Using light for communication purposes could seem an approach that has been recently thought of. However, it is a very old idea. Fire and smoke signals were used to convey a single piece of information in Ancient civilizations. For example, ancient Greeks used mirrors and sunlight, Chinese started using fire beacons as early as 800BC followed by the Romans in Europe and the American Indians using smoke signals. As soon as prehistoric humans controlled the use of fire (by 1.4 million BC) a continuous development of the optical communications has been made. In the next pages, a chronology of optics, fiber optics and integrated optics will be given.

12,000 BC Earliest known use of oil burning lamps.
2000 - 1000 BC Mirrors in Egyptian tombs, in book of Exodus
900-600 BC The Babylonians make convex lenses from crystals, but since they have poor magnifying qualities, they were probably used more for ornamentation or as curiosities. rock crystal lenses in Assyria
423 BC Greek writer Aristophanes writes a comedy, ***Clouds***, in which a character uses an object to reflect and concentrate the Sun's rays, melting an IOU recorded on a wax tablet.
400-300 BC Greek scholars speculate about light and optics: Platon proposes that the soul is the source of vision, with light rays emanating from the eyes and illuminating objects. Democritus makes the first attempt to explain perception and color in terms of the size, shape and "roughness" of atoms. Euclid publishes ***Optica***, in which he defines the law of reflection and states that light travels in straight lines. Aristotle speculates about perception, but rejects the theory about human vision emanating as light rays from the eyes.
~300 BC Euclides (Alexandria) In his ***Optica*** 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.
280 BC The Egyptians complete construction of the world's first lighthouse, Pharos of Alexandria, one of the Seven Wonders of the World and the archetype of all future lighthouses.

1st cent BC Chinese fortune tellers begin using loadstone to construct their divining boards, eventually leading to the first compasses. (Mentioned in Wang Ch'ung's Discourses of 83 B.C.)

250 BC-100 AD The Chinese are perhaps the first to use optical lenses and the first documented case of a corrective lens occurs around this time. Roman philosopher Seneca describes the magnification of objects seen through transparent globes filled with water.

Hero (Alexandria) publishes a work entitled ***Catoptrica*** (Reflections) and demonstrates that the angle of reflected light is equal to the angle of incidence. He showed by a geometrical method that the actual path taken by a ray of light reflected from a plane mirror is shorter than any other reflected path that might be drawn between the source and point of observation.

~140 AD Claudius Ptolemy (Alexandria). In a twelfth-century Latin translation from the Arabic that is assigned to Ptolemy, a study of refraction, including atmospheric refraction, was described. He derived the law of reflection from the assumption that light rays travel in straight lines (from the eyes), and tries to establish a quantitative law of refraction, suggesting that the angle of refraction is proportional to the angle of incidence. He also suggested that the Sun turns around the Earth.

In **525 AD**, Roman scholar and mathematician Anicus Boethius attempts to document the speed of light, but is decapitated for his efforts after being accused of treason and magic.

965-1020 Abu Ali Hasan Ibn al-Haitham (also known as Alhazen) (present-day Iraq). In his investigations, he used spherical and parabolic mirrors and was aware of spherical aberration. He also investigated the magnification produced by lenses, reflection, refraction and atmospheric refraction. He gave the first accurate account of vision - that the eye receives light, rather than transmits it and writes about the anatomy of the human eye and describes how the lens forms an image on the retina. His work was translated into Latin as ***Opticae thesaurus Alhazeni libri VII*** in 1270 and became accessible to later European scholars.

1000-1199 Chinese philosopher Shen Kua writes ***Meng ch'i pi t'an*** (Dream Pool Essays), where he discusses concave mirrors and focal points. He notes that images reflected in a concave mirror are inverted. He is also said to have constructed a celestial sphere and a bronze sundial. He makes the first reference to compasses used in navigation.

~1220 Robert Grosseteste (England) proposed that a theory can only be validated by testing its consequences with experimentation, a remarkable deviation from Aristotelian philosophy and the beginning of scientific method in the Western world. In his ***book De Iride and De Luce*** on optics and light, Grosseteste considered that the properties of light and stressed the importance of mathematics and geometry in their study. He believed that colors are related to intensity and that they extend from white to black, white being the purest and lying beyond red with black lying below blue. The rainbow was conjectured to be a consequence of reflection and refraction of sunlight by layers in a 'watery cloud' but the effect of individual droplets was not considered. He has the idea, shared by the earlier Greeks, that vision involves emanations from the eye to the object perceived.

~1267 Roger Bacon (England). A Grosseteste's follower at Oxford, Bacon extended Grosseteste's work on optics. He considered that the speed of light is finite and that it is propagated through a medium in a manner analogous to the propagation of sound. In his ***Opus Maius***, Bacon described his studies of the magnification of small objects using convex lenses and suggested that they could find application in the correction of defective eyesight. In ***Perspectiva***, Bacon postulates, but cannot demonstrate, that the colors of a rainbow are due to the reflection and refraction of sunlight through individual raindrops.

~1270 Witelo (Silesia). Completes a volume entitled ***Perspectiva***. This would become the most important medieval treatise on optics and the standard text on the subject until the 17th century. Amongst other things, Witelo described a method of machining parabolic mirrors from iron and carried out careful observations on refraction. He recognized that the angle of refraction is not proportional to the angle of incidence but was unaware of total internal reflection.

1275 The English Dominican scholar Albertus Magnus (later St. Albertus Magnus, the patron saint of the natural sciences), studies the rainbow effect of light and speculates that the velocity of light is extremely fast, but finite.

1304~1310 Theodoric of Freiberg. Working with prisms and transparent crystalline spheres, Theodoric explained the rainbow as a consequence of refraction and internal reflection within individual raindrops, proving Roger Bacon's theory and disproving Aristotle's theory that it arises from the entire cloud. However, following earlier notions, he considered color to arise from a combination of darkness and brightness in different proportions

1480 Leonardo de Vinci (Italy) studies the reflection of light and compares it to the reflection of sound waves.

1584 Giordano Bruno, an Italian philosopher and scholar, writes ***On the Infinite Universe and Worlds*** , rejecting the Aristotelian view of an Earth-centered universe and theorizing that the universe is infinite with perhaps an infinite number of worlds. He is burned at the stake in 1600 for refusing to recant his views.

1585 Giovanni Benedetti, an Italian mathematician, writes ***Diversarum Speculationum Mathematicarum***, and describes the use of concave mirrors and convex lenses to correct images.

1589 Abandoning the accepted thinking of the times, Italian physicist and astronomer Galileo Galilei proposes theories of motion that contradict those of Aristotle. He records his theories and experimental results in ***De motu.***

1590 A Dutch lensmakers, Hans Jansen and his son Zacharias, invent the first compound microscope (and telescope). The device is made using a convex objective and concave eyepiece.

1600 William Gilbert, after 18 years of experiments with loadstones, magnets and electrical materials, finishes his book ***De Magnete***. The work included: the first major classification of electric and non-electric materials; the relation of moisture and electrification; showing that electrification effects metals, liquids and smoke; noting that electrics were the

attractive agents (as opposed to the air between objects); that heating dispelled the attractive power of electrics; and showing the earth to be a magnet.

1604 Johannes Kepler (Germany). In his book ***Ad Vitellionem Paralipomena, Quibus Astronomiae Pars Optica Traditur***. Kepler suggested that the intensity of light from a point source varies inversely with the square of the distance from the source, that light can be propagated over an unlimited distance and that the speed of propagation is infinite. He explained vision as a consequence of the formation of an image on the retina by the lens in the eye and correctly described the causes of long-sightedness and short-sightedness

1606 Della Porta first describes the heating effects of light rays.

1608 Dutch lensmaker Hans Lippershey (also called Hans Lippersheim) builds a telescope consisting of a converging objective lens and a diverging eye lens. He reports his invention to Galileo.

1609 Galileo Galilei (Italy) builds a telescope modeled from Lippershey's telescope and uses it for astronomical observations. Later in the year, he draws pictures of the Moon's phases as seen through the telescope and in January 1610 he discovers that Jupiter has four moons.

1611 Johannes Kepler (Germany). In his ***Dioptrice***, Kepler presented an explanation of the principles involved in the convergent/divergent lens microscopes and telescopes. He discovered total internal reflection, but was unable to find a satisfactory relationship between the angle of incidence and the angle of refraction

1618 April 2nd, Francesco Maria Grimaldi discovers diffraction patterns of light and becomes convinced that light is a wave-like phenomenon. The theory is given little attention.

1621 Willebrord van Roijen Snell (Leiden) discovers the law of refraction and determines that transparent materials have different indices of refraction depending upon their composition. He does not publish his discovery, however, and it remains unknown until 1703 when it is published by Christiaan Huygens.

1633 Galileo is forced by the Inquisition to recant his support of the Copernican theory that the Earth and other planets revolve around the Sun.

1637 René Descartes publishes his ***Dioptics*** and ***On Meteors*** as appendices to his ***Discourse on the Method and Essays***, explains rainbows and publishes his discoveries about the laws of reflection and refraction. He discovers Snell's law of refraction independently, but he is the first to publish it.
1647 B Cavalieri. Derived a relationship between the radii of curvature of the surfaces of a thin lens and its focal length
1657 Pierre de Fermat (France). Enunciated his principle of 'least time', according to which, a ray of light follows the path which takes it to its destination in the shortest time. This principle is consistent with Snell's law of refraction. In 1661 Fermat is able to apply his principle of least time to understand the refractive indices of different materials.
1665 Two years after his death, Francesco Maria Grimaldi's book ***Physicomathesis de lumine, coloribus, et iride, aliisque annexis*** is published. His observations of diffraction when he passed white light through small apertures were described. In his book, the Italian physicist concludes that light is a liquid capable of wave-like motion, one of the earliest indications that light behaves like a wave.
1669 Erasmus Bartholinus (Denmark). Published ***A Study of Iceland Spar***, about his discovery of double refraction in calcite
1672 In his first letter published in the Royal Society's ***Philosophical Transactions***, Newton reports about his prism experiment, concluding that white light is composed of different colors that are refracted at different angles by a prism.
1676 Olaf Römer (Denmark) Deduced that the speed of light is finite from detailed observations of the eclipses of the moons of Jupiter. From Römer's data, a value of about 225.000 Km.s-1 is obtainable.
1678 Christiaan Huygens (Netherlands). In a communication to the Academie des Science in Paris, Huygens propounded his wave theory of light (published in his Traite de Lumiere in 1690). He considered that light is transmitted through an all-pervading aether that is made up of small elastic particles, each of which can act as a secondary source of wavelets.

On this basis, Huygens explained many of the known propagation characteristics of light, including the double refraction in calcite discovered by Bartholinus

1690 Huyghens formulates his wave theory of light in ***Traité de la Lumière***, giving the first numerical quote for the speed of light, usually attributed to Rømer, of 2.3 x 108 m/s.

1704 Isaac Newton (England). In his ***Opticks***, Newton wrote that light is corpuscular but that the corpuscles are able to excite waves in the aether. His adherence to a corpuscular nature of light was based primarily on the presumption that light travels in straight lines whereas waves can bend into the region of shadow

1733 Chester Moor Hall (England) invents the achromatic lens for telescopes, which eliminates many optical distortions by combining a convex crown glass lens with a concave lens made of lead-based flint glass.

1738 Johann Nathanael Lieberkühn (Germany) invents a reflective attachment (speculum) for microscopes. Made of polished metal, it increases the amount of light illuminating a specimen.

1752 Benjamin Franklin (USA) performs a series of experiments, including the celebrated kite flying experiment, and establishes that lightning is an electrical phenomenon.

1772 French mineralogist Jean-Baptiste Romé de l'Isle publishes his ***Traitise on Crystallography*** in which he confirms that the angles between corresponding faces are always the same. In addition, he shows that these angles are always characteristic of the particular mineral.

1785: John Dolland invents color-corrected lenses

In 1793, Claude Chappe builds an optical telegraph in France. It comprised a chain of towers with movable arms where human operators relayed messages from one tower to the next (see fig. 1). As an example, a message from Paris to Lille, a distance of 230Km, could travel from end to end in about 15 minutes. This fast communciation media was widely used in Europe until the by the mid-19th century, when it was replaced by the electric telegraph.

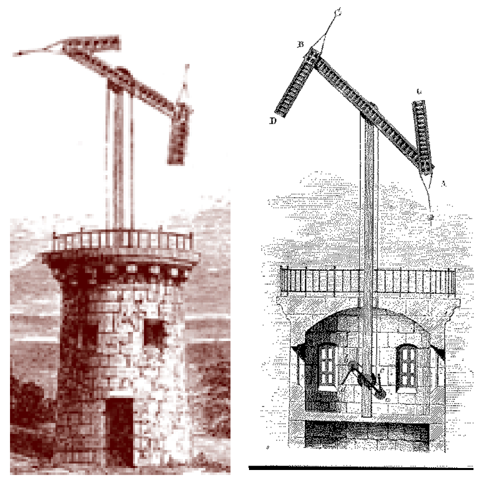

Fig. 1: Drawing of the optical telegraph invented by C. Chappe, after **[1]**

1800 William Herschel, a German-born British astronomer, discovers the infrared region of sunlight. This is the first observation of a form of light that is invisible to the human eye.

1801 Thomas Young's work on interference revives interest in the wave theory of light, challenging Issac Newton's corpuscular theory of light. He also accounts for the recently discovered phenomenon of light polarization by suggesting that light is a vibration in the aether transverse to the direction of propagation.

1801 Physicist Johann Wilhelm Ritter (Germany) finds that the Sun emits invisible ultraviolet radiation. His discovery expands the Sun's spectrum beyond the violet range of the visible light spectrum.

1808 Etienne Louis Malus (France). As a result of observing light reflected from the windows of the Palais Luxembourg in Paris through a calcite crystal as it is rotated, Malus discovered an effect that later led to the conclusion that light can be polarized by reflection

1811 Two French physicists, Augustin-Jean Fresnel and François Arago discover that two beams of light, polarized in perpendicular directions, do not interfere.

1814 Augustin Jean Fresnel independently discovers the interference phenomena of light and explains its existence in terms of wave theory.

1815 David Brewster (Scotland) describes a simple mathematical relationship between the refractive index of a reflective substance and the angle at which light striking the substance will be polarized.

1816 Augustin Jean Fresnel (France). Presented a rigorous treatment of diffraction and interference phenomena showing that they can be explained in terms of a wave theory of light. In 1817, as a result of investigations by Fresnel and Dominique Francois Arago on the interference of polarized light and their subsequent interpretation by Thomas Young, it was concluded that light waves are transverse and not longitudinal, as had been previously thought.

1819 Joseph Fraunhofer (Germany). Described his investigations of the diffraction of light by gratings which were initially made by winding fine wires around parallel screws

1819 Siméon-Denis Poisson (France) objects to Fresnel's mathematical theory of diffraction. The Paris Académie calls for an experiment, which proves Fresnel's theory to be correct. Fresnel's paper wins a prize that had been offered for a memoir on diffraction.

1821 Augustin Jean Fresnel (France). Presented the laws which enable the intensity and polarization of reflected and refracted light to be calculated

1823 Joseph Fraunhofer (Germany). Published his theory of diffraction and builds the first diffraction grating, made up of 260 close parallel wires.

1834 John Scott Russell (Scotland). Observed a 'wave of translation' caused by a boat being drawn along the Union Canal in Scotland, and noted how it traveled great distances without apparent change of shape. Such waves subsequently became known as 'solitary waves' and their study led to the idea of solitons, optical analogues of which have been propagated in optic fibers

1835 George Airy (England). Calculated the form of the diffraction pattern produced by a circular aperture

1835 Gauss formulates separate electrostatic and electrodynamical laws, including "Gauss's law." All of it remains unpublished until 1867.

An American portrait painter Morse started researching the characteristic of electromagnets in 1830, whereby they became magnets only while the current flows. As a result, he invented a method of sending and receiving code representing letters by the intermittence of the current. This code was represented first by successive waveforms but later by points and lines, what we call the Morse code (fig. 2).

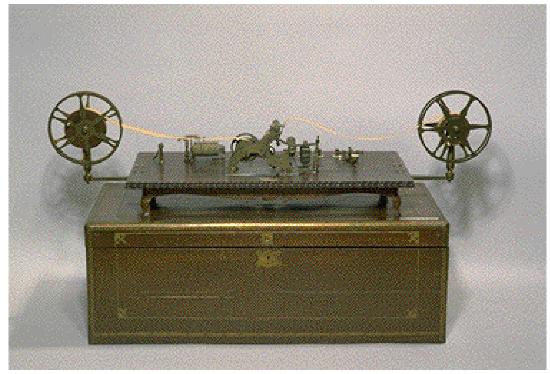

Fig. 2: Picture of the telegraph invented by Morse, Chappe, after **[2]**

In **1837**, Morse succeeded in a public experiment with his first telegraph at New York University where he worked. Thus, the use of light was replaced by electricity. The era of electrical communications had begun, increasing the bit rate to about 10 bit/second. And by using the intermediate relay stations, communication over 1000km could be achieved.

1840 John Herschel (England) discovers Fraunhofer lines in the infrared region, the spectral region his father, William, discovered 40 years earlier.

1840 Pierre Louis Guinaud (Switzerland) develops a method for producing uniform optical glass.

1850 J L Foucault (France). Foucault determined the speed of light in air using a rotating mirror method. Obtained a value of 298,000 km.s-1.In the same year, Foucault used a rotating mirror method to measure the speed of light in stationary water and found that it was less than in air

1852 Stokes names and explains the phenomena of fluorescence.

1855 David Alter (USA). Described the spectrum of hydrogen and other gases

1858 Riemann generalizes Weber's unification program and derives his results via a solution to a wave function of a electrodynamical potential (finding the speed of propagation, correctly, to be c). He claimed to have found the connection between electricity and optics. (Results published postumously in 1867.)

1858 The first Transatlantic cable is installed, but stops working after 20 days, having carried only 800 telegrams.

1859 H L Fizeau (France). Performed an experiment to determine whether the velocity of light in water is affected by flow of the water. He found that it is, the change in the velocity of light being about a half the velocity of the flowing water

1865 Maxwell's ***A Dynamical Theory of the Electromagnetic Field***, formulating an electrodynamical formulation of wave propagation using Lagrangian and Hamiltonian techniques, obtaining the theoretical possibility of generating electromagnetic radiation. (The derivation is independent of the microscopic structures which may underlie such phenomena.). It was found that the speed of an electromagnetic wave should, within experimental error, be the same as the speed of light. Maxwell concluded that light is a form of electromagnetic wave. This confirms Michael Faraday's insight (1846) but still requires experimental proof.

1865 The "Great Eastern" starts to lay the transatlantic cable, but after 1,000 miles the cable breaks off and an act of sabotage is suspected. The second attempt in July of 1866 is successful and the two continents have been connected since. It transmitted telegraph messages at 7 words per minute (fig. 3).

Fig. 3: The Great Eastern under weigh, July 23 1865 **[3]**

One of the earliest pioneers in the study of guiding light through a dielectric medium was English physicist John Tyndall. **In 1870**, during an exhibition before the Royal Society, Tyndall demonstrates light guiding in water jets (fig. 4), duplicating but not acknowledging an earlier experiment by Daniel Colladon. He proved that light could be guided within a curved stream of water by the reflection of the light at the water/air boundary. This phenomenon is now called total internal reflection.

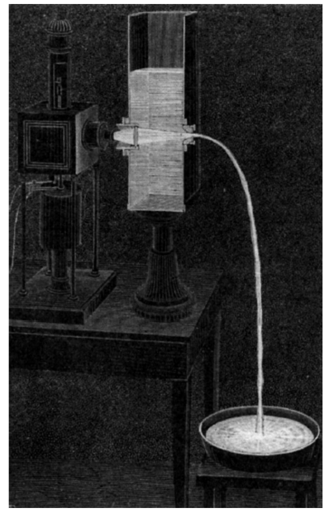

Fig. 4: Tyndall's light guiding experiment, After **[4]**

1871 John William Strutt, third Baron Rayleigh (England). Presented a general law which related the intensity of light scattered from small particles to the wavelength of the light when the dimensions of the particles is much less than the wavelength. He also made a 'zone plate' which produced focussing of light by Fresnel diffraction

1873 Glass fibers that can be woven into cloth are made by Jules de Brunfaut.

1874 Marie Alfred Cornu (France). Described a graphical approach (the Cornu spiral) to the solution of diffraction problems

1875 John Kerr (Scotland). Demonstrated the quadratic electro-optic effect (the Kerr effect) in glass

1875 Heinrich Antoon Lorentz, in his doctoral thesis, derives the phenomena of reflection and refraction in terms of Maxwell 's theory.

1876 While Ernest Abbe experiments with the effects of diffraction on image formation, he discovers that if you completely correct all of a lens aberration, the actual resolution will be near that of the maximum theoretical resolution. He suggests various theories for improving current microscope design.

The invention of the telephone in **1876** by Alexander Graham Bell (USA) (fig. 5) brought a major change in the communication. The first voice was "Mr. Watson, come here, I want you". The early telegraphy (1830) was based on digital-like transmission schemes through two electrical pulses of different duration (dots and dashes of the Morse code). However, early telephone were transmitted in the "analog" form through a continuously varying electrical current: The analog electrical techniques were to dominate communication systems for nearly a century.

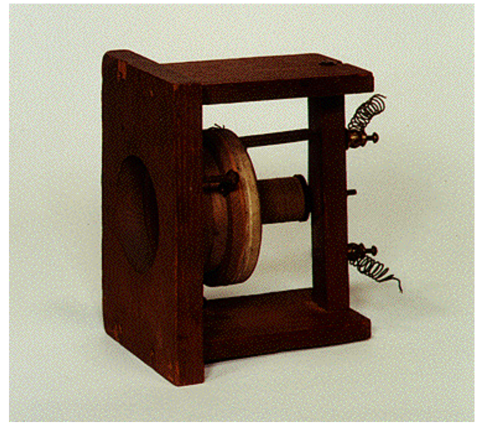

Fig. 5: Bell's telephone, after **[5]**

In **1880** Alexander Graham Bell (USA) was working on what he considered his greatest invention, the photophone (fig. 6). Bell was intrigued by the idea of sending signals without wires. He thought of optical communication. Bell's photophone reproduced voices by detecting variations in the amount of sunlight or artificial light reaching a receiver. The transmitter portion of the photophone used mirrors, lenses and unguided modulated sunlight to carry speech. The receiver was built around a photoelectric cell made of selenium. The sound waves would strike the mirror in the transmitter and cause it to modulate the sunlight reflected from the mirror. The selenium cell in the receiver would then demodulate the speech from the sunlight. Although the photophone functioned as expected, it was not a reliable form of communication because the transmission medium was free space which allowed only line of sight communication and there was no way, at that time, to protect the beam of light from obstacles in the light path. Moreover, it was extremely limited since sunlight was an unpredictable light source. Bell's photophone is today acknowledged as the progenitor of the modern fiber optics

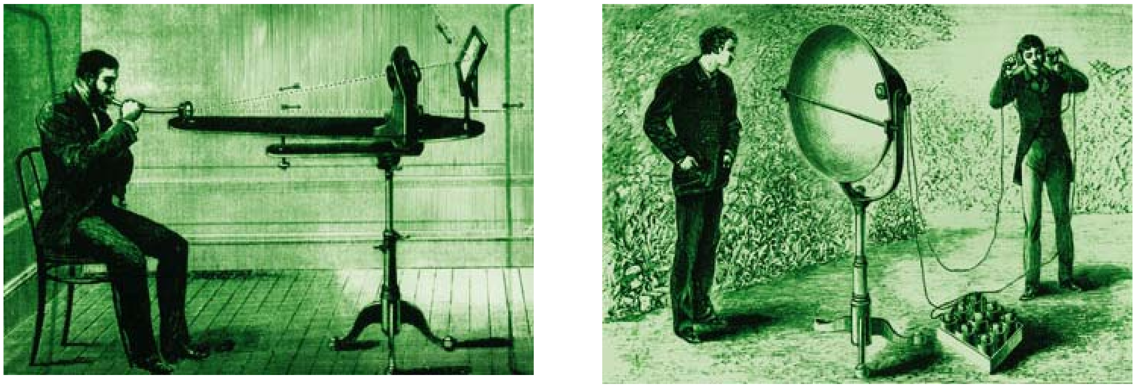

Fig. 6: Photophone Transmitter and receiver, after **[6]**

In the **1880**s the first glass fibers were also developed. Charles Vernon stretched molten quartz into thin fibers by attaching it to an arrow and firing it from a bow. His fibbers couldn't transmit light, but they were lightweight and strong.

1881 An American engineer, William Wheeler, patents a system of internally reflective pipes to guide light from a central intense source to locations throughout a building. This form of lighting is impractical at the time and the light bulb becomes the more practical method of artificial lighting.

1881 Albert Abraham Michelson (USA) invents the interferometer and makes his first measurements to determine the speed of the Earth as it travels through the hypothetical ether

1885 Johann Jakob Balmer (Switzerland). Presented an empirical formula describing the position of the emission lines in the visible part of the spectrum of hydrogen ("Balmer series").

1885 to 1887 Oliver Heaviside writes Electromagnetic induction and its propagation over the course of two years, re-expressing Maxwell's results in 3 (complex) vector form, giving it much of its modern form and collecting together the basic set of equations from which electromagnetic theory may be derived (often called "Maxwell's equations"). In the process, He invents the modern vector calculus notation, including the gradient, divergence and curl of a vector.

1887 Albert A Michelson and Edward W Morley (USA). Described their unsuccessful attempts to detect the motion of the earth with respect to the 'Luminiferous Aether' by investigating whether the speed of light depends upon the direction in which the light beam moves (The Michelson-Morley experiment, fig. 7)

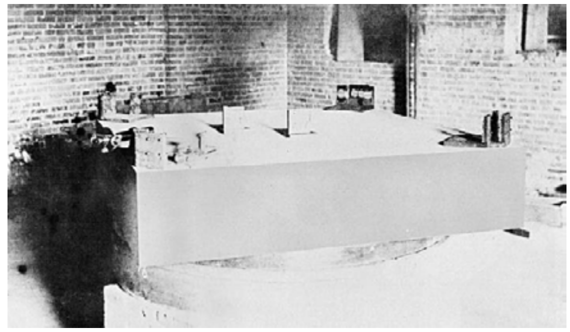

Fig. 7: Michelson-Morley interferometer. after **[7]**

1887 Heinrich Rudolf Hertz experimentally produces electromagnetic radiation with radio waves in the GHz range, also discovering the photoelectric effect and predicting that gravitation would also have a finite speed of propagation.

In **1888**, the medical team of Roth and Reuss of Vienna used bent glass rods to illuminate body cavities.

1890 O Wiener observed standing waves in light reflected at normal incidence from a silver mirror. Nodes and antinodes in the standing wave were detected photographically and it was concluded that a node exists at the mirror surface. From this it is concluded that, at least as far as photographic effects are concerned, the electric component of the electomagnetic wave has the more important effect

1891/92 L Mach and L Zehnder separately described what has become known as the Mach-Zehnder interferometer which could monitor changes in refractive index, and hence density, in compressible gas flows. The instrument has subsequently been applied in the field of aerodynamics