The Rise of Light – Discovering Its Secrets

Massimo Guarnieri, *Member, IEEE*

Department of Industrial Engineering, University of Padua, Italy
e-mail: massimo.guarnieri@unipd.it

***Abstract*—Inspired by the celebration of the year of light in 2015, this article considers the long lasting interaction among man, vision and light. It moves from the oldest traces of scientific investigations on light, dating back to ancient India, China and Greece, and outlines the long march of science that has led to the modern theories of light, thanks to the revolutionary contributions of scientists like Maxwell and Einstein. In fact, the evolution of the theories on light has accompanied the major steps in the history of science up to the modern concepts and models upon which many technologies that pervade our life are based.**

I. INTRODUCTION

When the United Nations Educational, Scientific and Cultural Organization (UNESCO) decided to appoint 2015 the International Year of Light and Light-based Technologies [1], they did not have in mind the groundbreaking contribution of James Clerk Maxwell, who first published his theory in *A Dynamical Theory of the Electromagnetic Field* 150 years ago. Instead, they looked one thousand years back in history to a time when Muslim science was peaking and the seeds of modern knowledge on light were laid by Iraqi polymath and philosopher Ibn al-Haytham (Latinized as Alhazen, 965–1039). Moving from such an authoritative celebration, this article tracks the history of the knowledge of light since ancient times to modern science.

Fig. 1. Light dispersion of a mercury-vapor lamp with a prism made of flint glass (D-Kuru/Wikimedia Commons). The spectrum of light was first studied by Isaac Newton 1666.

II. LIGHT IN ANCINET TIMES

To our knowledge, the earliest speculations on light were developed in ancient India, beginning in the 6th–5th centuries BCE, in the schools of Samkhya and Vaisheshika, which considered light as a fundamental subtle element or fast-moving fire atoms [2]. Early written records on light were also left by the Chinese scholar and philosopher Mozi (or Mo Tzu, ca.470–ca.391 BCE), who affirmed that it travels along straight lines, thus explaining why the images of what we now call a pinhole *camera obscura* are flipped upside down [3]. Even earlier, lenses made from polished crystals, such as the Nimrud lens, made by the Assyrians around 750–710 BCE, were known in the Near East. Likewise, magnifying meniscal lenses are reported in Egyptian hieroglyphs of the 5th century BCE. In the Greek world, very early investigations where centered on vision rather than on the nature of light. The philosophers Empedocles (ca.490–ca.430 BCE) and Plato (ca.427–ca.348 BCE) affirmed the emission theory [4], which assumed that vision gushes from rays emitted by the eyes, but it was only in the 3rd century BCE that the mathematician Euclid (ca.367–283 BCE) reported the first systematic investigation on light in *Optics* [5], studying direct vision and using a *camera obscura* to demonstrate that light travels in straight lines. The opposing intromission theory, that vision is produced by rays hitting the eyes, was proposed by philosophers such as the atomist Democritus (ca.460–ca.370 BCE), Epicurus (341–270 BCE), and, notably, Aristotle (384–322 BCE), who used a *camera obscura* in sun-eclipse observations. The intromission theory was claimed again by the Roman atomist Lucretius (ca.99–ca.55 BCE) in the first century BCE, not long before transparent glass and glassblowing were invented in Roman Syria around 20 BCE and scholars started experimenting with the optical effects that could be obtained. Strabo (63 BCE–24) noted the refraction of sunlight produced by atmospheric water vapor. Both Seneca the Younger (3 BCE–65) and Pliny the Elder (23–79) described the magnifying effect of a glass globe filled with water. Heron of Alexandria (ca.10–ca.70) first formulated reflection laws in *Captotrica*, demonstrating that rays reflected by a plane mirror take the shortest path. In contrast with Lucretius, these authors adhered to the emission theory. One century later, the great astronomer Claudius Ptolemy (90–168) wrote his *Optics* (originally, *Optics' questions*) [6], where he provided a deeper insight into reflection and first studied refraction (dioptrics) in the passage from air to water, from air to glass and from glass to water, correctly measuring the refraction angle of light in passing from air to water. He was also the first to describe the persistence of vision, the effect that allows the perception of motion exploited by the cinema. But this was developed eighteen centuries later, whereas, at the time of Ptolemy, optical technology was still too rudimentary to provide any practical observation instrument and astronomical investigations still relied on naked-eye observations. Together with the physician Claudius Galen (129–216), Ptolemy sustained the emission theory of vision, and the authoritativeness of these two scholars maintained this belief for almost a thousand years.

III. AL-HAYTHAM'S CONTRIBUTION AND LEGACY

During the Middle Ages, scientific knowledge languished for centuries in the Western world while Muslim science, after absorbing Greek-Roman culture, flourished from central Asia to Spain. Early speculations were carried out by al-Kindi (ca.801–873), and, later, Ibn Sahl (ca. 940–1000) discovered how curved mirrors and lenses reflect light, anticipating Snell's refraction law, which he used to shape focusing lenses and mirrors and reported in the book *On Burning Mirrors and Lenses* [7]. Ibn-Sīnā (Avicenna, ca.980–1037) and al-Bīrūnī (973–1048) argued that the speed of light is finite. Al-Haytham (965–1039) was, with them, one of the most prominent Muslim scholars at the turn of the first millennium. His interests expanded from astronomy to mathematics and meteorology, which he approached by exploring the scientific method six centuries before Galileo Galilei. His over 200 books (survived only in part) include the *Book of Optics* (*Kitab al-Manazir* in Arabic), a treatise in seven volumes written between 1011 and 1021 [8] that set the transition between ancient and modern optics and light science. Building on Ptolemy's optics, he rejected the emission theory and demonstrated that light travels along straight lines, studied reflection and refraction in depth and proposed an advanced model of vision based on perpendicularly incident rays. He provided great advancements in the knowledge of the visual system, anticipating several later discoveries of Western science. To develop his investigations, he ground lenses and curved mirrors and used a pinhole *camera obscura*, providing the first clear explanation of its operation outside of China. He geometrically resolved the so-called Alhazen's problem: "Given a light source and a spherical mirror, find the point on the mirror where the light will be reflected to the eye of an observer" (originally proposed as a geometry problem by Ptolemy in 150 AD, the analytical solution of the corresponding fourth-degree equation was found only in 1997 [9]). Al-Haytham's book inspired later Islamic scientists, and, after a Latin translation of the twelfth century, it was influential to Western science too and then cultivated by religious people. Early investigations were developed in England by Bishop Robert Grosseteste (ca.1175–1253) and the Franciscan John Pecham (died 1292), who authored *Perspectiva communis*. Roger Bacon (ca.1214–1292), another English Franciscan, scientifically researched on light, reflection and lenses, and used a *camera obscura* to observe solar eclipses. The Polish monk Witelo (1230–ca.1300) expanded Al-Haytham's results, and the German Dominican friar Theodoric of Freiberg (ca.1250–ca.1310) executed original experiments with glass globes filled with water, which simulated water droplets suspended in air, after which he could correctly attribute the shape and colors of the rainbow to the refraction of sunlight in raindrops [10]. Similar results were achieved at the same time by the Persian Kamāl al-Dīn al-Fārisī (1267–1319), anticipating Newton's investigations of the seventeenth century.

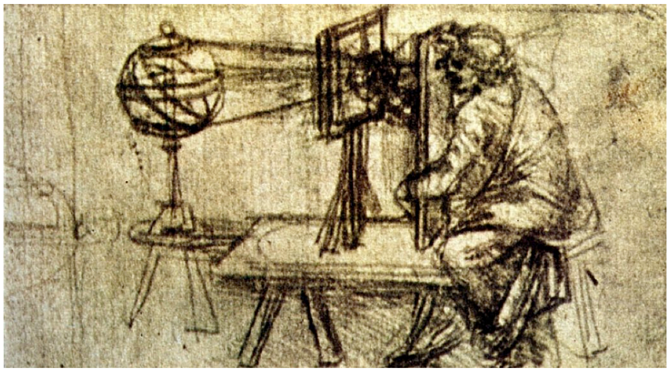
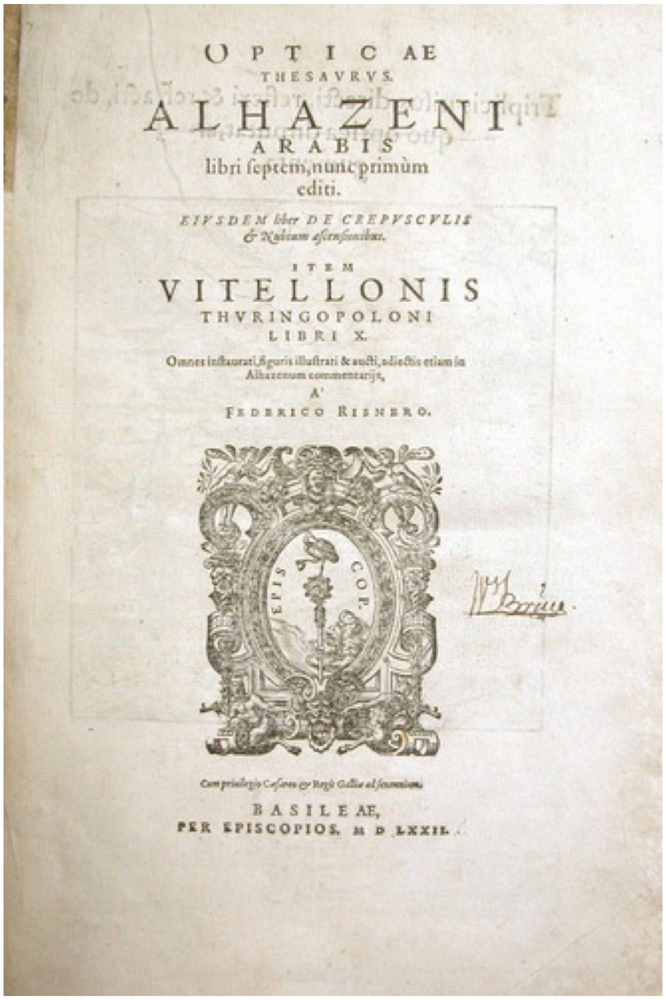


Fig. 2. The *camera obscura* sketched by Leonardo da Vinci in *Codex Atlanticus* (1515), preserved in Biblioteca Ambrosiana, Milan (Italy).

Over the centuries, al-Haytham's book continued inspiring the investigations of other Western experimenters. In the fifteenth century, Leonardo da Vinci (1452–1519) gave an accurate description of the *camera obscura* in the *Codex Atlanticus* (1515, Fig. 2), and the German Albrecht Dürer (1471–1528) and the Dutch Gemma Frisius (1508–1555) also used it. The masters of the Italian Renaissance Filippo Brunelleschi (1377–1446), Leon Battista Alberti (1404–1472) and Piero della Francesca (1415–1492) studied vision on a scientific basis, defining the laws of perspective, which allow the two-dimensional representation of a three-dimensional space [11]. They were instrumental not only to figurative arts but also to the technical representation of machines, boosting the publication of many "theatres of machines", which then promoted the spread of machinery. In the late sixteenth century, the Venetian Scientist Daniele Barbaro (1514–1570), in *La pratica della prospettiva* (the practice of perspective), gave the first description of a *camera obscura* provided with a lens in place of the pinhole and aimed at studying perspective. Soon after, the Neapolitan polymath Giambattista della Porta (1535–1615) built his *camera obscura* provided with a biconvex lens, and his book *Natural Magic* (*Magia Naturalis*, 1558) made it popular to the point that it became a common tool of many artists for achieving precise pictorial compositions. Most likely, they included the Dutch master Johannes Vermeer (1632–1675) (Fig. 3) and, for sure, the Italian Giovanni Antonio Canal (Canaletto, 1697–1768), whose original device is preserved at Museo Correr in Venice, and the English Joshua Reynolds (1723–1792), whose device is now at the Science Museum in London.

Fig. 3. *Officer and Laughing Girl* by Johannes Vermeer (ca 1660). Art critics have argued that the exceptional accuracy of proportions has been achieved with a *camera obscura*.



OPTICAE
THESAVRVS.
ALHAZENI
ARABIS
libri ſeptem, nunc primùm
editi.
EIVSDEM liber DE CREPVSCVLIS
& Nubium aſcenſionibus.
ITEM
VITELLONIS
THVRINGOPOLONI
LIBRI X.
Omnes inſtaurati, figuris illuſtrati & aucti, adiectis etiam in
Alhazenum commentarijs,
A'
FEDERICO RISNERO.

Cum priuilegio Cæſareo & Regis Galliæ ad ſexennium.

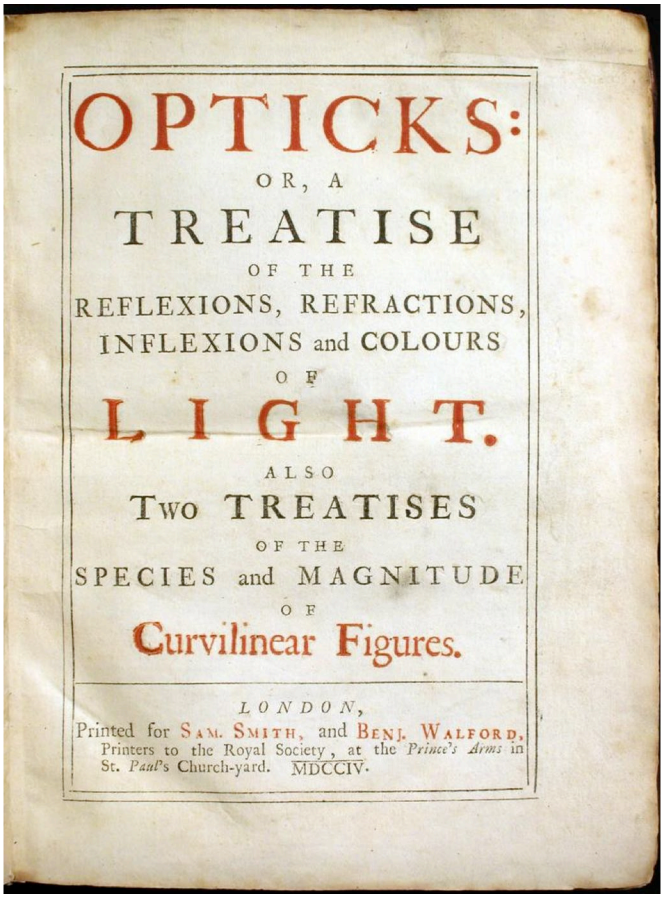
BASILEAE,
PER EPISCOPIOS. M D LXXII.

Fig. 4. Cover page of Ibn al-Haytham's *Book of Optics* with comments by Witelo. First printed edition, by Friedrich Risner (1572).

IV. Enlightened by the Scientific Revolution

The printed edition of the *Book of Optics*, published by the German mathematician Friedrich Risner (c.1533–1580) in 1572 (Fig. 4) [12], ensured the widespread diffusion of Al-Haytham's ideas and promoted further investigations and achievements at a time when the scientific revolution was blossoming. Johannes Kepler (1571–1630) of Germany combined his astronomical research with optical studies regarding eclipses, the intensity of light, parallax and the apparent size of far bodies, and the principle of the pinhole *camera obscura*. His *Astronomiae Pars Optica* (1604) is regarded as the beginning of modern optics. The microscope (1595) and the telescope (1608) were developed in the Netherlands by use of a proper combination of lenses. It was by using one early telescope that Galileo Galilei (1564–1642) revolutionized astronomy starting in 1609 [13]. And it was thanks to these early microscopes that the way was paved for the investigation of the extremely small world. In 1621, the Dutch Willebrord Snellius (1580–1626) rediscovered the law of refraction, now known as Snell's law, and, soon after, Descartes enounced and first published the law of reflection. After experiments with prisms, Isaac Newton (1642–1727) discovered the spectrum of sunlight in 1666 and developed a corpuscular theory of light that gained wide acceptance. After investigating the chromatic aberration of lenses, he invented the reflecting telescope (1668), first reporting his results in 1672 and finally publishing them in *Opticks* in 1704 (Fig. 5) [14]. Newton also argued on the diffraction of light, which was first accurately described by Francersco Maria Grimaldi (1618–1663), an Italian Jesuit, and published by him posthumously in 1665. The portable *camera obscura* was conceived by Johann Zahn (1641–1707) of Germany, who described it, together with other optical instruments, in *Oculus Artificialis* (1685).

Building on Galileo's observation of Jupiter's satellites (the Galilean Moons) and observing the apparently different durations of the eclipses of Io, the inner of them, depending on the earth's position along its revolutionary motion around the Sun, the Danish astronomer Ole Christensen Rømer (1644–1710), in 1676, discovered that the speed of light is finite [15]. Opposing Newton's corpuscular theory of light, in 1678, the Dutch Christiaan Huygens (1629–1695) began to develop the first wave theory of the propagation of light (conjecturing longitudinal elastic waves) and, working on Rømer's data, estimated its speed at 212,000 km/s. He later reported his results in *Traité de la lumière* in 1690 [16]. This astonishing result was not fully accepted for some fifty years. And it was also a fairly good estimation if we consider the instrumentation then available. As early as 1727, the English astronomer royal James Bradley 1693–1762) used stellar aberration to deduce a much better value of the speed of light at 304,000 km/s [17]. In 1801, light interference observed by



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

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

Fig. 5 – The cover of the first edition of Isaac Newton's *Opticks: or, a treatise of the reflexions, refractions, inflexions and colours of light*, published in 1704.

Thomas Young (1773–1829) vindicated Huygens' wave theory, and Newton's corpuscular theory was put aside [18]. A few years later, in 1809, Jean-Baptiste Delambre (1749–1822), the French astronomer who had measured the Earth's meridian to define the meter, resorted to astronomical measurements to achieve a quite accurate value of the speed of light at 300,000 km/s. From 1815–18, another Frenchman, Augustin-Jean Fresnel (1788–1827), published advanced results on diffraction, providing more support to the wave theory.

V. BLOSSOMING OF MODERN SCIENCE

The technological and scientific advancements of the nineteenth century opened the way to terrestrial measurement of the speed of light. Armand-Hippolyte-Louis Fizeau (1819–1896) was a fine French experimenter who, in 1849, developed an optomechanical method consisting of a toothed wheel and a mirror placed 8.633 km apart from it. He sent a beam of light through the gaps between the wheel teeth and increased the wheel rotation speed until he could see the light through the next gap. Fizeau could thus calculate the speed of light at 313,300 km/s. The following year, he also measured the speed of light in water with a similar device. Another French physicist, Jean Bernard Léon Foucault (1819–1868), in 1862, used a rotating mirror, still an optomechanical method, to obtain 298,000 km/s [19].

Around the middle of the nineteenth century, research on electromagnetism was also advancing remarkably, and one of its intriguing problems remained the speed of the propagation of electricity. As early as 1746, the French scientist and jurist Jean-Antoine Nollet (1700–1770) had performed experiments on the propagation speed of electricity. By involving 200 monks connected from hand to hand by a 7-m iron wire so as to form a circle of about 1.6 km, he was able to prove that this speed is finite, even though very high. Determining how high remained an open question [20]. In 1856, German physicist Wilhelm Eduard Weber (1804–1891) discovered that the ratio between the values of the units of the electrical charge in the electromagnetic and electrostatic systems, the two measurement systems then used (corresponding to $1/\sqrt{\varepsilon_0\mu_0}$ in the not-yet born International System of Units), was close to the speed of light measured by Fizeau seven years earlier. Only two years before, William Thomson (later Lord Kelvin, 1824–1927) had obtained the second-order partial differential equation of the electromagnetic propagation in a telegraph line (namely, the telegrapher equation) and determined that the signal speed was inversely proportional to the square of the line length while laying the transatlantic telegraph cables [21]. The same equation was derived in 1857 by another German, Gustav Robert Kirchhoff (1824–1887), who also computed the propagation speed of an electrical signal in a non-dissipative line, finding it equal to the speed of light. These results were the basis of James Clerk Maxwell's (1831–1879) analyses. With the aim of mathematizing Faraday's lines of force, in 1862, he started developing his groundbreaking theory. In 1865, he published *A Dynamical Theory of the Electromagnetic Field* [22], where he introduced the displacement current, a truly original concept, in order to provide soundness to Ampere's law in dynamic conditions. He then combined it with Faraday's law of induction, deducing that they merge into wave equations, which travel at the same speed as light and consequently postulating that the light itself is an electromagnetic wave. Two years later, the Danish physicist Ludvig Valentin Lorenz (1829–1891) obtained similar deductions and consistent results. Maxwell reordered and completed his model in his masterpiece, *A Treatise on Electricity and Magnetism*, published in 1873 [23]. His achievements were so advanced that, at the beginning, most physicists rejected them, regarding his theory as a mere freak mathematical occurrence. But a handful of enthusiastic young pioneers, later dubbed the Maxwellians, were fascinated by the waves of Maxwell. They included George Francis FitzGerald (1851–1901), Oliver Lodge (1851–1901), Oliver Heaviside (1850–1925) and, above all, Heinrich Hertz (1857–1894). In 1887, Hertz performed one of the most celebrated experiments in the history of physics. Resorting to an oscillating circuit (conceived by FitzGerald) that included a high-frequency (50 MHz) oscillator-transmitter, he demonstrated, with great accuracy and beyond any reasonable doubt, the existence of electromagnetic waves as predicted by Maxwell [24]. Unfortunately, the Scot could not enjoy his triumph. He had passed away eight years before.

The progresses in electromagnetism were flanked by the discoveries of the interactions between electricity and light. In the first decades the nineteenth century, electrochemistry was a frontier field, with many scientists engaged in developing more and more advanced cells [25]. Among them, the French father and son Antoine-César (1788–1878) and Alexandre-Edmond (1820–1891) Becquerel observed the electrochemical effects produced by light in electrolytic solutions, in 1839. These effects remained mere curiosities until the action of light on solid materials was discovered. This first happened in 1873, when the English engineer Willoughby Smith (1828–1891) observed the photoconductivity of selenium, namely the variations of its electrical resistance with incident light. Three years later, the British William Grylls Adams (1836–1915) found that this material generates electricity when exposed to light. In 1887, Heinrich Hertz observed that ultraviolet light facilitated the passage of current in a spark gap [26], but he quit researching in this direction and turned to electromagnetic waves instead. The following year, Wilhelm Hallwachs (1859–1922), a young assistant of Hertz, discovered that ultraviolet light can produce a stronger effect specifically on selenium. The phenomenon was dubbed Hallwachs-Effekt and later photoelectric effect. It was after results like these that the young Albert Einstein (1876–1955) was attracted to investigate light quanta some years later.

VI. SPECIAL RELATIVITY AND QUANTUM REVOLUTION

The experiment performed by Albert A. Michelson (1852–1931) and Edward Morley (1838–1923) in 1887, aimed at detecting the effect of the relative velocity between inertial systems on the speed of light but demonstrated instead the constancy of the speed of light in inertial reference systems, against Galilean relativity. It triggered a reflection on electromagnetism and on the concepts of space and time, with major contributions from the Dutch Hendrik A. Lorentz (1853–1928), who introduced the so-called local time as a mathematical ruse and proposed that moving bodies undergo a length contraction, and the French Henri Poincaré (1854–1912), who achieved several insights regarding the constancy of the speed of light. On the other hand, in 1900, Max Planck (1858–1947), in an effort to model blackbody radiation, contrived the breakthrough of the energy quanta, also considering it a mathematical ruse. Einstein settled both problems in 1905, his *annus mirabilis*, when he published four papers in *Annalen der Physik*, each a milestone in theoretical physics. In the first of them, "On a heuristic viewpoint concerning the production and transformation of light" [27], Einstein, justifying Planck's results, deduced that light consists of discrete quantized packets of energy and enunciated the law of the photoelectric effect. In the third paper, "On the electrodynamics of moving bodies" [28], he set out the theory of special relativity, which, postulating the constancy of the speed of light, provided a new unitary interpretation of electromagnetism, changing the notions of space and time, which had been the indisputable base of Newton's physics for more than two centuries (the second and fourth of Einstein's 1905 papers dealt with the Brownian motion and the mass-energy equivalence, $E = mc^2$, respectively). Einstein's ideas remained controversial until American Robert Millikan's (1868–1953) experimental confirmation of the photoelectric effect [29] in 1914 and Arthur Eddington's astronomical relativistic observations in 1919. Ultimately, both Einstein and Millikan won the Nobel Prize in physics, in 1921 for the photoelectric effect and in 1923 for its experimental demonstration (and for the related work on the elementary charge) respectively. In 1913, the Danish Niels Bohr (1885–1962) had demonstrated that the discrete emission and absorption spectra depend on the energy quanta emitted by atoms, for which he was awarded the 1922 Nobel Prize in physics. The name photon for the light quantum, introduced by the American Gilbert N. Lewis (1875–1946) in 1926, was accepted after its use by Arthur Compton (1892–1962) two years later. Compton, an America physicist, had received the 1927 Nobel Prize in physics for demonstrating the particle nature of electromagnetic waves. The discovery of the interaction between light and matter furthered the development of quantum optics and, to a larger extent, of quantum mechanics. In this line, in 1948, the Japanese Sin-Itiro Tomonaga (1906–1979) and the Americans Julian S. Schwinger (1918–1994) and Richard P. Feynman (1918–1988) formulated their independent but consistent models of quantum electrodynamics, presenting in quantum form the electromagnetic interactions between subatomic electrons and photons (i.e. between matter and light) [30]. For their work, they shared the 1965 Nobel Prize in physics. Further major advancements came from the Indian-American Ennackal C. Sudarshan (born 1931), the American Roy J. Glauber (born 1925), and the German-British-American Leonard Mandel (1927–2001), who provided a deep understanding of the nature of light and photodetection and developed the statistics of light.

VII. CONCLUSION

Our knowledge of light has greatly evolved in time together with the development of our civilization, with a tremendous boost in the last two centuries thanks to the outstanding contributions of many scholars and scientists from so many different countries. This presentation has highlighted the main steps upon which the knowledge of light has emerged, tracing the great phases in the history of science. At the same time, the use we make of light has enormously changed from ancient times when we used it to light our dwellings at night, but this is another story out of the scope of this paper. From a certain point of view, we can say that our knowledge of light, broadening in time, has increasingly enlightened our understanding of the world we live in, and, after all, the comprehension of ourselves.

REFERENCES

[1] 2015 International Year of Light and Light-based Technologies, http://www.light2015.org/Home.html (retrieved 2015–12–07.)

[2] Olivier Darrigol, *A History of Optics from Greek Antiquity to the Nineteenth Century,* Oxford: Oxford University Press, 2012.

[3] J. Needham, *Science and Civilization in China: Volume 4, Physics and Physical Technology, Part 1, Physics*. Taipei: Caves Books Ltd, 1986.

[4] A. M. Smith, *From Sight to Light. The Passage from Ancient to Modern Optics*, Chicago & London: The University of Chicago Press, 2014.

[5] Euclid, "The Optics of Euclid", translated by H. E. Burton, *Journal of the Optical Society of America*, vol. 35, no. 5, May 1955, pp. 357–372.

[6] A. M. Smith, "Ptolemy's theory of visual perception: An English translation of the Optics with introduction and commentary", *Transactions of the American Philosophical Society*, vol. 86, Part 2, 1996.

[7] D. C. Lindberg, *Theories of Vision from al-Kindi to Kepler*, Chicago: University of Chicago Press, 1976.

[8] N. El-Bizri, "A Philosophical Perspective on Alhazen's Optics", *Arabic Sciences and Philosophy*, vol. 15, no. 2, Aug. 2005, pp. 189–218.

[9] P. M. Neumann, "Reflections on Reflection in a Spherical Mirror," *Amer. Math. Monthly*, vol. 105, 1998, pp. 523-528.

[10] Grant, Edward, *A source book in medieval science*, Cambridge, MA: Harvard University Press, 1974.

[11] Martin Kemp, "Science, Non-science and Nonsense: The Interpretation of Brunelleschi's Perspective", *Art History*, vol. 1, no. 2, 1978, pp. 134–161.

[12] F. Risner (Ed.), *Opticae thesaurus*, Basel, 1572 (reprint: NY: Johnson Reprint, 1972).

[13] W. R. Shea, T. Bascelli (Ed.) *Galileo's Sidereus Nuncius or Sidereal Message*, Translated into English by W. R. Shea and T. Bascelli, Sagamore Beach, MA: Science History Publications/USA, 2009.

[14] I. Newton, "The Optical Papers of Isaac Newton," Vol. 1: *The Optical Lectures*, 1670–1672, Cambridge Univ. Press, 1984.

[15] P. Friedrichsen, C. Gorm Tortzen, *Ole Rømer – Korrespondance og afhandlinger samt et udvalg af dokumenter*, Copenhagen: C. A. Reitzels Forlag, 2001 (in Danish).

[16] C. Huygens, *Traité de la lumière* (*Treatise on Light*), 1690. Translated into English by Silvanus P. Thompson, online at Project Gutenberg, www.gutenberg.org/catalog/world/readfile?fk_files=164378 (retrieved on 2015–12–07.)

[17] J. Bradley, "Account of a new discovered Motion of the Fix'd Stars," *Philosophical Transactions of the Royal Society of London,* vol. 35, 1729, pp. 637–660. Online at http://gallica.bnf.fr/ark:/12148/bpt6k55840n.image.f375.langEN (retrieved on 2015–12-7.)

[18] R. Baierlein, *Newton to Einstein: the trail of light: an excursion to the wave-particle duality and the special theory of relativity*, Cambridge UK: Cambridge University Press, 2001.

[19] H. Poincaré, F. V. Vreeland, "Experiments of MM. Fizeau and Gounelle", in *Maxwell's Theory and Wireless Telegraphy*, McGraw Publishing Co., 1904.

[20] M. Guarnieri, "Electricity in the age of Enlightenment", *IEEE Ind. Elect. Magazine*, Vol. 8, no. 3, Sept. 2014, pp. 60-63.

[21] M. Guarnieri, "The Conquest of the Atlantic", *IEEE Ind. Elect. Magazine*, vol. 8, no. 1, Mar. 2014, pp. 53-55/67.

[22] J. C. Maxwell, "Dynamical theory of the electromagnetic field," *Philosophical Transactions of the Royal Society of London*, vol. 155, 1865, pp. 459-512.

[23] J. C. Maxwell, *A treatise on electricity and magnetism*, Vol I and II, Oxford: Clarendon Press, 1873.

[24] H. R. Hertz: "Ueber sehr schnelle electrische Schwingungen", *Annalen der Physik*, vol. 267, no. 7, pp. 421–448, May 1887 (in German).

[25] M. Guarnieri: "The Big Jump from the Legs of a Frog", *IEEE Ind. Electr. Magazine*, vol. 8, no. 4, Dec. 2014, pp. 59-61+69.

[26] H. Hertz, "Ueber den Einfluss des ultravioletten Lichtes auf die electrische Entladung," *Annalen der Physik*, vol 267, no. 8, 1887, pp. 983–1000 (in German).

[27] A. Einstein, "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt," *Annalen der Physik*, vol. 17, no. 6, March 1905, pp. 132–148. (English translation: "On a Heuristic Point of View about the Creation and Conversion of Light," on line at http://www.physik.fu-berlin.de/~kleinert/files/eins_lq.pdf Retrieved 2015-12-07).

[28] A. Einstein, "Zur Elektrodynamik bewegter Körper," *Annalen der Physik,* vol. 17, no. 10, Sept. 1905, pp. 891–921. (English translation: "On the Electrodynamics of Moving Bodies," on line at http://www.fourmilab.ch/etexts/einstein/specrel/www/ Retrieved 2015-12-07).

[29] R. Millikan, "A Direct Determination of "*h*."". *Physical Review* vol. 4, no. 1, 1914, pp. 73–75.

[30] R. Feynman, *QED: The Strange Theory of Light and Matter*. Princeton University Press, Princeton, 1985.

Massimo Guarnieri was born near Venice, Italy in 1955. He graduated with honors in electrical engineering at Padua in 1979 and received a diploma degree in plasma and thermonuclear fusion research in 1982 and a PhD in electrical science in Rome in 1987. He became an ICS Member in 2008, an IEEE Member in 2012 and an ECS Member in 2014. In 1982, he joined the CNR (Italian National Council of Research), and, in 1983, he joined the University of Padua, where he has been full professor of electrical engineering since 2000. Initially, he centered his work on the analysis and design of large electromagnetic devices for the thermonuclear fusion research experiments Eta-Beta II and RFX. For the latter, he worked in and eventually led the Magnetic System Group, which designed the device's major inductor systems (diameter up to 8 m, 50 kA, 200 kV). He later centered his interests in the area of numerical computation for electromagnetic and coupled problems. For ten years he has been involved in the analysis, optimization and design of fuel cells and electrochemical storage devices, including modeling and parameter identification. He is also widely interested in the history of technology and science. His scientific production of nearly 200 items (nearly 100 indexed by Scopus) includes papers in journals and in conference proceedings and several textbooks. He chairs the Education & Profession Group of the AEIT-ASTRI Italian Electrical Engineers Institution. He is the official representative of the University of Padua in N.ERGHY, the European Union association representing the universities and research institution in the Fuel Cell and Hydrogen Joint Technology Initiative (FCH JTI). He is a columnist and editorial board member of the IEEE Industrial Electronics Magazine.