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सूर्यस्य विवधवर्णाः पवनेन
विघट्टिताः कराः साभ्रे ।
वियति धनुः संस्थानाः
ये दृश्यन्ते तदिन्द्रधनुः ।।

Bruhatsamhita-chapter 35
(6th century CE)

The multicolored rays of the Sun, being dispersed
in a cloudy sky, are seen in the form of a bow,
which is called the Rainbow.

ABOUT THE AUTHOR

Ajoy Ghatak is currently Professor Megh Nad Saha Fellow of NASI (The National Academy of Sciences, India). He received his BSc from Agra College, MSc from Delhi University and PhD from Cornell University. After a short tenure as a Research Associate at Brookhaven National Laboratory, he joined IIT Delhi in 1966. Professor Ghatak's research interests have been in Fiber Optics & also in Quantum Mechanics. He has written a few books including *Quantum Mechanics: Theory & Applications* (coauthored with Professor S. Lokanathan), *Optical Electronics, Fiber Optics, Lasers* (all 3 coauthored with Professor K. Thyagarajan) and his popular book on *Albert Einstein: The Story of a Genius.* An earlier edition of this book on ***OPTICS*** has been translated to Mandarin and Persian. He is recipient of several awards including the 2008 SPIE Educator award in recognition of "*his unparalleled global contributions to the field of fiber optics research, and his tireless dedication to optics education worldwide*.."; the 2003 Esther Hoffman Beller award (instituted by The Optical Society of America) in recognition of his "*outstanding contributions to optics education*…"; International Commission for Optics 1998 Galileo Galilei award and also the CSIR 1979 S.S. Bhatnagar award for "*outstanding contributions in physical sciences*". His latest award has been the 2015 Shri Om Prakash Bhasin award.

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Edition

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Ajoy Ghatak

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I dedicate this book to my students: my continuous interactions with them have led to a deeper understanding of optics.

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PREFACE TO THE SIXTH EDITION

The first laser was fabricated in 1960, and since then there has been a renaissance in the field of optics. From optical amplifiers to laser physics, fiber optics to optical communications, optical data processing to holography, optical sensors to DVD technology, ultrashort pulse generation to super continuum generation, optics now finds important applications in almost all branches of science and engineering. Indeed, to recognize the tremendous applications of light in our everyday lives, United Nations General Assembly proclaimed 2015 as the International Year of Light (IYL 2015) and to celebrate this, numerous events were organized globally.

In addition to numerous practical applications of light, it is said that it was the quest to understand the "nature of light" that brought about the two revolutions in science: the development of quantum mechanics which began with an attempt to understand the "light quanta", and the starting point of the special theory of relativity was Maxwell's equations which synthesized the laws of electricity and magnetism with those of light. Because of all this, an undergraduate course in optics has become a "must" not only for students of physics but also for students of engineering. Although, it is impossible to cover all areas in a single book, this book attempts to give a comprehensive account of a large number of important topics in this exciting field and should meet the requirements of a course on optics meant for undergraduate students of science and engineering.

Organization of the Book

The book attempts to give a balanced account of traditional optics as well as some of the recent developments in this field. The plan of the book is as follows:

- **Chapter 1** gives a brief history of the development of optics. I have always felt that one must have a perspective of the evolution of the subject that she or he wants to learn. Optics is such a vast field that it is extremely difficult to give a historical perspective of all the areas. My own interests lie in fiber optics, and hence there is a bias toward the evolution of fiber optics and related areas. In the process, I must have omitted the names of many individuals who made important contributions to the growth of optics. Fortunately, there is now a wealth of information available through the Internet; I have also included a number of references to various books and websites.
- **Chapter 2** gives a brief historical evolution of different models describing the nature of light. It starts with the corpuscular model of light and then discusses the evolution of the wave model and the electromagnetic character of light waves. We next discuss the early twentieth-century experiments, which could only be explained by assuming a particle nature of light, and we end with a discussion on "wave-particle duality."
- **Chapters 3** to **6** cover geometrical optics. Chapter 3 starts with Fermat's principle and discusses ray tracing through graded index media; explaining in detail the phenomena of mirage and looming, ray propagation through graded index optical waveguides, and reflection from the ionosphere. Chapter 4 covers ray tracing in lens systems and Chapter 5 discusses the matrix method in paraxial optics which is used in the industry. Chapter 6 gives a brief account of aberrations.
- **Chapters 7** to **12** discuss the origin of refractive index and the basic physics of wave propagation including Huygens' Principle. Many interesting experiments (such as the redness of the setting Sun, water waves, etc.) are discussed. The concepts of group velocity and the dispersion of an optical pulse as it propagates through a dispersive medium are discussed in detail. Self-phase modulation, which is one of the phenomena leading to the super continuum generation, is also explained.
- **Chapters 13** to **16** cover the very important and fascinating area of interference and many beautiful experiments associated with it—the underlying principle is the superposition principle, which is discussed in Chapter 13. Chapter 14 discusses interference by division of the wave front including the famous Young's double-hole interference experiment. In Chapter 15, interference by division of amplitude is discussed, which allows us to understand the colors of thin films and applications such as antireflection films. The basic working principle of the Fiber Bragg Gratings

(usually abbreviated as FBG) is discussed along with some of their important applications in the industry. In the same chapter, the Michelson interferometer is discussed for which Michelson received the 1907 Nobel Prize in Physics in 1907. Chapter 16 discusses the Fabry–Perot interferometer which is based on multiple-beam interference and is characterized by a high resolving power and, hence, finds applications in high-resolution spectroscopy.

- **Chapter 17** discusses the basic concept of temporal and spatial coherence. The ingenious experiment of Michelson, which used the concept of spatial coherence to determine the angular diameter of stars, is discussed in detail. Topics such as optical beats and Fourier transform spectroscopy are also discussed.
- **Chapters 18, 19,** and **20** cover the very important area of diffraction and discuss the principle behind topics such as the diffraction divergence of laser beams, resolving power of telescopes, laser focusing, X-ray diffraction, Fourier optics and spatial frequency filtering.
- **Chapter 21** discusses the underlying principle of holography and some of its applications. Dennis Gabor received the 1971 Nobel Prize in Physics for discovering the principle of holography.
- **Chapters 22** to **24** cover the electromagnetic character of light waves. All chapters have been significantly revised in the 6th edition. Chapter 22 discusses the polarization phenomenon and propagation of electromagnetic waves in anisotropic media including first-principle derivations of wave and ray velocities. Phenomena such as optical activity and Faraday rotation (and its applications to measuring large currents) are explained from first principles. In Chapter 23, starting with Maxwell's equations, the wave equation is derived which led Maxwell to predict the existence of electromagnetic waves and to propound that light is an electromagnetic wave. Reflection and refraction of electromagnetic waves by a dielectric interface are discussed in Chapter 24. Results derived in this chapter directly explain phenomena such as polarization by reflection, total internal reflection, evanescent waves, and Fabry–Perot transmission resonances.
- **Chapter 25** covers the particle nature of radiation, for which Einstein received the 1921 Nobel Prize. The chapter also discusses the Compton Effect (for which Compton received the 1927 Nobel Prize in Physics), which established that the photon has a momentum equal to $h\nu/c$.
- **Chapter 26** is a new chapter and discusses the basic concepts of quantum theory, solutions of the Schrödinger equation, Entanglement and Bell's inequality.
- **Chapter 27** is on lasers—a subject of tremendous technological importance. The basic physics of optical amplifiers and of lasers along with their special characteristics is also discussed.
- **Chapters 28** to **30** discuss waveguide theory and fiber optics, an area that has revolutionized communications and has found important applications in sensor technology. Chapter 28 (which has also been considerably revised) discusses the light guidance property of the optical fiber (using ray optics) with applications in fiber-optic communication systems; the chapter also gives a very brief account of fiber-optic sensors. Chapter 29 discusses basic waveguide theory and concept of modes with Maxwell's equations as the starting point. Chapter 30 discusses the propagation characteristics of single-mode optical fibers, which are now extensively used in optical communication systems.
- In 1905 Einstein put forward the special theory of relativity which is considered one of the revolutions of the 20th century. The starting point of the Special Theory of Relativity was Maxwell's equations, which synthesized the laws of electricity and magnetism with those of light. **Chapters 31, 32** and **33** describe briefly the important consequences of the special theory of relativity, i.e., time dilation, length contraction, the mass-energy relation, and Lorentz transformations.
- Very often a good photograph clarifies an important concept and also sustains the student's interest in the subject. It is with this intention that we have given a few colored photographs (in the beginning of the book) that describe important concepts in optics.

In summary, the book discusses some of the important topics that have had a tremendous impact in the growth of science and technology.

Other Important Features of the Book

- A large number of figures correspond to actual numerical calculations, which were generated using software such as GNUPLOT and Mathematica. There are also some diagrams which give a three-dimensional perspective of the phenomenon.

- Most chapters start with important milestones in the area. This gives a historical perspective of the topic.
- All important formulae have been derived from first principles so that the book can also be used for self-study.
- Numerous worked out examples are scattered throughout the book to help clarify difficult concepts.
- Each chapter ends with a summary of important results derived in the chapter.

Experiments in fiber optics

My own research interests are in the general area of fiber optics. I have found that there are many beautiful experiments in fiber optics, which are not very difficult to set up, that allow us not only to understand difficult concepts but also to find very important applications. For example,

- Chapter 10 discusses in great detail the dispersion of an optical pulse as it propagates through a dispersive medium. This is an extremely important concept. The chapter also discusses self-phase modulation (usually abbreviated as SPM) that is probably the simplest nonlinear optical phenomenon which can be easily understood from first principles. Indeed, when a monochromatic laser pulse propagates through a special optical fiber, SPM (along with other phenomena) can lead to the awesome super continuum generation; we discuss this in Chapter 10.
- The working of a Fiber Bragg Grating (usually abbreviated as FBG) is a beautiful application of the interference phenomenon, and FBGs find very important applications in sensors and other optical devices. In Chapter 15, the basic physics of an FBG is discussed along with its very important application in temperature sensing at places where no other device would work.
- The experiment on Faraday rotation in optical fibers (discussed in Chap. 22) allows one to understand the concept of rotation of plane of polarization in the presence of a longitudinal magnetic field. This experiment finds important application in the industry for measuring very large currents (about 10,000 amperes or more). The theory of Faraday rotation is also given from first principles. In Chapter 22, the change in the state of polarization (usually abbreviated as SOP) of a light beam as it propagates through an elliptic core single-mode optical fiber has been discussed; the experiment not only allows one to understand the changing SOP of a beam propagating through a birefringent fiber, but also helps one to understand the radiation pattern of an oscillating dipole.
- Erbium-doped fiber amplifier (usually abbreviated as EDFA) and fiber lasers are discussed in Chapter 27. The working of an EDFA allows one to easily understand the concept of optical amplification.
- Optical fibers with parabolic index variation are used in optical communication systems. Ray paths in such fibers and their dispersion characteristics are of great importance. This is discussed from first principles in Chapters 3 and 28.
- Chapters 28 through 30 are on waveguide theory and fiber optics, an area that has revolutionized communications and finds important applications in sensor technology. Optical fibers are now widely used in endoscopy, display illumination, and sensors, and of course the most important application is in the field of fiber-optic communication systems. We discuss all this in Chapter 28. Chapter 29 discusses basic waveguide theory (and concept of modes) with Maxwell's equations as the starting point. The chapter allows one to understand the transition from geometrical optics to wave optics, which happens to be similar to the transition from classical mechanics to quantum mechanics. Chapter 30 discusses the waveguiding properties of single-mode optical fibers, which are now extensively used in optical communication systems. The prism film coupling experiment (discussed in Chapter 29) allows one to understand the concept of quantization, an extremely important concept in physics and electrical engineering.

  There are many such examples scattered throughout the book, and each example is unique and not usually found in other textbooks.

Online Resources for Instructors

Various resources are available to instructors for this text, including solutions to end-of-chapter problems, lecture Power Points and the text images in PowerPoint form. All these can be found at the text's website: **http://www.mhhe.com/ghatak/optics6**

Acknowledgments

At IIT Delhi, I was very fortunate to have the opportunity to interact with outstanding colleagues and outstanding students, so it was always a pleasure and challenge to teach any course there. We had the opportunity and freedom to modify and develop any course and present it in a form that would make the subject more interesting. That is how the present book evolved. After retiring from IIT Delhi, I have been giving short courses in various topics at many colleges; the response from these short courses have motivated me to revise the book extensively and put some of the topics in an easy to understand form.

In the writing of the six editions of this book, many people have helped me and have also made important suggestions. First, I would like to mention the name of my very close friend and colleague Professor Ishwar Goyal, who used earlier Indian editions of this book many times while teaching Optics at IIT Delhi and offered numerous suggestions and offered constructive criticism; I am sure he would have been very happy to see this edition of the book, but unfortunately, he is no longer with us—I greatly miss my interactions with him. I am very grateful to Professor M. S. Sodha for his constant encouragement and support. My sincere thanks to Professor K. Thyagarajan for continuous collaboration and for letting me use some of his unpublished notes. My grateful thanks to Professors Arun Kumar, Lalit Malhotra, Bishnu Pal, Anurag Sharma, and K. Thyagarajan (from IIT Delhi); Dr. Kamal Dasgupta and Dr. Mrinmay Pal (from CGCRI, Kolkata); Professors Vengu Lakshminarayanan (from University of Waterloo, Canada) and Professor Enakshi Sharma (now at University of Delhi South Campus) for their help in writing some portions of the book. I am also very grateful to Professor Anirban Pathak (from Jaypee Institute of Information Technology, Noida) for our recent collaboration and introducing me to new areas related to optics. I thank Dr. Gouranga Bose, Dr. Parthasarathi Palai (now at Tejas Networks in Bangalore), Professor Chandra Sakher, Professors R. S. Sirohi, K. Thyagarajan, and Ravi Varshney (from IIT Delhi); Professors Vengu Lakshminarayanan and Govind Swarup (from GMRT, Pune); Dr. Somnath Bandyopadhyay, Dr. Shyamal Bhadra, Dr. Kamal Dasgupta, Dr. Tarun Gangopadhyay, Atasi Pal, and Dr. Mrinmay Pal (from CGCRI, Kolkata); Dr. Suresh Nair (from NeST, Cochin); Avinash Pasricha (from the U.S. Information Service at New Delhi); Dr. R. W. Terhune, Professor R. A. Phillips, and Dr. A. G. Chynoweth (from the United States) and Dr. R. E. Bailey (from Australia) for providing me important photographs that I have used in this book. I also thank V. V. Bhat for providing me very important literature on the scientific contributions made in ancient India. I would also like to thank my other colleagues, Professor B. D. Gupta, Professor Sunil Khijwania, Professor Ajit Kumar, Dr. Vipul Rastogi, Professors M. R. Shenoy and Kehar Singh, and Mr Varghese Paulose for many discussions. I also thank all the authors and their publishers for allowing me to use many diagrams from their published work. I thank Professor G. I. Opat of University of Melbourne for his invitation to attend the 1989 conference on teaching of optics which gave me many ideas on how to make difficult concepts in optics easy to understand.

Finally, I owe a lot to my family—particularly to my wife, Gopa—for allowing me to spend long hours in preparing this difficult manuscript and for her support all along. I will be very grateful for suggestions for further improvement of the book. My e-mail addresses are ajoykghatak@yahoo.com and ajoykghatak@gmail.com.

Ajoy Ghatak
New Delhi
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PHOTOGRAPHS

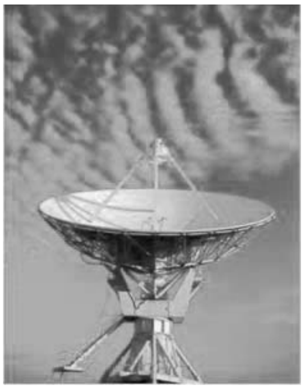


Fig. 1 A paraboloidal satellite dish.

[*Photograph courtesy*: *McGraw-Hill Digital Access Library*].

Fig. 2 Fully steerable 45 m paraboloidal dishes of the Giant Metrewave Radio Telescope (GMRT) in Pune, India. The GMRT consists of 30 dishes of 45 m diameter with 14 antennas in the Central Array. [*Photograph courtesy: Professor Govind Swarup, GMRT, Pune*].

Fig. 3 This is actually *not* a reflection in the ocean, but the miraged (inverted) image of the Sun's lower edge. A few seconds later (notice the motion of the bird to the left of the Sun), the reflection fuses with the erect image. The photographs were taken by Dr. George Kaplan of the U. S. Naval Observatory and are on the Naval Observatory and are on the website *http://mintake.sdsu.edu/GF/explain/simulations/infmir/Kaplan_photos.html created by Dr. A Young*. [*Photographs used with kind premissions from Dr. Kaplan and Dr. Young.]*

Fig. 4 A typical mirage as seen on a hot road on a warm day. *Photograph adapted from http://fizyka.phys.put.poznan.p1/~peiransk/Physics%20Around%20Us%20UsAir%20%mirror.jpg.* [*The Photograph was taken by Professor Piotr Pieranski of Ponz Universty of Technology in Poland; used with permission from Professor Pieranski*].

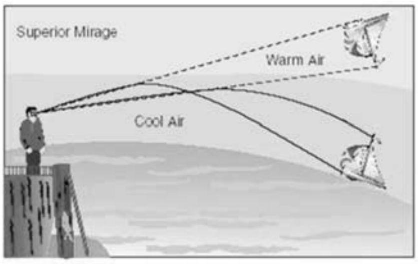


Fig. 5 If we are looking at the ocean on a cold day, we find that the air near the surface of the water is cold and it gets warmer as we go up. Thus, as we go up, the refractive index decreases continuously and because of curved ray paths, one will observe an inverted image of the ship (at a greater height) as shown in the figure above; this is known as the *superior mirage.*

Fig. 6 A house in the archipelago with a superior mirage. *Figure adapted from http://virtual.finland.fi/netcomm/news/showarticle.asp?intNWSAID=25722*. [*Photograph was taken by Dr. Pekka Parviainen in Turku, Finland; used with kind permission from Dr. Parviainen*].

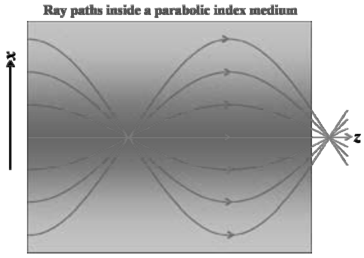


Fig. 7 Ray paths in a graded index medium characterized by a refractive index variation which decreases parabolically in the transverse direction. Because of focusing properties, it has many important applications.

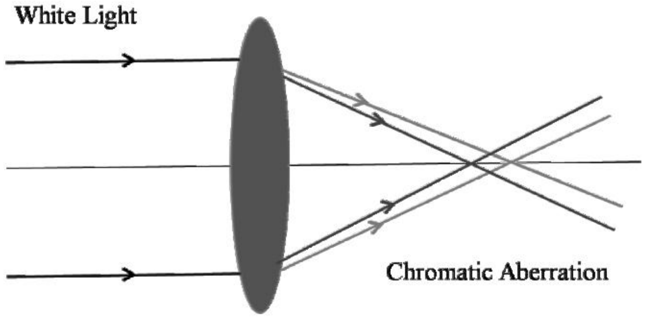


Fig. 8 A parallel beam of white light is incident on a lens. Different wavelengths of light have slightly differing focal lengths leading to chromatic aberration.

Fig. 9 The non circular shape of the setting sun. [*Photograph courtesy McGraw Hill Digital Access Library.*]

Fig. 10 The Earth rising over moon surface in a computer altered image. [*Photograph courtesy*: *McGraw Hill Digital Library*].

Fig. 11 Full moon over landscape at dusk. Notice the blue sky and the red glow of the setting Sun. Both phenomena are due to Rayleigh scattering. [*Photograph courtesy*: *McGraw Hill Digital Library*].

Fig. 12 The glass on the right contains distilled water and the glass on the left glass contains distilled water with few drops of milk. Because of scattering, the laser beam can be easily seen as it traverses through the liquid. *Figure adapted from http://silver-lightning.com/tyndall/*. [*The Photograph was taken by Mr. Marshall Dudley; used with kind permission from Mr. Marshall Dudley*].

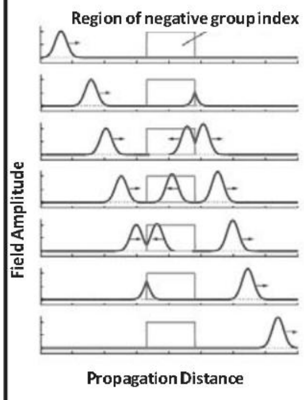


Fig. 13 Propagation of a pulse through a material characterized by negative group velocity. The peak of the transmitted pulse appears to emerge from the material medium before the peak of the incident pulse enters the medium. It may be seen that the pulse appears to move backward in the medium. Such backward propagation has been observed in the laboratory. The plots are based on a simple model that assumes that all spectral components of the pulse propagate without loss at the same group velocity. [*Adapted from Boyd and Gauthier, Controlling the velocity of light pulses, Science, 326, 1074 (2009); used with permission from Professor Boyd and Professor Gauthier*].

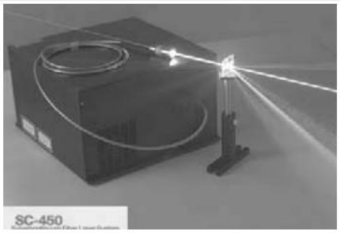


Fig. 14 Supercontinuum white light source. Laser pulses of 6ps duration are incident on a special optical fiber characterized by a very small mode field diameter which leads to very high intensities. Because of the high intensities we have SPM (Self-Phase Modulation) and other non-linear effects; these non-linear effects result in the generation of new frequencies. In this experiment, the entire visible spectrum gets generated which can be observed by passing the light coming out of the optical fiber through a grating. The repetition rate of the laser pulses is 20 MHz. The wavelengths generated range from 460 nm to 2200 nm. [*Photograph courtesy* : *Fianium, UK.*].

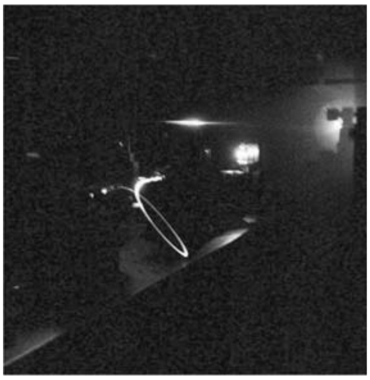


Fig. 15 Supercontinuum generation by 350 fs laser pulses (at 1060 nm wavelength) as it passes through a Photonic Crystal Fiber. Notice the color of light changing as the pulses propagate through the fiber. The output is passed through a prism to generate the supercontinuum. The fiber was fabricated at CGCRI, Kolkata and the experiment was carried out by Dr. Shyamal Bhadra and Mr. John McCarthy in Professor Ajoy Kar's Laboratory at Heriot Watt University in Edinburgh. [*Photograph courtesy: Dr. Shyamal Bhadra of CGCRI, Kolkata*].

Fig 16 Refraction of a spherical wave at an interface. *The diagram is by Dr. Oleg Alexandrov and is in public domain.*

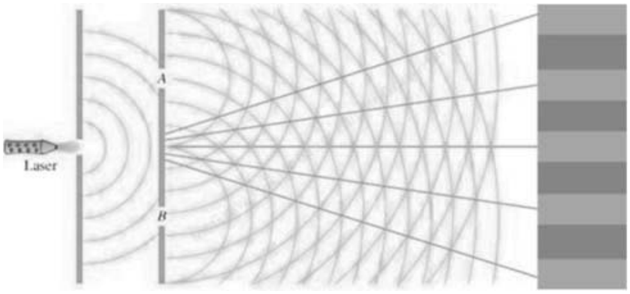


Fig. 17 Two slit experiment demonstrating the interference phenomenon. [*Photograph courtesy: McGraw Hill Digital Library*].

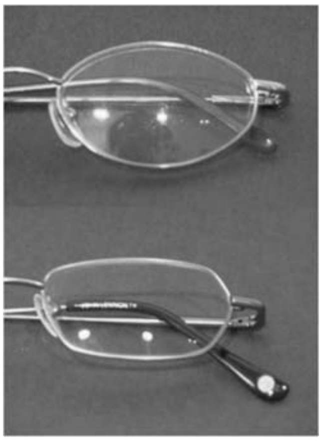
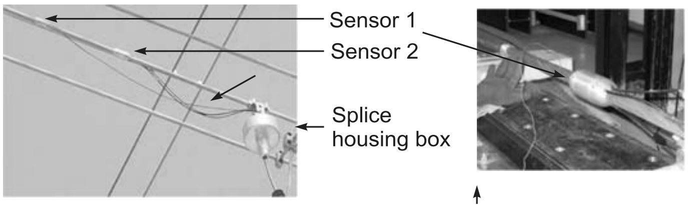


Fig. 18 The top photograph is a glass lens without anti-reflective coating and the bottom photograph is of a lens with anti-reflective coating. Note the reflection of the photographer in the top lens and the tinted reflection in the bottom. [*Photograph taken by Justin Lebar; used with kind permission from Mr Lebar*].



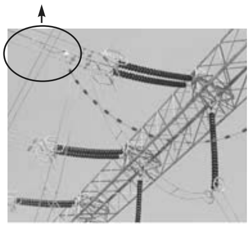


Fig. 19 FBG-based temperature sensor system on 400 KV power conductor at Subhashgram substation of Powergrid Corporation of India. [*Slide Courtesy: Dr. Tarun Gangopadhyay and Mr. Kamal Dasgupta, CGCRI, Kolkata.*]

Fig. 20 The substation of Powergrid Corporation of India (near Kolkata, India) where the FBG temperature sensors have been installed. In the photograph, the author is with Dr. Tarun Gangopadhyay and Mr. Kamal Dasgupta. [*Slide Courtesy: Dr. Gangopadhyay and Mr. Dasgupta, CGCRI, Kolkata*].

Fig. 21 Wings of these butterflies have naturally occurring multiple stacks of layers; interference of light reflected from the multiple layers is responsible for their beautiful colors. [*Adapted from J.C. Gonzato and B. Pont's article " A phenomenological representation of iridescent colors in butterfly wings" in http://www.labri.fr/perso/gonzato/Articles/GONZATO_Butterfly_WSCG2004.pdf*].

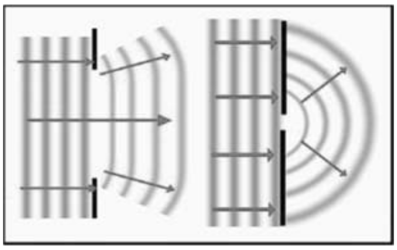


Fig. 22 If an obstacle with a small gap is placed in the tank the ripples emerge in an almost semicircular pattern; the small gap acting almost like a point source. If the gap is large however, the diffraction is much more limited. *Small*, in this context, means that the size of the obstacle is comparable to the wavelength of the ripples. [*Drawing by Ms. Theresa Knott; used with her kind permission*].

Fig. 23 The laser beam, launched from VLT´s 8.2-metre Yepun telescope, crosses the sky and creates an artificial star at 90 km altitude in the high Earth´s mesosphere. Notice that the spreading of the beam is extremely small. [*Photograph by Dr. G Huedepohl. The photograph (in the public domain) is adapted from http://www.eso.org/public/images/gerd_huedepohl_4/*].

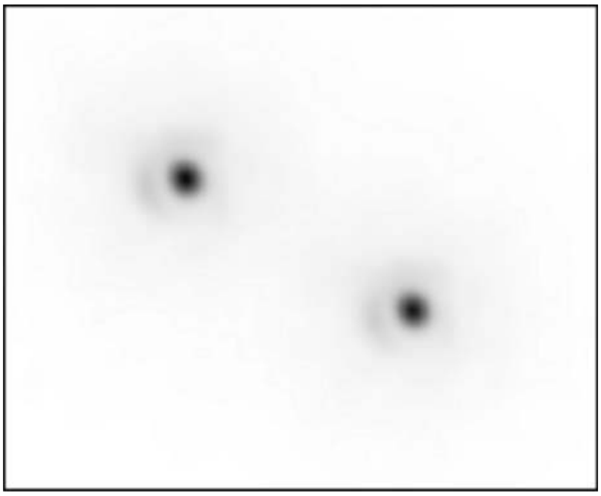


Fig. 24 Image of the binary star Zeta Bootis by a 2.56 m telescope aperture; the Airy disc around each of the stars can be seen. [*The photograph is by Dr. Bob Tubbs; used with kind permission from Dr. Tubbs*].

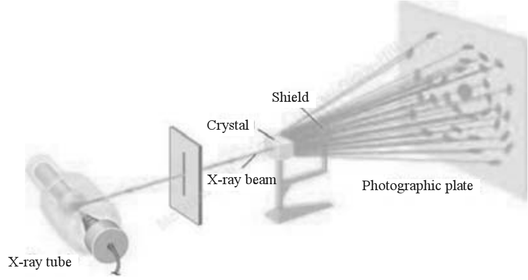


Fig. 25 Arrangement for obtaining the X-ray diffraction pattern of a crystal. [*Photograph courtesy: McGraw Hill Digital Access Library*].

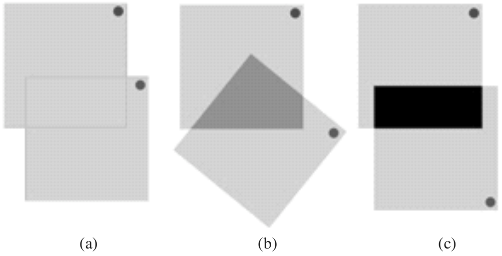


Fig. 26 Actual photographs with two Polaroids at different angles of relative orientation. (a) If the two Polaroids are parallel to each other, almost the entire light passes through. (b) when the two Polaroids are oriented at with respect to each other about 50% of the light passes through; this is because . (c) when the two Polaroids are at right angles to each other (notice the position of the blue dot) almost no light will pass through. [*Photographs adapted from http://www.a-levelphysicstutor.com/about.php; used with kind permission from Dr. Alan J. Reed.*]

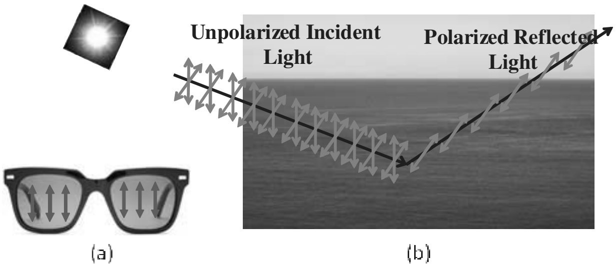


Fig. 27 (a) (commercially available) polarized sunglass blocks the horizontal component and allows only the vertical component to pass through. (b) If the sunlight is incident on the water surface at an angle close to the Brewster angle, then the reflected light will be almost polarized and if we now wear polarized sunglasses, the glare, i.e., the light reflected from the water surface will not be seen. Polarized sunglasses are often used by fishermen to remove the glare on the surface and see the fish inside water.

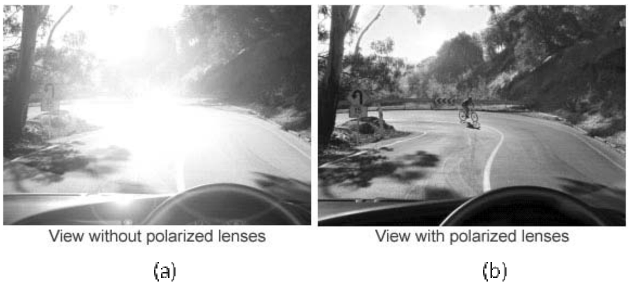


Fig. 28 (a) A photograph on the road with ordinary glasses. (b) If we use polarized lenses, the glare can be considerably reduced. [*Photographs adapted from www.esaver.com.my/index.php?option=com_content&view=article&id=95&Itemid=220*]

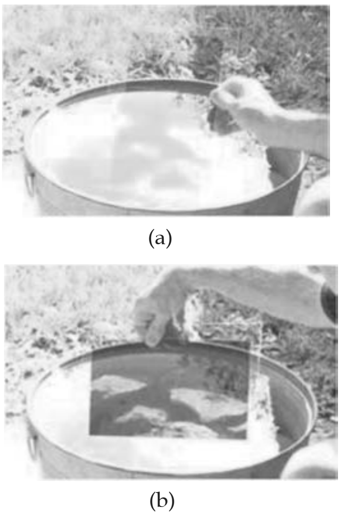


Fig. 29 If the sunlight is incident on the water surface at an angle close to the Brewster angle, then the reflected light will be almost polarized. (a) If the polaroid allows the (almost polarized) reflected beam to pass through, we see the glare from water surface. (b) The glare can be blocked by using a vertical polarizer and one can see the inside of the water. [*Figure adapted from http://polarization.com/water/water.html. Photographs were taken by Dr. J Alcoz; used with kind permission from Dr. Alcoz*].

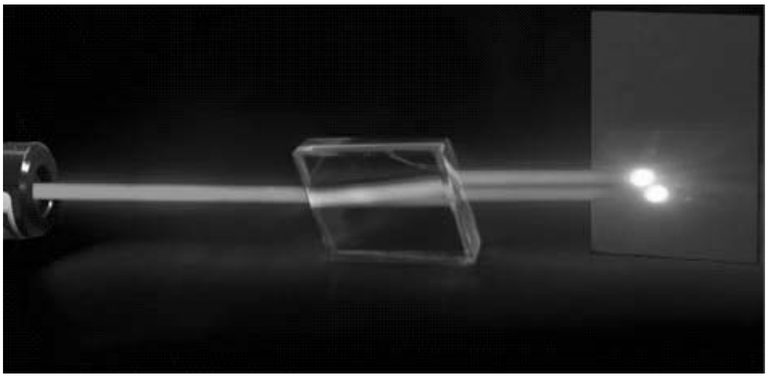
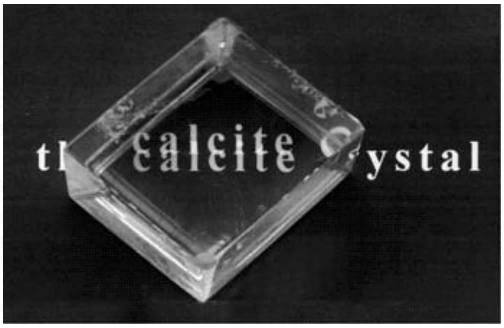


Fig. 30 When an unpolarized light beam is incident normally on a calcite crystal, it usually splits up into two linearly polarized beams. [*Photograph courtesy Professor Vasudevan Lakshminarayanan* and adapted from *The sunstone and polarised skylight: ancient Viking navigational tools* by G. Ropars, A. Le Flocha and V. Lakshminarayanan, Contemporary Physics, 2014.]

Fig. 31 Typical double image of a sentence in a printed text. The ordinary image is fixed, while the upper extraordinary image is shifted and can rotate. [Photograph courtesy Professor Vasudevan Lakshminarayanan and adapted from *The sunstone and polarised skylight: ancient Viking navigational tools* by G. Ropars, A. Le Flocha and V. Lakshminarayanan, Contemporary Physics, 2014].



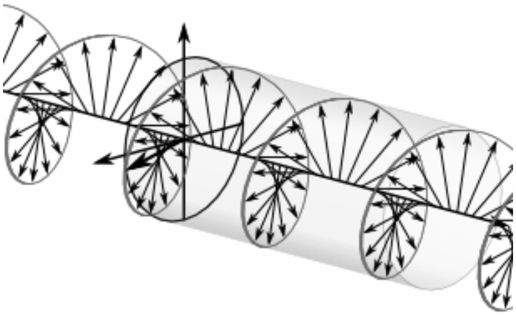


Fig. 32 Circularly polarized light. The drawing is by Dr Dave and is in the public domain.
[Animation of circularly polarized light can be seen at http://en.wikipedia.org/wiki/File:Circular.Polarization.Circularly.Polarized.Light_Left.Hand.Animation.305x190.255Colors.gif]

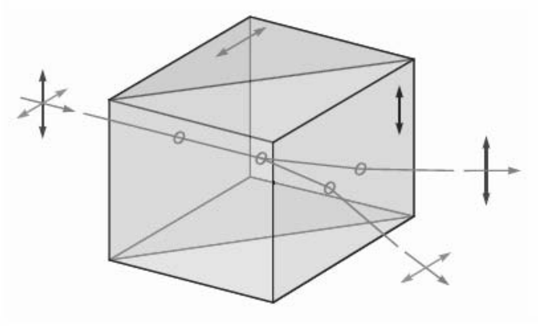


Fig. 33 Schematic of an actual Wollaston prism. The prism separates an unpolarized light beam into two linearly polarized beams. It consists of two calcite prisms (so that the optic axes are perpendicular to each other), cemented together with Canada balsam. A commercially available Wollaston prism has divergence angles from 15° to about 45°.

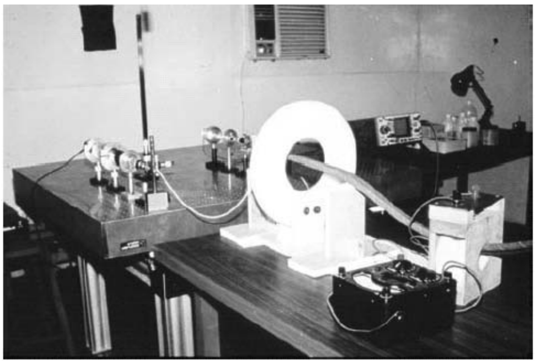


Fig. 34 As experimental setup to measure Faraday rotation in optical fibers because of large current passing through a conductor. Photograph courtesy: Professor Chandra Sakher, IIT Delhi.

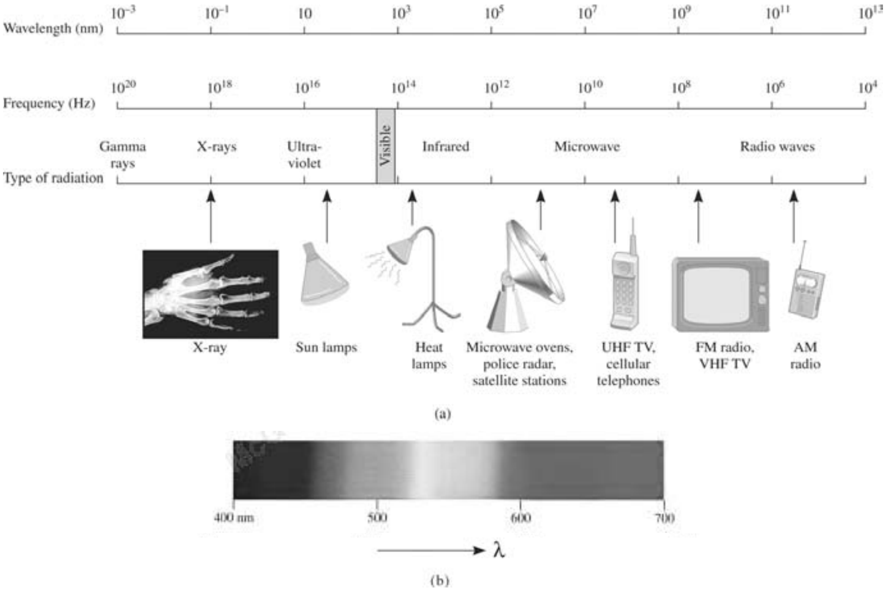


Fig. 35 **(a)** The electromagnetic spectrum; gamma rays have the highest frequency (and the shortest wavelength) and radio waves have the lowest frequency (and the longest wavelength). All wavelengths travel with an identical velocity in vacuum. *Photograph courtesy: McGraw Hill Digital Access Library.* (b) Wavelengths associated with the visible portion of the electromagnetic spectrum (which is sensitive to the retina of our eye) ranges from about 0.4 μm (blue region of the spectrum) to about 0.7 μm (red region of the spectrum), the corresponding frequencies are about 750 THz and 420 THz; 1 THz = 10^{12} Hz. A wavelength of 0.5 μm corresponding to the bluish green region of the spectrum has a frequency of 600 THz and a wavelength of 0.6 μm (corresponding to the reddish yellow green region of the spectrum) has a frequency of 500 THz.

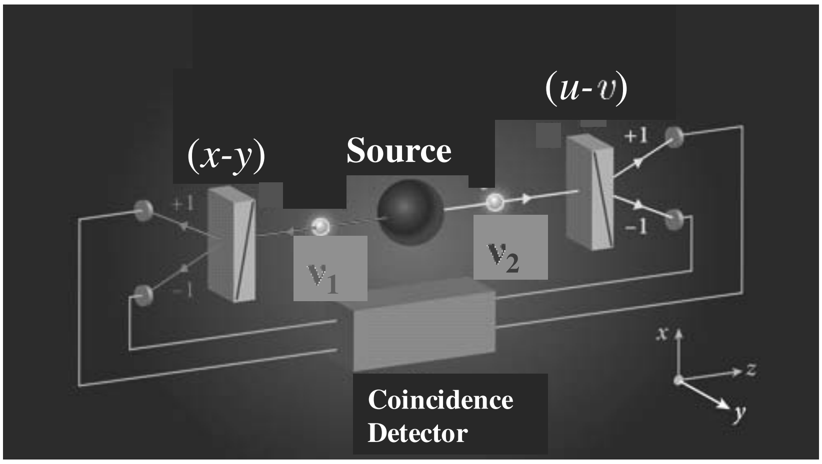


Fig. 36 An apparatus for performing Bell test. The photon

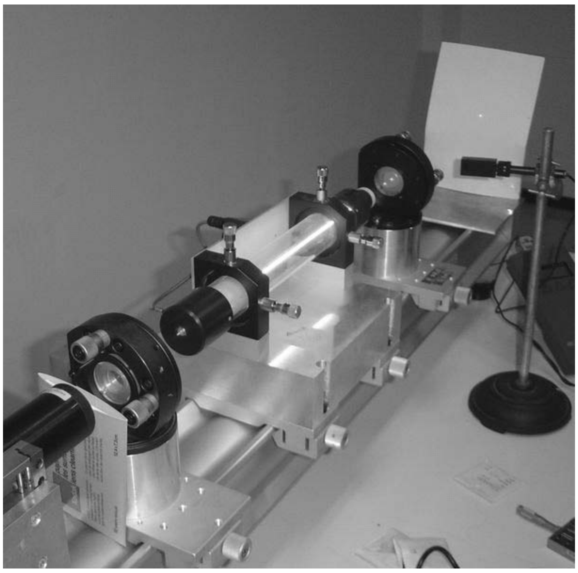


Fig. 37 A helium-neon laser demonstration at the University of Paris. The glowing ray in the middle is an electric discharge producing light in much the same way as a neon light. It is the gain medium through which the laser passes, *not* the laser beam itself, which is visible there. The laser beam crosses the air and marks a red point on the screen to the right. [*Photograph by Dr David Monniaux; used with kind permission of Dr Monniaux.*]

Fig. 38 A compact EDFA (Erbium Doped Fiber Amplifier) manufactured by NUPHOTON Technologies. It provides up to 16 dBm output power and has a 70 mm × 43 mm × 12 mm footprint; the size can be estimated by the 25 cent coin on the side. The unit works at 3.3V with a power consumption < 1.5 W. [*Photograph courtesy: Dr Ramadas Pillai of NUPHOTON Technologies*.]

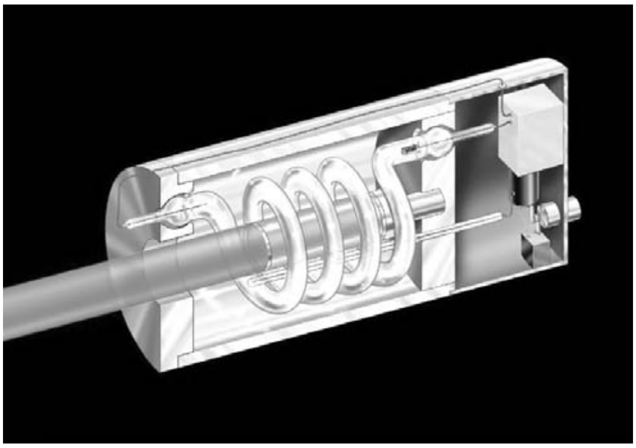


Fig. 39 The first ruby laser.

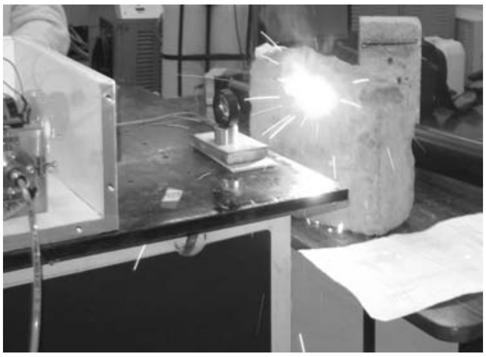


Fig. 40 Laser Drilling in Concrete at RRCAT using 1 kW Nd:YAG Laser. [*Photograph courtesy: Dr. Brahma Nand Upadhyay, Raja Ramanna Centre for Advanced Technology, Indore.*]

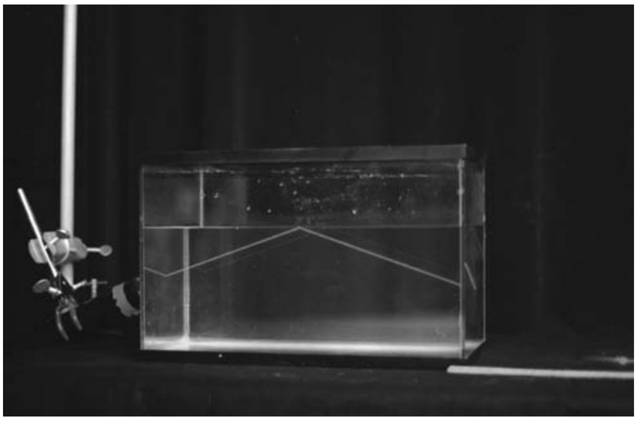


Fig. 41 Total internal reflection of a laser beam at the interface of water and air. [*Photograph adapted from http://ecphysicsworld.blogspot.in/2012/03/total-internal-reflection.html*]

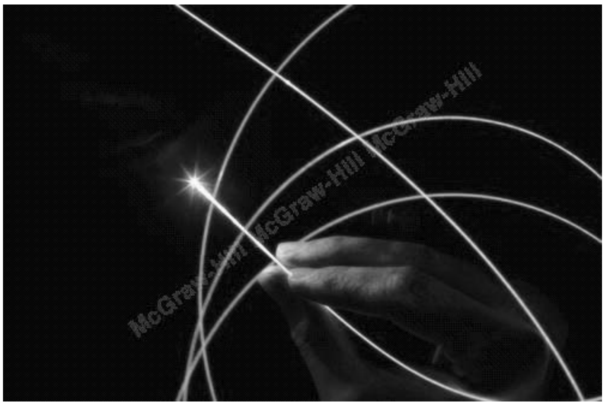


Fig. 42 Guidance of light beam through an optical fiber held by a hand; the light scattered out of the fiber is due to Rayleigh scattering. [*Photograph courtesy McGraw Hill Digital Library.*]

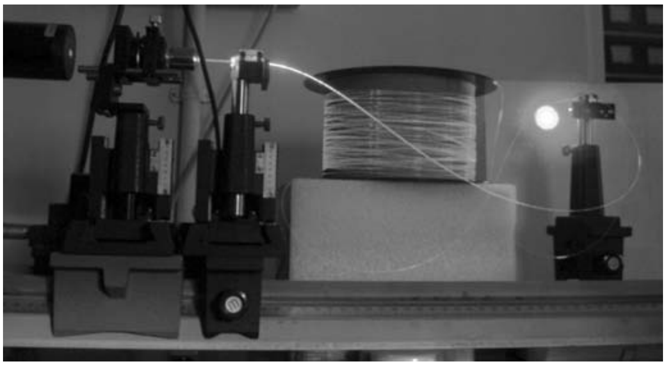
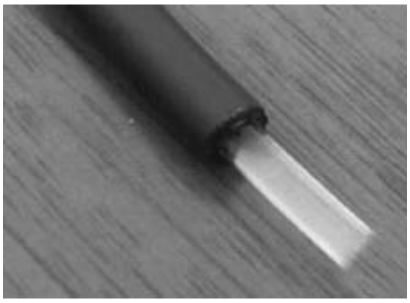
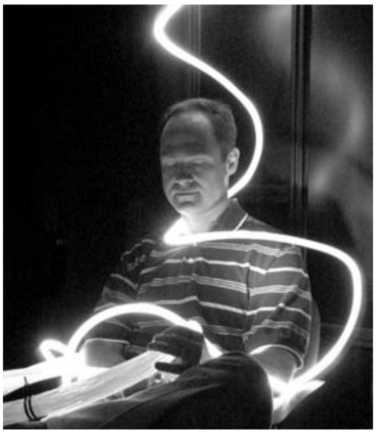


Fig. 43 A step index multimode fiber illuminated by HeNe laser with bright output light spot. The light coming out of the optical fiber is primarily due to Rayleigh scattering. [*The fiber was produced at the fiber drawing facility at CGCRI, Kolkata; figure courtesy Dr Shyamal Bhadra and Ms Atasi Pal*].



(a)



(b)

Fig. 44 (a) Commercially available 8mm/11mm solid core end glow cable with black PVC jacket. [*Ref. http://www.aliexpress.com.* (b) Wrapped in optical fiber carrying sunlight from the roof. The person shown is Jeff Muhs who at Oak Ridge National Laboratory developed this solar technology; adapted from *http://web.ornl.gov/info/ornlreview/v38_1_05/article09.shtml]*

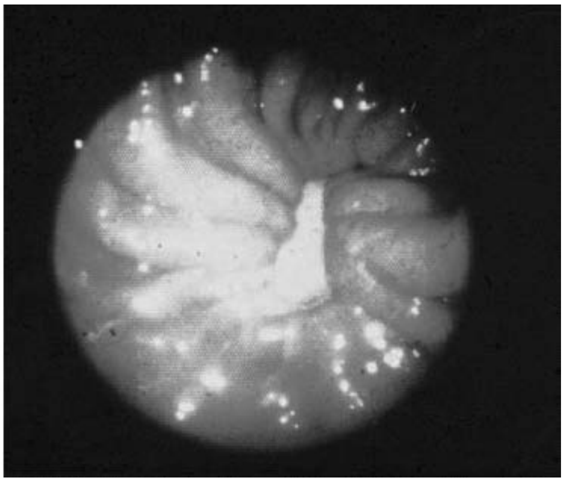


Fig. 45 A stomach ulcer as seen through an endoscope. (*Photograph courtesy: United States Information, Service, New Delhi*).

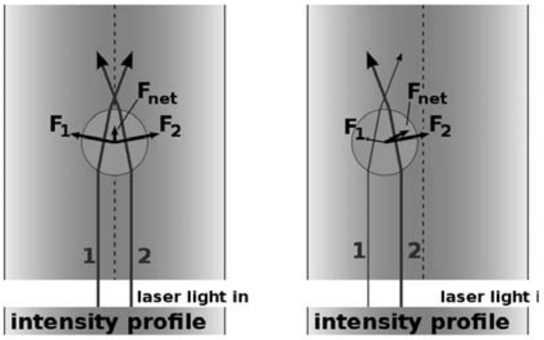


Fig. 46 The optical tweezer: When the diameter of a trapped particle is significantly greater than the wavelength of light, the trapping phenomenon can be explained using ray optics. As shown in the figure, individual rays of light emitted from the laser will be refracted as it enters and exits the dielectric bead. As a result, the ray will exit in a direction different from which it originated. Since light has a momentum associated with it, this change in direction indicates that its momentum has changed. When the bead is displaced from the beam center (right image), the larger momentum change of the more intense rays cause a net force to be applied back toward the center of the laser; thus the bead is held near the center of the laser beam. [*Writeup and photographs courtesy*: *Ronald Koebler; used with his permission*].

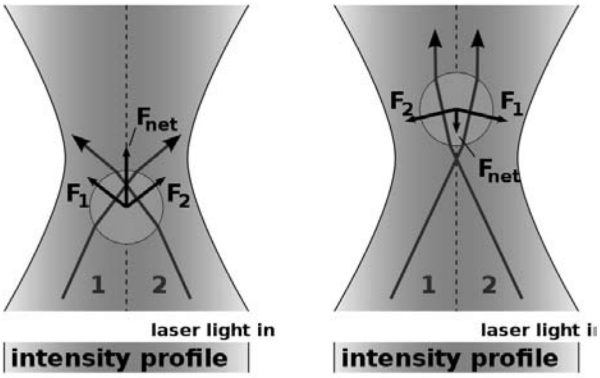


Fig. 47 A focused laser beam, in addition to keeping the bead in the center of the laser, also keeps the bead in a fixed axial position. The momentum change of the focused rays causes a force towards the laser focus, both when the bead is in front (left image) or behind (right image) the laser focus. The bead will stay slightly behind the focus. Standard tweezers work with the trapping laser propagating in the direction of gravity. [*Writeup and photographs courtesy Dr. Ronald Koebler; used with his kind permission*].

LIST OF PHYSICAL CONSTANTS

Velocity of electromagnetic waves in free space $c = 299792458$ m/s

Magnetic permeability of free space $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{Ns^2\ C^{-2}}$

Dielectric permittivity of free space $\varepsilon_0 = \dfrac{1}{\mu_0 c^2} = 8.8542... \times 10^{-12}\ \mathrm{C^2\ N^{-1}\ m^{-2}}$

Planck constant $h = 6.626\,070\,040(81) \times 10^{-34}$ J·s

Reduced Planck constant $\hbar = \dfrac{h}{2\pi} = 1.054\,571\,800(13) \times 10^{-34}$ J·s

Electron charge $q_e = 1.602\,176\,565(35) \times 10^{-19}$ C

Electron mass $m_e = 9.109\,382\,91(40) \times 10^{-31}$ kg

Proton mass $m_p = 1.672\,621\,777(74) \times 10^{-27}$ kg

$1\ \mathrm{eV} \approx 1.60218 \times 10^{-19}\ \mathrm{J}$

Gravitational constant $G = 6.67408(31) \times 10^{-11}\ \mathrm{m^3\ kg^{-1} s^{-2}}$

Chapter One

HISTORY OF OPTICS

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 in *Feynman Lectures on Physics*

Optics is the study of light that has always fascinated humans. In his famous book, *On The Nature of Light,* Vasco Ronchi wrote:

> *Today we tend to remember only Newton and Huygens and consider them as the two great men who laid the foundations of physical optics. This is not really true and perhaps this tendency is due to the distance in time which as it increases tends to strengthen the contrast and to reduce the background. In reality, the discussion on the nature of light was fully developed even before these two men were born...*

It is with this perspective that I thought it would be appropriate to give a very brief history of the development of optics. For those who want to know more of the history, fortunately, there is a wealth of information that is now available through the Internet.

Archytas (428–347 BC) was a Greek philosopher, mathematician, astronomer, and statesman. It is said that he had propounded the idea that vision arises as the effect of an invisible “fire” emitted from the eyes so that on encountering objects it may reveal their shapes and colors.

Euclid, also known as **Euclid of Alexandria**, was a Greek mathematician who was born between the years of 320 and 324 BC. In his *Optica*, (about 300 BC) he noted that light travels in straight lines and described the law of reflection. He believed that vision involves rays going from the eyes to the object seen, and he studied the relationship between the apparent sizes of objects and the angles that they subtend at the eye. It seems that Euclid’s work on optics came to the West mainly through medieval Arabic texts.

Hero (or **Heron**) **of Alexandria** (c.10–70 AD) lived in Alexandria, Roman Egypt, and was a teacher of mathematics, physics and mechanics at the University of Alexandria. He wrote *Catoptrica*, which described the propagation of light, reflection, and the use of mirrors.

Claudius Ptolemaeus (c. 90–(c.90–168 AD) known in English as **Ptolemy**, was a mathematician and astronomer who lived in Roman Egypt. Ptolemy’s *Optics* is a work that survives only in a poor Arabic translation and in Latin translation of the Arabic. In it, he wrote about properties of light, including reflection, refraction, and color. He also measured the angle of refraction in water for different angles of incidence and made a table of it.

Āryabhatta (476–550 AD) is the first of the great mathematician-astronomers of the classical age of Indian mathematics and Indian astronomy. According to the ancient Greeks, the eye was assumed to be a source of light; this was also assumed by the early Indian philosophers. In the fifth century, Aryabhatta reiterated that it was light arriving from an external source at the retina that illuminated the world around us.

Ibn al-Haytham (965–1039 AD), often called as **Alhazen**, was born in Basra, Iraq (Mesopotamia). Alhazen is considered the father of optics because of the tremendous influence of his *Book of Optics* (Arabic: *Kitab al-Manazir*, Latin: *De Aspectibus* or *Perspectiva*). Robert S. Elliot wrote the following about the book:

> *Alhazen was one of the ablest students of optics of all times and published a seven-volume treatise on optics which had great celebrity throughout the medieval period and strongly influenced Western thought, notably that of Roger Bacon and Kepler. This treatise discussed concave and convex mirrors in both cylindrical and spherical geometries, anticipated Fermat's law of least time, and considered refraction and the magnifying power of lenses. It contained a remarkably lucid description of the optical system of the eye, which study led Alhazen to the belief that light consists of rays which originate in the object seen, and not in the eye, a view contrary to that of Euclid and Ptolemy.*

Alhazen had also studied the reverse image formed by a tiny hole and indicated the rectilinear propagation of light. In fact, in December 2013, the United Nations General Assembly proclaimed the year 2015 as the International Year of Light (IYL 2015) and since January 2015, there have been numerous events celebrating the Year of Light. And, one of the main reasons for 2015 being chosen as the International Year of Light was the fact that in 1015, exactly 1000 years back, Alhazen wrote the first book on Optics. There are many books written on the work of Alhazen; some discussion on Alhazen's work can be found in Ref. 1.1.

Erazmus Ciolek Witelo (born c. 1230 and died around 1275) was a theologian, physicist, natural philosopher, and mathematician. Witelo called himself, in Latin, *Turingorum et Polonorum filius,* meaning "a son of Poland and Thuringia." Witelo wrote an exhaustive 10-volume work on optics entitled *Perspectiva*, which was largely based on the work of Ibn al-Haytham and served as the standard text on the subject until the seventeenth century (Refs. 1.2–1.4).

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Leonardo da Vinci (April 15, 1452–May 2, 1519), some people believed, was the first person to observe diffraction.

Although Alhazen had studied the reverse image formed by a tiny hole, the first detailed description of the pinhole camera (*camera obscura*) was given in the manuscript *Codex atlanticus* (c. 1485) by Leonardo da Vinci, who used it to study perspective.

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Johannes Kepler (Dec. 27, 1571 – Nov. 15, 1630) was a German mathematician, astronomer, and astrologer, and a key figure in the seventeenthcentury astronomical revolution. In 1604, he published the book, *Ad Vitellionem Paralipomena, Quibus Astronomiae pars Optica Traditur*. An English translation (by William H. Donahue) has recently been published as *Johannes Kepler Optics*. The announcement (see Ref. 1.5) says, "*Optics* was a product of Kepler's most creative period. It began as an attempt to give astronomical optics a solid foundation, but soon transcended this narrow goal to become a complete reconstruction of the theory of light, the physiology of vision, and the mathematics of refraction. The result is a work of extraordinary breadth whose significance transcends most categories into which it might be placed."

Hans Lippershey (1570–1619) was a Dutch eyeglass maker. Many historians believe that in 1608, Lippershey saw two children playing with lenses in his shop and discovered that images were clearer when seen through two lenses. This inspired Lippershey to the creation of the first telescope. Some historians credit Galileo Galilei for the invention of the first telescope. Many historians believe that Lippershey also invented the compound microscope; however, there is controversy on that. See Ref. 1.6.

Galileo Galilei (Feb. 15, 1564–Jan. 8, 1642) is often referred to as the father of modern physics. In 1609, Galileo was among the first to use a refracting telescope as an instrument to observe stars and planets. The improvements to the telescope and consequent astronomical observations were his breakthrough achievements. He became the first man to notice the craters of the moon, and to discover the sunspots, the four large moons of Jupiter, and the rings of Saturn. In 1610, he used a telescope as a compound microscope, and he made improved microscopes in 1623 and after. This appears to be the first clearly documented use of the compound microscope.

Willebrord Snel van Royen (1580–1626) was a Dutch astronomer and mathematician. In 1621, he discovered the law of refraction that is referred to as Snell's law.

Pierre de Fermat (Aug. 17, 1601–Jan. 12, 1665) was a French mathematician and never went to college. In a letter to Cureau de la Chambre (dated January 1, 1662), Fermat