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 showed that the law of refraction can be deduced by assuming that the path of a refracted ray of light was that which takes the least time! Fermat's principle met with objections. In May 1662, Clerselier, an expert in optics, wrote: *The principle you take as a basis for your proof, to wit, that nature always acts by the shortest and simplest path, is only a moral principle, not a physical one—it is not and can not be the cause of any effect in nature.*

René Descartes (Mar. 31, 1596–Feb. 11, 1650) was a highly influential French philosopher, mathematician, scientist, and writer. Descartes, in his book entitled *Dioptrique* (1638), gave the fundamental laws of propagation of light, the laws of reflection and refraction. He also put forward the corpuscular model, regarding *lumen* as a swarm of spherical corpuscles (see Refs. 1.7 and 1.8). In Ref. 1.8, it has been shown that "Descartes insightful derivation of Snell's law is seen to be largely equivalent to the mechanical-particle or corpuscular derivation often attributed to Newton (who was seven years old at Descartes' death)."

Francesco Maria Grimaldi (Apr. 2, 1618–Dec. 28, 1663). Around 1660, Grimaldi discovered the diffraction of light and gave it the name *diffraction*, which means "breaking up." He interpreted the phenomenon by stating that *light had to consist of a very fine fluid of some sort in a state of constant vibration.* He laid the groundwork for the later invention of diffraction grating. He formulated a geometrical basis for a wave theory of light in his *Physico-mathesis de lumine* (1666). It was this treatise which attracted Isaac Newton to the study of optics. Newton discussed the diffraction problems of Grimaldi in Part III of his *Opticks* (1704); Robert Hooke observed diffraction in 1672. For more details see Ref. 1.9.

Robert Hooke (Jul. 18, 1635–Mar. 3, 1703). In his 1664 book *Micrographia*, Robert Hooke was the first to describe "Newton's rings." The rings are named after Newton because Newton explained it (incorrectly) in a communication to the Royal Society in December 1675 and presented it in detail in his book *Opticks* (1704). Hooke had also observed the colors from thin sheets of mica which was much later explained through interference of light.

Rasmus Bartholin (Latinized *Erasmus Bartholinus*; Aug. 13, 1625–Nov. 4, 1698) was a Danish scientist. In 1669, he discovered double refraction of a light ray by calcite and wrote a 60-page memoir about the results; the explanation came later. See Ref. 1.10.

Christiaan Huygens (Apr. 14, 1629–Jul. 8, 1695) was a Dutch mathematician, astronomer, and physicist. In 1678, in a communication to the *Académie des Sciences* in Paris, he proposed the wave theory of light and in particular demonstrated how waves might interfere to form a wave front, propagating in a straight line. In 1672, Huygens gave the theory of double refraction which was discovered by Bartholinus in 1669. In 1690, he produced his famous book on optics, *Traite de la Lumière*; the English translation of the book is now available as a Dover reprint (Ref. 1.11), and the entire book can be read at the website given in Ref. 1.12.

Ole Christensen Rømer (Sep. 25, 1644–Sep. 19, 1710) was a Danish astronomer who in 1676 made the first quantitative measurements of the speed of light.

Isaac Newton (Jan. 4, 1643–Mar. 31, 1727) is considered one of the greatest figures in the history of science. In addition to his numerous contributions to science and mathematics, he made a systematic study of light and published it in the form of a book in 1704. The fourth edition of the book is available as a Dover reprint (Ref. 1.13) and also in the website given in Ref. 1.14.

In this book, Newton describes his experiments, first reported in 1672, on dispersion, or the separation of light into a spectrum of its component colors. Grimaldi had earlier observed light entering the shadow of a needle—Newton explained this by saying that the needle exerts a force that "pulled" the light from the straight-line path. Hooke had earlier observed the colors from thin sheets of mica—Newton explained this by "fits of easy transmission and reflection" of the light rays.

Thomas Young (Jun. 13, 1773–May 10, 1829) was an English scientist. In 1801, Young demonstrated the wave nature of light through a simple two-hole interference experiment; this experiment is considered one of 10 most beautiful experiments in physics (Refs. 1.15 and 1.16).

Thomas Young used his wave theory to explain the colors of thin films (such as soap bubbles); and relating color to wavelength, he calculated the approximate wavelengths of the seven colors recognized by Newton. In 1817, he proposed that light waves were transverse and thus explained polarization. For more details see Refs. 1.17–1.18.

François Jean Dominique Arago (Feb. 26, 1786–Oct. 2, 1853) was a French mathematician, physicist, astronomer, and politician; he became the twenty-fifth Prime Minister of France. In 1811, Arago observed the rotation of the plane of polarization in quartz. In 1818, Poisson deduced from Fresnel's theory the necessity of a bright spot at the center of the shadow of a circular opaque obstacle. With this result, Poisson had hoped to disprove the wave theory; however, Arago experimentally verified the prediction. Although this spot is usually referred to as the *Poisson* spot, many people call it *Arago's spot*.

Joseph von Fraunhofer (Mar. 6, 1787–Jun. 7, 1826) was a German optician. In 1814, Fraunhofer invented the spectroscope and discovered 574 dark lines appearing in the solar spectrum; these lines are referred to as *Fraunhofer lines*. In 1859, Kirchhoff and Bunsen explained these lines as atomic absorption lines. In 1823, Fraunhofer published his theory of diffraction. He also invented the diffraction grating and demonstrated accurate measurement of the wavelength.

Augustin-Jean Fresnel (May 10, 1788–Jul. 14, 1827) was a French physicist. Fresnel contributed significantly to the establishment of the wave theory of light. In 1818, he wrote a memoir on diffraction for which in the following year he received the prize of the *Académie des Sciences* at Paris. In 1819, he was nominated Commissioner of Lighthouses, for which he was the first to construct a special type of lens, now called a *Fresnel lens*, as substitutes for mirrors. By the year 1821, he showed that polarization could be explained only if light was *entirely* transverse.

Joseph Nicephore Niepce (Mar.7, 1765–Jul. 5, 1833) was a French inventor and in 1925, he produced world's first known photograph.

Michael Faraday (Sep. 22, 1791–Aug. 25, 1867) contributed significantly to the fields of electromagnetism and electrochemistry. Faraday had established that a changing magnetic field produces an electric field. This relation subsequently was one of the four equations of Maxwell and is referred to as *Faraday's law*. In 1845, Faraday discovered the phenomenon that is now called the *Faraday rotation*. In this experiment, the plane of polarization of linearly polarized light (propagating through a material medium) gets rotated by the application of an external magnetic field aligned in the direction of propagation. The experiment established that magnetic force and light were related. Faraday wrote in his notebook: *"I have at last succeeded in . . . magnetising a ray of light.*"

Etienne-Louis Malus (Jul. 23, 1775–Feb. 24, 1812) was a French engineer, physicist, and mathematician.

David Brewster (Dec. 11, 1781–Feb. 10, 1868) was a Scottish scientist.

In 1809, Malus had published his discovery of the polarization of light by reflection; however, he was unable to obtain the relationship between the polarizing angle and refractive index. In 1811, David Brewster *repeated* the experiments of Malus for many materials and realized that when a ray is polarized by reflection, the reflected ray makes an angle of 90° with the refracted ray; he promptly called this *Brewster's law!* Malus is best known for the law named after him which states that the intensity of light transmitted through two polarizers is proportional to the square of the cosine of the angle between the polarization axes of the polarizers. In 1810, Malus published his theory of double refraction of light in crystals.

James Clerk Maxwell (Jun. 13, 1831–Nov. 5, 1879) was an outstanding Scottish mathematician and theoretical physicist. Around 1865, Maxwell showed that the laws of electricity of magnetism can be described by four partial differential equations; these equations are known as *Maxwell's equations* and appeared in his book *A Treatise on Electricity and Magnetism,* published in 1873. Maxwell also predicted the existence of electromagnetic waves (which were later observed by Hertz) and showed that the speed of propagation of electromagnetic waves is approximately equal to the (then) measured value of the speed of light; this made him predict that light must be an electromagnetic wave. In 1864, he wrote:

> *This velocity is so nearly that of light that it seems we have strong reason to conclude that light itself (including radiant heat and other radiations) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.*

This synthesis represents one of the great scientific achievements of the nineteenth century. In 1931 (during the birth centenary celebration of Maxwell), Max Planck had said: *(Maxwell's theory) . . . remains for all time one of the greatest triumphs of human intellectual endeavor.* Albert Einstein had said. *(The work of Maxwell was) . . . the most profound and the most fruitful that physics has experienced since the time of Newton.* For more details about Maxwell, see Ref. 1.19. Some of the original papers of Maxwell can be seen in the website in Ref. 1.20.

John William Strutt usually referred to as Lord Rayleigh (Nov. 12, 1842–Jun. 30, 1919). **John Tyndall** (Aug. 2, 1820 – Dec. 4, 1893) was an Irish natural philosopher. In 1869, John Tyndall had discovered that when light passes through a transparent liquid with small particles in suspension (such as a small amount of milk put in water), the shorter blue wavelengths are scattered more strongly than the red; thus from the side, the color looks blue and the light coming out straight appears reddish. Many people call this *Tyndall scattering,* but it is more often referred to as *Rayleigh scattering* because **Rayleigh** studied this phenomenon in great detail and showed (in 1871) that scattering is inversely proportional to the fourth power of the wavelength (see Ref. 1.21). Thus the blue color is scattered 10 times more than the red color (because the red color has a wavelength which is about 1.75 times the wavelength of blue). This is the reason why the sky appears blue. Although violet has an even smaller wavelength, the sky does not appear violet because there is very little violet in the sunlight! Some of the scientific papers of Lord Rayleigh can be seen at the website given in Ref. 1.22. Lord Rayleigh received the 1904 Nobel Prize in Physics.

In 1854, John Tyndall demonstrated light guidance in water jets, duplicating but not acknowledging Babinet (see Ref. 1.23 for more details).

Heinrich Rudolf Hertz (Feb. 22, 1857–Jan. 1, 1894) was a German physicist after whom the Hertz, the SI unit of frequency, is named. To quote from Ref. 1.24:

> *In 1888, in a corner of his physics classroom at the Karlsruhe Polytechnic in Berlin, Hertz generated electric waves using an electric circuit; the circuit contained a metal rod that had a small gap at its midpoint, and when sparks crossed this gap violent oscillations of high frequency were set up in the rod. Hertz proved that these waves were transmitted through air by detecting them with another similar circuit some distance away. He also showed that like light waves they were reflected and refracted and, most important, that they traveled at the same speed as light but had a much longer wavelength. These waves, originally called Hertzian waves but now known as radio waves, conclusively confirmed Maxwell's prediction on the existence of electromagnetic waves, both in the form of light and radio waves.*

Hertz was a very modest person; after the discovery he said: *This is just an experiment that proves Maestro Maxwell was right, we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there. So, what next*? asked one of his students at the University of Bonn. *Nothing, I guess. Hertz later said*: *I do not think that the wireless waves I have discovered will have any practical application.*

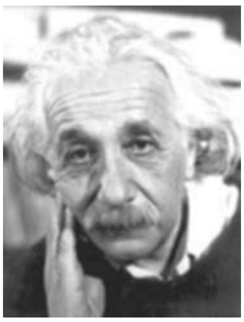
We should mention here that in 1842 (when Maxwell was only 11 years old) the U.S. physicist Joseph Henry had magnetized needles at a distance of over 30 ft (with two floors, each 14 in. thick) from a single spark. Thus, though Joseph Henry was not aware of it, he had produced and detected electromagnetic waves; for more details see e.g., the book by David Park (Ref. 1.25) and the original collection of Henry's papers referenced in Park's book.

Hertz was also the first scientist to observe the photoelectric effect. In 1887, while receiving the electromagnetic waves in a coil with a spark gap, he found that the maximum spark length was reduced when the apparatus was put in a black box (this is so because the box absorbed the ultraviolet radiation which helped the electrons to jump across the gap). Hertz reported the observations but did not pursue further and also did not make any attempt to explain them. In 1897, J. J. Thomson discovered electrons, and in 1899, he showed that electrons are emitted when light falls on a metal surface. In 1902, Philip Lenard observed that (1) the kinetic energy of the emitted electrons was independent of the intensity of the incident light and (2) the energy of the emitted electron increased when the frequency of the incident light was increased.

Alexander Graham Bell (Mar. 3, 1847–Aug. 2, 1922) was born and raised in Edinburgh, Scotland he emigrated to Canada in 1870 and then to the United States in 1871. The photophone was invented jointly by Alexander Graham Bell and his assistant Charles Sumner Tainter on February 19, 1880. Bell believed the photophone was his most important invention.

Albert Abraham Michelson (Dec. 19, 1852–May 9, 1931) was born in Strelno, Prussia, and moved to the United States at the age of 2. Michelson built the famous interferometer which was later called the *Michelson interferometer*. He was awarded the 1907 Nobel Prize in Physics (the first American to receive the Nobel Prize in Science) for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid. In the presentation speech, the President of the Royal Swedish Academy of Sciences said: . . . *Your interferometer has rendered it possible to obtain a non-material standard of length, possessed of a degree of accuracy never hitherto attained. By its means we are enabled to ensure that the prototype of the meter has remained unaltered in length, and to restore it with absolute infallibility, supposing it were to get lost.* In 1887, he and Edward Morley carried out the famous Michelson–Morley experiment, which proved that ether did not exist. David Park (Ref. 1.25) has written: *He (Michelson) was 34 when he established that ether cannot be found; he made delicate optical measurements for 44 more years and to the end of his days did not believe there could be a wave without some material substance to do the waving.*

Maurice Paul Auguste Charles Fabry (Jun. 11, 1867–Jul. 9, 1945) and **Jean-Baptiste Alfred Pérot** (Nov. 3, 1863–Nov. 28, 1925) were French physicists. In 1897, Fabry and Pérot published their important article on what we now call the *Fabry–Pérot interferometer*. For more details about them see Ref. 1.26.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Albert Einstein (Mar. 14, 1879–Apr. 18, 1955) was an outstanding theoretical physicist. Einstein is best known for his theory of relativity and specifically mass-energy equivalence $E = mc^2$. Einstein in 1905 put forward that light consists of quanta of energy; this eventually led to the development of quantum theory. In 1917, in a paper entitled, *On the Quantum Theory of Radiation*, Einstein, while rederiving Planck's law, was able to predict the process of stimulated emission, and almost 40 years later, this prediction led to the development of the laser. He received the 1921 Nobel Prize in Physics for his services to Theoretical Physics, and especially for his explanation of the photoelectric effect. Some of Einstein's early papers can be found in the website in Ref. 1.27.

Geoffrey Ingram Taylor (Mar. 7, 1886–Jun. 27, 1975) in 1909 demonstrated interference fringes by using an extremely feeble light source; this led the Nobel Prize–winning physicist P. A. M. Dirac to make the famous statement, *Each photon then interferes only with itself.* Taylor has often been described as one of the great physical scientists of the twentieth century. For more details, see Ref. 1.28.

William Henry Bragg (Jul. 2, 1862–Mar. 10, 1942) and **William Lawrence Bragg** (Mar. 31, 1890–Jul. 1, 1971). William Lawrence Bragg (the son) discovered the most famous *Bragg's law*, which makes it possible to calculate the positions of the atoms within a crystal from the way in which an X-ray beam is diffracted by the crystal lattice. He made this discovery in 1912, during his first year as a research student in Cambridge. He discussed his ideas with his father (William Henry Bragg), who developed the X-ray spectrometer in Leeds. In 1915, father and son were jointly awarded the Nobel Prize in Physics for their services in the analysis of crystal structure by means of X-rays. The collaboration between father and son led many people to believe that the father was the inventor of *Bragg's law*; of course, the son was never happy with such remarks!

Arthur Holly Compton (Sep. 10, 1892–Mar. 15, 1962) in 1922 found that the energy of an X-ray or gamma ray photon decreases due to scattering by free electrons. This discovery, known as the *Compton effect*, demonstrates the corpuscular nature of light. Compton received the 1927 Nobel Prize in Physics for his discovery of the effect named after him. The research papers of Compton can be found in the website given in Ref. 1.29.

Louis de Broglie (Aug. 15, 1892–Mar. 19, 1987) was a French physicist. In 1924, de Broglie (pronounced in French as *de Broy*) formulated the *de Broglie hypothesis*, claiming that *all* matter, not just light, has a wave-like nature; he related wavelength to the momentum. De Broglie's formula was confirmed three years later for electrons with the observation of electron diffraction in two independent experiments. De Broglie received the 1929 Nobel Prize in Physics for his discovery of the wave nature of electrons. In the presentation speech it was mentioned:

> *Louis de Broglie had the boldness to maintain that . . . matter is, by its nature, a wave motion. At a time when no single known fact supported this theory, Louis de Broglie asserted that a stream of electrons*

which passed through a very small hole in an opaque screen must exhibit the same phenomena as a light ray under the same conditions.

Paul Adrien Maurice Dirac (Aug. 8, 1902–Oct. 20, 1984) and **Werner Karl Heisenberg** (Dec. 5, 1901–Feb. 1, 1976) were both celebrated theoretical physicists. Heisenberg was one of the founders of quantum mechanics and is also well known for discovering one of the central principles of modern physics, the Heisenberg uncertainty principle, which he developed in an essay published in 1927. The uncertainty principle (which can be derived directly from the axioms of quantum mechanics) can be used to explain the diffraction of a photon (or an electron). Dirac can be considered as the creator of the complete theoretical formulation of quantum mechanics. Albert Einstien said that it was "*Dirac to whom in my opinion we owe the most logically perfect presentation of quantum mechanics.*"

Chandrasekhara Venkata Raman (Nov. 7, 1888–Nov. 21, 1970) and **Kariamanikkam Srinivasa Krishnan** (Dec. 4, 1898–Jun. 13, 1961) on February 28, 1928, observed the *Raman effect* in several organic vapors such as pentane, which they called "the new scattered radiation." Raman made a newspaper announcement on February 29, and on March 8, 1928 he communicated a paper entitled "A Change of Wavelength in Light Scattering to Nature," which was published on April 21, 1928. Although in the paper he acknowledged that the observations were made by K. S. Krishnan and himself, the paper had Raman as *the* author, and therefore the phenomenon came to be known as the Raman effect although many scientists (particularly in India) kept on referring to it as the Raman–Krishnan effect. Subsequently, there were several papers written by Raman and Krishnan. Raman got the 1930 Nobel Prize in Physics for "his work on the scattering of light and for the discovery of the effect named after him." At about the same time, Landsberg and Mandel'shtam (in Russia) were also working on light scattering, and according to Mandel'shtam, they observed the Raman lines on February 21, 1928. But the results were presented in April 1928, and it was only on May 6, 1928, that Landsberg and Mandel'shtam communicated their results to the journal *Naturwissenschaften*. But by then it was too late! Much later, scientists from Russia kept calling Raman scattering as Mandel'shtam–Raman scattering. For a nice historical account of Raman effect, see Ref. 1.30. In 1928, the Raman effect was discovered; 70 years later it has become an important mechanism for signal amplification in optical communication systems. Today we routinely talk about Raman amplification in optical fibers.

Dennis Gabor (Jun. 5, 1900, Budapest–Feb. 9, 1979, London). In 1947, while working in the area of electron optics at British Thomson-Houston Co. in the United Kingdom, Dennis Gabor invented holography. He was awarded the 1971 Nobel Prize in Physics for his invention and development of the holographic method. However, the field of holography advanced only after development of the laser in 1960. The first holograms that recorded 3D objects were made by Emmett Leith and Juris Upatnieks in Michigan, United States, in 1963 and Yuri Denisyuk in the Soviet Union.

Charles Hard Townes (Jul. 28, 1915) and (his sister's husband) **Arthur Leonard Schawlow** (May 5, 1921–Apr. 28, 1999) are both U.S. physicists. **Nikolay Gennadiyevich Basov** (Dec. 14, 1922–Jul. 1, 2001) was a Russian physicist and educator. **Aleksandr Mikhailovich Prokhorov** (Jul. 11, 1916–Jan. 8, 2002) was a Russian physicist born in Australia. **Gordon Gould** (Jul. 17, 1920–Sep. 16, 2005), was a U.S. physicist. The most important concept in the development of the laser is that of stimulated emission, which was introduced by Einstein in 1917. It took over 35 years to realize amplification through stimulated emission primarily because stimulated emission was long regarded as a purely theoretical concept which never could be observed, because under normal conditions absorption would always dominate over emission. According to Townes, he conceived the idea of amplification through population inversion in 1951 (see Ref. 1.31); and in early 1954, Townes, Gordon, and Zeiger (at the Physics Department of Columbia University) published a paper on the amplification and generation of electromagnetic waves by stimulated emission. They coined the word *maser* for this device, which is an acronym for *m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation. Around the same time, Basov and Prochorov at the Lebedev Institute in Moscow independently published papers about the maser. In 1958, Schawlow and Townes published a paper entitled "Infrared and Optical Masers" in *Physical Review* showing how stimulated emission would work with much shorter wavelengths and describing the basic principles of the optical maser (later to be renamed a *laser*), initiating this new scientific field. Townes, Basov, and Prokhorov shared the 1964 Nobel Prize in Physics for their fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle. Half of the prize was awarded to Townes and the other half jointly to Basov and Prokhorov. Schawlow got the Nobel Prize much later; he shared the 1981 Nobel Prize in Physics with Nicolaas Bloembergen and Kai Siegbahn for their contributions to the development of *laser spectroscopy*. However, many people believe that Gordon

Gould (while a graduate student at Columbia University) is the inventor of the laser. On the first page of Gould's laser notebook (written in November 1957) he coined the acronym *LASER* and described the essential elements for constructing the laser. In fact, the term *laser* was first introduced to the public in Gould's 1959 conference paper "The LASER, Light Amplification by Stimulated Emission of Radiation." Gould for 30 years fought the United States Patent and Trademark Office for recognition as the inventor of the laser; see, e.g., the books by Taylor (Ref. 1.32) and by Bertolotti (Ref. 1.33). A portion of Bertolotti's book can be read at the website given in Ref. 1.34.

Theodore Harold Maiman (Jul. 11, 1927–May 5, 2007). In *A Century of Nature: Twenty-One Discoveries that Changed Science and the World*, (Ref. 1.35), C. H. Townes wrote an article entitled "The First Laser" (Ref. 1.36). In this article, Townes wrote:

> *Theodore Maiman made the first laser operate on 16 May 1960 at the Hughes Research Laboratory in California, by shining a high-power flash lamp on a ruby rod with silver-coated surfaces. He promptly submitted a short report of the work to the journal Physical Review Letters, but the editors turned it down. Some have thought this was because Physical Review had announced that it was receiving too many papers on masers—the longer-wavelength predecessors of the laser—and had announced that any further papers would be turned down. But Simon Pasternack, who was an editor of Physical Review Letters at the time, has said that he turned down this historic paper because Maiman had just published, in June 1960, an article on the excitation of ruby with light, with an examination of the relaxation times between quantum states, and that the new work seemed to be simply more of the same. Pasternack's reaction perhaps reflects the limited understanding at the time of the nature of lasers and their significance. Eager to get his work quickly into publication, Maiman then turned to Nature, usually even more selective than Physical Review Letters, where the paper was better received and published on 6 August.*

On December 12, 1960, **Ali Javan**, **William Bennett**, and **Donald Herriott** produced, for the first time, a continuous laser light (at 1.15 μm) from a gas laser. (Refs. 1.37 and 1.38).

In 1961, within one year of the development of the first laser, **Elias Snitzer** and his coworkers developed the first fiber-optic laser. Snitzer also invented both neodymium- and erbium-doped laser glass; see, e.g., Refs. 1.39 and 1.40.

C. Kumar N. Patel developed the carbon dioxide laser in 1963; it is now widely used in industry for cutting and welding and also in surgery. See Ref. 1.41.

In 1966, in a landmark theoretical paper (published in *Proceedings of IEE*), **Charles Kuen Kao** and **George Hockham** of Standard Telecommunications Laboratories in the United Kingdom pointed out that the loss in glass fibers was primarily caused by impurities and therefore it was not a fundamental property of the fiber itself. They said that if the impurities could be removed, the loss could be brought down to about few decibels per kilometer—or may be even less. If this could be achieved, then (to quote from Ref. 1.42) "the new form of communication medium . . . compared with existing coaxial cable and radio systems, has a larger information capacity and possible advantages in basic material cost." After this paper, scientists in the United States, United Kingdom, France, Japan, and Germany started working on purifying glass, and the first breakthrough was reported in 1970. Charles Kao received half of the 2009 Nobel Prize in Physics for "ground breaking achievements concerning the transmission of light in fibers for optical communication".

In 1970, Corning Glass Works scientists **Donald Keck**, **Robert Maurer**, and **Peter Schultz** successfully prepared the first batch of optical fiber with sufficiently low loss as to make fiber-optic communication a reality—this breakthrough was the starting point of the fiber-optic revolution; see Ref. 1.43. In about 10 more years, as research continued, optical fibers became so transparent that more than 95% of the signal power would pass after propagating through 1 km of the optical fiber.

Semiconductor lasers that operate continuously at room temperature were first fabricated in May 1970 by Zhorev Alferov and his group in Leningrad, and in June 1970, by Izuo Hayashi and Morton Panish at Bell Labs (Ref. 1.44). This was a major turning point toward the development of the fiber-optic communication system. Alferov shared the 2000 Nobel Prize in Physics.

In 1978, the photosensitivity of germanium-doped-core optical fibers was discovered by **Kenneth Hill** while working at the Communications Research Centre in Ottawa, Canada. He also demonstrated the first in-fiber Bragg grating (see Ref. 1.45).

The erbium-doped fiber amplifier (usually abbreviated as EDFA) was invented in 1987 by a group including **David Payne**, **R. Mears**, and **L. Reekie**, from the University of Southampton, and a group from AT&T Bell Laboratories, including **E. Desurvire**, **P. Becker**, and **J. Simpson**. The EDFA brought about a revolution in fiber-optic communication systems.