q = 0$

R>>>

$q = -(n_2/n_1)p$

f=infinity

Thick Lens



Nonparaxial rays do not meet at the paraxial focus.

Biconvex spherical lens

We use Lens Maker's Equation

$1/p_1 - n/q_1 = (n-1)/R_1$

$n/p_1 + 1/q_2 = (1-n)/R_2$

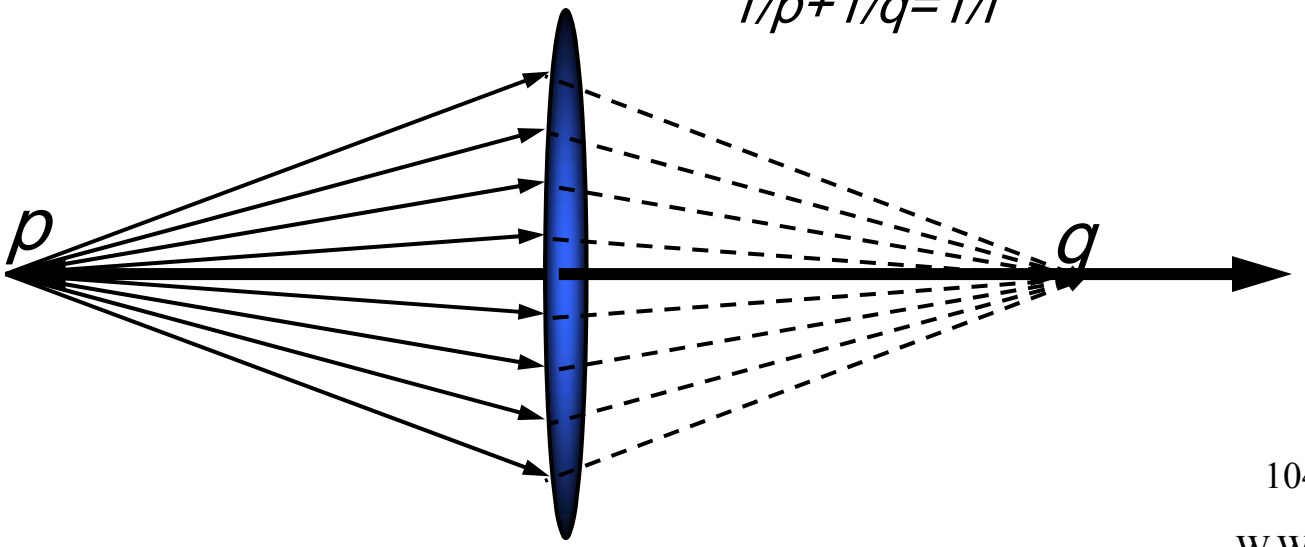
and

Paraxial approximation
Rays travel close to optical axis
$\sin\theta \sim \theta$

We get $1/p + 1/q = (n-1)\,(1/R_1 - 1/R_2)$

$1/f = (n-1)\,(1/R_1 - 1/R_2)$

$1/p+1/q=1/f$



Thin Lens

The Thin Lens Equation:

$$1/f = 1/p + 1/q$$

Lateral Magnification:

$$M = h'/h$$

$$M = -q/p$$

Focal length in terms of M:

$$f = pM/(1+M)$$

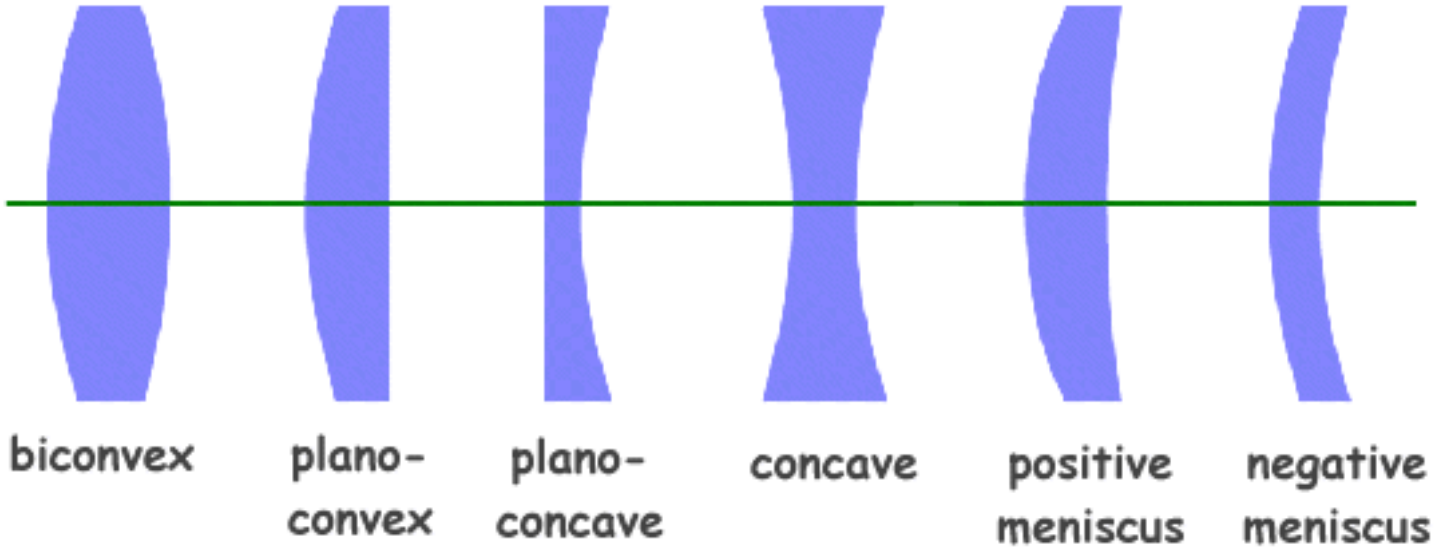
$$= M(p+q)/(1+M)^2$$

$$= (p+q)/(M+2+1/M)$$

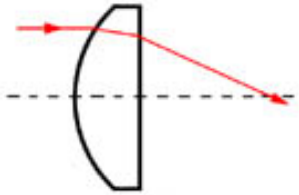
Object to image distance in terms of M:

$$p(1+M) = (p+q)$$

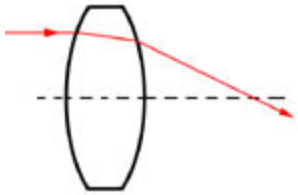
Different Types of Lenses



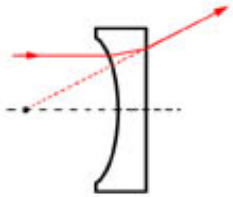
Plano-convex



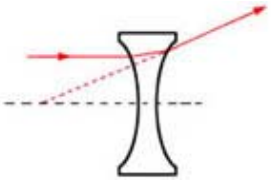
Double-convex



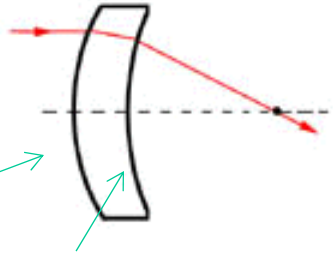
Plano-concave



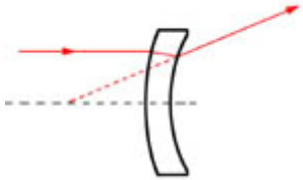
Double concave



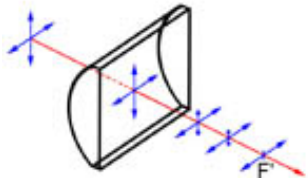
Meniscus positive



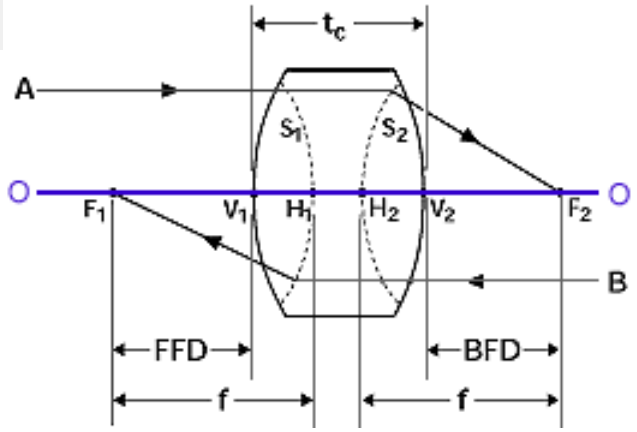
Meniscus negative



cylindrical



Lens Terminology



The following definitions refer to the singlet lens diagram shown left. In the paraxial limit, however, *any* optical system can be reduced to the specification of the positions of the principal

F1
Front Focal Point: Common focal point of all rays B parallel to optical axis and travelling from right to left.

V1
Front Vertex: Intersection of the first surface with the optical axis.

S1
First Principal Surface: A surface defined by the intersection of incoming rays B with the corresponding outgoing rays focusing at F1.

H1
First Principal Point: Intersection of the first principal surface with the optical axis.

f
Effective Focal Length: The axial distance from the principal points to their respective focal points. This will be the same on both sides of the system provided the system begins and ends in a medium of the same index.

FFD
Front Focal Distance: The distance from the front vertex to the front focal point

F2
Back Focal Point: Common focal point of all rays A parallel to optical axis and travelling from left to right.

V2
Back Vertex: Intersection of the last surface with the optical axis.

S2
Second Principal Surface: A surface defined by the intersection of rays A with the outgoing rays focusing at F2.

H2
Second Principal Point: Intersection of the second principal surface with the optical axis.

BFD
Back Focal Distance: The distance from the back vertex to the back focal point.

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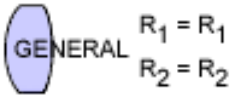
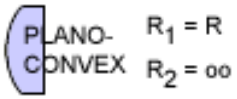
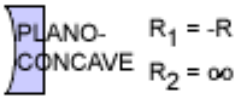
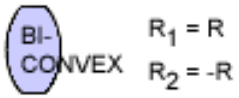
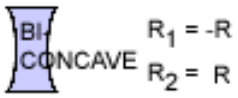
Thick Lens

TYPE ORIENTATION	Focal Length f	BFD	FFD
 GENERAL $R_1 = R_1$, $R_2 = R_2$	$\left[(n-1)\bullet\left(\frac{1}{R_1}-\frac{1}{R_2}\right)+\frac{t_c(n-1)^2}{nR_1R_2}\right]^{-1}$	$f\bullet\left[1-\frac{t_c(n-1)}{nR_1}\right]$	$f\bullet\left[1+\frac{t_c(n-1)}{nR_2}\right]$
 PLANO-CONVEX $R_1 = R$, $R_2 = \infty$	$\frac{R}{n-1}$	$f\bullet\left[1-\frac{t_c(n-1)}{nR_1}\right]$	f=infinity
 PLANO-CONCAVE $R_1 = -R$, $R_2 = \infty$	$\frac{-R}{n-1}$	$f\bullet\left[1+\frac{t_c(n-1)}{nR_2}\right]$	f= infinity
 BI-CONVEX $R_1 = R$, $R_2 = -R$	$\left[\frac{2(n-1)}{R}-\frac{t_c(n-1)^2}{nR^2}\right]^{-1}$	$f\bullet\left[1-\frac{t_c(n-1)}{nR_1}\right]$	$f\bullet\left[1-\frac{t_c(n-1)}{nR_1}\right]$
 BI-CONCAVE $R_1 = -R$, $R_2 = R$	$-\left[\frac{2(n-1)}{R}-\frac{t_c(n-1)^2}{nR^2}\right]^{-1}$	$f\bullet\left[1+\frac{t_c(n-1)}{nR_2}\right]$	$f\bullet\left[1+\frac{t_c(n-1)}{nR_2}\right]$

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F-number and Numerical Aperture

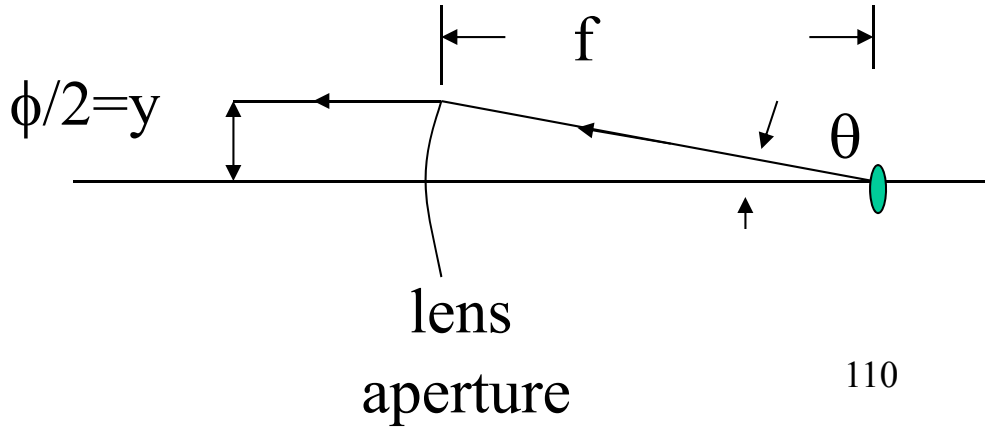
The f-number (focal ratio) is the ratio of the focal length f of the lens to its clear aperture ϕ (effective diameter). The f-number defines the angle of the cone of light leaving the lens which ultimately forms the image. This is important concept when the throughput or light-gathering power of an optical system is critical, such as when focusing light into a monochromator or projecting a high power image.):

$$\text{f-number} = f/\phi$$

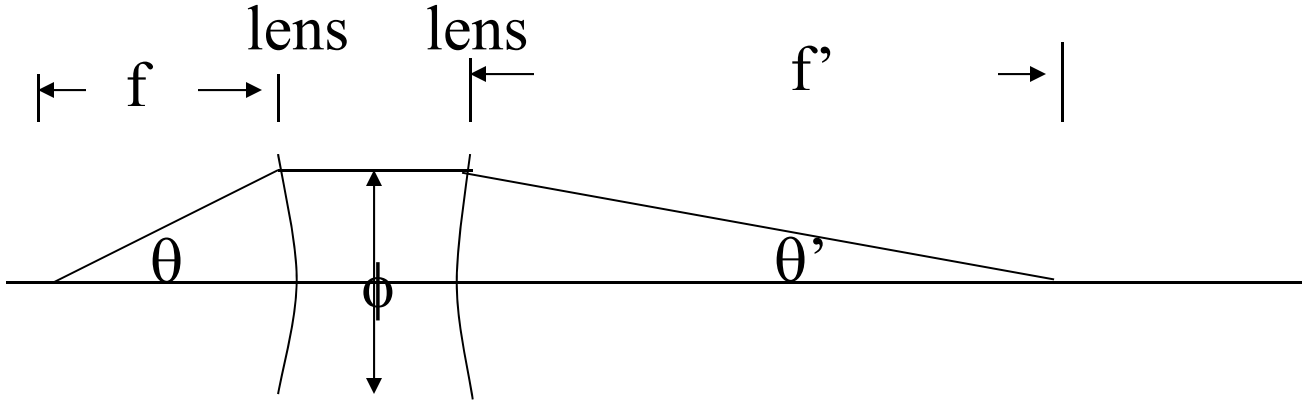
Numeric aperture is defined as sine of the angle made by the marginal ray with the optical axis:

$$NA = \sin\theta = \phi/(2f)$$

Acceptance angle



Numeric Aperture and Magnification



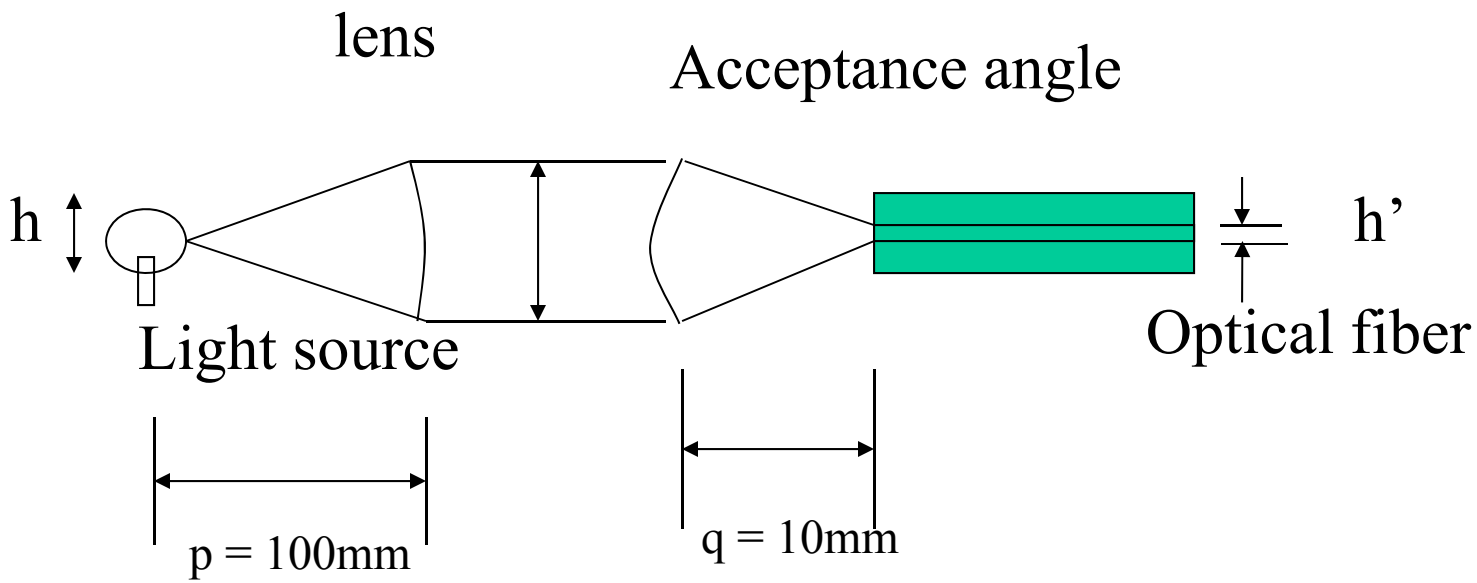
$NA = \sin\theta = \phi/2f$ $\qquad$ $NA' = \sin\theta' = \phi/2f'$

$2f \sin\theta = \phi$ $\qquad$ $2f' \sin\theta' = \phi$

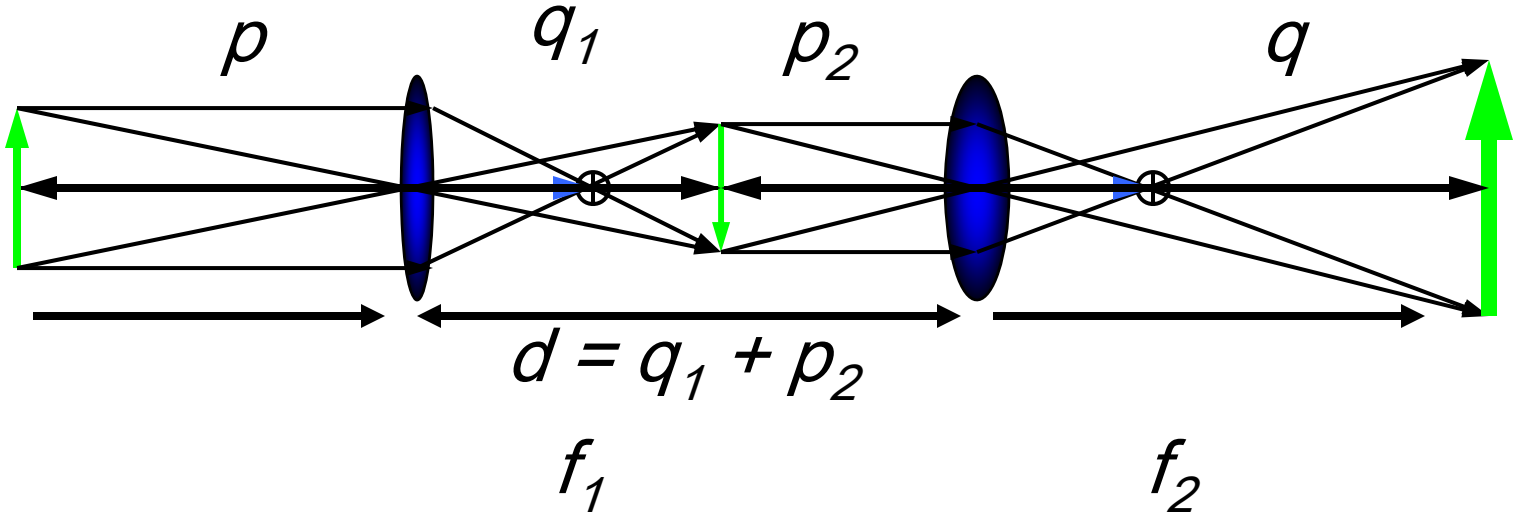
$$f'/f = \sin\theta/\sin\theta' = NA/NA' = m$$

Magnification is ratio of the numerical apertures on object and image sides. This result is Useful because it is completely independent of the specifics of optical system. Use in determining the lens diameter involving aperture constraints.

Coupling light into optical fiber

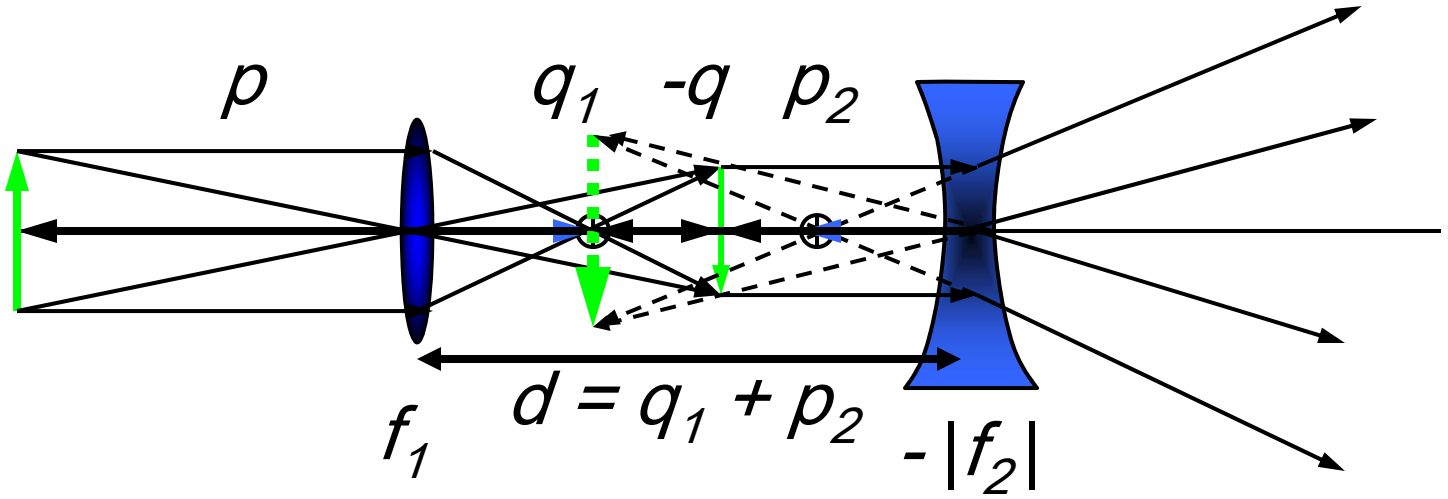


Combinations of Lenses



$$M = M_1 M_2 = (-q_1/p)(-q/p_2)$$

Combinations of Lenses



$$M = M_1 M_2 = (-q_1/p_1)(q/p_2)$$

Effective Focal Length

The expression for the combination focal length is the same whether lens separation distance (d), defined as the distance between the secondary principal point H_1" of the first (left-hand) lens and the primary principal point H_2 of the second (right-hand) lens, is large or small or whether the focal lengths f_1 and f_2 are positive or negative:

$$f = \frac{f_1 f_2}{f_1 + f_2 - d}$$

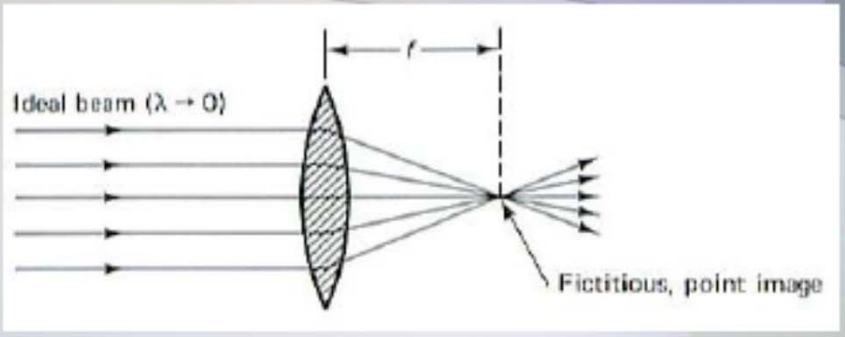
This may be more familiar in the form

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

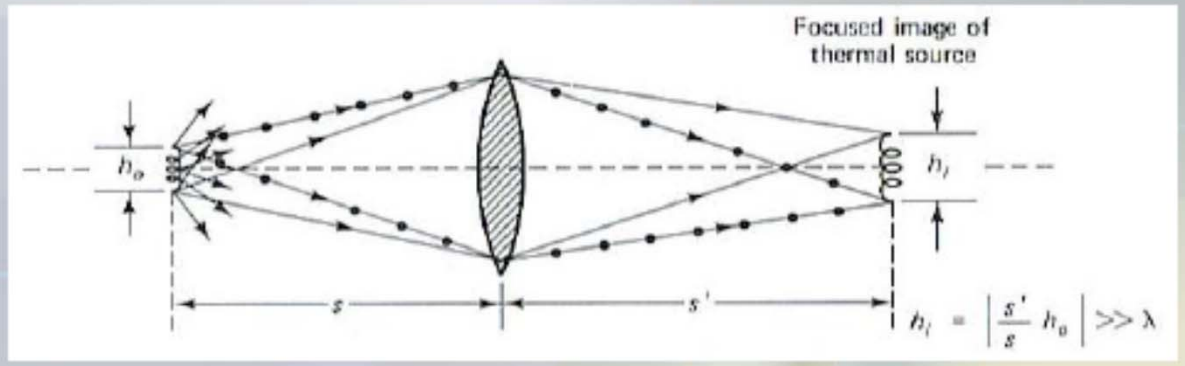
Notice that the formula is symmetric with the lenses (end-for-end rotation of the combination) at constant d.

Focusability of Light

Ideal situation



Focusing an incoherent light

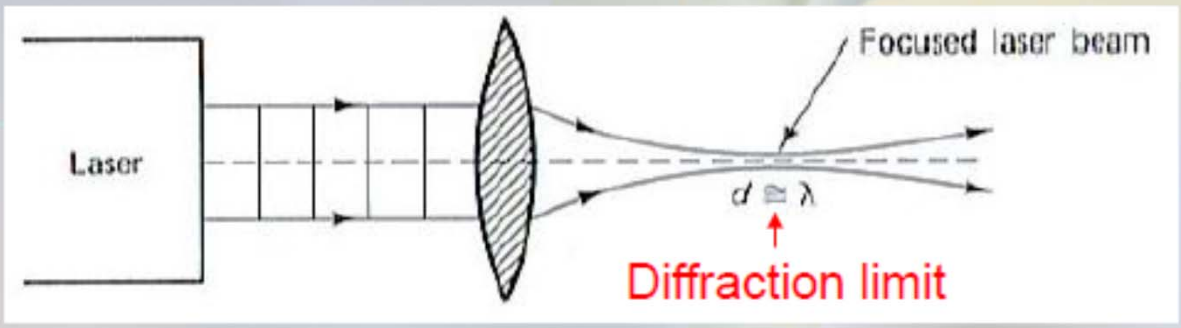


Focusing a laser light

$$\phi \sim 1.27\frac{\lambda}{d}$$

Reversibility $\rightarrow$

$$d \approx 1.27\frac{\lambda}{\phi} \geq \lambda, \text{ approximately}$$



Beam optics

- Diameter of focus spot: $2W_o^{'} = \frac{4}{\pi}\lambda(f/D);\ f/D = F\#$
- Depth of focus: $D_{im} = M^2(D_{ob})$
- Magnification: $M = \left|\frac{f}{p-f}\right|$

p = object length

Dim = depth of focus

Dob = depth of field

D = effective diameter = lens diameter

Beam spot size

$$\frac{W_s}{W_o} = \frac{\lambda R_o}{\pi W_o^2}$$

Where Ws = beam spot size at focus, Wo = beam spot size, L = operating wavelength, Ro = radius of curvature

Depth of Focus and Depth of Field (beam optics)

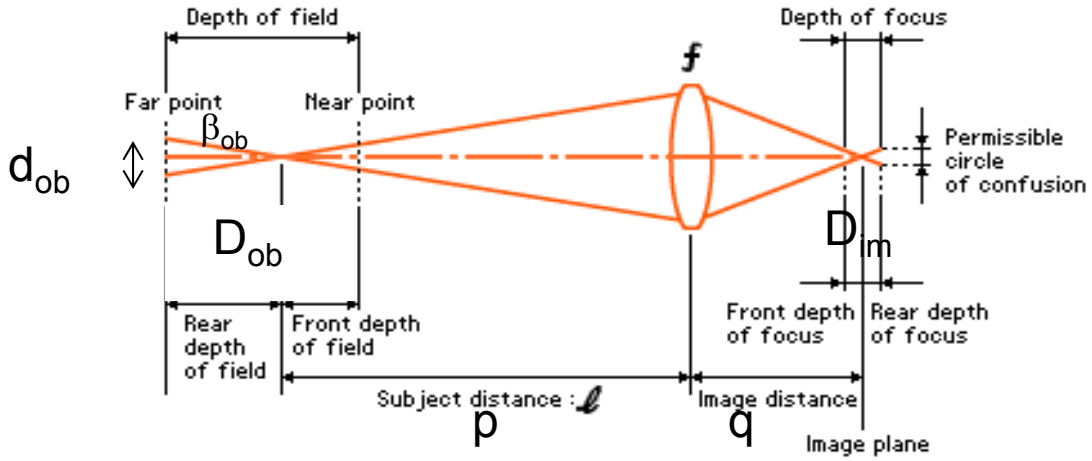
- The depth of focus, D_{im} is the extent of the region around the image plane in which the image will appear to be sharp. This depends on magnification, M.

$$D_{im} = \frac{d_{ob}}{\beta_{ob}} M^2$$

- The depth of field , D_{ob} is the range of distance along the optical axis in which the specimen can move without the image appearing to lose sharpness. This obviously depends on the resolution of the lens system.

$$D_{ob} = \frac{d_{ob}}{\beta_{ob}}$$

- Both depth of field and depth of focus are strongly dependent on changes in aperture (hence the semi-angle $\beta=\theta/2$) and working distance (d_{ob}).

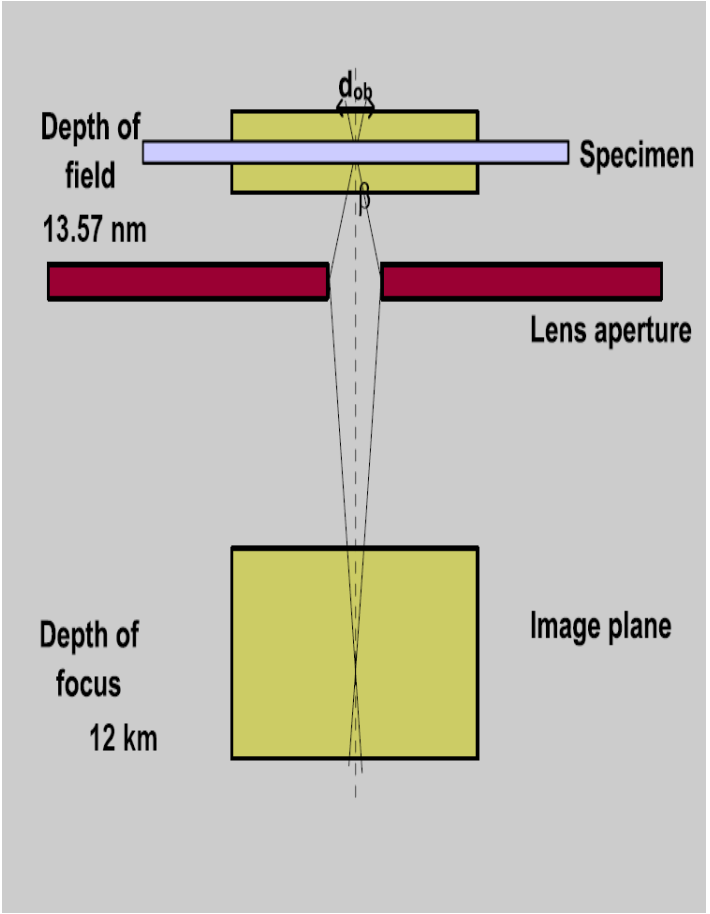


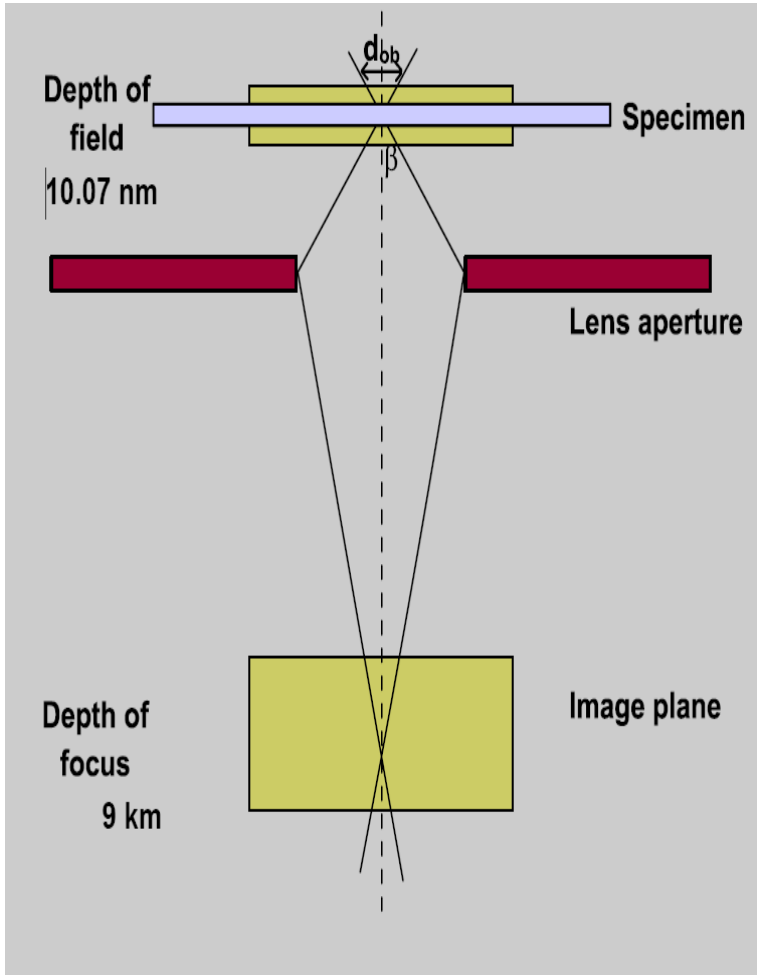
W.Wang

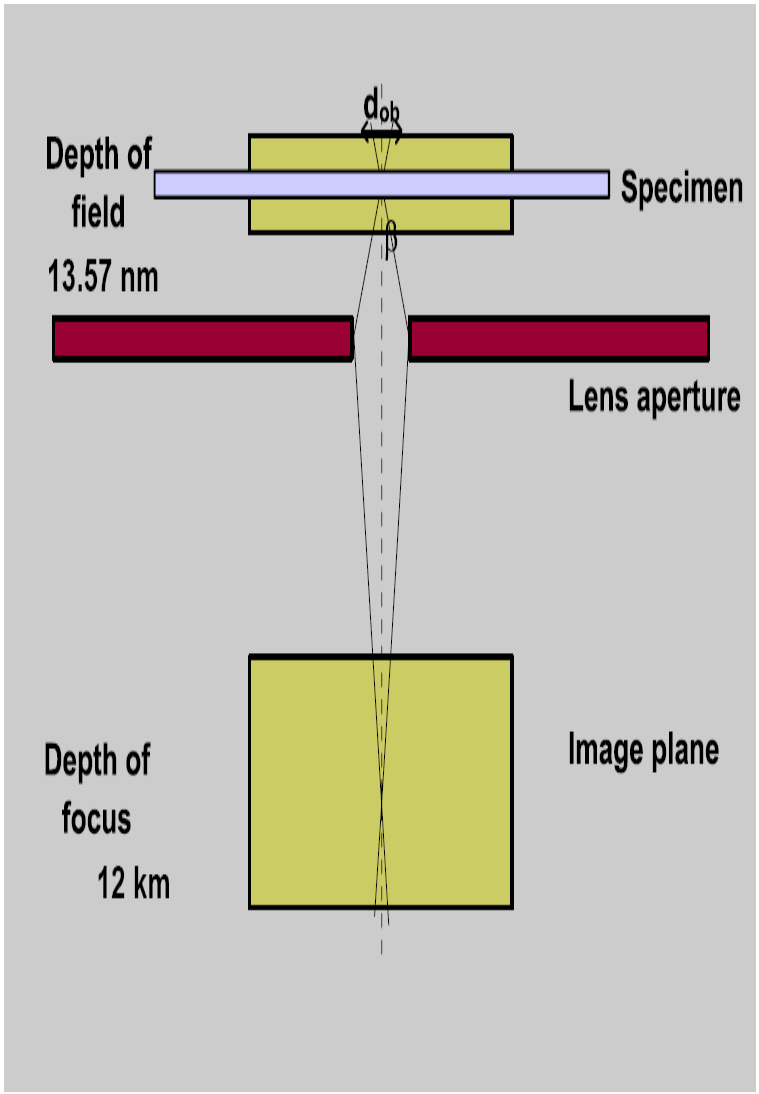
- What is the depth of focus at a magnification of ×20000 for a microscope with $\beta = 1$degree, $d_{ob} = 1$ mm?

http://www.matter.org.uk/tem/depth_of_field.htm#

(simulation software)

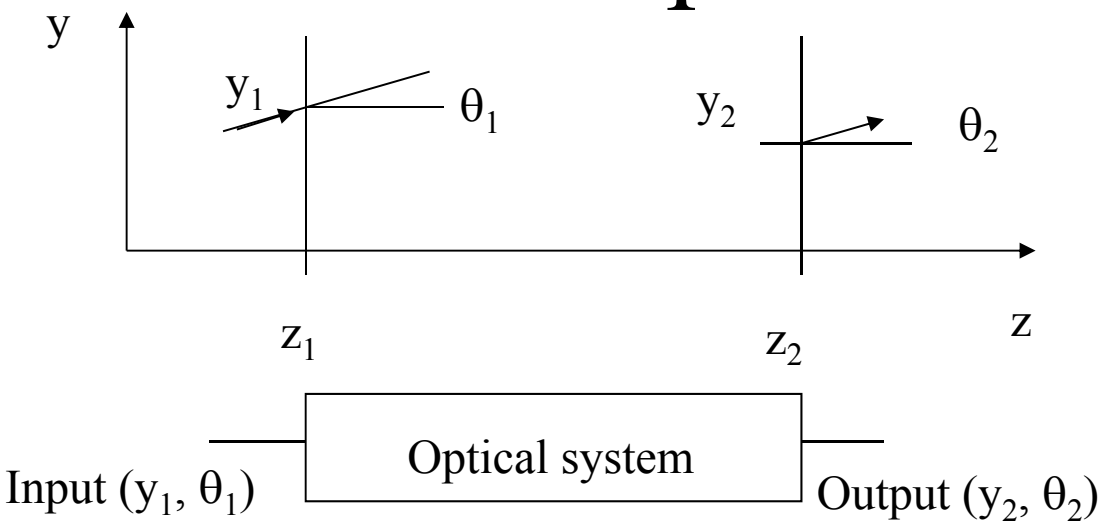



Depth of
field
10.07 nm
d_{ob}
β
Specimen
Lens aperture
Depth of
focus
9 km
Image plane


Depth of
field
13.57 nm
d_{ob}
β
Specimen
Lens aperture
Depth of
focus
12 km
Image plane

W.Wang

Matrix Optics



Matrix optics is a technique for tracing paraxial rays. The rays are assumed to travel only within a single plane (as shown in yz plane)

-A ray is described by its position y and its angle θ with respect to the optical axis. These variables are altered as the ray travels through the optical system, where The system can be represent by a transfer function like matrix to represent the relation between (y_2, θ_2) and (y_1, θ_1) as,

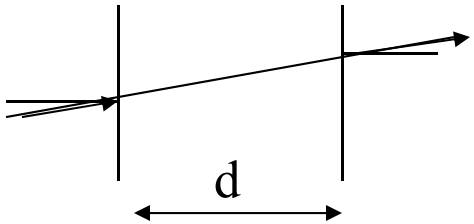
$$\begin{bmatrix} y_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix}$$

M

Where A,B,C,D are elements characterizes the optical system

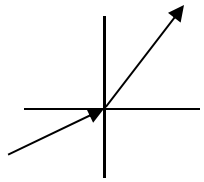
Matrices of Simple Optical Components

Free-space propagation



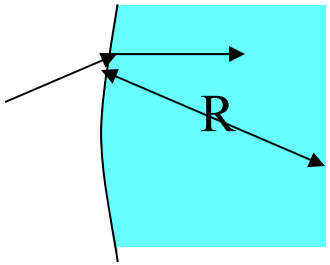
$$M = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$$

Refraction at a planar boundary



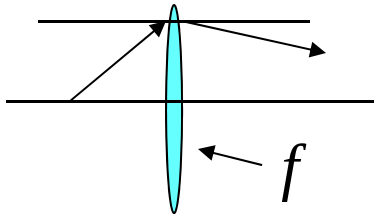
$$M = \begin{bmatrix} 1 & 0 \\ 0 & \dfrac{n_1}{n_2} \end{bmatrix}$$

Refraction at a spherical boundary



$$M = \begin{bmatrix} 1 & 0 \\ \dfrac{-(n_2 - n_1)}{n_2 R} & \dfrac{n_1}{n_2} \end{bmatrix}$$

Transmission through a thin lens

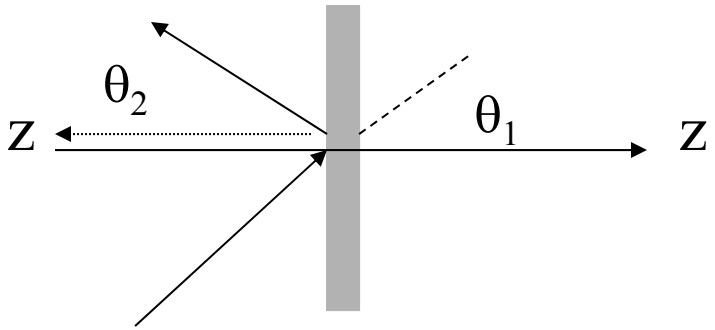


Convex f > 0
Concave f < 0

$$M = \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f} & 1 \end{bmatrix}$$

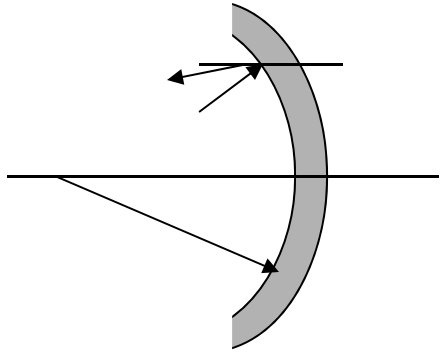
Matrices of Simple Optical Components

Reflection from a planar mirror



$$M = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Reflection from a spherical mirror



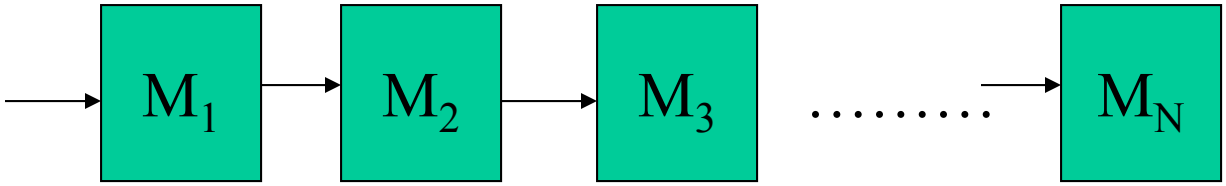
Concave R<0

Convex R>0

$$M = \begin{bmatrix} 1 & 0 \\ \frac{2}{R} & 1 \end{bmatrix}$$

Work only for simple refraction and reflection

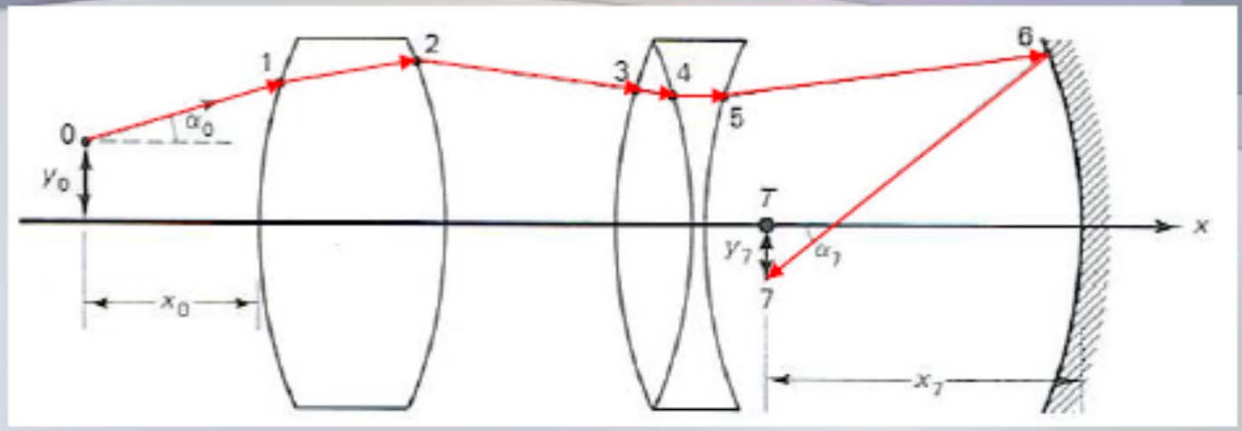
Cascaded Matrices

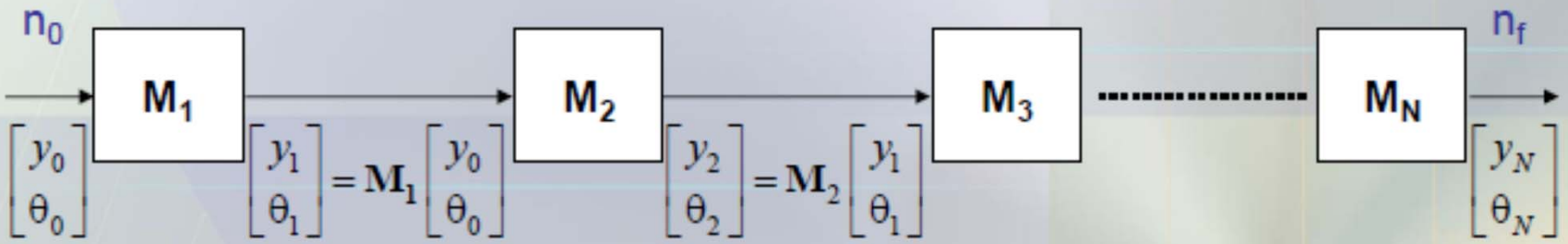


$$M = M_N \bullet \bullet \bullet \bullet M_2 M_1$$

Show opticlab and oslo software

Matrices of Cascaded Optical Components





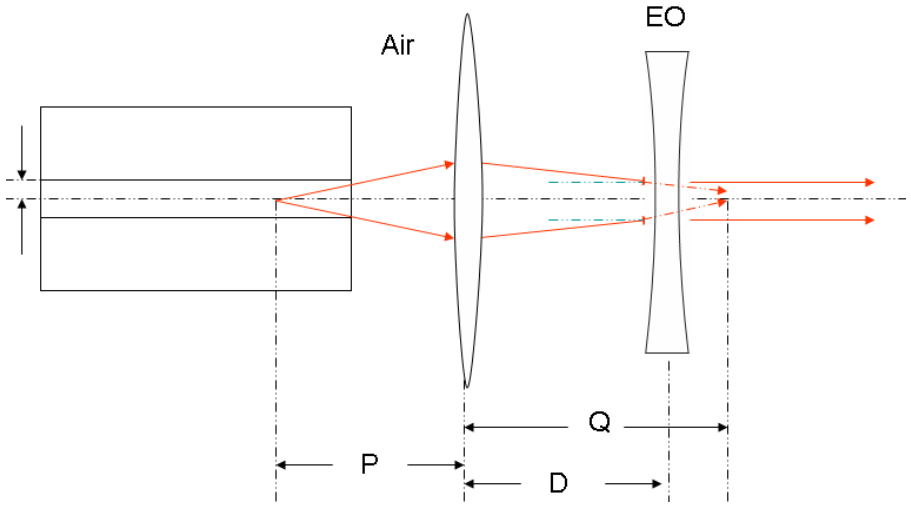
$$\begin{bmatrix} y_N \\ \theta_N \end{bmatrix} = \mathbf{M} \begin{bmatrix} y_0 \\ \theta_0 \end{bmatrix} \qquad \mathbf{M} = \mathbf{M}_N \cdots \mathbf{M}_2 \mathbf{M}_1 = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

Works particularly well with computer programming

A useful tip: $\text{Det}\,\mathbf{M} = AD - BC = \dfrac{n_o}{n_f}$

Example of Collimator

Figure 13, 2-D path of light via Convex-Concave lens combination



Assuming both of the lenses are thin lenses, the govern equations for this collimator are:

$$\frac{1}{P}+\frac{1}{Q}=\frac{1}{f_1}=(n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right) \quad \langle R_1{:}+\ R_2{:}\ - \rangle$$

$$Q-D=f_2=\frac{1}{(n-1)\left(\frac{1}{R_3}-\frac{1}{R_4}\right)} \quad \langle R_3{:}-\ R_4{:}\ + \rangle$$

There are two more design rules to follow:

1. **H/2>Rcone** , where H the height of the lens, Rcone the radius of the diverged beam
2. **H/W is relatively big to qualify thin lens,** where H the height of the lens, w is the thickness of the lens

Then, by defining the P , D and one of the focal lenghth(or radius), the other focal length will be determined.

Another approach to address the problem is by using ray-transfer matrics. The detail was addressed as following:

W.Wang

$$M = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_2} & 1 \end{pmatrix} * \begin{pmatrix} 1 & d_2 \\ 0 & 1 \end{pmatrix} * \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{pmatrix} * \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & d_2 \\ -\frac{1}{f_2} & 1-\frac{d_2}{f_2} \end{pmatrix} * \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{pmatrix} * \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 1-\frac{d_2}{f_1} & d_2 \\ -\frac{1}{f_2}-\frac{1}{f_1}(1-\frac{d_2}{f_2}) & 1-\frac{d_2}{f_2} \end{pmatrix} * \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 1-\frac{d_2}{f_1} & d_2 + d_1(1-\frac{d_2}{f_1}) \\ -\frac{1}{f_2}-\frac{1}{f_1}(1-\frac{d_2}{f_2}) & 1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2}) \end{pmatrix}$$

$$\begin{bmatrix} y_2 \\ \theta_2 \end{bmatrix} = M * \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix} = \begin{pmatrix} 1-\frac{d_2}{f_1} & d_2 + d_1(1-\frac{d_2}{f_1}) \\ -\frac{1}{f_2}-\frac{1}{f_1}(1-\frac{d_2}{f_2}) & 1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2}) \end{pmatrix} * \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix}$$

$$= \begin{bmatrix} (1-\frac{d_2}{f_1}) * y_1 + (d_2 + d_1(1-\frac{d_2}{f_1}))\theta_1 \\ (-\frac{1}{f_2}-\frac{1}{f_1}(1-\frac{d_2}{f_2}))y_1 + \theta_1(1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2})) \end{bmatrix}$$

W.Wang

To be collimated beam, θ2 must equal 0 for any input angle θ1, which means:
Let y1=0

$$\theta_1(1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2})=0$$

$$\Rightarrow 1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2})=0$$

$$\Rightarrow f_1 f_2 - f_1 d_2 - f_1 d_1 - f_2 d_1 + d_1 d_2 = 0$$

$$f = \frac{1}{(n-1)(\frac{1}{R_1}-\frac{1}{R_2})}$$

Lenses and Mirrors

Summary:

- *Lateral Magnification* $M = h'/h = -q/p$
- *Mirror Equation:*

$$1/p + 1/q = 2/R = 1/f$$

- *The object-image relation for a curved surface:*

$$n_1/p + n_2/q = [n_1 - n_2]/R$$

- *Len's Maker equation:*

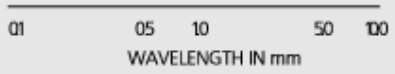
$$1/f = (n-1)(1/R_1 - 1/R_2)$$

- *Thin Lens Equation:*

$$1/p + 1/q = 1/f$$

Lens Materials

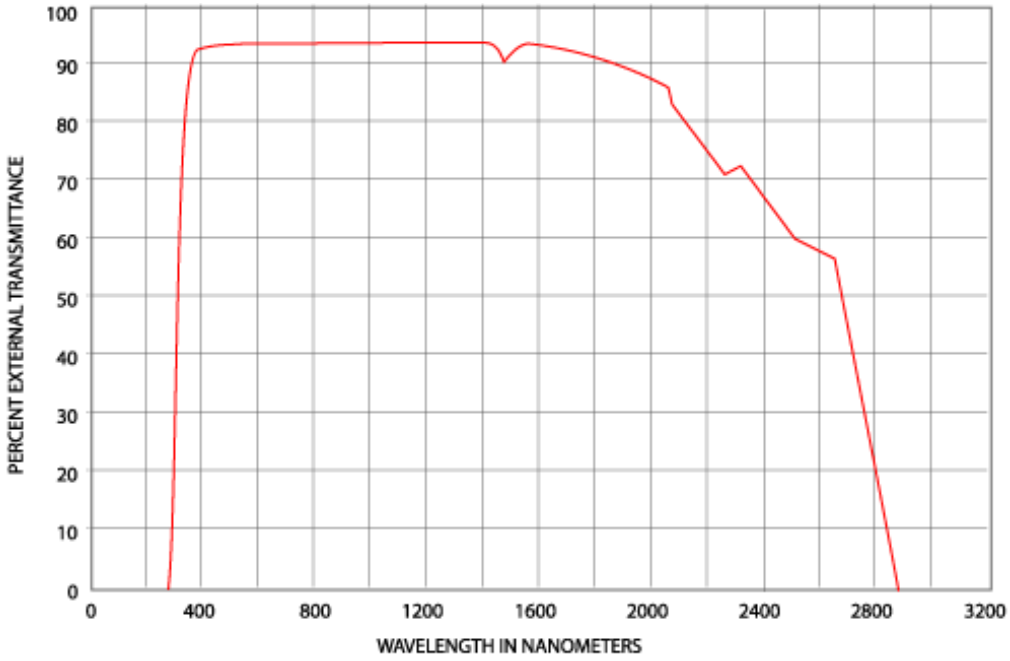
Material	Usable Transmission Range	Index of Refraction	Features
BK7	BK7	1.52 @ 0.55 μm	Excellent all-around lens material with broad transmission and excellent mechanical properties
LaSFN9	LaSFN9	1.86 @ 0.55 μm	High-refractive-index flint glass provides more power with less curvature
SF11	SF11	1.79 @ 0.55 μm	High-refractive-index flint glass provides more power with less curvature
F2	F2	1.62 @ 0.55 μm	A good compromise between higher index and acceptable mechanical properties
BaK1	BaK1	1.57 @ 0.55 μm	Excellent all-around lens material, but has weaker chemical characteristics than BK7
Optical-Quality Synthetic Fused Silica (OQSFS)	OQSFS	1.46 @ 0.55 μm	Material provides good UV transmission and superior mechanical performance
UV-Grade Synthetic Fused Silica (UVGSFS)	UVGSFS	1.46 @ 0.55 μm	Material provides excellent UV transmission and superior mechanical performance
Optical Crown Glass	OPTICAL CROWN	1.52 @ 0.55 μm	Lower tolerance glass for mirror substrates and noncritical applications
Low-expansion borosilicate glass (LEBG)	LEBG	1.48 @ 0.55 μm	Excellent thermal stability, homogeneity, and low cost. Ideal for high-temperature windows, mirror substrates, and condenser lenses
Sapphire	SAPPHIRE	1.77 @ 0.55 μm	Excellent mechanical and thermal characteristics. Ideal material for optical windows.
Calcium Fluoride	CALCIUM FLUORIDE	1.399 @ 5 μm	This popular UV excimer laser material is used for windows, lenses, and mirror substrates



BK7 Glass

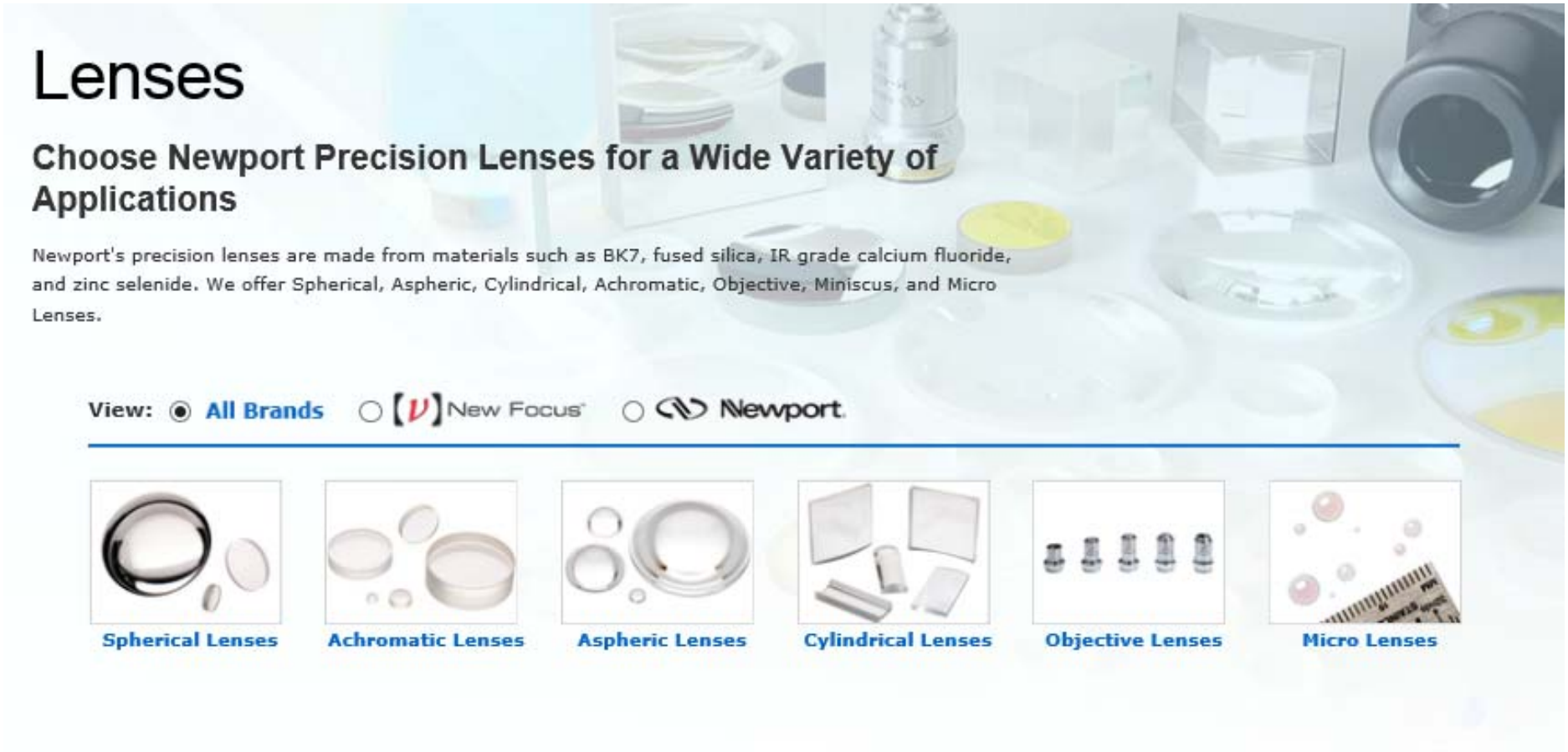
Abbé Constant: 64.17
Density:2.51 g/cm^{-3}
Young's Modulus: 8.20 x 10^9 dynes/mm^2
Poisson's Ratio: 0.206
Coefficient of Thermal Expansion (-30° to +70°C): 7.1 x 10^{-6}/°C
Coefficient of Thermal Expansion (20° to 3000°C): 8.3 x 10^{-6}/°C
Stress Birefringence, (Yellow Light): 10 nm/cm
Homogeneity within Melt: ±1x10^{-4}
Striae Grade (MIL-G-174-A): A
Transformation Temperature: 557°C
Climate Resistance: 2
Stain Resistance: 0
Acid Resistance: 1.0
Alkali Resistance: 2.0
Phosphate Resistance: 2.3
Knoop Hardness: 610
Dispersion Constants:

B_1 = 1.03961212
B_2 = 2.31792344x10^{-1}
B_3 = 1.01046945
C_1 = 6.00069867x10^{-3}
C_2 = 2.00179144x10^{-2}
C_3 = 1.03560653x10^2

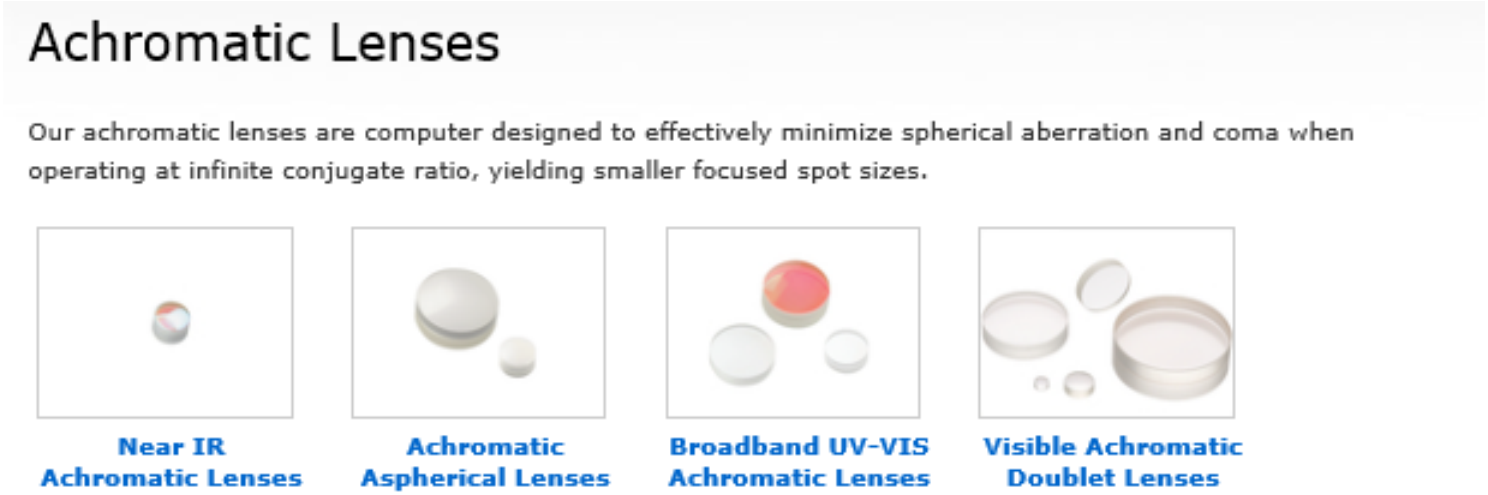


External transmission for 10-mm-thick BK7 glass

Optical Lenses



Achromatic Lens

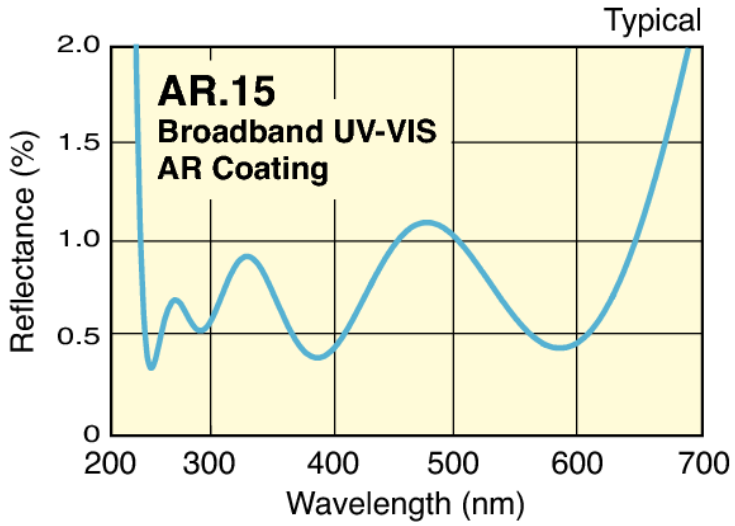


Achromatic Lenses are used to minimize or eliminate chromatic aberration. The achromatic design also helps minimize spherical aberrations. Achromatic Lenses are ideal for a range of applications, including fluorescence microscopy, image relay, inspection, or spectroscopy. An Achromatic Lens, which is often designed by either cementing two elements together or mounting the two elements in a housing, creates smaller spot sizes than comparable singlet lenses.

Example of Achromatic Lens

Newport Broadband Achromatic Lenses, 12.50 mm, 40.00 mm EFL, 360 nm to 700 nm

Model	PAC12AR.15
Lens Shape	Plano-Convex
Antireflection Coating	345-700 nm
Lens Material	N-FK5 & F2
Diameter	0.49 in. (12.5 mm)
Effective Focal Length	40.0 mm
Surface Quality	40-20 scratch-dig
Center Thickness	5.5 mm
T_e	4.30 mm
Lens Type	Achromatic Doublet
BFL	37.61 mm
f/#	3.2
R	24.47 mm
R_2	-19.17 mm
R_3	-50.19 mm
Clear Aperture	11.50 mm
Chamfers	0.25 mm
Chamfers Angle/Tolerance	45°
Center Thickness (T_c) Tolerance	± 0.1 mm
Edge Thickness (T_e) Tolerance	Reference
Focal length tolerance	±2%
Coating Code	AR.15
T_{c1}	3.50 mm
T_{c2}	2.00 mm



Achromatic Lenses

Achromatic Lenses

TECHSPEC®
Achromatic Lens Kits

TECHSPEC®
Aspherized Achromatic Lenses

TECHSPEC®
Broadband AR Coated Negative Achromatic Lenses

TECHSPEC®
C-Mount Achromatic Pairs

TECHSPEC®
Germanium Infrared (IR) Hybrid Aspheric Lenses

TECHSPEC®
Hastings Triplet Achromatic Lenses

TECHSPEC®
Infrared (IR) Achromatic Lenses

TECHSPEC®
Large Precision Achromatic Lenses

TECHSPEC®
NEW MgF_2 Coated Achromatic Lenses

TECHSPEC®
MgF_2 Coated Negative Achromatic Lenses

TECHSPEC®
Mounted Achromatic Lens Pairs

TECHSPEC®
Mounted Achromatic Lens Pairs Kits

TECHSPEC®
Mounted Near-IR (NIR) Achromatic Lens Pairs

TECHSPEC®
Near-IR (NIR) Achromatic Lenses

TECHSPEC®
Near-UV (NUV) Achromatic Lenses

Plastic Hybrid Acylinder Lenses

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Plastic Hybrid Aspheric Lenses

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TECHSPEC®
NEW Steinheil Triplet Achromatic Lenses

TECHSPEC®
UV-to-NIR Corrected Triplet Lenses

TECHSPEC®
VIS 0° Coated Achromatic Lenses

TECHSPEC®
NEW VIS-NIR Coated Achromatic Lenses

TECHSPEC®
NEW YAG-BBAR Coated Achromatic Lenses

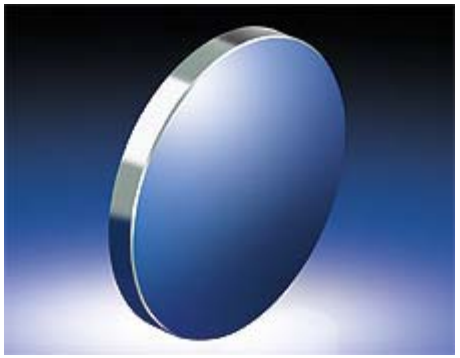
Aspherical Lens

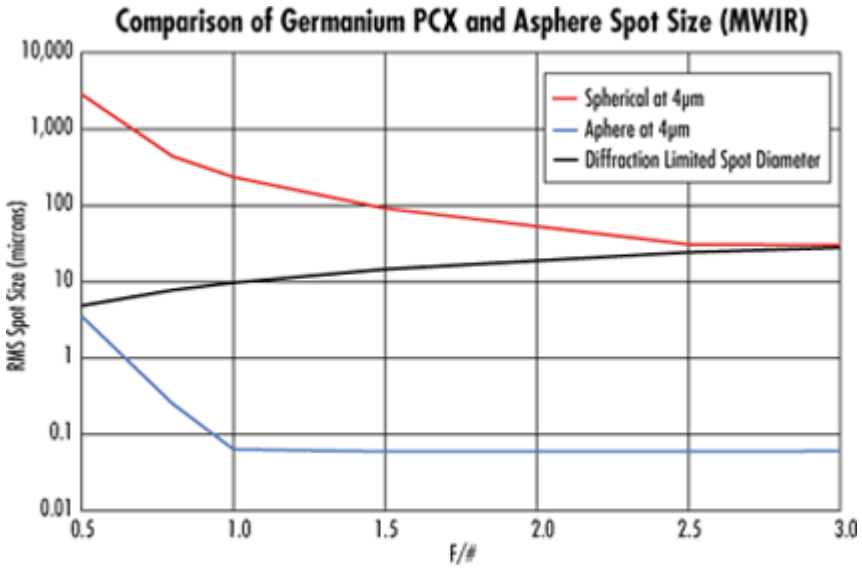
Aspheric Lenses are used to eliminate spherical aberration in a range of applications, including bar code scanners, laser diode collimation, or OEM or R&D integration. Aspheric lenses utilize a single element design which helps minimize the number of lenses found in multi-lens optical assemblies. Said another way, unlike conventional lenses with a spherical front surface, aspheric lenses have a more complex front surface that gradually changes in curvature from the center of the lens out of the edge of the lens. This reduction in total element count not only helps decrease system size or weight, but also simplifies the assembly process. Integrating aspheres into an application such as focusing the output of a laser diode may not only decrease total cost, but may also outperform assemblies designed with traditional spherical optical lenses.

Example of Aspheric Lens

Edmund Optics 25mm Dia x 12.5mm FL Uncoated, Ge Aspheric Lens

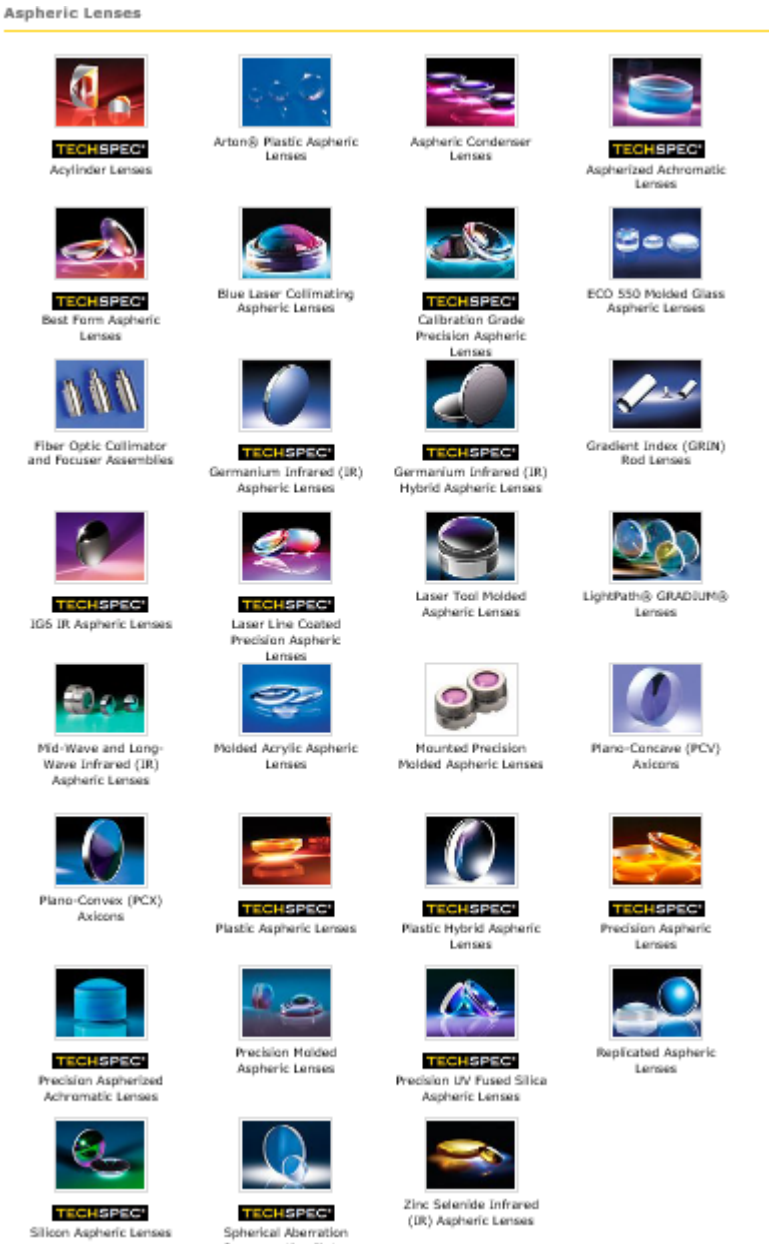
Type of Optics	DCX Lens
Diameter (mm)	25.0
Diameter Tolerance (mm)	+0.0/-0.1
Clear Aperture (%)	90
Effective Focal Length EFL (mm)	12.5
Numerical Aperture NA	1.00
Back Focal Length BFL (mm)	11.61
Center Thickness CT (mm)	4.24
Center Thickness Tolerance (mm)	±0.10
Surface Quality	60-40
Surface Accuracy, P-V (µm)	0.3
Centering (arcmin)	3 - 5
Edges	Diamond Turned
Coating	Uncoated
Focal Length Specification Wavelength (µm)	4
Substrate	Germanium (Ge)
f/#	0.5
Type	Aspheric Lens
Wavelength Range (µm)	2 - 14
Wavelength Range (nm)	2000 - 14000
RoHS	Compliant





W.Wang

Aspherical Lenses

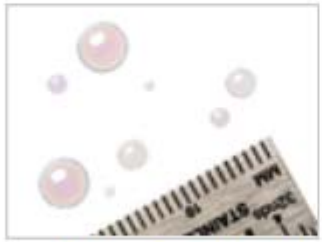


Micro Lenses

Micro Lenses

mico lenses are commonly used for laser collimating and focusing, laser-to-fiber coupling, fiber-to-fiber coupling, and fiber-to-detector coupling.

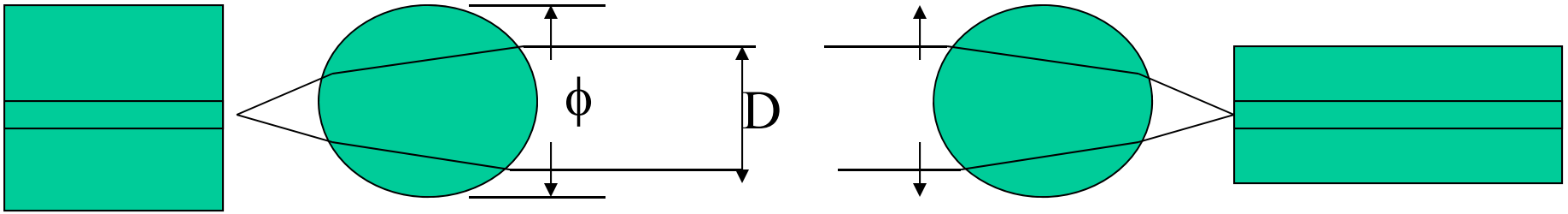
Gradient Index Micro Lenses



Spherical Ball Micro Lenses

Microlens Arrays

Micro Lens: Spherical ball lenses for fiber coupling



Spheres are arranged so that fiber end is located at the focal points. The output from the first sphere is then collimated. If two are Aligned axially to each other, the beam will be transferred from one focal point to another.

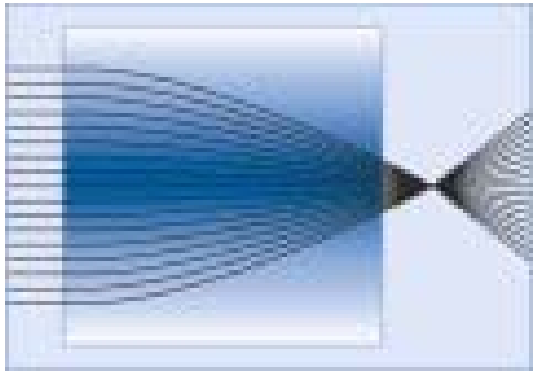
Example of Micro Lens

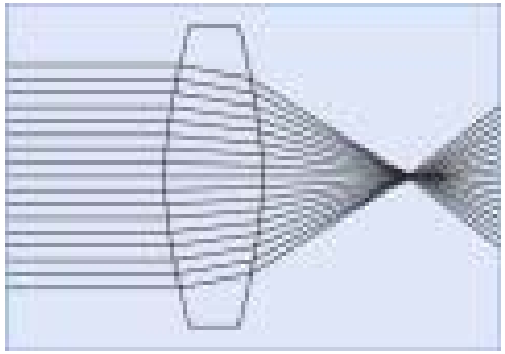
Newport Spherical Ball Micro Lens, 1.0 mm 0.55 mm FL, 0.05 mm WD, Uncoated

Model	LB1
Lens Shape	Ball
Diameter	0.04 in. (1.0 mm)
Lens Material	Grade A LaSF N9
Antireflection Coating	Uncoated
Effective Focal Length	0.55 mm
Working Distance	0.05 mm
Clear Aperture	0.8 mm
Diameter Tolerance	±1 μm

GRIN Lens

Gradient index micro lenses represent an innovative alternative to conventional spherical lenses since the lens performance depends on a continuous change of the refractive index within the lens material.





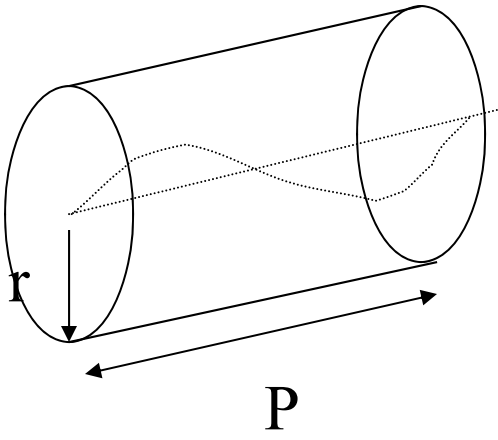
1. GRIN objective lenses with an angle of view of 60° are produced in standard diameters of 0.5, 1.0 und 1.8 mm. Typical object distances are between 5 mm and infinity.

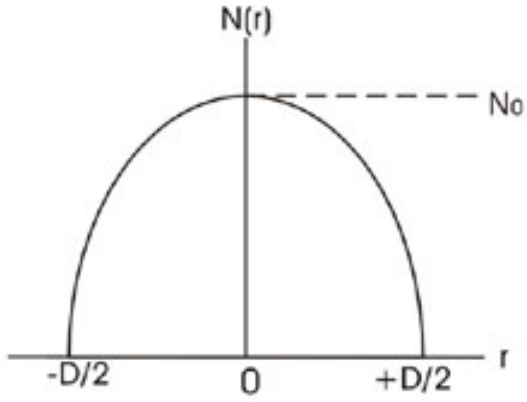
2. Instead of curved shaped surfaces only plane optical surfaces are used which facilitate assembly. The light rays are continuously bent within the lens until finally they are focused on a spot.

Why a GRIN ?

- Conventional designs
  - Conical elements
  - Aberrated lenses
  - Diffractive
- GRIN design
  - Well suited for small-diameter designs
  - Allows back-focal offset, unlike conical element
  - Simpler alignment than multiple lens solutions
  - Lower dispersion than diffractive axicon

GRIN Lenses





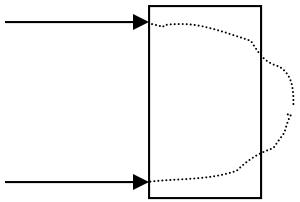
$n(r) = n_o(1-Ar^2/2)$

Where
n_0 -- Index of Refraction at the Center
r -- Diameter of Grin Lens
A -- Gradient Constant

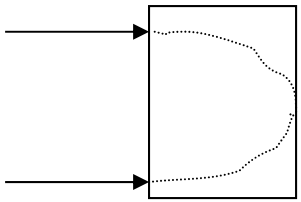
The quadratic n(r) results in a sinusoidal ray path

$P = 2\pi/A^{0.5}$

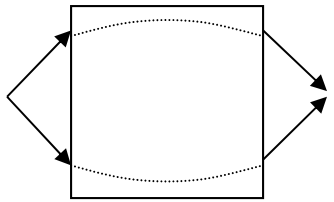
For length L = P/4 => quarter pitch lens
= P/2 => ½ pitch lens



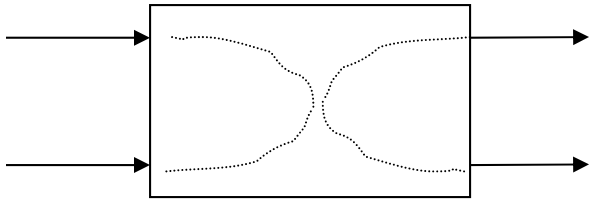
0.23P



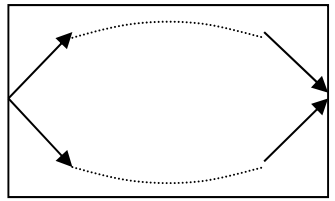
0.25P



0.29P

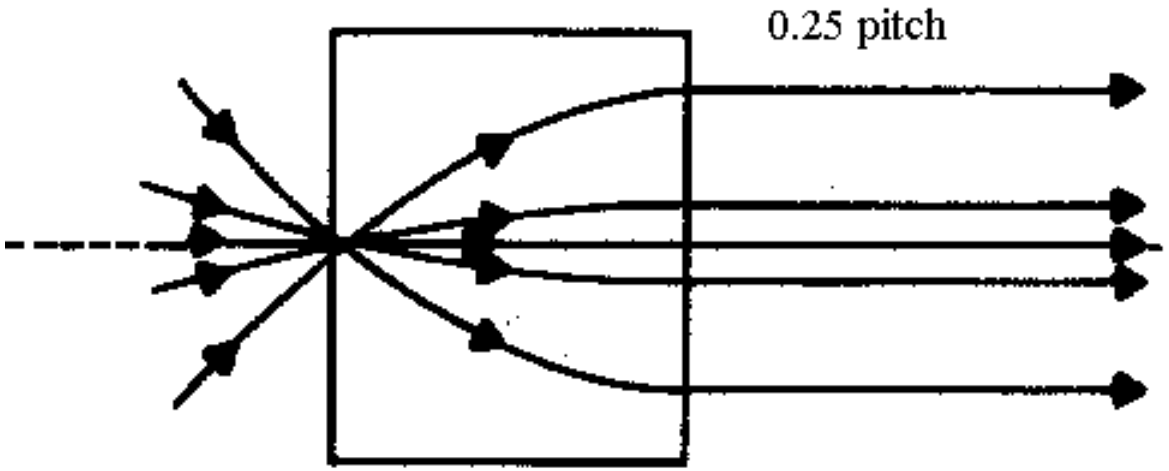


0.5P



0.5P

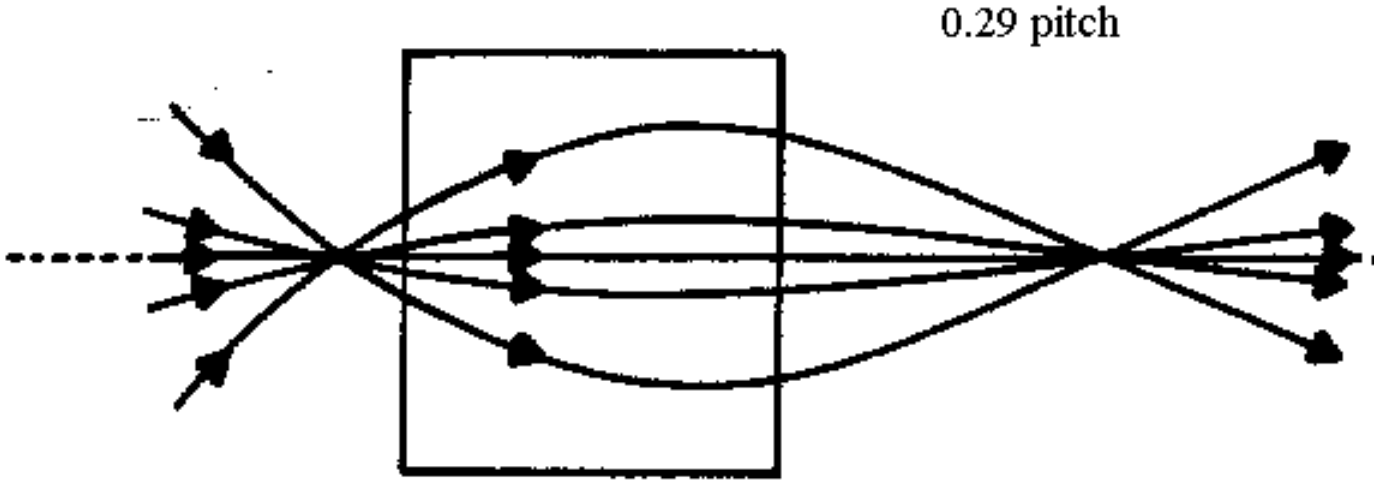
GRIN Lens



Light exiting a fiber can be collimated into a parallel beam when the output end of the fiber is connected to the GRIN lens. (0.25P)

GRIN Lens

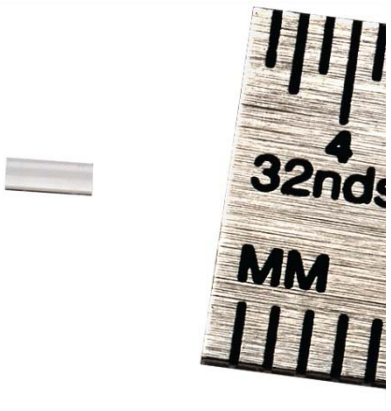
Focusing of the fiber output onto a small detector or focusing of the output of a source onto the core of a fiber can be accomplishing by increasing the length of the GRIN lens to 0.29 pitch. Then the source can be moved back from the lens and the transmitted light can be refocused at some point beyond the lens. Such an arrangement is useful for coupling sources to fibers and fibers to detectors.



Example of Grin Lens

NewPort Plano-Angled Gradient Index Micro Lens,1.8mm,.46 NA,1300nm,0.23 Pitch

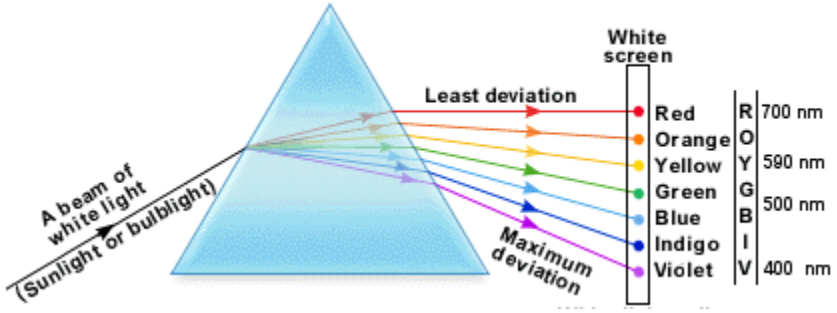
Model	LGI1300-1A
Lens Shape	Plano-Angled
Diameter	0.07 in. (1.8 mm)
Lens Material	SELFOC® radial gradient index oxide glass
Antireflection Coating	1300 nm
Working Distance	0.26 mm
Clear Aperture	Central 70% of diameter
Diameter Tolerance	+0.005/-0.010 mm

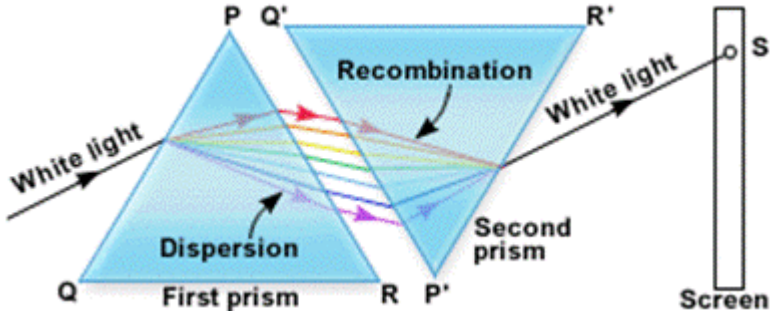


Prism

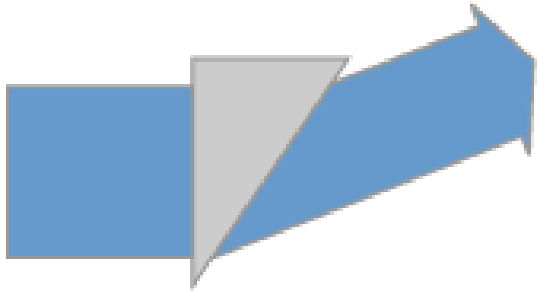
- Dispersing white light
- Deflect and steering light
- Beam expander and reducer
- Used in coupling light into integrated optical system
- Beam splitter and combiner

Dispersing White Light

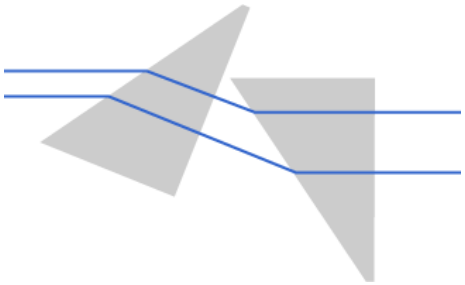




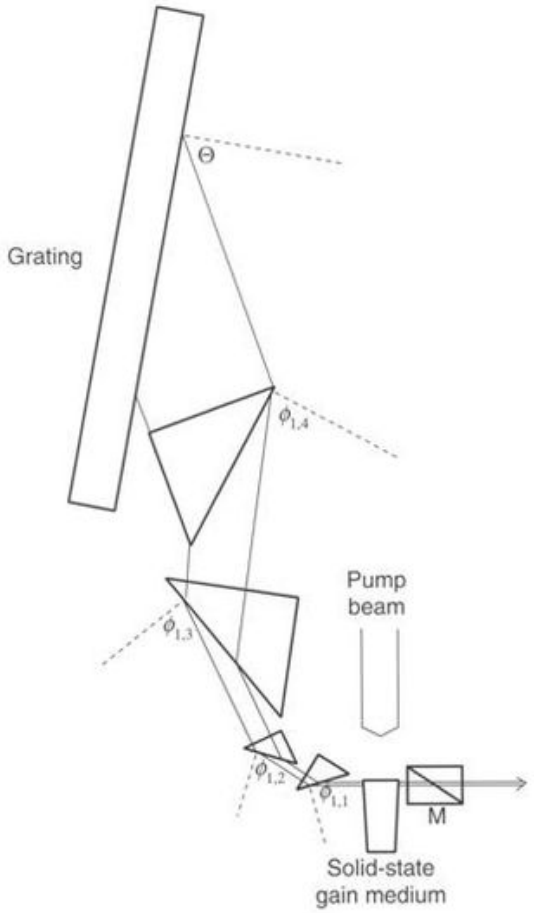
Beam Reduction and Expander



An anamorphic prism. The output beam is substantially narrower than the input beam



An anamorphic prism pair with refractive index of 1.5, where Brewster's angle is used on one side of each prism, and normal incidence on the other one. Two parallel beams passing through the prisms are shown. Their distance changes, and likewise their beam radii in the direction of the plane are changed. The prism pair thus works as a beam expander if the input beam comes from the left side. Of course, the beam radius in the direction perpendicular to the drawing plane is not changed.

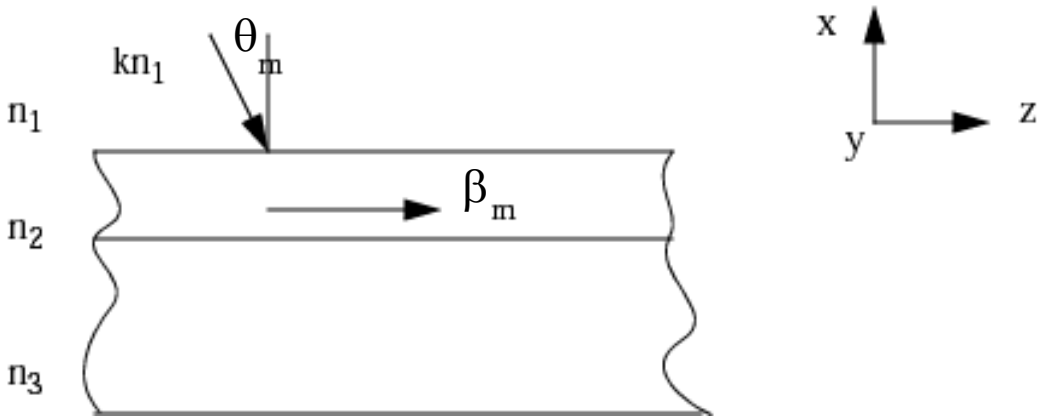


Long-pulse tunable laser oscillator utilizing a multiple-prism beam expander

Prism Coupler

One of the ways to coupl the ligh into the waveguide is to utilize a prism.

The prsim coupler allows light to be coupled at an oblique angle. For this to happen, the components of phase velocities of the waves in the z direction be the same in both the waveguide and the incident beam



Thus, a phase-matching condition must be satisfied in z direction, which requires

$$\beta_m = kn_1 \sin\theta_m = \frac{2\pi}{\lambda_o} n_1 \sin\theta_m$$

However, we know for a waveguided mode, $\beta_m > kn_1$, this leads to the result that $\sin\theta_m > 1$.

One solution to the problem of phase matching is to use a prism.

W.Wang

Prism Coupler

If prism spacing is small enough so that tail of waveguide modes overlap the tail of the prism mode, there is a coherent coupling of energy from prism mode to the mth waveguide mode when θ_m is choosen so trhat $\beta_p = \beta_m$ (phase matching condition based on E field is contious). The condition for matching of the β terms is given by

$$\beta_p = \frac{2\pi}{\lambda_o} n_p \sin\theta_m = \beta_m$$

a single prism can be used to couple to many different modes by merely changing the angle of incidence of the optical beam.

The modes in the waveguide are only weakly coupled to the mode in the prism. Hence, negligible perturbation of the basic mode shapes occurs. Of course, the condition

$$\theta_m > \theta_c = \text{asin}\ \frac{n_1}{n_p}$$

must be satisified if total internal reflection is to occur in the prsin, where θ_c is the critical angle.

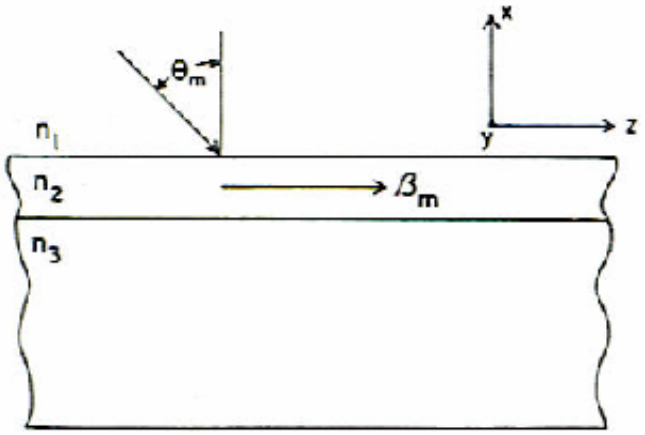


Fig. 7.6. Diagram of an attempt to obliquely couple light into a waveguide through its surface

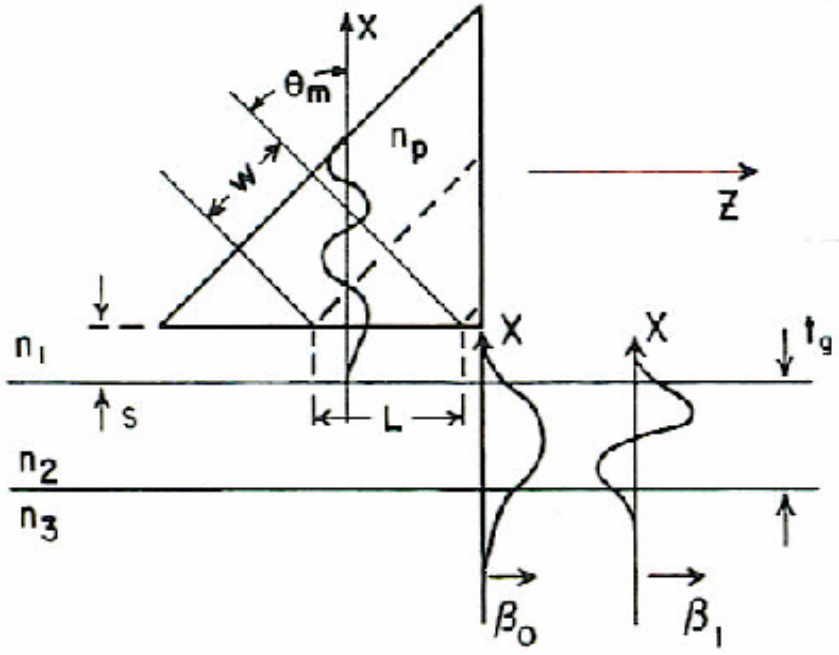
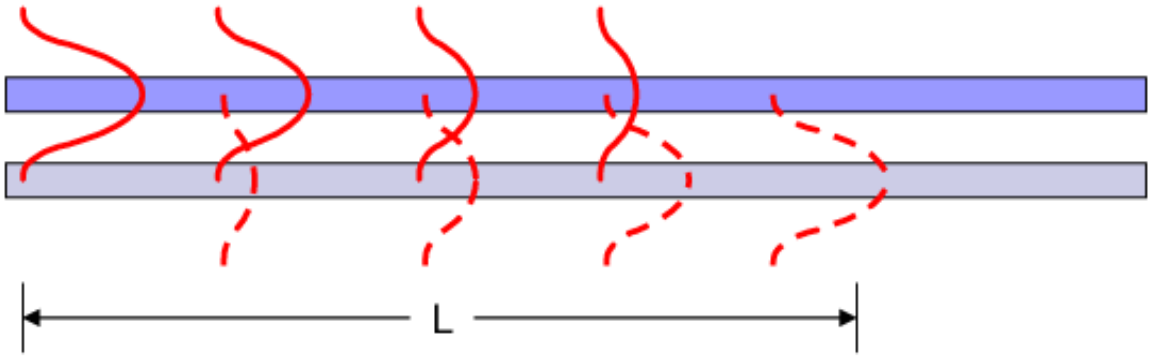


Fig. 7.7. Diagram of a prism coupler. The electric field distributions of the prism mode and the $m = 0$ and $m = 1$ waveguide modes in the x direction are shown

Coupled-Mode Theory



$$\kappa L = \frac{\pi}{2}$$

κ : Coupling efficient (overlap integral between the prism mode and the waveguide mode)

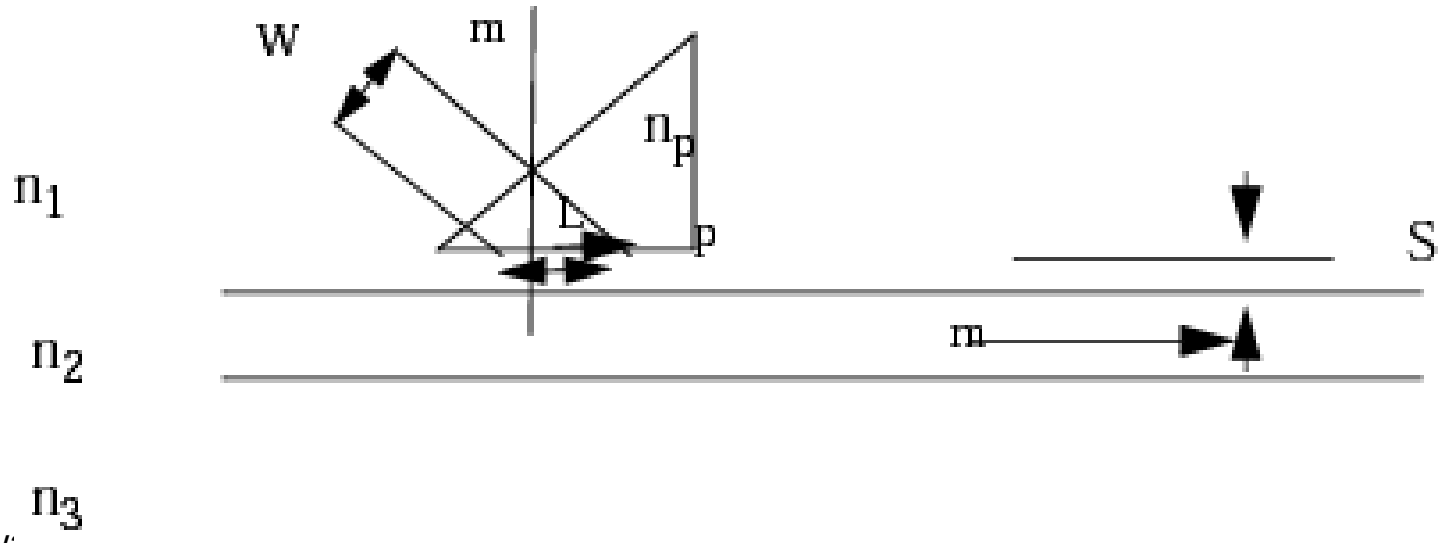
$$L = \frac{W}{\cos\theta_m} = \frac{\pi}{2\kappa}$$

For a given L, the coupling coefficient required for complete coupling:

$$\kappa = \frac{\pi \cos\theta_m}{2W}$$

w. war

This condition for complete coupling assumes that the amplitude of the electric field is uniform over the entire width W of the beam. In praticial case this is never true. Also the trailing edge of the beam must exactly inte5rsect the righ-angle corner of the prism. If the intersects too far to the right, some of the incident power will be either reflected or transmitted directly into the waveguide and will not enter the prism mode. If the beam is incident too far to the left, some of the power coupled into the waveguide will be coupled back out into the prsim.



Why prism coupler?

The advantage of prism coupler is that it can be use as an input and output coupling devices.

If more than one mode is propagating in the guide, light is coupled in and out at specific angles corresponding to each mode.

If a gas laser is used, the best method for coupling is using either prism or grating coupler

Disparage is is that mechanical pressure must be applied to prism during each measurement sot hat spacing between prism and waveguide remains constant to get consistent coupling coefficient.

Other disadvantage is prism coupler index must be greater than the waveguide.

Another disadvantage is that the incident beam must be highly collimated because of the angular dependence of the coupling efficiency on the lasing mode.

w. wang

For most semiconductor waveguides, $\beta_m \sim kn_2$ ->
Difficult to find prism materials

Table 7.1. Practical prism materials for beam couplers

Material	Approximate refractive index	Wavelength range
Strontium titanat	2.3	visible – near IR
Rutile	2.5	visible – near IR
Germaium	4.0	IR

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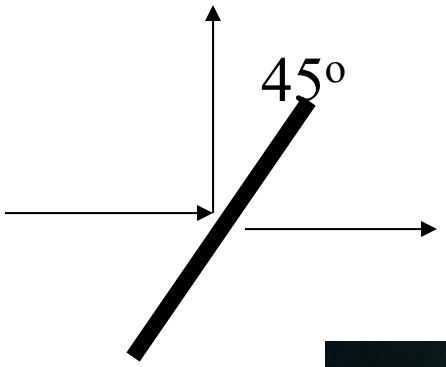
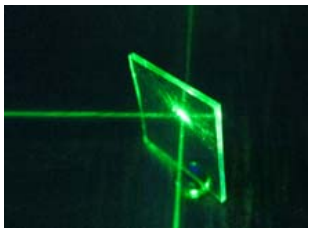
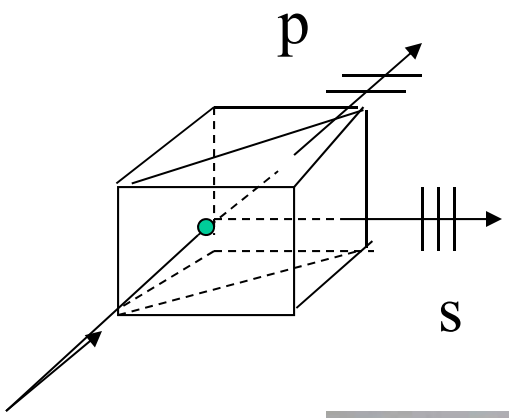
Beam Splitters





Aluminum coated beam splitter.

Reflective
Beam splitter
-Specific operating wavelength
-Split ratio
-45° incident angle
-Unsually unpolarized



Cube
Beam splitter
-Broadband
-Split ratio
-Polarized or
nonpolarized

Another design is the use of a half-silvered mirror. This is a plate of glass with a thin coating of aluminium (usually deposited from aluminium vapor) with the thickness of the aluminium coating such that part, typically half, of light incident at a 45-degree angle is transmitted, and the remainder reflected. Instead of a metallic coating, a dielectric optical coating may be used. Such mirrors are commonly used as output couplers in laser construction. A half-silvered mirror used in photography is often called a pellicle mirror. Depending on the coating that is being used, reflection/transmission ratios may differ in function of the wavelength.

A third version of the beam splitter is a dichroic mirrored prism assembly which uses dichroic optical coatings to divide an incoming light beam into a number of spectrally distinct output beams. Such a device was used in multi-tube color television cameras, in the three-film Technicolor movie cameras as well as modern, three-CCD cameras. It is also used in the 3 LCD projectors to separate colors and in ellipsoidal reflector spotlights to eliminate heat radiation. Beam splitters are also used in stereo photography to shoot stereo photos using a single shot with a non-stereo camera. The device attaches in place of the lens of the camera. Some argue that "image splitter" is a more proper name for this device. Beam splitters with single mode fiber for PON networks use the single mode behavior to split the beam. The splitter is done by physically splicing two fibers "together" as an X.

Beam Splitters

Examples of Cubic Beam Splitters

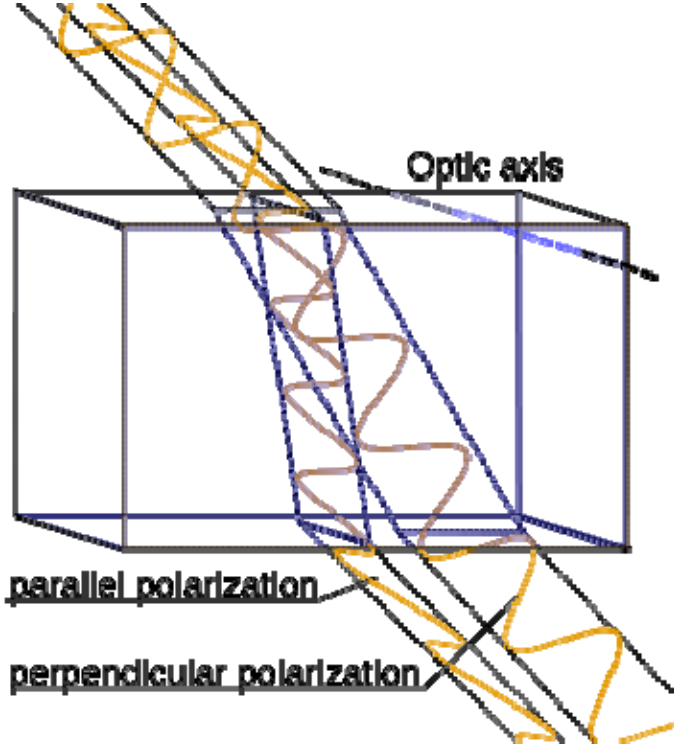
Birefringence

Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light.[1] These optically anisotropic materials are said to be birefringent (or birefractive). The birefringence is often quantified as the maximum difference between refractive indices exhibited by the material. Crystals with asymmetric crystal structures are often birefringent, as are plastics under mechanical stress.

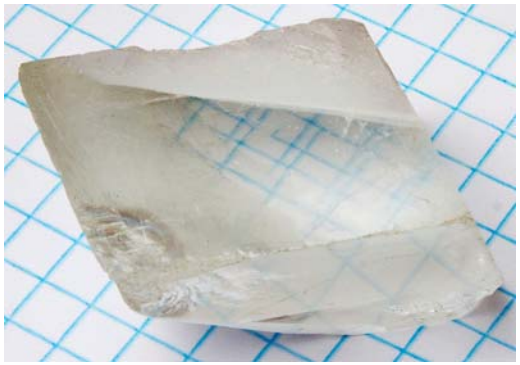
Birefringence is responsible for the phenomenon of double refraction whereby a ray of light, when incident upon a birefringent material, is split by polarization into two rays taking slightly different paths. This effect was first described by the Danish scientist Rasmus Bartholin in 1669, who observed it[2] in calcite, a crystal having one of the strongest birefringences. However it was not until the 19th century that Augustin-Jean Fresnel described the phenomenon in terms of polarization, understanding light as a wave with field components in transverse polarizations (perpendicular to the direction of the wave vector).

(wiipedia)

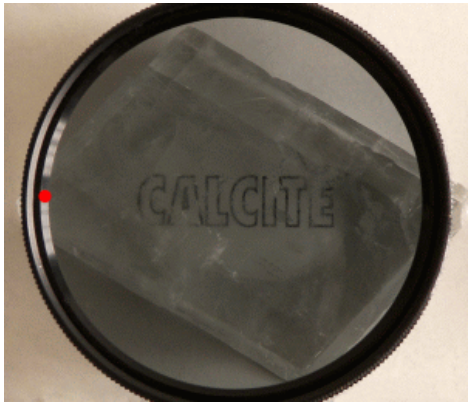
Birefringence



Incoming light in the parallel (s) polarization sees a different effective index of refraction than light in the perpendicular (p) polarization, and is thus refracted at a different angle.



A calcite crystal laid upon a graph paper with blue lines showing the double refraction



Doubly refracted image as seen through a calcite crystal, seen through a rotating polarizing filter illustrating the opposite polarization states of the two images

Uniaxial crystals, at 590 nm

Material	Crystal system	n_o	n_e	Δn
barium borate BaB_2O_4	Trigonal	1.6776	1.5534	-0.1242
beryl $Be_3Al_2(SiO_3)_6$	Hexagonal	1.602	1.557	-0.045
calcite $CaCO_3$	Trigonal	1.658	1.486	-0.172
ice H_2O	Hexagonal	1.309	1.313	+0.004
lithium niobate $LiNbO_3$	Trigonal	2.272	2.187	-0.085
magnesium fluoride MgF_2	Tetragonal	1.380	1.385	+0.006
quartz SiO_2	Trigonal	1.544	1.553	+0.009
ruby Al_2O_3	Trigonal	1.770	1.762	-0.008
rutile TiO_2	Tetragonal	2.616	2.903	+0.287
sapphire Al_2O_3	Trigonal	1.768	1.760	-0.008
silicon carbide SiC	Hexagonal	2.647	2.693	+0.046
tourmaline (complex silicate)	Trigonal	1.669	1.638	-0.031
zircon, high $ZrSiO_4$	Tetragonal	1.960	2.015	+0.055
zircon, low $ZrSiO_4$	Tetragonal	1.920	1.967	+0.047

Biaxial crystals, at 590 nm

Material	Crystal system	n_α	n_β	n_γ
borax $Na_2(B_4O_5)(OH)_4 \cdot 8(H_2O)$	Monoclinic	1.447	1.469	1.472
epsom salt $MgSO_4 \cdot 7(H_2O)$	Monoclinic	1.433	1.455	1.461
mica, biotite $K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$	Monoclinic	1.595	1.640	1.640
mica, muscovite $KAl_2(AlSi_3O_{10})(F,OH)_2$	Monoclinic	1.563	1.596	1.601
olivine $(Mg,Fe)_2SiO_4$	Orthorhombic	1.640	1.660	1.680
perovskite $CaTiO_3$	Orthorhombic	2.300	2.340	2.380
topaz $Al_2SiO_4(F,OH)_2$	Orthorhombic	1.618	1.620	1.627
ulexite $NaCaB_5O_6(OH)_6 \bullet 5(H_2O)$	Triclinic	1.490	1.510	1.520

Application

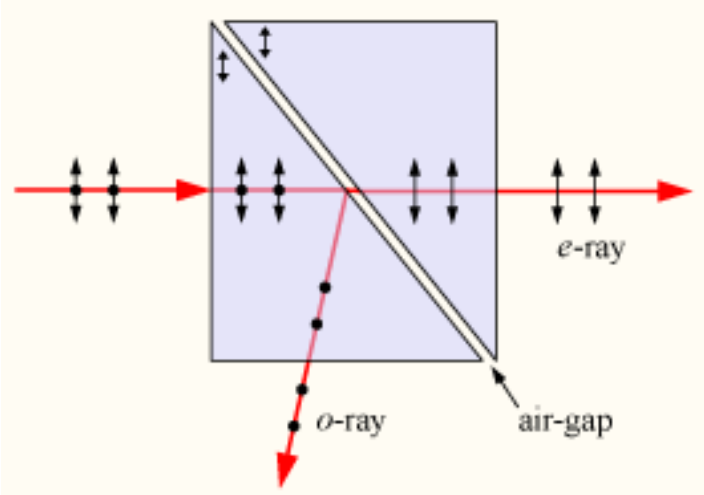
Birefringence is used in many optical devices. Liquid crystal displays, the most common sort of flat panel display, cause their pixels to become lighter or darker through rotation of the polarization (circular birefringence) of linearly polarized light as viewed through a sheet polarizer at the screen's surface. Similarly, light modulators modulate the intensity of light through electrically induced birefringence of polarized light followed by a polarizer. The Lyot filter is a specialized narrowband spectral filter employing the wavelength dependence of birefringence. Wave plates are thin birefringent sheets widely used in certain optical equipment for modifying the polarization state of light passing through it.

Birefringence also plays an important role in second harmonic generation and other nonlinear optical components, as the crystals used for this purpose are almost always birefringent. By adjusting the angle of incidence, the effective refractive index of the extraordinary ray can be tuned in order to achieve phase matching which is required for efficient operation of these devices.

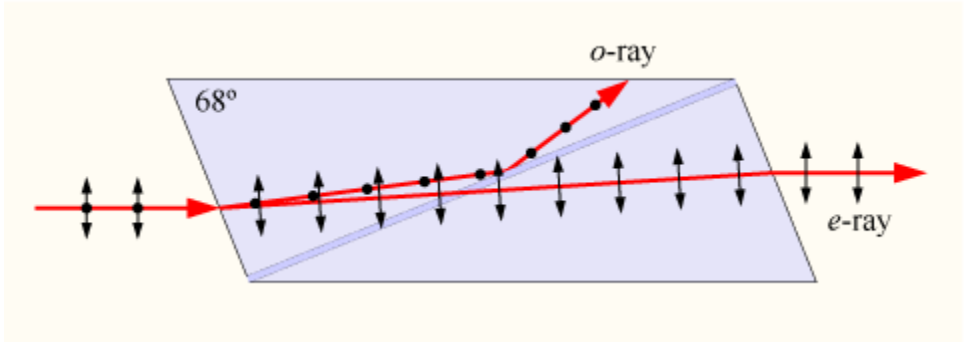
Glan–Taylor prism (Brewster angle)

A **Glan–Taylor prism** is a type of prism which is used as a polarizer or polarizing beam splitter.[1] It is one of the most common types of modern polarizing prism. It was first described by Archard and Taylor in 1948.[2]

The prism is made of two right-angled prisms of calcite (or sometimes other birefringent materials) which are separated on their long faces with an air gap. The optical axes of the calcite crystals are aligned parallel to the plane of reflection. Total internal reflection of *s*-polarized light at the air-gap ensures that only *p*-polarized light is transmitted by the device. Because the angle of incidence at the gap can be reasonably close to Brewster's angle, unwanted reflection of *p* polarized light is reduced, giving the Glan–Taylor prism better transmission than the Glan–Foucault design.[1][3] Note that while the transmitted beam is 100% polarized, the reflected beam is not. The sides of the crystal can be polished to allow the reflected beam to exit, or can be blackened to absorb it. The latter reduces unwanted Fresnel reflection of the rejected beam.



A variant of the design exists called a **Glan–laser prism**. This is a Glan–Taylor prism with a steeper angle for the cut in the prism, which decreases reflection loss at the expense of reduced angular field of view.[1] These polarizers are also typically designed to tolerate very high beam intensities, such those produced by a laser. The differences may include using calcite which is selected for low scattering loss, improved polish quality on the faces and especially on the sides of the crystal, and better antireflection coatings. Prisms with irradiance damage thresholds greater than 1 GW/cm^2 are commercially available.



A **Nicol prism** is a type of polarizer, an optical device used to produce a polarized beam of light from an unpolarized beam. See polarized light. It was the first type of polarizing prism to be invented, in 1828 by William Nicol (1770–1851) of Edinburgh. It consists of a rhombohedral crystal of Iceland spar (a variety of calcite) that has been cut at an angle of 68° with respect to the crystal axis, cut again diagonally, and then rejoined as shown using, as a glue, a layer of transparent Canada balsam.

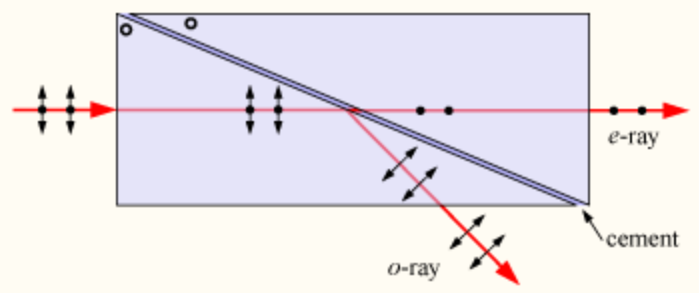
Unpolarized light enters through the left face of the crystal, as shown in the diagram, and is split into two orthogonally polarized, differently directed, rays by the birefringence property of the calcite. One of these rays (the *ordinary* or *o*-ray) experiences a refractive index of $n_o = 1.658$ in the calcite and it undergoes total internal reflection at the calcite-glue interface because its angle of incidence at the glue layer (refractive index $n = 1.55$) exceeds the critical angle for the interface. It passes out the top side of the upper half of the prism with some refraction as shown. The other ray (the *extraordinary* ray or *e*-ray) experiences a lower refractive index ($n_e = 1.486$) in the calcite, and is not totally reflected at the interface because it strikes the interface at a sub-critical angle. The *e*-ray merely undergoes a slight refraction, or bending, as it passes through the interface into the lower half of the prism. It finally leaves the prism as a ray of plane polarized light, undergoing another refraction as it exits the far right side of the prism. The two exiting rays have polarizations orthogonal (at right angles) to each other, but the lower, or *e*-ray, is the more commonly used for further experimentation because it is again traveling in the original horizontal direction, assuming that the calcite prism angles have been properly cut. The direction of the upper ray, or *o*-ray, is quite different from its original direction because it alone suffers total internal reflection at the glue interface as well as a final refraction on exit from the upper side of the prism.

Nicol prisms were once widely used in microscopy and polarimetry, and the term "using crossed Nicols" (abbreviated as **XN**) is still used to refer to the observing of a sample placed between orthogonally oriented polarizers. In most instruments, however, Nicol prisms have been replaced by other types of polarizers such as Polaroid sheets and Glan–Thompson prisms.

W.Wang

Glan–Thompson prism

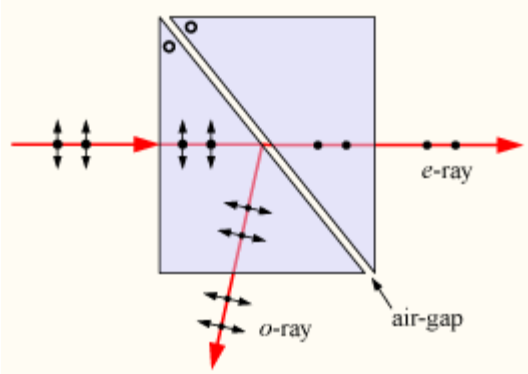
A **Glan–Thompson prism** is a type of polarizing prism similar to the Nicol and Glan–Foucault prisms. It consists of two right-angled calcite prisms that are cemented together by their long faces. The optical axes of the calcite crystals are parallel and aligned perpendicular to the plane of reflection. Birefringence splits light entering the prism into two rays, experiencing different refractive indices; the *p*-polarized ordinary ray is totally internally reflected from the calcite-cement interface, leaving the *s*-polarized extraordinary ray to be transmitted. The prism can therefore be used as a polarizing beam splitter. Traditionally Canada balsam was used as the cement in assembling these prisms, but this has largely been replaced by synthetic polymers.[1] Compared to the similar Glan–Foucault prism, the Glan–Thompson has a wider acceptance angle, but a much lower limit of maximum irradiance (due to optical damage limitations of the cement layer).



Glan–Foucault prism

A Glan–Foucault prism (also called a Glan–air prism) is a type of prism which is used as a polarizer. It is similar in construction to a Glan–Thompson prism, except that two right-angled calcite prisms are spaced with an air-gap instead of being cemented together.[1] Total internal reflection of p-polarized light at the air gap means that only s-polarized light is transmitted straight through the prism.

Compared to the Glan–Thompson prism, the Glan–Foucault has a narrower acceptance angle over which it will work, but because it uses an air-gap rather than cement, much higher irradiances can be used without damage. The prism can thus be used with laser beams. The prism is also shorter (for a given usable aperture) than the Glan–Thompson design, and the deflection angle of the rejected beam can be made close to 90°, which is sometimes useful. Glan–Foucault prisms are not typically used as polarizing beamsplitters because while the transmitted beam is 100% polarized, the reflected beam is not.



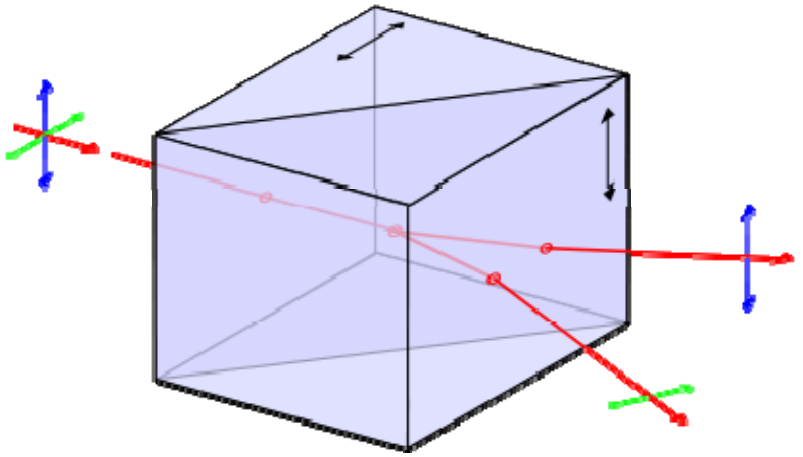
The Glan–Taylor prism is very similar, except that the crystal axes and transmitted polarization direction are orthogonal to the Glan–Foucault design. This yields higher transmission, and better polarization of the reflected light.[2] Calcite Glan–Foucault prisms are now rarely used, having been mostly replaced by Glan–Taylor polarizers and other more recent designs.

Yttrium orthovanadate (YVO4) prisms based on the Glan–Foucault design have superior polarization of the reflected beam and higher damage threshold, compared with calcite Glan–Foucault and Glan–Taylor prisms.[3] YVO4 prisms are more expensive, however, and can accept beams over a very limited range of angles of incidence.

Wollaston prism

A Wollaston prism is an optical device, invented by William Hyde Wollaston, that manipulates polarized light. It separates randomly polarized or unpolarized light into two orthogonal linearly polarized outgoing beams.

The Wollaston prism consists of two orthogonal calcite prisms, cemented together on their base (traditionally with Canada balsam) to form two right triangle prisms with perpendicular optic axes. Outgoing light beams diverge from the prism, giving two polarized rays, with the angle of divergence determined by the prisms' wedge angle and the wavelength of the light. Commercial prisms are available with divergence angles from 15° to about 45°.



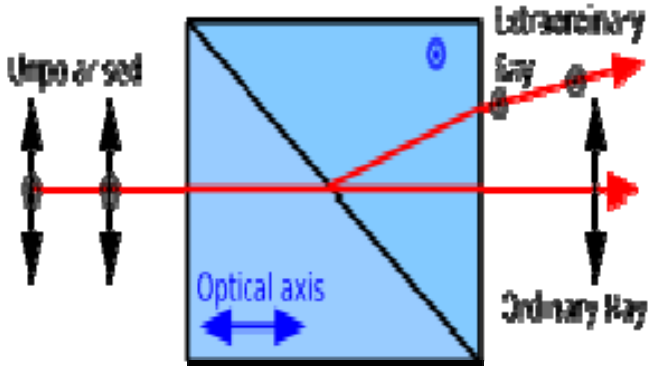
Nomarski prism

- A Nomarski prism is a modification of the Wollaston prism that is used in differential interference contrast microscopy. It is named after its inventor, Polish physicist Georges Nomarski. Like the Wollaston prism, the Nomarski prism consists of two birefringent crystal wedges (e.g. quartz or calcite) cemented together at the hypotenuse (e.g. with Canada balsam). One of the wedges is identical to a conventional Wollaston wedge and has the optical axis oriented parallel to the surface of the prism. The second wedge of the prism is modified by cutting the crystal in such a manner that the optical axis is oriented obliquely with respect to the flat surface of the prism. The Nomarski modification causes the light rays to come to a focal point outside the body of the prism, and allows greater flexibility so that when setting up the microscope the prism can be actively focused.

Rochon prism

A Rochon prism is a type of polariser. It is made from two prisms of a birefringent material such as calcite, which are cemented together.[1]

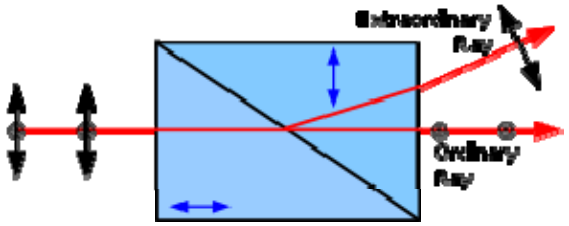
The Rochon prism was invented by and is named after Abbé Alexis Marie Rochon. It is in many ways similar to the Wollaston prism, but one ray (the ordinary ray) passes through the prism undeviated. The Sénarmont prism is similar but transmits the s-polarized ray undeviated. In both the Rochon and the Sénarmont prisms the undeviated ray is ordinary on both sides of the interface. Rochon prisms are commercially available, but for many applications other polarisers are



Sénarmont prism

The Sénarmont prism is a type of polariser. It is made from two prisms of a birefringent material such as calcite, usually cemented together.[1] The Sénarmont prism is named after Henri Hureau de Sénarmont. It is similar to the Rochon and Wollaston prisms.

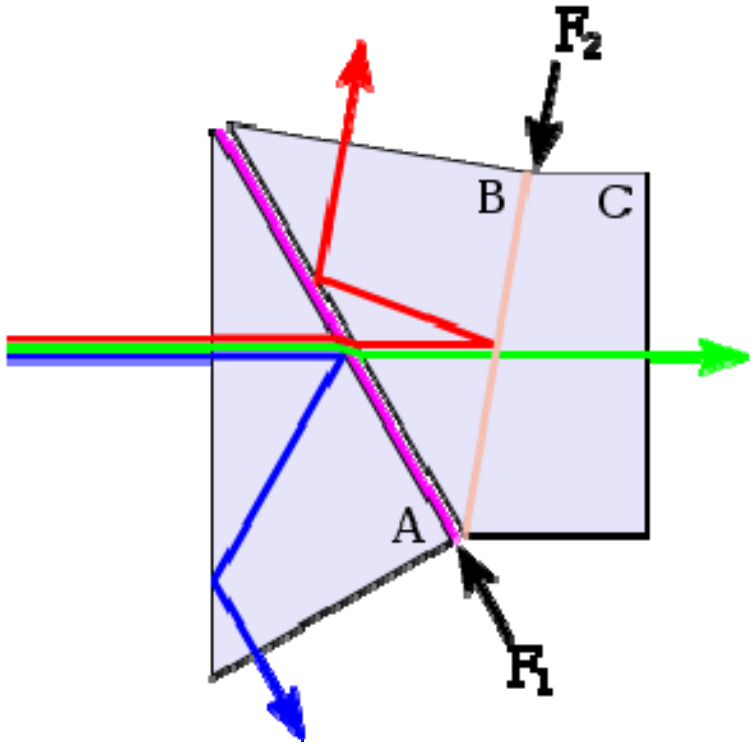
In the Sénarmont prism the s-polarized ray (i.e., the ray with polarization direction perpendicular to the plane in which all rays are contained, called the plane of incidence) passes through without being deflected, while the p-polarized ray (with polarization direction in the plane of incidence) is deflected (refracted) at the internal interface into a different direction. Both rays correspond to ordinary rays (o-rays) in the first component prism, since both polarization directions are perpendicular to the optical axis, which is the propagation direction. In the second component prism the s-polarized ray remains ordinary (o-ray, polarized perpendicular to the optical axis), while the p-polarized ray becomes extraordinary (e-ray), with a polarization component along the optical axis. As a consequence, the s-polarized ray is not deflected since the effective refractive index does not change across the interface. The p-polarized wave, on the other hand, is refracted because the effective refractive index changes upon changing from o-ray to e-ray.



The Sénarmont prism is similar in construction and action to the Rochon prism, as in both polarizers the ray that is not deflected is the o-ray after the internal interface, while the deflected ray is the e-ray. However, in the Rochon prism, it is the p-polarized ray that remains an o-ray on both sides of the interface, and is therefore not deflected, while the s-polarized ray changes from o-ray to e-ray and is therefore deflected.

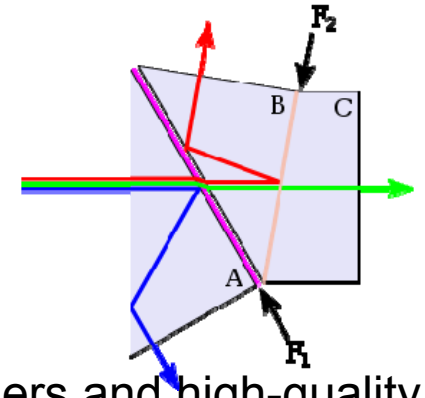
Dichroic Prisms

A dichroic prism is a prism that splits light into two beams of differing wavelength (colour). A trichroic prism assembly combines two dichroic prisms to split an image into 3 colours, typically as red, green and blue of the RGB colour model. They are usually constructed of one or more glass prisms with dichroic optical coatings that selectively reflect or transmit light depending on the light's wavelength. That is, certain surfaces within the prism act as dichroic filters. These are used as beam splitters in many optical instruments. (See: Dichroism, for the etymology of the term.) wikipedia



A trichroic prism assembly

Application



One common application of dichroic prisms is in some camcorders and high-quality digital cameras. A trichroic prism assembly is a combination of two dichroic prisms which are used to split an image into red, green, and blue components, which can be separately detected on three CCD arrays.

A possible layout for the device is shown in the diagram. A light beam enters the first prism (A), and the blue component of the beam is reflected from a low-pass filter coating (F1) that reflects blue light (high-frequency), but transmits longer wavelengths (lower frequencies). The blue beam undergoes total internal reflection from the front of prism A and exits it through a side face. The remainder of the beam enters the second prism (B) and is split by a second filter coating (F2) which reflects red light but transmits shorter wavelengths. The red beam is also totally internally reflected due to a small air-gap between prisms A and B. The remaining green component of the beam travels through prism C.

The trichroic prism assembly can be used in reverse to combine red, green and blue beams into a coloured image, and is used in this way in some projector devices. Assemblies with more than 3 beams are possible.

Thin Film Beam Splitters

Beamsplitting Optics

Our standard beamsplitters are designed to provide general purpose laser beamsplitting and combining for visible through near infrared applications.

Broadband Dielectric Beamsplitters

Ultrashort Pulse Beamsplitters

Ultrafast Laser Harmonic Beamsplitters

High Energy Nd:YAG Laser Harmonic Beamsplitters

High-Energy Nd:YAG Laser 50 Percent Beamsplitters

Laser Line Non-Polarizing Plate Beamsplitters

UV Plate Beamsplitters

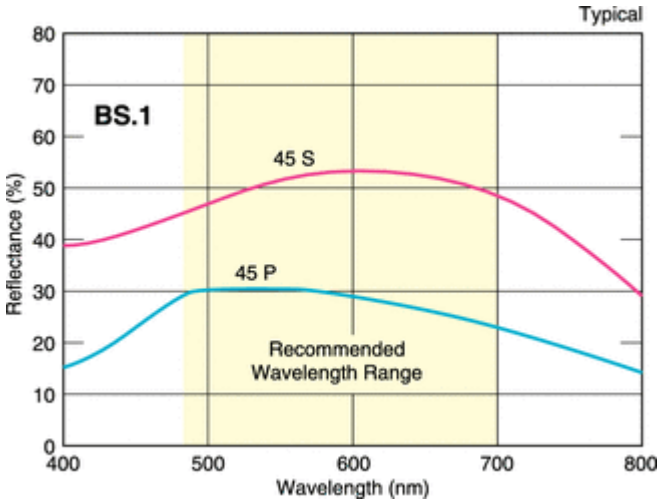
IR Plate Beamsplitters

Pellicle Beamsplitter

Example of Dielectric Thin Film Beam Splitter

Newport N-BK7 Broadband Dielectric Beamsplitter, 50.8mm, λ/10, 480-700 nm

Model	20B20BS.1
Material	Grade A N-BK7
Diameter	2.00 in. (50.8 mm)
Antireflection Coating	480-700 nm
Angle of Incidence	45 °
Surface Quality	15-5 scratch-dig
Damage Threshold	500 W/cm^2 CW, 0.5 J/cm^2 with 10 nsec pulses, typical
Efficiency	R_{avg} < 0.75% @ 400-700 nm
Clear Aperture	> central 80% of diameter
Coating Code	BS.1
Wedge	30 ±15 arc min
Thickness	0.37 in. (9.4 mm)
Thickness Tolerance	±0.38 mm
Diameter Tolerance	+0/-0.13 mm
Chamfers	0.38-1.14 mm face width
Chamfers Angle/Tolerance	45° ±15°
Cleaning	Non-abrasive method, acetone or isopropyl alcohol on lens tissue recommended see Care and Cleaning of Optics



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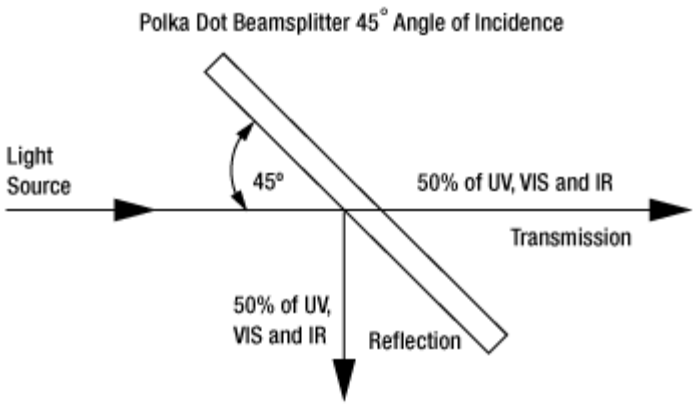
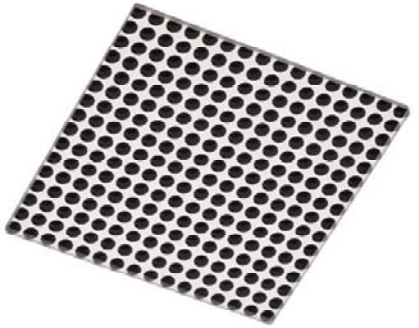
Polka Dots Beam Splitter





The metal coating is applied in a regularly repeating array, which lends the beamsplitter its "polka dot" appearance, as shown to the right. Light is reflected by the metal-coated portion of the beamsplitter and transmitted through the uncoated portion of the beamsplitter. To maximize the reflected intensity, light should be incident on the coated side of the beamsplitter. The square dots have 0.0040" (100 µm) [UVFS, B270, and CaF_2] or 0.0042" (107 µm) [ZnSe] sides. The spacing between the dots is 0.0022" (56 µm) [UVFS, B270, and CaF_2] or 0.0018" (46 µm) [ZnSe] in all directions.

Polka dot beamsplitters are typically used at a 45° angle relative to the incident beam as shown in the diagram above. Our polka dot beamsplitters transmit 50% ± 5% (±10% for ZnSe) when a beam is larger than 2 mm in diameter.

Light transmission for different substrate

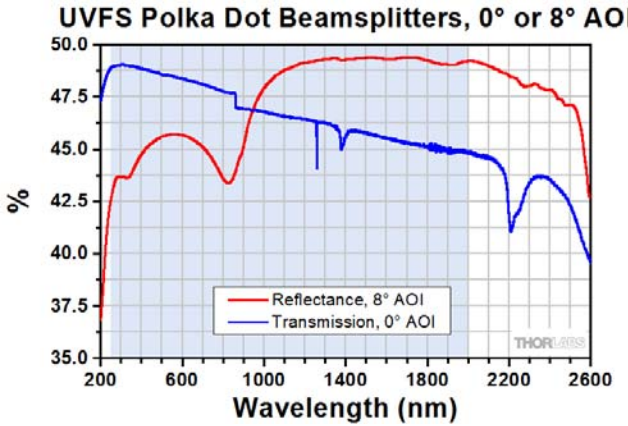
•50:50 Beamsplitting Over Broad Transmission Range
◦UVFS: 250 nm to 2.0 μm
◦B270: 350 nm to 2.0 μm
◦CaF2: 180 nm to 8.0 μm
◦ZnSe: 2.0 to 11.0 μm

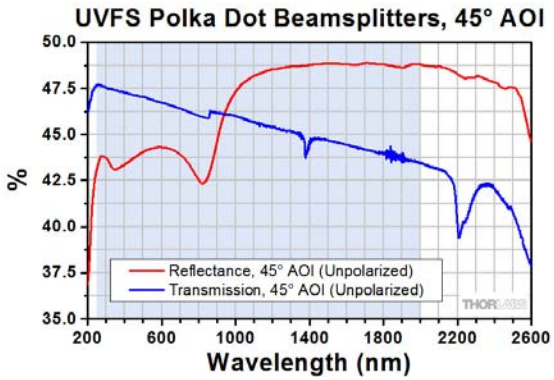
•Four Substrate Options: UV Fused Silica, B270 Glass, Calcium Fluoride (CaF2), or Zinc Selenide (ZnSe)

Example of Polka Dots Beam Splitter

UV Fused Silica Polka Dot Beamsplitters: 250 nm - 2.0 µm

Specifications	
Available Sizes	Ø1", Ø2", or 1" Square
Beamsplitting Ratio	50% ± 5%
Minimum Beam Diameter for 50/50 Split	2 mm
Material	UV Fused Silica
Wavelength Range	250 nm - 2.0 µm
Coating Pattern	Square-Coated Apertures 0.0040" (100 µm) Sides, 0.0022" (56 µm) Spacing
Clear Aperture	>90% Diameter (Round Optics) >90% Length and Height (Square Optics)
Thickness	1.5 mm (Nominal)
Dimensional Tolerance	+0.0 / -0.5 mm
Angle of Incidence	0 to 45°





Design Project 2

- Using Prisms for optical beam manipulation
- Spectrometer (dispersing light, birefringent effect)
- Stereoscope (3D imaging)
- Image coupling

Dichroism

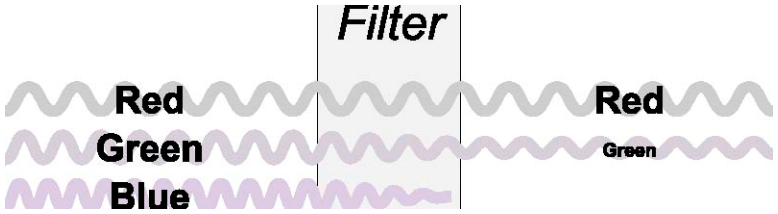
In optics, a dichroic material is either one which causes visible light to be split up into distinct beams of different wavelengths (colours) (not to be confused with dispersion), or one in which light rays having different polarizations are absorbed by different amounts. wikipedia

Filter

Neutral density- decrease intensity (broadband, metallic)

Interference filter – utilizing etalon created by thin layer(s) of dielectric or metallic coating to selectively filter certain Wavelength (narrow band)

Gel film– usually braodband, either passband or lowpass or highpass



Transmission: Beer-Lambert or Bouger's Law

Absorption by a filter glass varies with wavelength and filter thickness. Bouger's law states the logarithmic relationship between internal transmission at a given wavelength and thickness.

$$\log_{10}(\tau_1) / d_1 = \log_{10}(\tau_2) / d_2$$

Internal transmittance, τ_i, is defined as the transmission through a filter glass after the initial reflection losses are accounted for by dividing external transmission, T, by the reflection factor P_d.

$$\tau_i = T / P_d$$

Example

The external transmittance for a nominal 1.0 mm thick filter glass is given as $T_{1.0} = 59.8$ % at 330 nm. The reflection factor is given as $P_d = 0.911$. Find the external transmittance $T_{2.2}$ for a filter that is 2.2 mm thick.

Solution:

$\tau_{1.0} = T_{1.0} / P_d = 0.598 / 0.911 = 0.656$

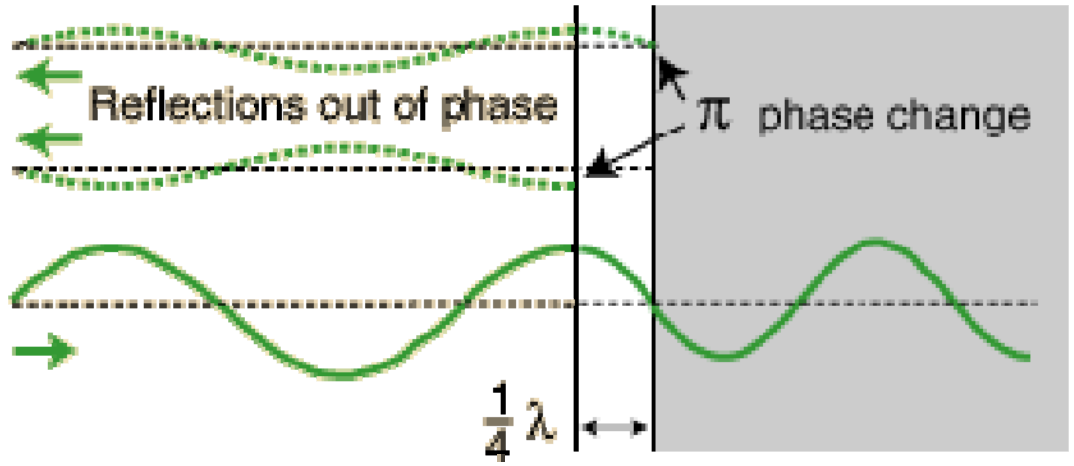
$\tau_{2.2} = [\tau_{1.0}]^{2.2/1.0} = [0.656]^{2.2} = 0.396$

$T_{2.2} = \tau_{2.2} * P_d = (0.396)(0.911) = 0.361$

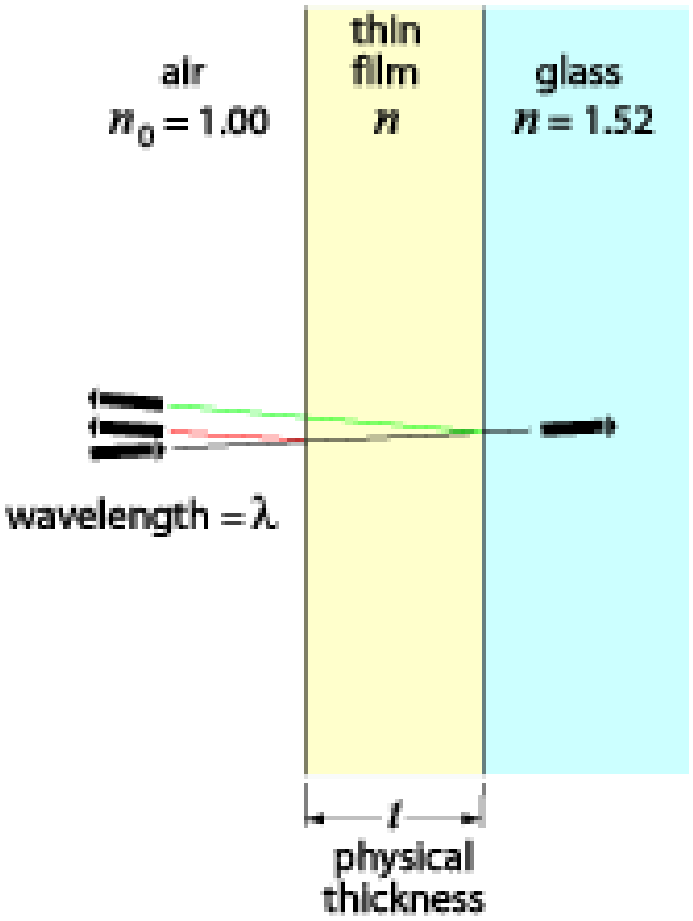
So, for a 2.2 mm thick filter, the external transmittance at 330 nm would be 36.1%

Anti-Reflection Coatings

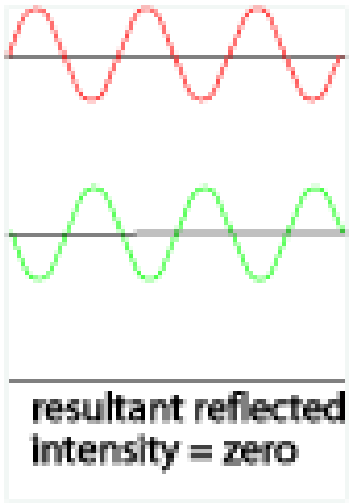
Anti-reflection coatings work by producing two reflections which interfere destructively with each other.



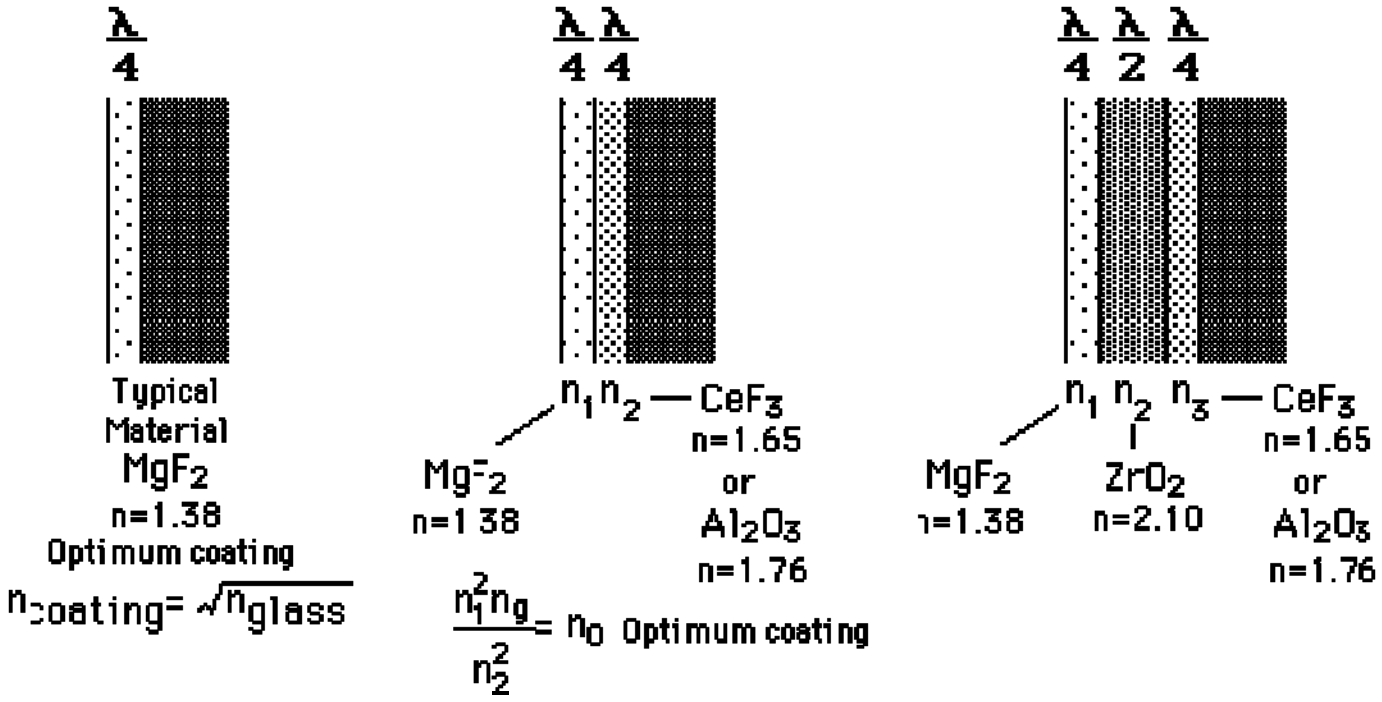
Antirefelction coating



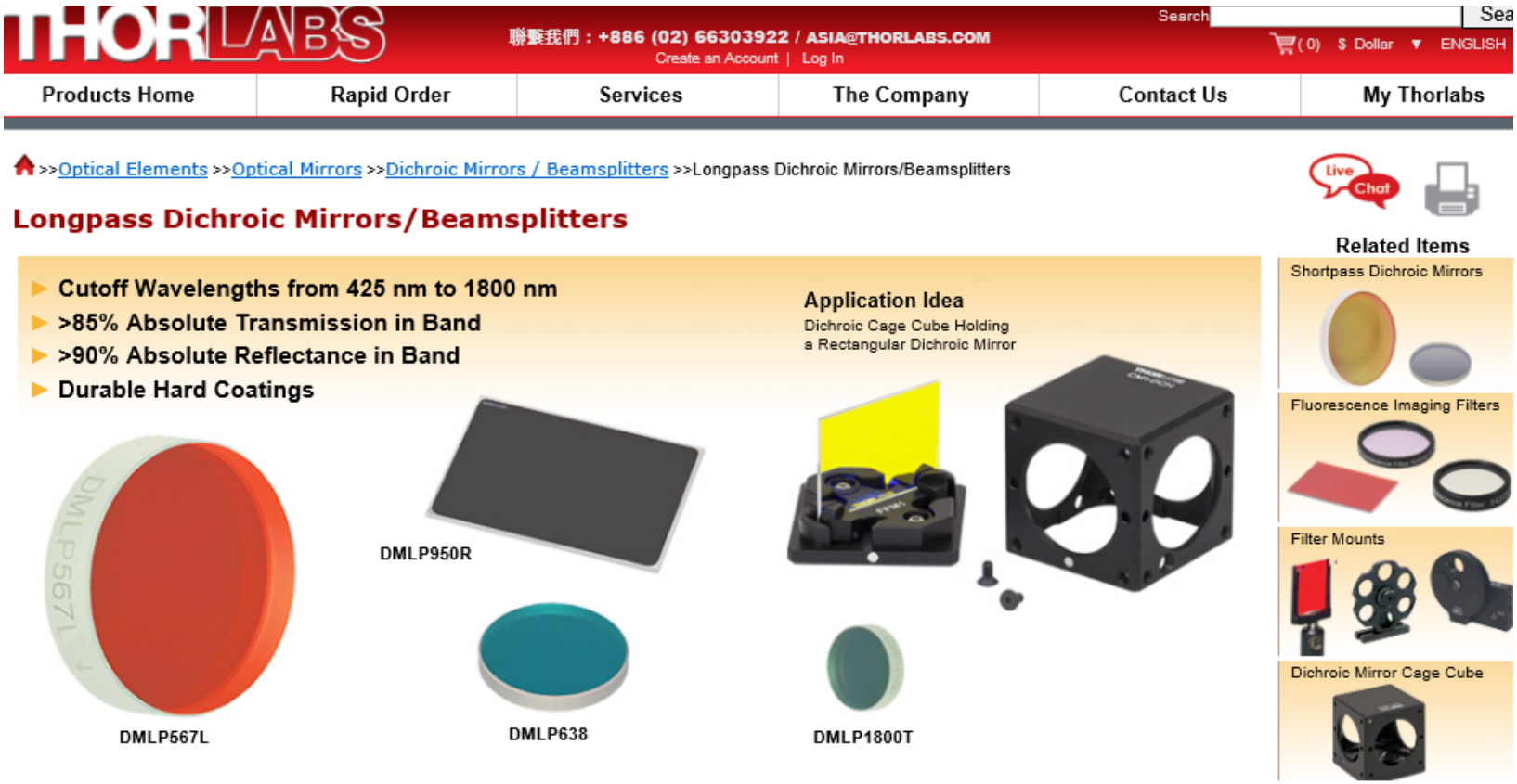
If t_{op}, the optical thickness $(nt) = \lambda/4$, then reflections interfere destructively



Multi-Layer Anti-Reflection Coatings



Long pass Dichroic Mirrors/Beamsplitters



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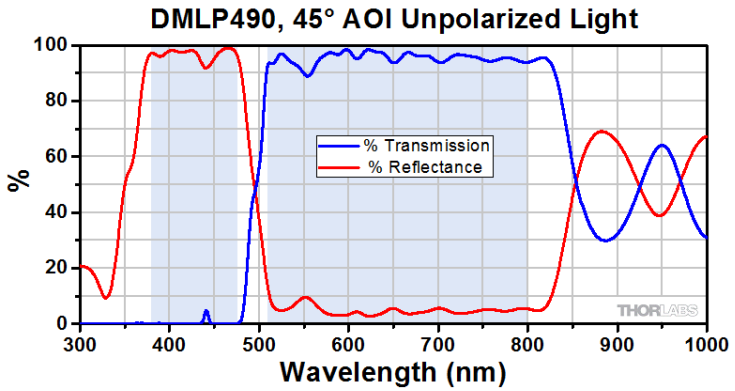
Example of Dichroic Mirrors/Beamsplitters

Thorlab Longpass Dichroic Mirrors/Beamsplitters: 490 nm Cutoff Wavelength

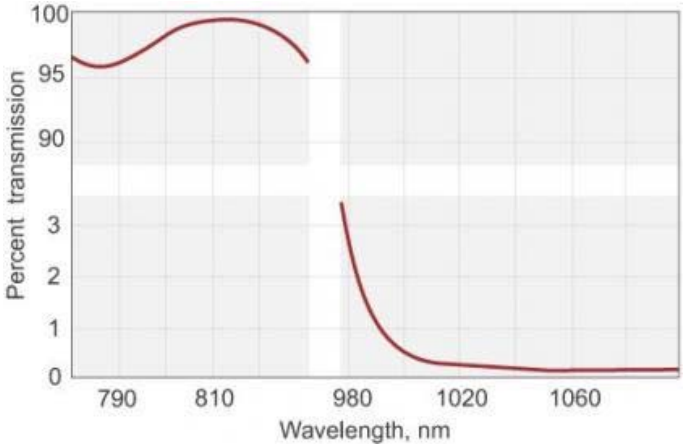
Specification:

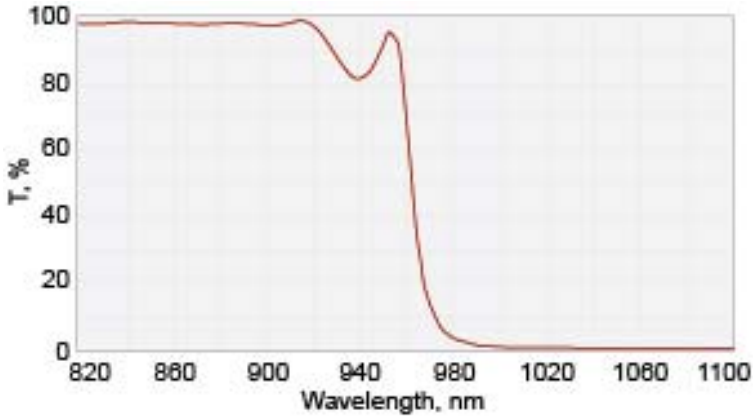
Cutoff Wavelength 490 nm
Transmission Band (Tabs > 85%, Tavg > 90%)
510 - 800 nm
Reflection Band (Rabs > 90%, Ravg > 95%)
380 - 475 nm



Dichroic Mirrors

Harmonic separators are dichroic beamsplitters used to reflect one wavelength and to transmit the others. Reflectance is higher than 99.5% for the wavelength of interest and transmittance is at least 90% for the rejected wavelengths. The rear surface of harmonic separators is antireflection coated.





031-6800. HR>99.5@1064 nm, HT>95%@808 nm, AOI=0°

- Laser Damage Threshold: >2J/cm2, 8 ns pulse, 1064 nm typical for BK7 substrates; >5J/cm2 8 ns pulse, 1064 nm typical for UVFS substrates
- Back side antireflection coated: R<0.5%
- Parallelism: 30 arcsec

EKSMA OPTICS offers BK7 dichroic mirrors for fast off-the-shelf delivery. Available substrate types of Non-Standard BK7 Dichroic Mirrors are Concave/Convex, Plano/Concave, Plano/Convex and Plano.

Polarizer

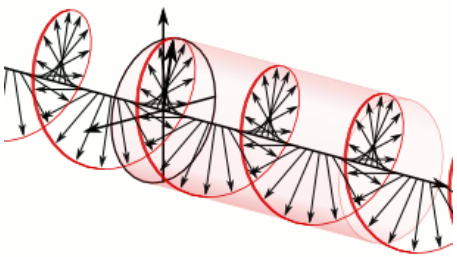
Polarization states are linear, circular and elliptical according to
The path traced by electric field vectors in a propagating wave train.

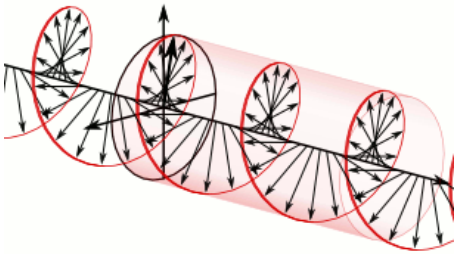
-Quartz (e.g. calcite),
- polarized by reflection (brewster angle from glass)
 - metal film
-dichroic (sheet-type polarizers are manufactured from an organic
-Materials embedded into a plastic. When stretched, aligning molecules
and causing them to be biregfringent, and then dyed. Dye molecules
Selevtively attach to aligned polymer molecules, so absorption is high
In one and weak in other. (Polaroid)

Polarizer

The second meaning of dichroic refers to a material in which light in different polarization states traveling through it experiences a different absorption coefficient. This is also known as diattenuation. When the polarization states in question are right and left-handed circular polarization, it is then known as circular dichroism. Since the left- and right-handed circular polarizations represent two spin angular momentum (SAM) states, in this case for a photon, this dichroism can also be thought of as Spin Angular Momentum Dichroism.

In some crystals, the strength of the dichroic effect varies strongly with the wavelength of the light, making them appear to have different colours when viewed with light having differing polarizations.[dubious – discuss] This is more generally referred to as pleochroism,[2] and the technique can be used in mineralogy to identify minerals. In some materials, such as herapathite (iodoquinine sulfate) or Polaroid sheets, the effect is not strongly dependent on wavelength.

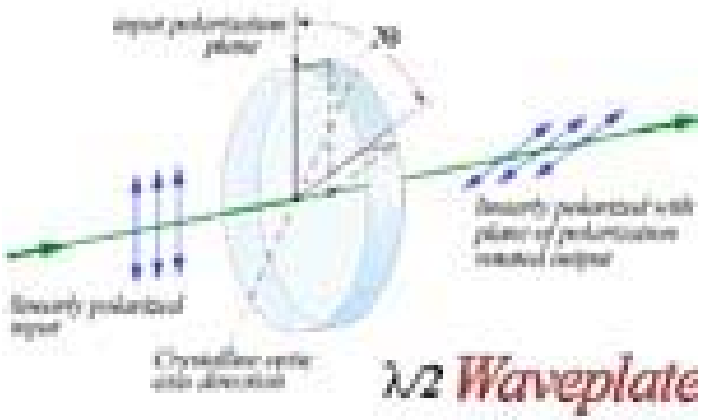


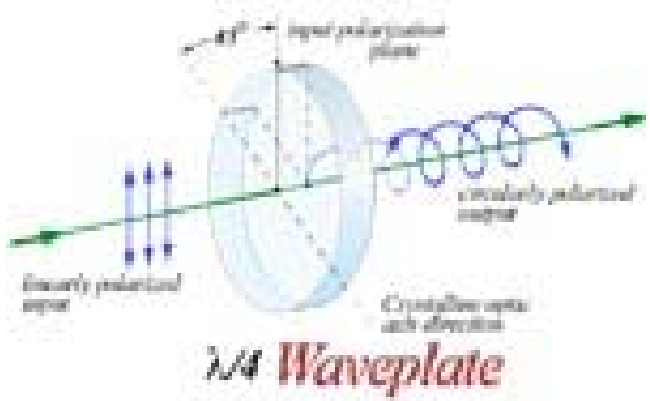


Retardation plates

Retardation plates or phase shifters, including ¼ or ½ wave plates,
Are usually used primarily for synthesis and analysis of light
In various polarization states.

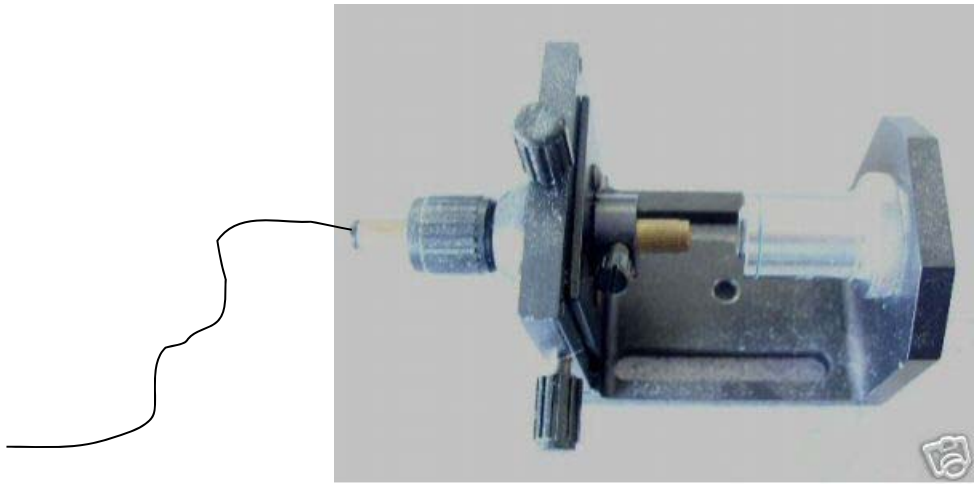
When combine with polarizer, it either rotates the polarization or change linear polarized light into circularly polarized light.





Light Coupling System

Fiber Direct Focusing



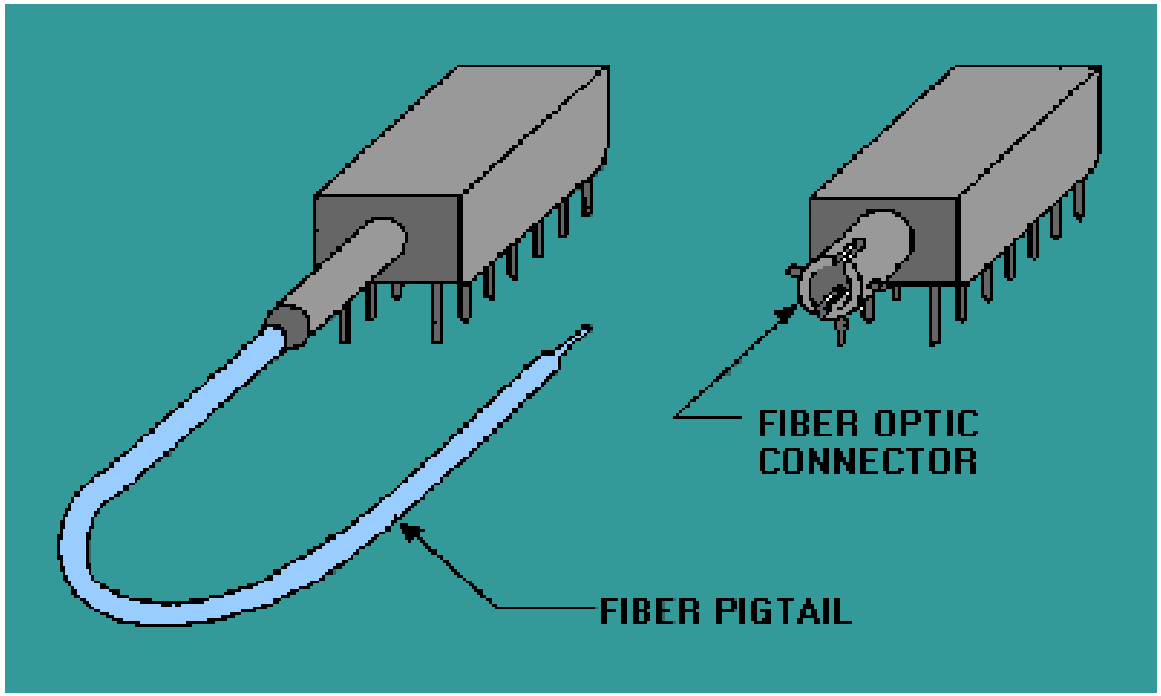
fiber

X-Y stage

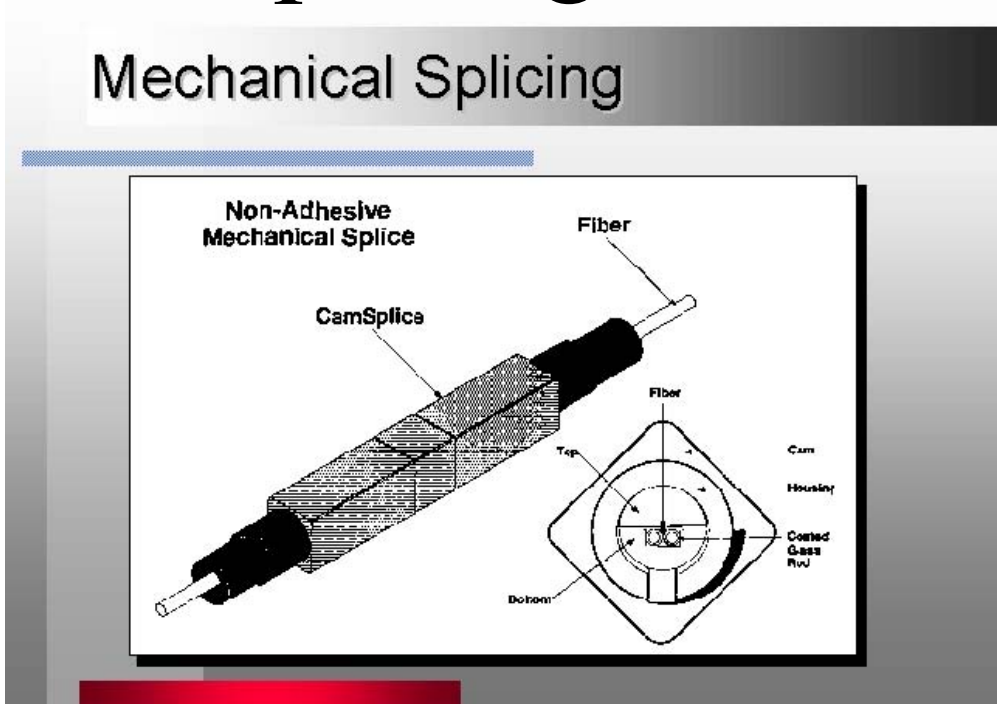
lens

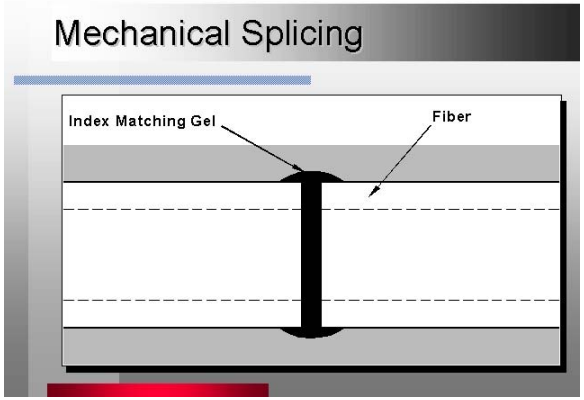
Bare fiber coupling

Pigtailed and connectorized fiber optic devices



Mechanical Splicing



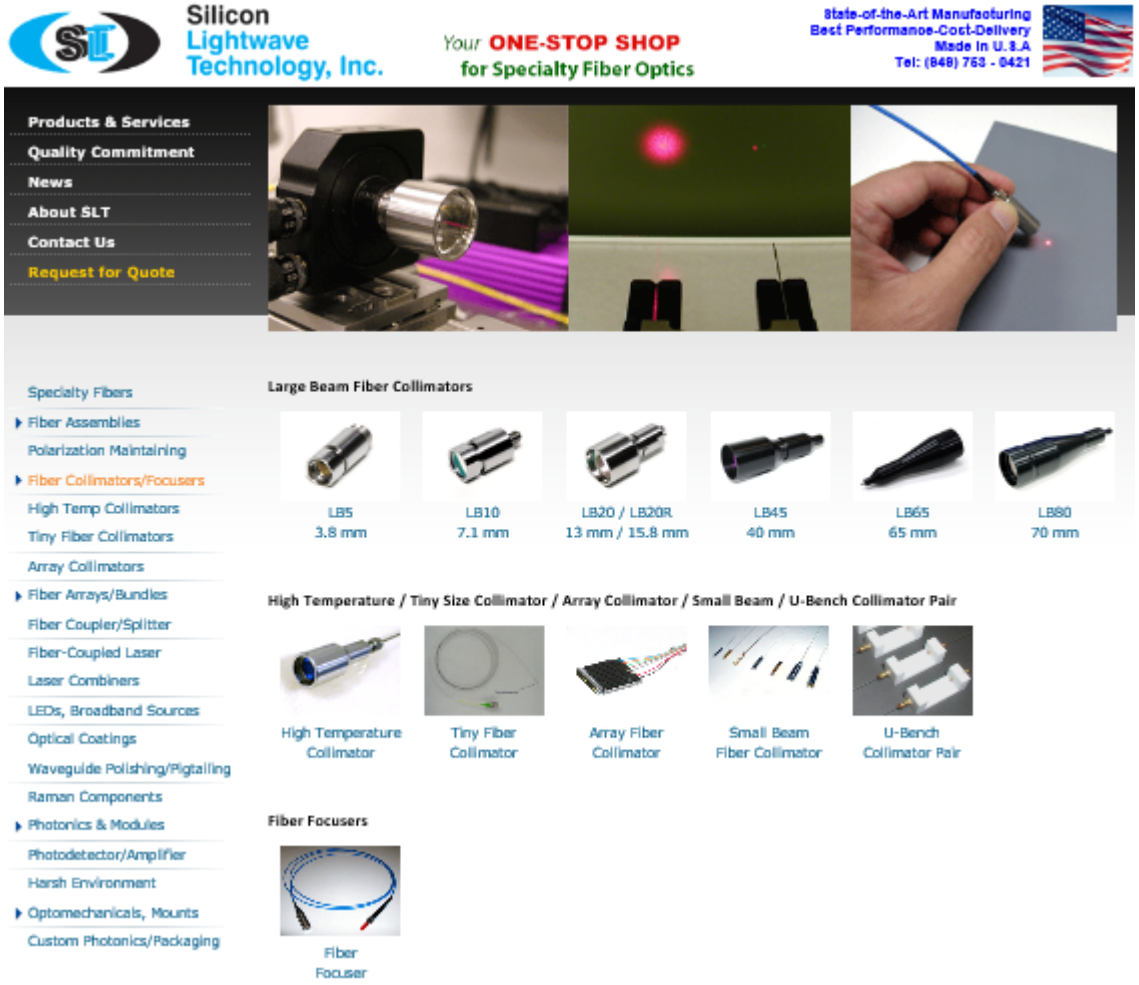


Bare Fiber to Fiber Connection

Mechanical coupler

SMA Fiber Optic Coupler

Pigtail Grin Lens



Tapered Mode Size Converters

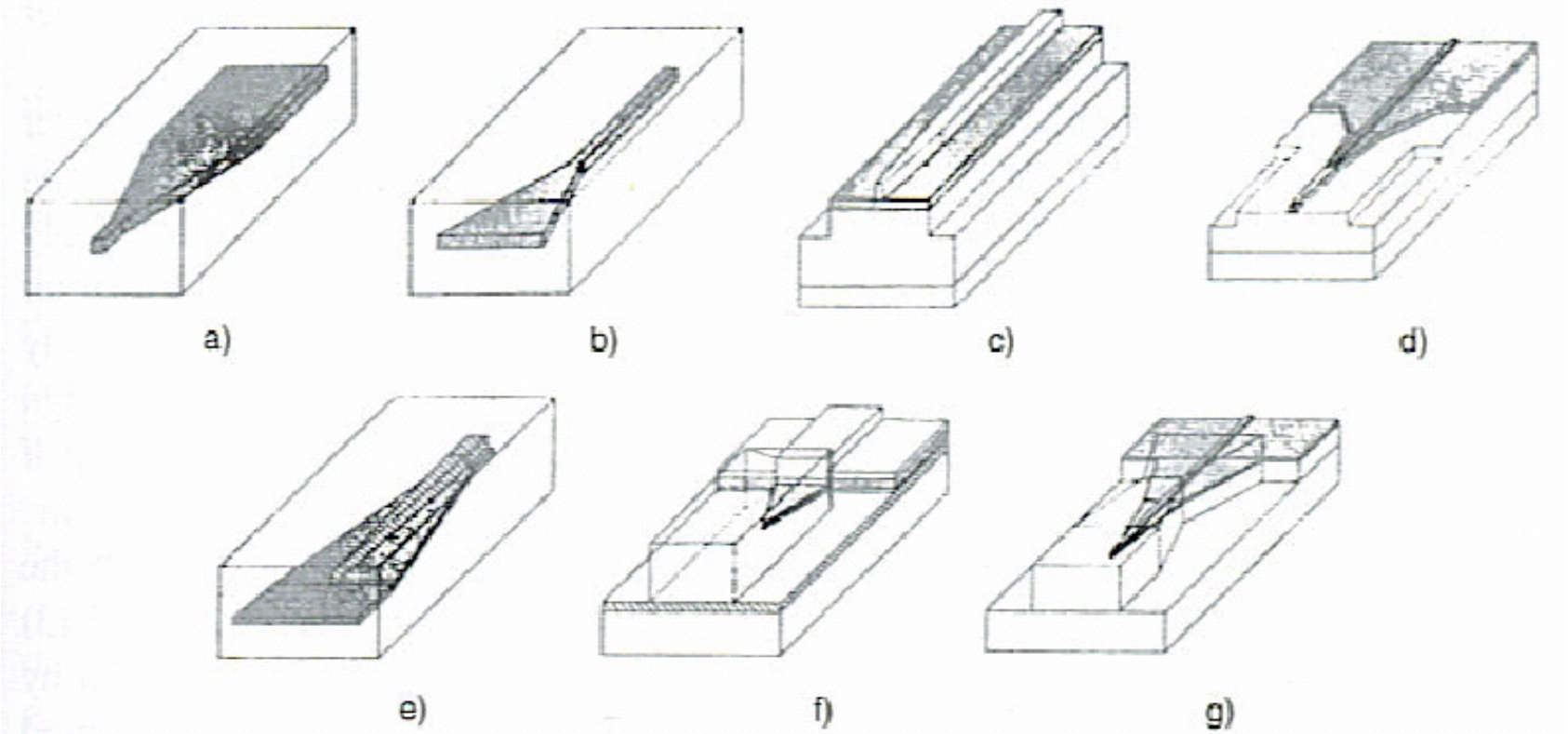


Fig. 7.12a–g. Lateral taper designs. **a** Lateral down-tapered buried waveguide. **b** Lateral up-tapered buried waveguide. **c** Single lateral taper transition from a ridge waveguide to a fiber-matched waveguide. **d** Multisection taper transition from a ridge waveguide to a fiber-matched waveguide. **e** Dual lateral overlapping buried waveguide taper. **f** Dual lateral overlapping ridge waveguide taper. **g** Nested waveguide taper transition from a ridge waveguide to a fiber-matched waveguide [7.25] ©1997 IEEE

Performance factors

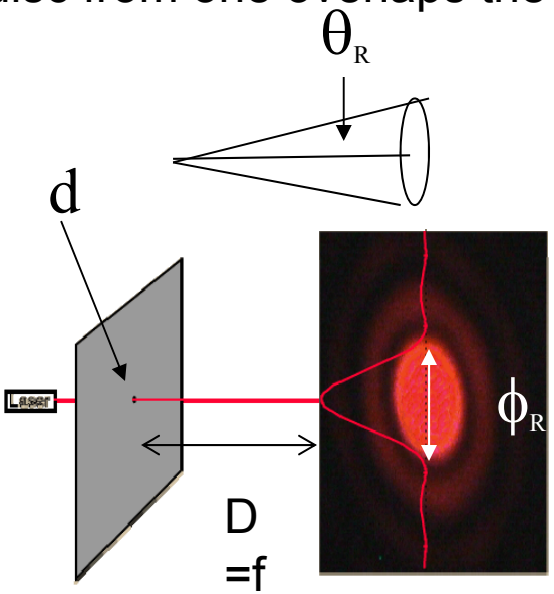
Diffraction effect
Aberrations- Spherical (geometry), chromatic (wavelength)
Astigmatism
Coma
Field curvature
Distortion
Lateral color

Gaussian Beam (Beam Optics)
Fourier Optics

Diffraction effect

Rayleigh criterion- spatial resolution is limited by diffraction.

Assume two separate point sources can be resolved when the center of the airy disc from one overlaps the first dark ring in the diffraction pattern of second one



θ_R (angular separation between two images)

$$\sin\theta_R = \frac{\lambda}{d}$$

$\phi_R = \lambda f/ d$

Single slit

$$\sin\theta_R = 1.22\frac{\lambda}{d}$$

$\phi_R = 2.44\lambda f/d$

Circular aperture

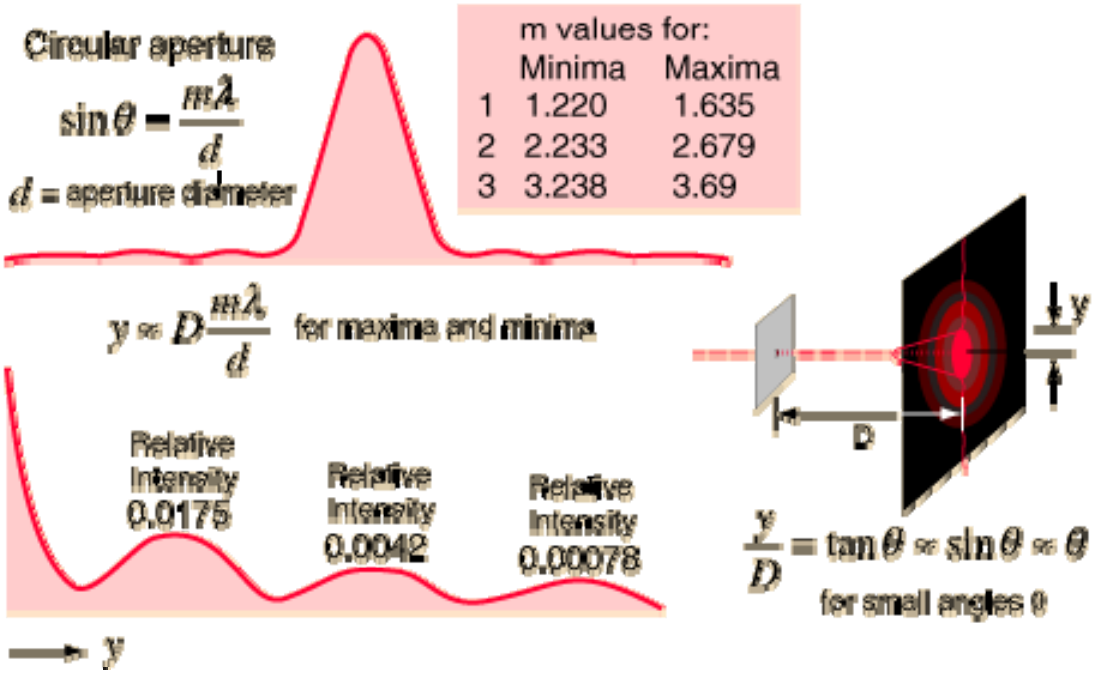
$\phi_R = 1.27\lambda f/d$ (Gaussian beam)

ϕ_R represents the smallest spot size that can be achieved by an optical system with a circular or slit aperture of a given f-number (diffraction-limit spot size)

Diffraction–limited spot size

As we will see later when we derive irradiance distribution in the diffraction pattern of a slit is defined as

$$I = I_o\,[2J_1(\delta)/\delta]^2$$



Where $\delta = \pi d\sin\theta/m\lambda$

Since m=1.22 for 1st min.

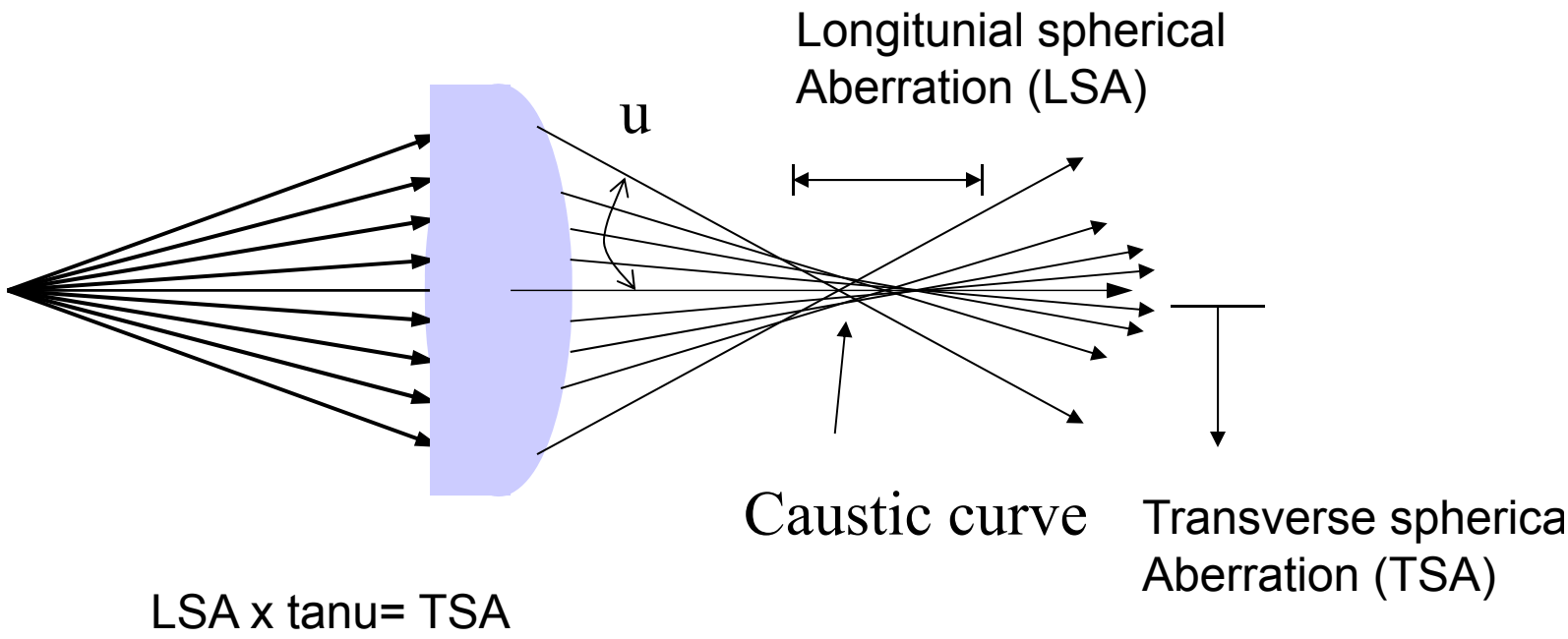
$\sin\theta = 1.22\lambda/d$

NA=Sinθ =ϕ/2f= 1/2f-number

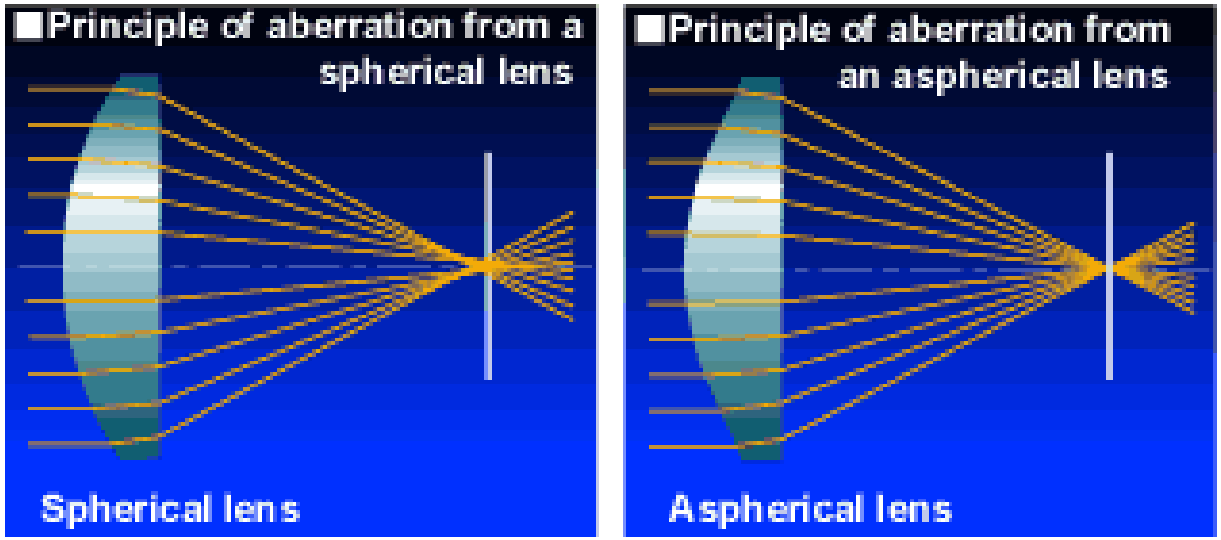
Spot size limited by spherical aberration

- Spot size due to spherical aberration is

$$0.067 f/\text{f-number}^3$$



Aspherical lens

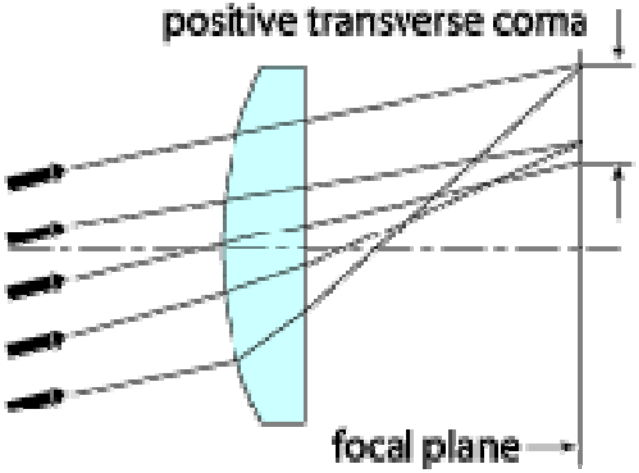


Canon)

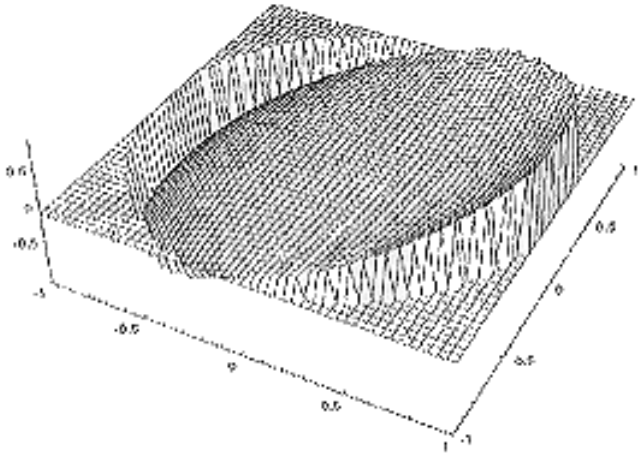
With the spherical lens, rays coming from the lens periphery form the image before the ideal focal point. For this reason, the spherical aberration (blurred image) occurs at the center portion of the image formed. With the aspherical lens, on the contrary, even the rays coming from the lens periphery agree on the focal point, thus forming a sharp image.

Coma

In spherical lenses, different parts of the lens surface exhibit different degrees of magnification. This gives rise to an aberration known as coma. Even if spherical aberration is corrected and the lens brings all rays to a sharp focus on axis, a lens may still exhibit coma off axis. As with spherical aberration, correction can be achieved by using multiple surfaces. Alternatively, a sharper image may be produced by judiciously placing an aperture, or stop, in an optical system to eliminate the more marginal rays.



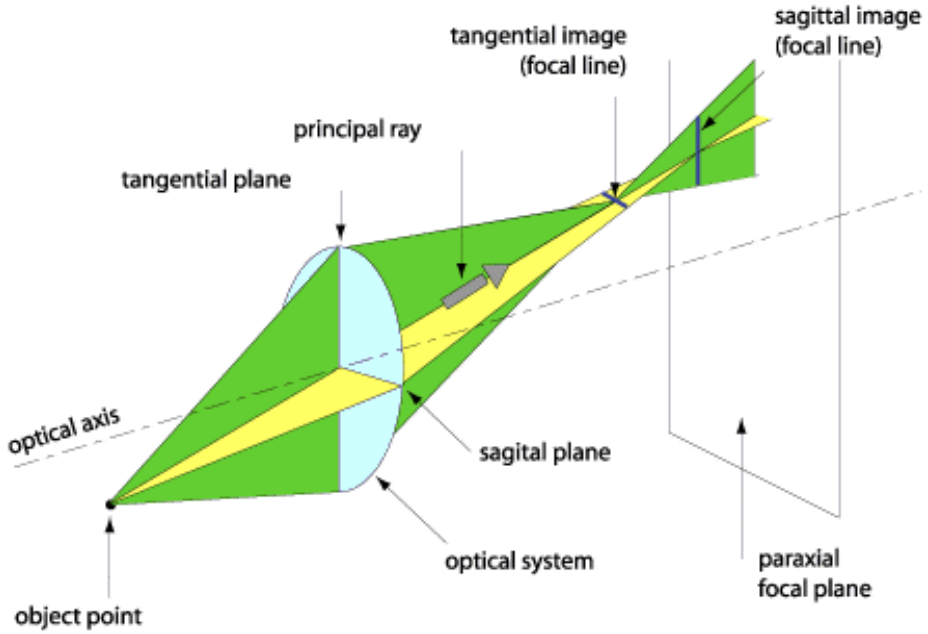
Melles Griot

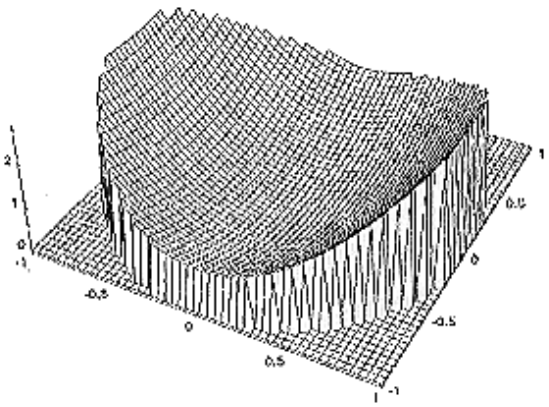


A wavefront with coma

Astigmatism

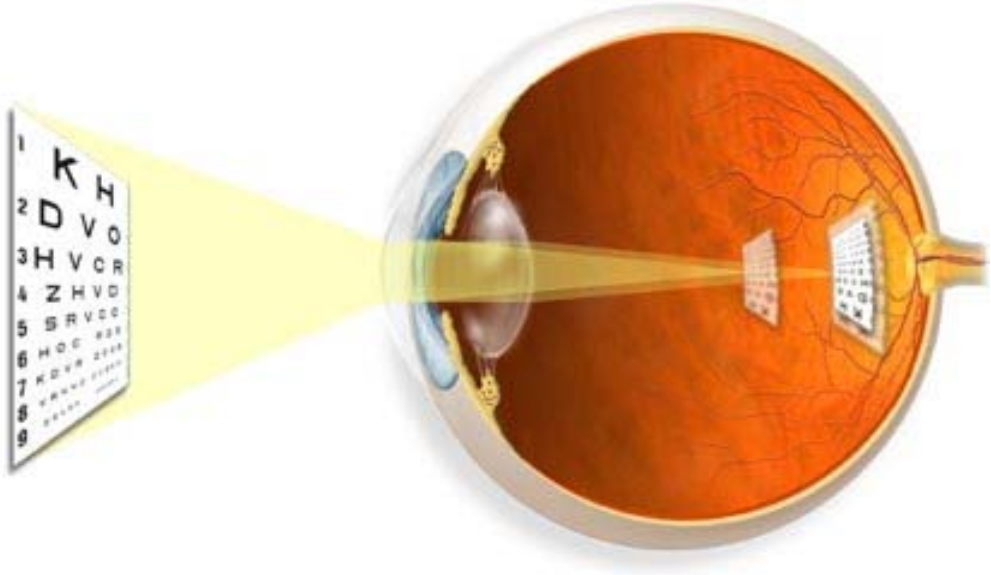
When an off-axis object is focused by spherical lens, the natural asymmetry leads to astigmatism. The amount of astigmatism in a lens depends on lens shape. The figure illustrates that tangential rays from the object come to a focus closer to the lens than do rays in the sagittal plane. When the image is evaluated at the tangential conjugate, we see a line in the sagittal direction. A line in the tangential direction is formed at the sagittal conjugate. Between these conjugates, the image is either an elliptical or a circular blur. Astigmatism is defined as the separation of these conjugates.





An astigmatic wavefront

Melles Griot

Astigmatism means that the cornea is oval like a football instead of spherical like a basketball. Most astigmatic corneas have two curves – a steeper curve and a flatter curve. This causes light to focus on more than one point in the eye, resulting in blurred vision at distance or near. Astigmatism often occurs along with nearsightedness or farsightedness.

Astigmatism usually occurs when the front surface of the eye, the cornea, has an irregular curvature. Normally the cornea is smooth and equally curved in all directions and light entering the cornea is focused equally on all planes, or in all directions. In astigmatism, the front surface of the cornea is curved more in one direction than in the other. This abnormality may result in vision that is much like looking into a distorted, wavy mirror. The distortion results because of an inability of the eye to focus light rays to a point.