OPTICS
PHY F213

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OPTICS

- **Text Book (TB):**
- Optics by Ghatak, 3rd Edition, Tata Mcgraw Hill (2003)
-
- **Reference Book (RB):**
- Principles of Optics, B. K. Mathur
- Optical Physics by A. Lipson, S. G. Lipson, H. Lipson, cambridge university press, 2010
- Introduction to Electrodynamics, David J.Griffiths, 3rd Ed., Pearson, 1999.
- Lecture notes
- Lasers and non-linear optics, B. B. Laud, 2nd Ed., Wiley Eastern Ltd

Lecture No.	Learning Objectives	Topics to be covered	Reference Chap./ Sec. #
1-2	Introduction	Basic introduction to optics, laws of reflection and refraction	1 & 2
3-6	Matrix methods in ray tracing	Matrices for translation, refraction and reflection, eigenvalues and eigenvectors of transformation matrices	4.1-4.5
7-10	Aberrations	Chromatic and Spherical Aberration	5.1-5.3
11	Huygen's principle and Applications	Huygen's theory	10.1-10.5
12-18	Origin of refractive index and scattering theory and applications	Origin of refractive index, Rayleigh Scattering, Dynamic light scattering	6.11-6.15, Lecture notes
19-23	Diffraction and Dispersion	Fresnel and Fraunhofer diffraction, normal and anomalous dispersion	Lecture notes
24-25	Basic of wave motion	1D wave equation and its general solution, dispersion and group velocity	RB 3
26-27	Polarization	Malus' law, double refraction Optical activity,	19.1-19.8
28-32	Maxwell's equations and Electromagnetic waves, Plane wave propagation in anisotropic media, Reflection and Refraction of EM waves	Wave Equation, Poynting vector, oscillating dipole, wave propagation in anisotropic media, Reflection and transmission coefficients	20.3-20.5, 19.12, 21.1-21.2 & RB 3
33-36	Lasers	Einstein coefficients, threshold condition, some laser systems	23.1-23.5, RB 5
37-38	Holography	Basic concepts of holography	RB 5
39-40	Recent trends in Optics	Negative RI, Laser cooling, photonics, nano-optics	Lecture notes

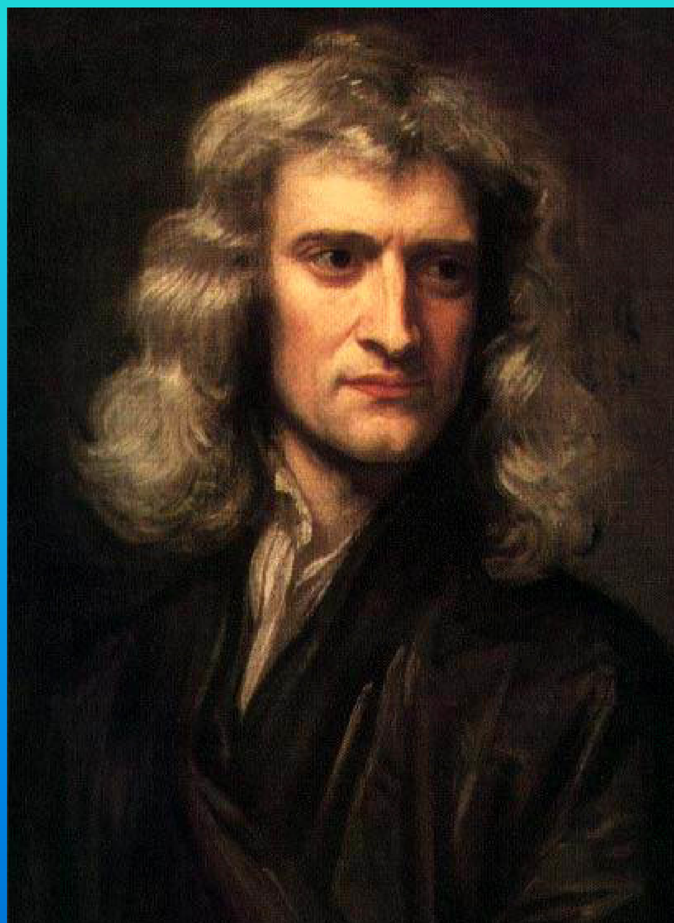
Evaluation Scheme

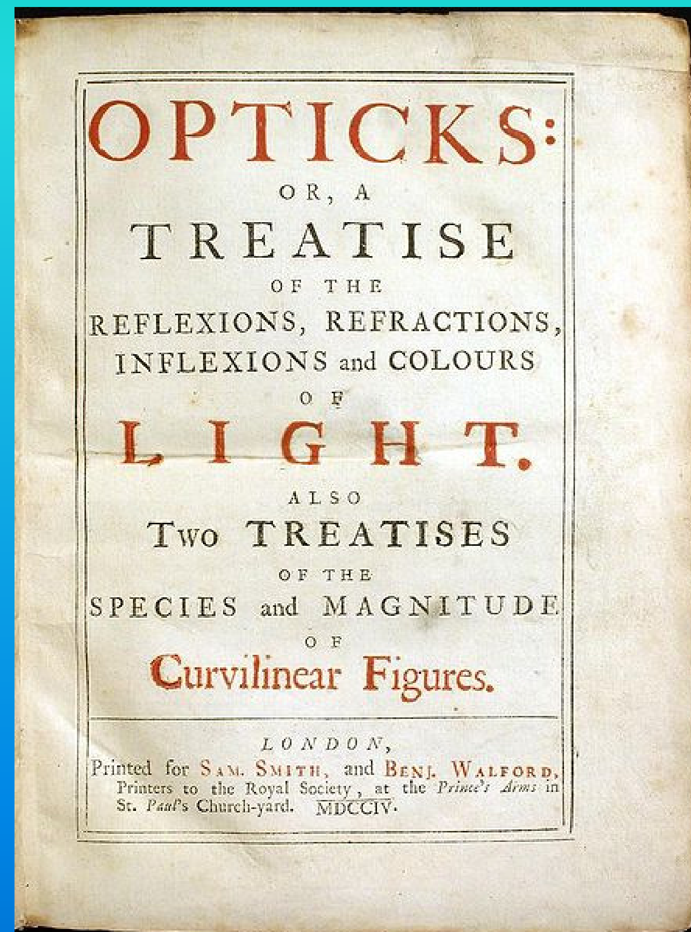
Component	Duration	Weightage (%)	Date, Time & Venue	Remarks
Mid-sem Test	90 mins	25 %	08/10/12 10-11:30AM	Closed Book
Quiz/Viva/Assignment	----	30%		------
Compre. Exam	3 hrs	45%	04/12/12 FN	Open book & Closed Book

Plan of the course

- Revisiting Basics: Reflection, Refraction…
- Geometrical Optics: Matrix Methods, Aberrations
- Scattering
- Wave Optics: Fresnel and Fraunhoffer Diffraction
- Dispersion
- Polarization, Crystal Optics
- Propagation of EM waves in different media
- Lasers & Applications

OPTICS





OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD,
Printers to the Royal Society, at the *Prince's Arms* in
St. *Paul's* Church-yard. MDCCIV.

1642-1747

OPTICS

ΟπΤΙΚη (Ancient Greek): appearance or look

OPTICKS - 1704 -English- Isaac Newton

OPTICS: properties and behavior of light and interaction of EM waves with matter, fabrication of instruments that detect or use light.

Geometrical Optics: Ray optics- light is considered to be a collection of rays that travel in straight lines and bend whenever they encounter obstacles (pass through or reflect from surfaces)

Physical Optics: wave nature : diffraction, interference

Quantum Optics: wave-particle dual nature

Phenomenon	Can be explained in terms of waves.	Can be explained in terms of particles.
Reflection	✓	✓
Refraction	✓	✓
Interference	✓	⊗
Diffraction	✓	⊗
Polarization	✓	⊗
Photoelectric effect	⊗	✓

Important Milestones of optics

- 140 AD Ptolemy table: angle of refraction in water for different angle of incidence in air

:

:

- 1608 Lippershey: first telescope with a converging objective lens and diverging eye lens
- 1609 Galieleo: Telescope with Magnification 9
- 1621 Snell: law of refraction
- 1637 Descarts derived snell's law: corpuscular model of light
- 1657: Fermat: Principle of least time
- 1864 Maxwell : EM waves and light is a EM wave
- 1887 Hertz: photoelectric effect
- 1905: Einstein: light quanta- photelectric effect
- 1960 : First laser fabrication by Maiman

:

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- 2000 John Pendry: negative refractive index
- 2006: Invisibility cloak(possibility)

:

:

Historical view of development in optics

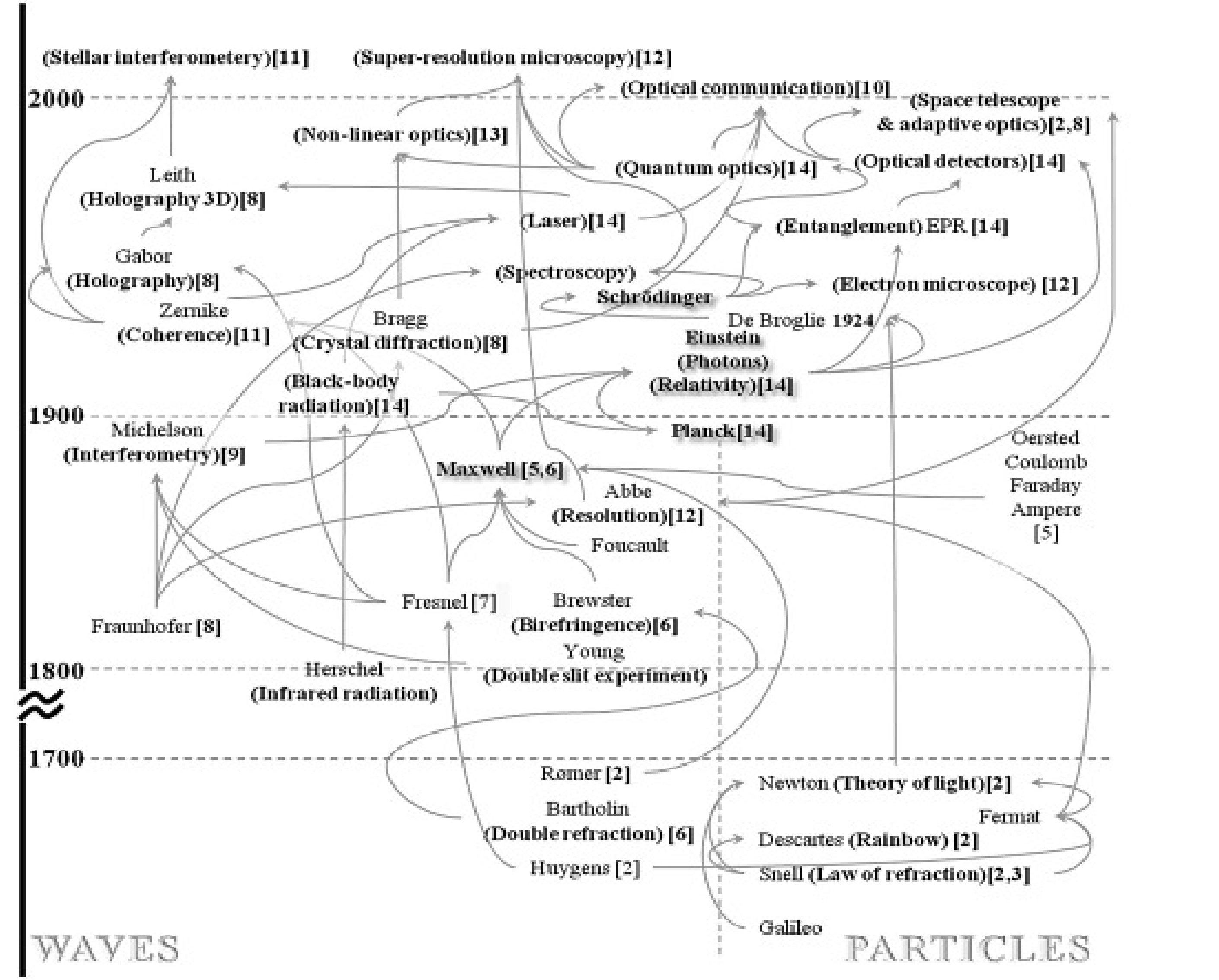
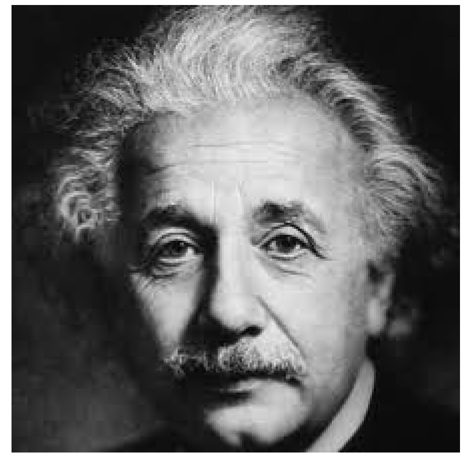


Figure 1.1 The development of optics, showing many of the interactions. Notice that there was little development in the eighteenth century, mainly because of Newton's erroneous idea of light particles. The numbers in square brackets indicate the chapters where the topics are discussed.

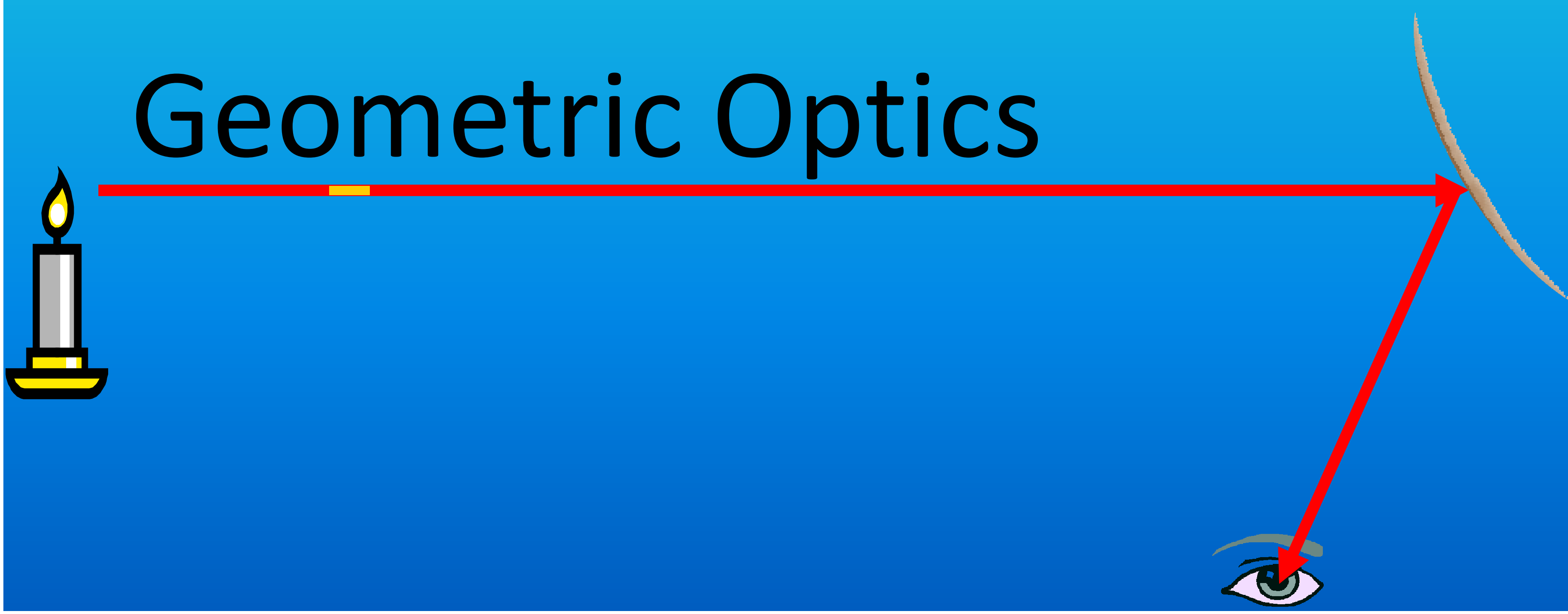
- For the rest of my life I will reflect on what light is ……… Albert Einstein, 1917

- All the fifty years of conscious brooding have brought me no close to the answer to the question, ‘What are light quanta?’ Of course today every rascal thinks he knows the answer, but he is deluding himself. --Albert Einstein 1951



1879-1955

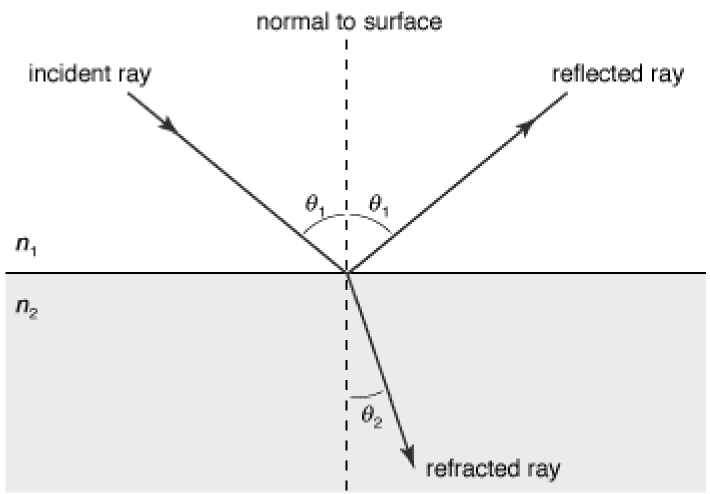
Geometric Optics



Outline

- Basics
- Reflection
- Mirrors
  - Plane mirrors
  - Spherical mirrors
    - Concave mirrors
    - Convex mirrors
- Refraction
- Lenses
  - Concave lenses
  - Convex lenses

Geometric optics



Snell's law:

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

Corpuscular theory

- **Descartes-1637 – snells's law**
- **Newton 1704- OPTICKS**

- **A luminous body emits a stream of particles in all directions.**
- **Particles or corpuscles: tiny so that a collision between particles rarely occurs**
- **Once collision occurs, the ray of light will not travel in straight line**
- **Different colors ascribed to different corpuscules**

Corpuscular theory

A particle is incident at a plane surface y=0
Conserving x-component of the momentum

$$p_1 \sin\theta_1 = p_2 \sin\theta_2$$

I

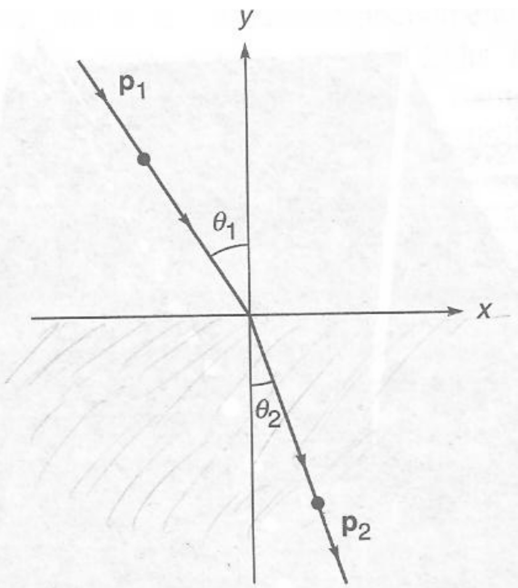


Fig. 1.1 Refraction of a corpuscle.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{p_2}{p_1}$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_2}{v_1}$$

Prediction: if the ray moves towards the normal (i.e.,refraction occurs in a denser medium) its speed will be higher which is inconsistent with experimental observations

Corpuscular theory

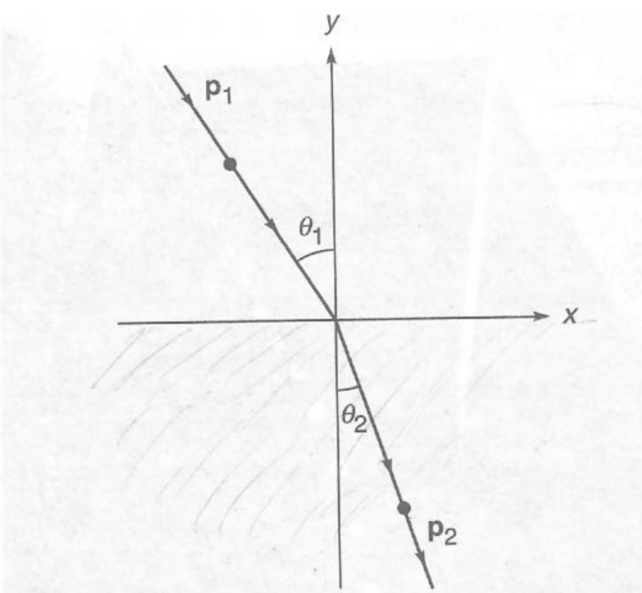


Fig. 1.1 Refraction of a corpuscle.

$$p_1 \sin\theta_1 = p_2 \sin\theta_2$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{p_2}{p_1}$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_2}{v_1}$$ X

Prediction: if the ray moves towards the normal (i.e.,refraction occurs in a denser medium) its speed will be higher which is inconsistent with experimental observations

Failure of Corpuscular theory

Fails to explain:

- Snell's law
- Diffraction
- Interference
- Polarisation

Huygens wave theory

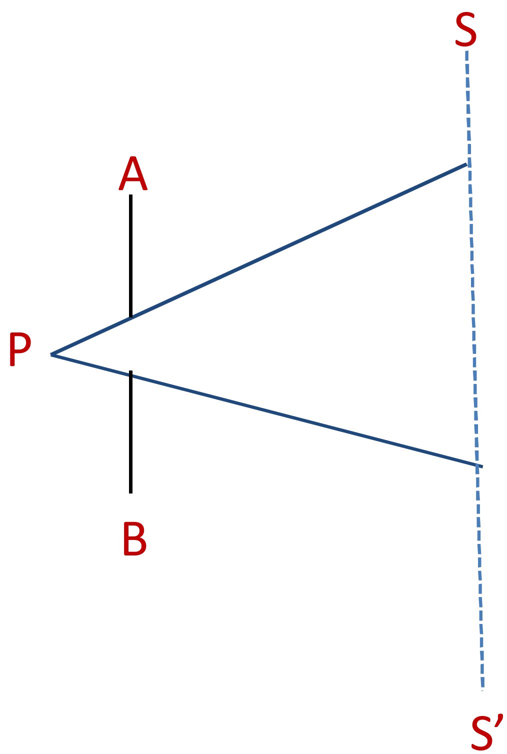
Explains all these.

Belief on corpuscular theory:

Rectilinear propagation of light

Light could propagate through vacuum i.e. it is not an elastic wave which requires medium for porpagation. So if light is composed of corpuscules it will propagate through vacuum

Geometrical Optics



$\lambda <<$ aperture size

Optical components: $\sim 10^{-3}$m

Wavelength of light : $\sim 10^{-6}$m

$\lambda \rightarrow 0$ geometrical optics

Geometrical optics : find the path of rays as it travels through optical components

Fermat’s Principle

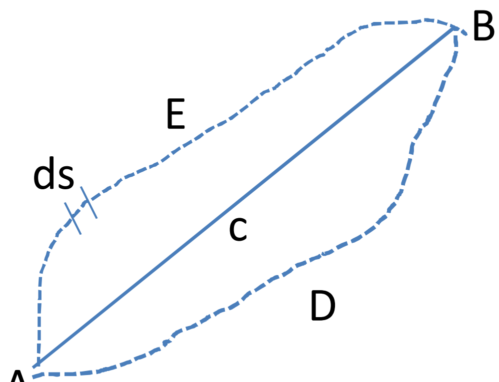
Principle of least time or Fermat’s principle:

"The actual path between two points taken by a beam of light is the one which is traversed in the least time ".

Or

"A light ray, in going between two points, must traverse as optical path length which is stationary with respect to variations of the path.”

Fermat’s Principle and its applications



For a homogeneous medium
refractive index n(x,y,z) is constant,
so the minimum optical path length
corresponds to a straight line

$$t_i = \frac{ds}{v} = \frac{n_i ds_i}{c}$$

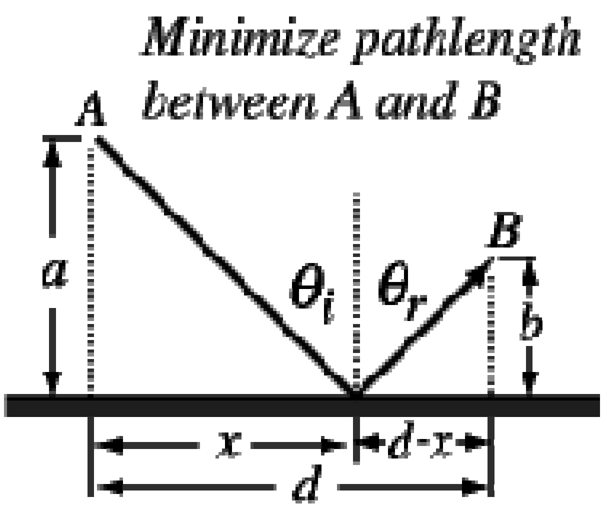
$$\tau = \frac{1}{c}\sum n_i ds_i = \frac{1}{c}\int_{A \xrightarrow[c]{} B} nds$$

$$\int_{A \xrightarrow[c]{} B} nds$$ is an extremum

$$\delta \int_{A \longrightarrow B} nds = 0$$

The actual ray path between two points is
the one for which the optical path length is
stationary with respect to variations of the path.

Fermat’s Principle and its applications



$$L_{op} = \sqrt{a^2 + x^2} + \sqrt{b^2 + (d - x)^2}$$

$$\frac{dL_{op}}{dx} = \frac{x}{\sqrt{a^2 + x^2}} - \frac{(d - x)}{\sqrt{b^2 + (d - x)^2}} = 0$$

$$\Rightarrow \sin\theta_i = \sin\theta_r$$

$$\therefore \theta_i = \theta_r$$

Law of Reflection

http://hyperphysics.phy-astr.gsu.edu

Fermat's Principle and its applications

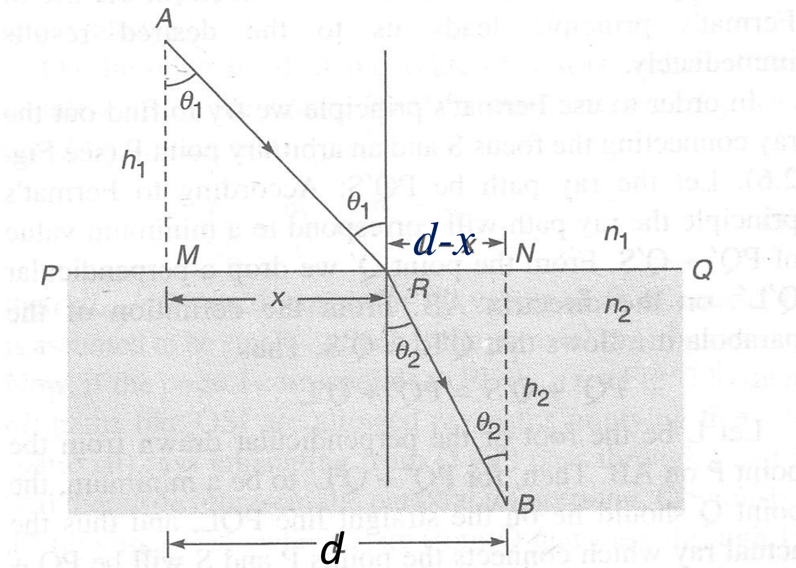


Fig. 2.5 A and B are two points in media of refractive indices n_1 and n_2. The ray path connecting A and B will be such that $n_1 \sin \theta_1 = n_2 \sin \theta_2$.

$$L_{op} = n_1\sqrt{h_1^{\ 2} + x^2} + n_2\sqrt{h_2^{\ 2} + (d-x)^2}$$

$$\frac{dL_{op}}{dx} = 0$$

$$\frac{n_1 x}{\sqrt{h_1^{\ 2} + x^2}} - \frac{n_2(d-x)}{\sqrt{h_2^{\ 2} + (d-x)^2}} = 0$$

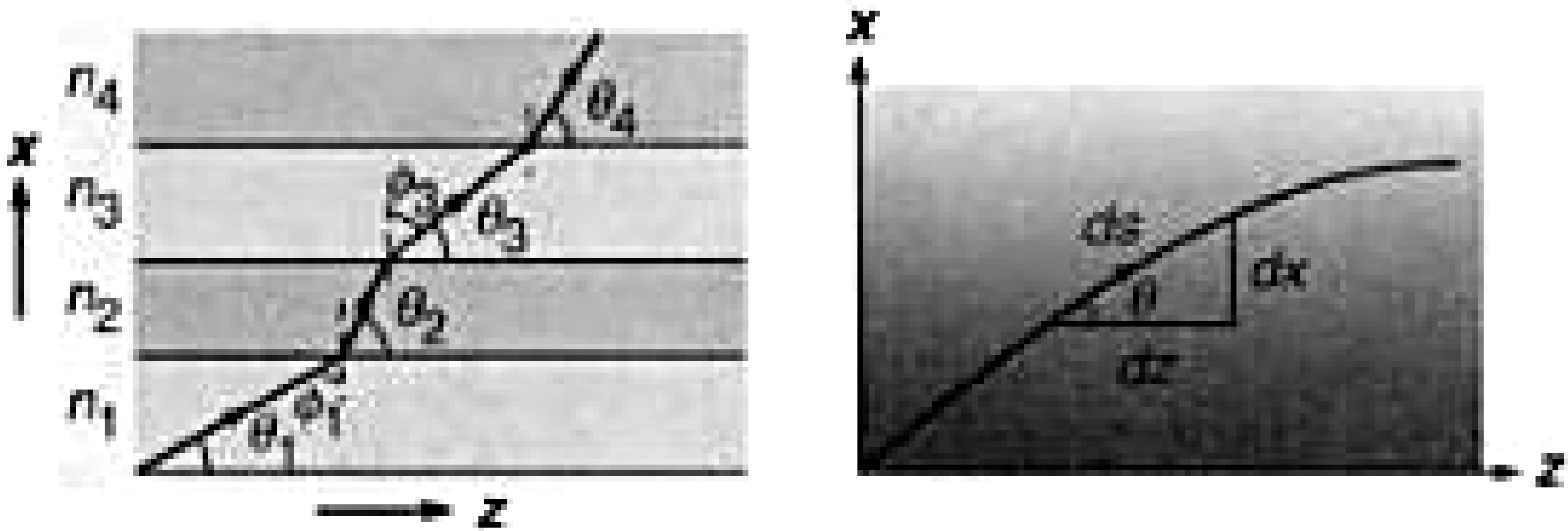
$$\sin\theta_1 = \frac{x}{\sqrt{h_1^{\ 2} + x^2}}$$

$$\sin\theta_2 = \frac{(d-x)}{\sqrt{h_2^{\ 2} + (d-x)^2}}$$

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

Snell's law of refraction

Ray paths in an inhomogeneous medium



$$n_1 \sin \phi_1 = n_2 \sin \phi_2 = n_3 \sin \phi_3 = \ldots.$$

$$n(x) \cos \theta(x) = n(x) \sin \phi(x)$$

$$n(x) \cos \theta(x) = n_1 \cos \theta_1 = \tilde{\beta}$$

Ray equation and its solution

$$n(x)\cos\theta(x) = \tilde{\beta}$$

$$ds^2 = dz^2 + dx^2$$

$$\left(\frac{ds}{dz}\right)^2 = \left(\frac{dx}{dz}\right)^2 + 1$$

$$\frac{dz}{ds} = \cos\theta = \frac{\tilde{\beta}}{n(x)}$$

$$\left(\frac{dx}{dz}\right)^2 = \frac{n^2(x)}{\tilde{\beta}^2} - 1$$

$$2\frac{dx}{dz}\frac{d^2x}{dz^2} = \frac{1}{\tilde{\beta}^2}\frac{dn^2}{dx}\frac{dx}{dz}$$

$$\frac{d^2x}{dz^2} = \frac{1}{2\tilde{\beta}^2}\frac{dn^2}{dx}$$

Ray equation and its solution

Consider a medium characterized by refractive index variation of type: $n(x)=n_0+kx$

$$\frac{d^2x}{dz^2}=\frac{1}{2\tilde{\beta}^2}\frac{dn^2}{dx}$$

$$\frac{d^2x}{dz^2}=\frac{k}{\tilde{\beta}^2}\left(n_0+kx\right)$$

$$\frac{d^2X}{dz^2}=\frac{k^2}{\tilde{\beta}^2}X(z)$$

Where, $X=x+\frac{n_0}{k}$

Ray equation and its solution

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$$\frac{d^2X}{dz^2}=\frac{k^2}{\tilde{\beta}^2}X(z)$$

Where, $X=x+\frac{n_0}{k}$

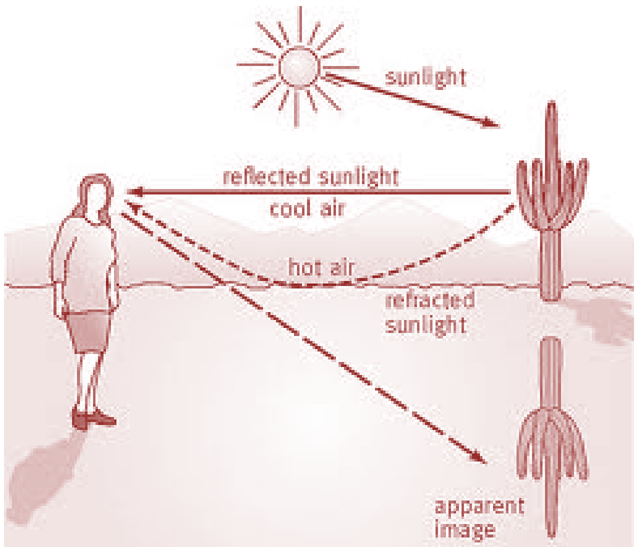
$$x(z)=C_1e^{(k/\tilde{\beta})z}+C_2e^{(-k/\tilde{\beta})z}-\frac{n_0}{k}$$

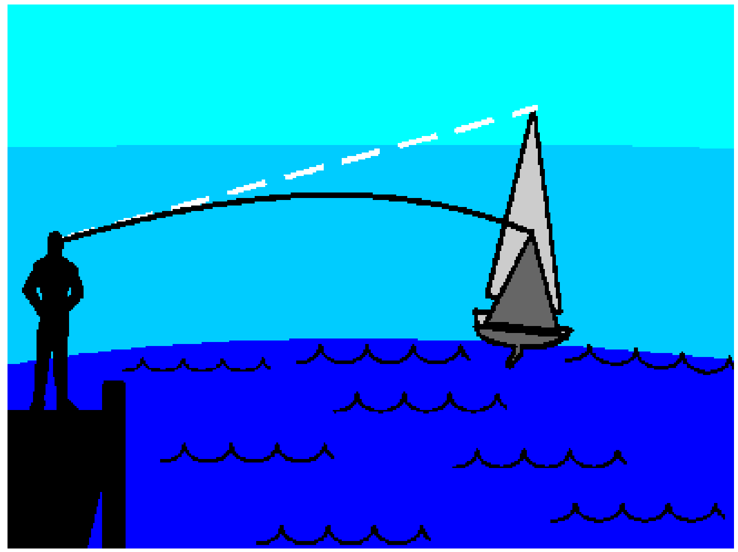
$$x(z=0)=x_1$$

$$\left.\frac{dx}{dz}\right|_{z=0}=\tan\theta_1$$

$$C_1=\frac{1}{2}\{x_1+\frac{1}{k}(n_0+n_1\sin\theta_1)\}$$

$$C_2=\frac{1}{2}\{x_1+\frac{1}{k}(n_0-n_1\sin\theta_1)\}$$


sunlight
reflected sunlight
cool air
hot air
refracted
sunlight
apparent
image



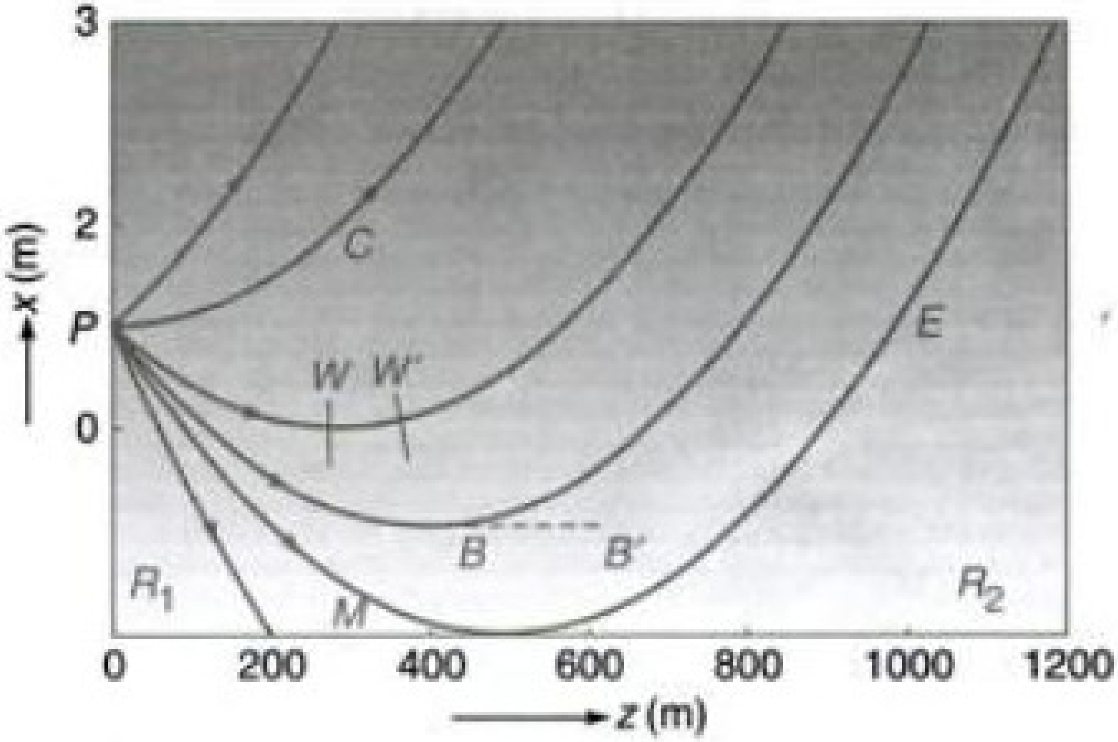


Fig. 3.13 Ray paths in a medium characterized by a linear variation of refractive index [see Eq.(16)] with $k = 1.234 \times 10^{-5}\ \mathrm{m}^{-1}$. The object point is at a height of 1.5 m and the curves correspond to +0.2°, 0°, −0.2°, −0.28°, −0.3486° and −0.5° The shading shows that the refractive index increases with x.


© Joe Orman

Artificial Mirage

An artificial mirage, using sugar solutions to simulate the inversion layers. A cat is seen looking through a glass, which has three layers of solution, with decreasing refractive index from bottom to top. The cat appears in multiple images. This simulates an atmosphere with two inversion layers.

http://en.wikipedia.org/

Ray equation and its solution

Consider a parabolic index medium characterized by refractive index variation of type: $n^2(x)=n_1^2-\gamma^2x^2$

$$\frac{dx}{dz}=\frac{\sqrt{n^2(x)-\tilde{\beta}^2}}{\tilde{\beta}}$$

$$\int\frac{dx}{\sqrt{n^2(x)-\tilde{\beta}^2}}=\pm\frac{1}{\tilde{\beta}}\int dz$$

$$\int\frac{dx}{\sqrt{(x_0^2-x^2)}}=\pm\frac{\gamma}{\tilde{\beta}}\int dz$$

$$x_0=\frac{\sqrt{n_1^2-\tilde{\beta}^2}}{\gamma}$$

Ray equation and its solution

Consider a parabolic index medium characterized by refractive index variation of type: $n^2(x)=n_1^2-\gamma^2x^2$

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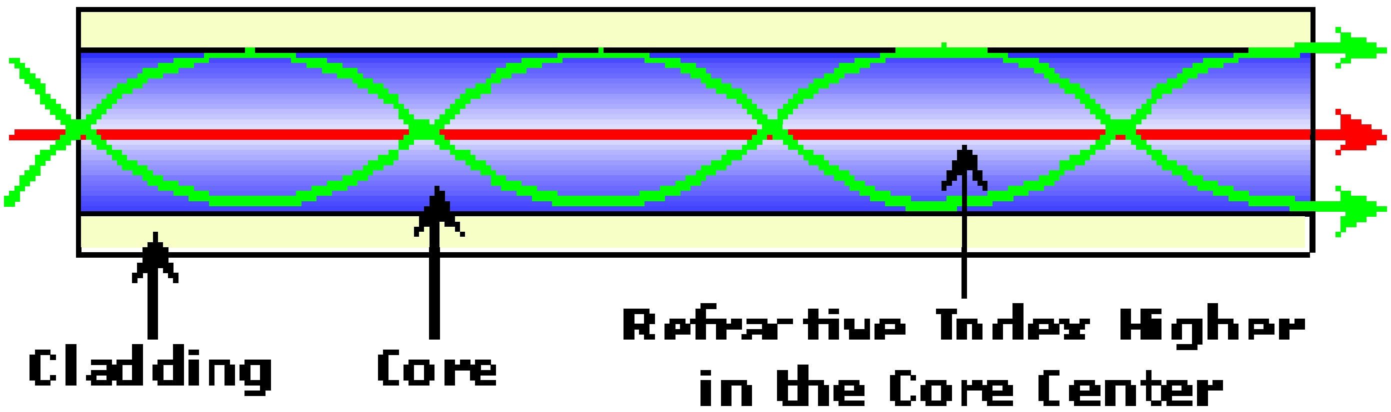
$$\int\frac{dx}{\sqrt{(x_0^2-x^2)}}=\pm\frac{\gamma}{\tilde{\beta}}\int dz$$

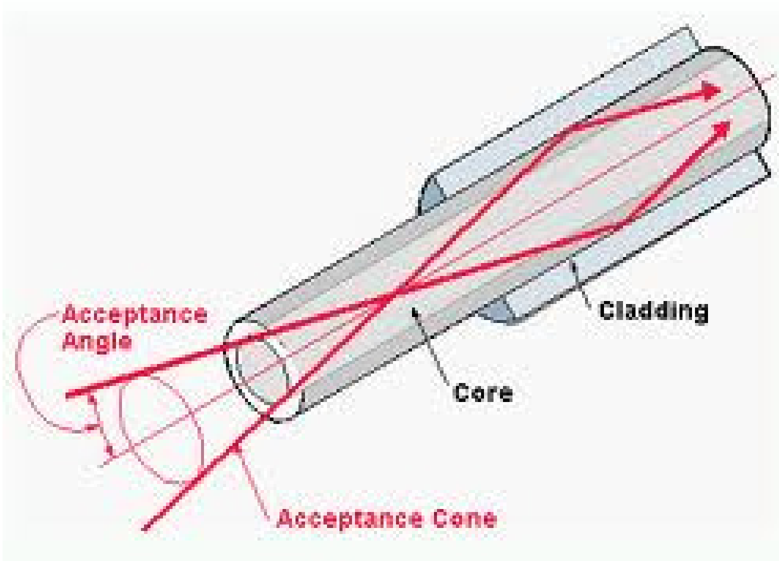
$$x_0=\frac{\sqrt{n_1^2-\tilde{\beta}^2}}{\gamma}$$

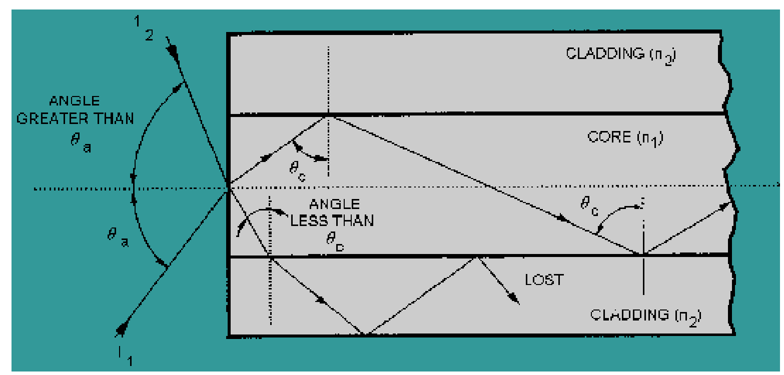
$$x=x_0\sin\theta$$

$$\theta=\pm\frac{\gamma}{\tilde{\beta}}(z-z_0)$$

$$x=x_0\sin\{\frac{\gamma}{\tilde{\beta}}(z-z_0)\}$$


Cladding
Core
Refractive Index Higher
in the Core Center


Acceptance Angle
Cladding
Core
Acceptance Cone


1
2
ANGLE GREATER THAN θ_a
CLADDING (n_2)
CORE (n_1)
θ_c
ANGLE LESS THAN θ_c
θ_c
θ_a
LOST
CLADDING (n_2)
I_1

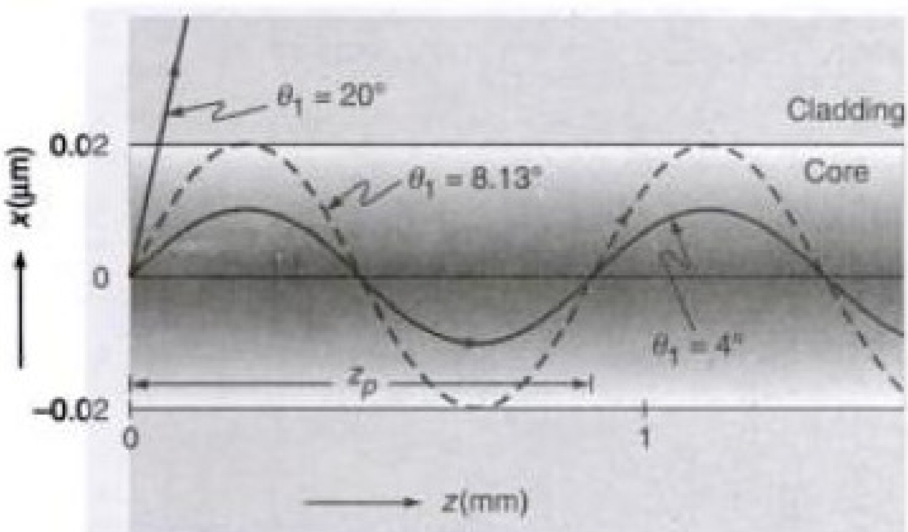


Fig. 3.23 Typical ray paths in a parabolic index medium for parameters given by Eq.(45) for $\theta_1 = 4°$, 8.13° and 20°.

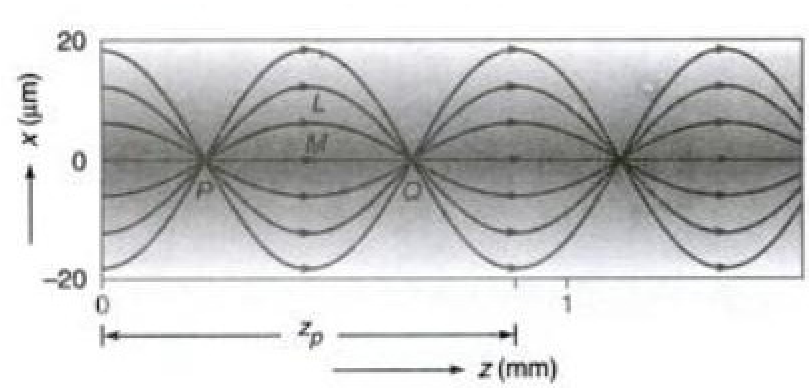


Fig. 3.25 Paraxial ray paths in a parabolic index medium. Notice the periodic focussing and defocussing of the beam.

(i) In the paraxial approximation ($\tilde{\beta} \simeq n_1$) all rays launched horizontally come to a focus at a particular point. Thus the medium acts as a converging lens of focal length given by:

$$f = \frac{\pi}{2} \frac{a}{\sqrt{2\Delta}} \tag{48}$$

(ii) Rays launched at different angles with the axis (see, for instance, the rays emerging from point P) get trapped in the medium and hence the medium acts like a 'guide'. Indeed such media are referred to as optical waveguides and their study forms a subject of great contemporary interest.

(iii) Ray paths would be allowed only in the region where $\tilde{\beta}$ is less than or equal to $n(x)$ [see Eq. (26)]. Further, dx/dz would be zero (i.e., the ray would become parallel to the z-axis) when $n(x)$ equals $\tilde{\beta}$; this immediately follows from Eq. (27).

(iv) The rays periodically focus and defocus as shown in Fig. 3.25. In the paraxial approximation, all rays emanating from P will focus at Q and if we refer to our discussion in Example 3.3, all rays must take the same time to go from P to Q. Physically, although the ray PLQ traverses a larger path in comparison to PMQ, it does so in a medium of 'lower' average refractive index—thus the greater path length is compensated for by a greater 'average speed' and hence *all* rays take the same time to propagate through a certain distance of the waveguide (see Sec. 3.4.2 for exact calculation). It is for this reason that parabolic index waveguides are extensively used in fiber-optic communication systems (see Sec. 27.7).