Classical and Quantum Optics and Their Influences on Science and Society

Cristino Jose dos Santos Ferreira [1]
Gabriela Rodrigues Vaz [2]
Clodoaldo Valverde [3]
Basílio Baseia [4]

ABSTRACT

In this work we present a brief history of Optics, begun several centuries BC in its evolution characterized as Classical Optics; later on, this theory became also characterized as Quantum Optics. The first of these two theories was completed in the great work of J. C. Maxwell while the second actually started in 1977 with the discovery of the first quantum effect in Optics, having in Roy Glauber one of its greatest representatives. Here, a quick walk along these two theories was made, including the various technological applications of both in science and society

Keywords: Classical and Quantum Optics; Maxwell's Equations; Nonlinear Effects; Laser Light Applications.

---

[1] Doutorado em andamento em Física pela Universidade Federal da Paraíba, UFPB, Brasil. cristinojsf66@gmail.com
[2] Graduação em Física pela Universidade Estadual de Goiás, UEG, Brasil. gvazfisica@gmail.com
[3] Doutorado em Física Computacional pela Universidade Federal de Goiás, UFG, Brasil. Docente na Universidade Estadual de Goiás, UEG, Brasil; e na Universidade Paulista, UNIP, Brasil. valverde@ueg.br
[4] Doutorado em Física pela Universidade de São Paulo, USP, Brasil. Docente na Universidade Federal de Goiás, UFG, Brasil. basiliobaseia@yahoo.com.br

Since 1977 the discipline named Optics has been treated along two theoretical approaches: Classical Optics and Quantum Optics. On the side of Classical Optics, it is entirely described by the Maxwell's theory, proposed in 1865. It consists of four equations selected from twenty available at the time, two of them originated in the Gauss law, another being the Faraday equation, and the fourth being the Ampère equation modified by Maxwell by the addition of an especially relevant term. Now, before we come Classical Optics via the Maxwell's equations, many precursors in the study of phenomena on light had already done important contributions in the creation of this theory; we highlight some of them: Galilei Galileu, Johannes Kepler, Willebrord Snell, René Descartes, Isaac Newton, Pierre Fermat, E- Luis Malus, David Brewster, A-Jean Fresnel, B. Leon Foucault and others. However, it is also worth mentioning those researchers who discovered laws related to phenomena outside of Optics, also leading to the theoretical construction of the four Maxwell1 equations; they are: Carl F. Gauss (first and second law), André-Marie Ampère (third law), and Michael Faraday (fourth law), the latter partially modified by J. C. Maxwell.

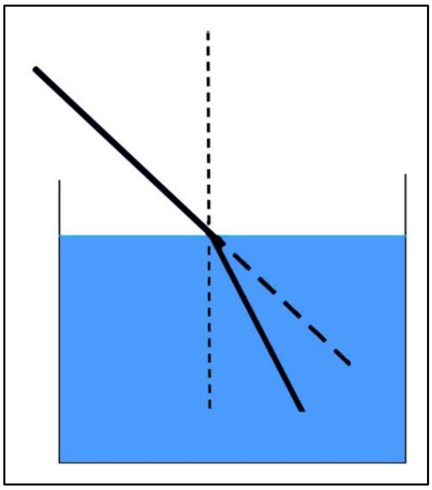
On the side, Quantum Optics, this theory is entirely described by the Schrödinger equation, proposed in 1926. This equation came from relevant contributions of many physicists, as follows in chronological order: Max Planck (1900) and Albert Einstein (1905, 1907, 1917), Ernest Rutherford (1911), Niels Bohr and Arnold Sommerfeld (1913), Arthur H. Compton (1922), Otto Stern and Walther Gerlach (1922), Wolfgang Pauli (1924), and Louis de Broglie (1924). A different approach for quantum theory, showing similar results, was also presented in 1926 by Werner Heisenberg. The equivalence between the Schrodinger and Heisenberg approaches was proved by P. M. Dirac also in 1926.

CLASSICAL OPTICS

Optics is one of the oldest branches of physics whose development began in ancient Greece around 9th centuries BC, including the contributions by the poet Homer (8th centuries BC), the mathematician Pythagoras (6th centuries BC), the philosophers Plato and his disciple Aristotle (5th to 4th centuries BC). The concern at that time was to explain how we see objects: for some, this was due to particles that our eyes emit in the direction of objects; for others it was the reverse, the particles going from object to our eyes, while for a third group vision was a combination of these two effects in presence of some light source.

Long after, around 300 years BC, the optical subjects under discussion were related to the effects of reflection and refraction of light, the latter meaning the change of direction that light undergoes when it passes from one transparent medium to another with different density, such as passing from air to water (Figure 1) and the reverse. According to the literature, very little has happened since then until around the Middle Ages (~5th to 15th centuries AC) and the little learning about optics was lost in the West, fortunately recovered later, among the Arabs.

Figure 1. Effect of refraction that is seen by an observer when a bar passes from a less refringent medium (say air) to a more refringent one (say water).

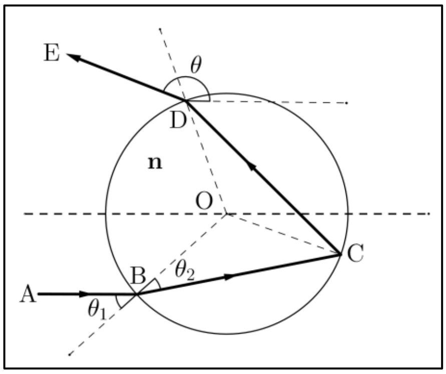


Source: Authors.

Then, as early as the 17th century, an Iranian discovered the Snell-Descartes's first law, which concerns the three luminous rays, that incident, reflected and refracted rays belong to the same plane. The next developments were related to the study and applications of optics in the construction of lenses for glasses, magnifiers and lenses, based on the effects of reflection and refraction of light on surfaces. Speculations on the rainbow phenomenon were based on the combined effects of refraction and reflection on water droplets in the sky: the light coming from the Sun at our backs, affects a drop in the heights penetrating refracted, being reflected in its interior and returning to the medium after a new refraction (Figure 2). The greatest experimental advance using these two effects is due to Galilei Galileo in the 17th century; it is also attributed to him the invention of the telescope and the microscope in 1609.

Still in the 17th century, René Descartes was the first to make use of refraction and reflection effects to explain the rainbow and Tycho Brahe took advantage of the invention of the telescope to make long nocturnal observations of planets and stars, having built a large data table which, after his death, was passed on to the theoretical physicist Johannes Kepler. It was on the basis of these data from T. Brahe that J. Kepler deduced his three "Kepler's Laws" from celestial mechanics related to the orbits of the planets around the Sun: the laws of elliptic orbits, translation periods, and the swept areas by planets. At that time people's understanding was that there were two distinct mechanics, celestial and terrestrial, until that Isaac Newton inspired by Kepler's laws joined the two mechanics into one through his equation of universal gravitation law: $F = G(M_1M_2)/R^2$, G standing for the gravitational constant, M_1 and M_2 being the masses of two attracting bodies or planets, R being the distance between them. This discovery by Newton constitutes the first unification in Physics, "by unifying the Earth with the Sky". Other important unifications would appear later, as mentioned below.

Figure 2. The diagram shows a sun ray (ABCDE) penetrating into a drop of water where this ray undergoes a single internal reflection before emerging from the gout (in some cases, multiple internal reflections may occur with partial outward transmissions). The rainbow happens when the deviation angle $\boldsymbol{\theta}$ is minimal.

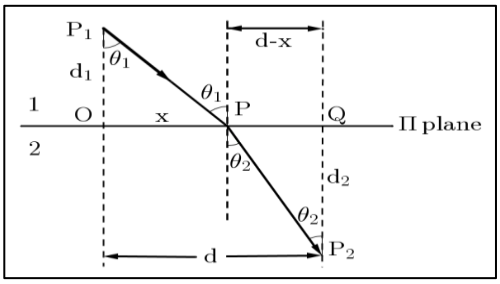


Source: adapted from Nussenzveig (1998).

Returning to light, when measuring its speed (now represented by letter c in literature) some pioneers since Empedocles to Galileo have failed, the latter using two lanterns distanced ~1.5 km from each other. The failure was attributed to the very high speed of light propagation. While Empedocles thought light having finite velocity, Galileo followed Aristotle and attributed his failed measure as being due to infinite speed of light. Little is said about why Aristotle had this feeling on light velocity; his opinion had great influences during long time, even when wrong. At this point, it is worth mentioning a similar dispute in science occurred with the controversial theory by Charles Darwin against creationism, a religious theory based only in faith: to give a very illustrative example, Lord Kelvin, one of the greatest physicists at the end of 19th century, led the scientific opposition to Darwin's evolutionist theory on the basis of his thermodynamic calculations that Earth was between 24 and 400 million years old, a time interval so short that would not allow the evolution of the species to be consummated. However, an error was done by Kelvin, which assumed the light energy coming from the Sun based on the burning of coal, while it was later proven to be of nuclear origin, namely, from Hydrogen transforming in Helium. This correction leads the Earth being more than 4 billion years old, instead of 4 million. Some years later Darwin theory was again confirmed by scientific findings in genetic.

It was in the 17th century AC that another physicist, Ole Roemer, took advantage of the knowledge about lunar eclipses (one of the Jupiter's moons) to make the first technical measurement and obtained a finite result of light velocity: $c = 200.000\text{km/s}$. The result was questioned by Aristotelians, among them the followers of René Descartes, for whom the light would have infinite velocity. Also, in this century the principle of 'minimum time' was proposed by Pierre de Fermat: accordingly, when the light can follow several paths to go from an arbitrary point P_1 to another P_2, it prefers to follow the path having the minimum distance (Figure 3).

Figure 3. Fermat's principle of minimum time (or minimum path) of light.



Source: adapted from Nussenzveig (1998).

In this case the optical path is $[P_1PP_2]$. Then we can write, with n_1 and $n_2$being the refraction index,

$$[P_1PP_2] = n_1\overline{P_1P} + n_2\overline{PP_2} = n_1\left(d_1{}^2 + x^2\right)^{1/2} + n_2\left[d_2{}^2 + (d-x)^2\right]^{1/2} \tag{1}$$

whose minimum occurs when the following condition is obeyed,

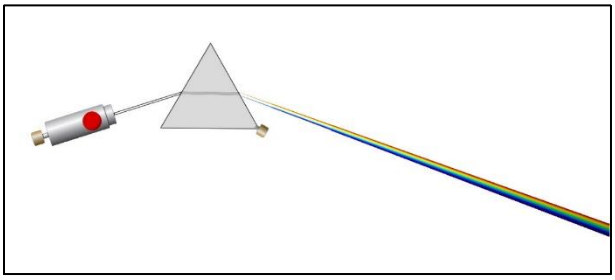
$$0 = \frac{n_1 x}{\left(d_1{}^2 + x^2\right)^{\frac{1}{2}}} - \frac{n_2(d-x)}{\left[d_2{}^2 + (d-x)^2\right]^{\frac{1}{2}}} = \frac{n_1 x}{\overline{P_1P}} - \frac{n_2(d-x)}{\overline{PP_2}} = n_1 \sin\theta_1 - n_2 \sin\theta_2\,, \tag{2}$$

which coincides with the Snell-Descartes law of refraction: ${}^{n_1}/_{n_2} = {}^{sin\theta_2}/_{sin\theta_1}$

We also had in this 17th century the Newton's discoveries on color theory, where an important role is played by the dispersion of light, an effect that occurs because light beams of different colors (frequencies) have different velocities as they pass through a transparent medium: it means that the refractive index of the medium varies with light color (frequency). Also in this direction, I. Newton made experiences with prisms where he decomposed the white light into its various component colors (Figure 4). He also obtained the reverse, white color from its component colors: to this end he showed that a colored wheel acquires white color by spinning rapidly around its axis (Figure 5). On the other hand, the Huygens-Fresnel superposition principle was also presented: it means that each point of wave front of a traveling wave, say on a surface of water or on air, etc, functions as an antenna emitting spherical or circular waves of the same frequency from the original source (Figure 6).

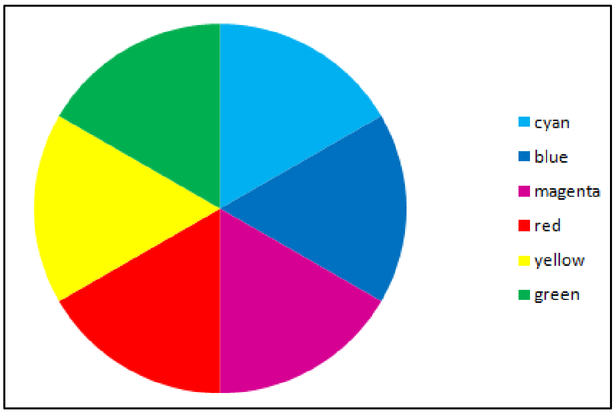
In the 18th century Isaac Newton proposed his corpuscular theory of light. One of his arguments was based on the refraction effect that a light ray suffers when it penetrates a more dense transparent medium: when the light penetrates the medium, inclined to normal to the surface, the refracted ray suddenly approaches the normal; then, as the matter does not attract the light wave but attract particles, this took to his conclusion that light is made up of particles. The same applies to the case of the repulsion that occurs when the light propagates reversely, from the more dense medium to the less dense one; then the refracted ray moves away from the normal. This corpuscular theory remained accepted until the early 19th century when Thomas Young made his famous double-slit experiment in 1801: he obtained interference effects in Figures constructed by diffraction of light rays displaying dark lines separated by white lines: The dark (white) lines signifying destructive (constructive) interference of waves coming from two neighboring narrow slits (see Figure 6).

Figure 4. Dispersion of white light by a glass prism.



Source: Authors.

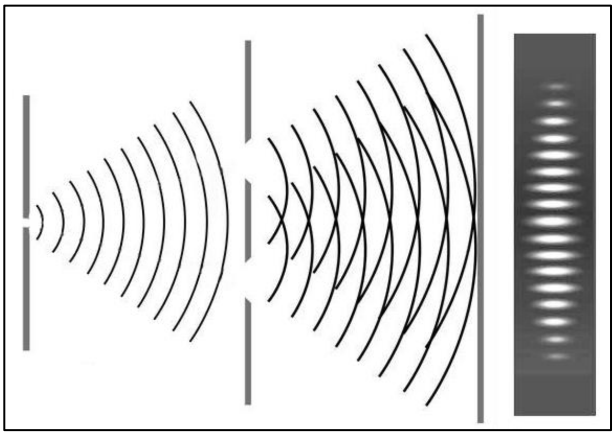
Figure 5. Newton's disc: when the disc rotates, it 'becomes' white.



Source: Authors.

Then, at the beginning of the 19th century, Newton's corpuscular theory of light fell by land in the realm of Classical Optics, because in the double-slit experiment by Young the interference Figure could only be explained when assuming light behaving like waves. In a sense, however, Newton's corpuscular light theory will be partially rehabilitated by Einstein in 1905; however, this change occurs outside the domain of Classical Optics, i.e., in the Quantum Optics scenario, where the Einstein's "quanta" (photons) are proposed to explain the photoelectric effect (Planck 1900). The name "photon" was coined by the chemist Gilbert N. Lewis in 1926.

Figure 6. Scheme of wave fronts being refracted by a double slit showing interference in the screen on the right side of the Figure.



Source: Authors.

Actually, the wave theory of light could not withstand the photoelectric effect; for example, even for a light beam having high intensity this effect did not occur with light having small frequencies; on the other hand, the effect occurs with a light having low intensity and high frequency. Both behaviors being in contradiction with Classical Optics that would affirm: "since photoelectric effect consists of pulling electrons from a metallic surface, the higher the intensity the greater the effect, no matter the frequency of light". The quantum explanation by Einstein was based on the definition of the photon energy, $E = hf$, where h stands for the Planck constant and f stands for the light frequency; this argument solved the contradiction raised in Classical Optics. It is worth mentioning and repeat that the photon has no place in the Classical Optics.

Meanwhile, another double-slit experiment was made in 1927, by Clinton Davison and Lester Germer; it was similar to Young's experiment but using electrons instead of light: they concluded that, such as the case of light, electrons also behave like waves in the double-slit experiment. Now, remembering that in the photoelectric effect the light behaves as particles, one can conclude that all lights and particles manifest the wave or corpuscular behavior depending on the type of experience in which waves and particles are observed.

This type of double character gave rise to the so-called "principle of complementarity", also called "wave-particle duality" introduced in quantum theory in 1928 by Niels Bohr: electrons are particles, but they behave like waves in the double-slit experiment made by Davison and Germer; the same occurs with electrons, behaving as wave in the tunnel effect. On the other hand, light is wave, but it behaves like particles (photons) in the photoelectric effect, as explained by Einstein in 1905; the same occurs with light behaving like particles in the Compton experiment made in 1922. In summary, in the microscopic world the wave or corpuscle character of objects depends on the experimental situation considered - an exotic example of 'double personality'.

Here we conclude these few words on Classical Optics with a highlight to the 19th century, in which it reached its supreme position in physics, whether in precision or in beauty, being fully formulated by only four equations chosen among many others at the time: the famous equations of James Clerk Maxwell, published in 1864, currently written in the form (in MKS units),

$$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\varepsilon_0}, \tag{3}$$

$$\vec{\nabla}\cdot\vec{B}=0, \tag{4}$$

$$\vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}, \tag{5}$$

$$\vec{\nabla}\times\vec{B}=\mu_0\vec{J}+\mu_0\varepsilon_0\frac{\partial\vec{E}}{\partial t}, \tag{6}$$

with $\vec{E}(\vec{B})$ being the electric (magnetic) field, $\rho(\vec{J})$ being the density of electric charge (magnetic corrent), $\varepsilon_0(\mu_0)$ being the electric suscetibility (magnetic permeability) of vacuum, $\vec{\nabla}(\vec{E})$ and $\vec{\nabla}\times(\vec{E})$ are well known mathematical operators acting upon the electric field $\vec{E}$. The same being valid for $\vec{B}$.

According to physicist Richard P. Feynman, the Maxwell's equations constitute the most beautiful set of equations of Physics. Often we find in the literature important physicists praising the beauty of a certain theory. Although rare, there are also the reverse, those who disagree with this position. In this direction we mention an alert given by Sabine Hossenfelder (Roy 1998), for whom beauty does not always lead to truth, nor does truth lead to beauty: accordingly "(...) I think it's time to take a lesson from the history of science. Beauty does not have a good track record as a guide for theory-development. Many beautiful hypotheses were just wrong, like Johannes Kepler's idea that planetary orbits are stacked in regular polyhedrons known as 'Platonic solids', or that atoms are knots in an invisible aether, or that the Universe is in a 'steady state' (Einstein 1917) rather than undergoing expansion (Friedmann 1922)

James C. Maxwell is also attributed the first colored photo. After Isaac Newton, who carried out the first unification in physics, joining Mechanics with Gravitation through his famous equation of universal gravitation (1687), $F = \frac{G(M_1 M_2)}{R^2}$, and also after Michael Faraday, who made the second unification in physics, joining Electricity with Magnetism (1831), J. C. Maxwell realized the third unification in physics, joining electricity, magnetism, electromagnetism, and optics (1861). The great unification, which seeks out a set of equations describing all forces of nature, was attempted by A. Einstein and, apparently, remaining to be done yet.

QUANTUM OPTICS

As mentioned before, in the early 20th century Newton's corpuscular theory of light had already been refuted in the previous century by the work of Thomas Young (double-slit experiment); later, it was again refuted by Christian Huygens (concerning the principle of classical superposition), also by Augustin J. Fresnel (the mathematical formulator of wave theory) and James Clerk Maxwell (through his four equations). However, in 1905 Albert Einstein appeared with a new revolutionary proposal which, in a certain sense, the light recovered some degree of the corpuscular behavior. The name quantum to designate the elementary particle representing the photon of light in the photoelectric effect caused a certain confusion originated from dispute between Classical Optics and the Max Planck's pioneer proposal in 1900 to explain the light spectrum emitted by the "black body"; to this end he discretized the spectral energy emitted by the walls of incandescent cavity in form of packets having energy $E_n = nhf$, f standing for the frequency of electromagnetic radiation.

Planck's proposal was followed by Einstein to explain the photoelectric effect (Einstein 1905) and also to explain the specific heat of solids (Einstein 1907); this procedure brought people the idea that it meant quantization of the theory. Indeed, "discretization of energy" does not mean "quantization of theory". Since Classical Optics failed to explain the various effects that arose in new experiments made after 1900, the idea that light is constituted by particles (named photons in 1926) was only a preliminary attempt to get a new theory being able to describe the matter, the light and their interactions. In fact the quantization of matter (atoms, protons, electrons, neutrons, etc) was only achieved by Werner Heisenberg in 1926 and by Erwin Schrödinger in 1926 in two different but equivalent versions. In respect to light field, its quantization was achieved by Max Born, Werner Heisenberg and Pascual Jordan (Born et al. 1926; Schrödinger 1926).

Although the light field being quantized in 1926, the results obtained with this quantization seemed to be of no relevance because it only reproduced the same results obtained in Classical Optics. The point was that, at that time, effects whose explanations we thought belonged to this new theory, such as the photoelectric effect (1905) and the Compton effect (1923) among others, could also be explained in the classic or neo-classic theory; we have selected some classic and representative works showing this in Notes 4.1 and 4.2 of Ref. (Baseia 1995). Thus, from 1926 to 1977, the understanding of most physicists was that quantization of the matter is necessary to explain much of nature's phenomena, but the same is not required for the light field, since Classical Optics seemed to account for explaining all new effects at the time. This explains why the quantization of the light field in 1926 remained neglected for almost 50 years.

However, an important experiment carried out in 1977 detected a new effect in Optics that had no classical explanation: named as "antibunching" effect (Kimble et al. 1977) this year would mark the true birth of Quantum Optics as a necessary theory. In this effect, photons behave differently, as if there were a repulsion between them, somewhat similar to what occurs with fermions (electrons, protons, etc). The effect appears when one measures the 2nd order coherence function $g^2(\tau) = \langle \hat{a}^\dagger(0)\hat{a}^\dagger(\tau)\hat{a}(\tau)\hat{a}(0)\rangle / \langle \hat{a}^\dagger \hat{a}\rangle^2$ and obtain values in the interval $0 < g^2(\tau) < 1$ (Figure: see Ref. Maia & Baseia (1999) Fig II.1).

This experimental result stimulated the physicists in the search of other non-classical effects and, after 1985, a new quantum effect, the "compression of vacuum state" of light ("squeezing") was observed (Slusher et al. 1985). It meant that the basic relation of quantum mechanics $\Delta\hat{x} \cdot \Delta\hat{p} \geq \frac{h}{2}$ can also be obeyed when the uncertainty in the position x is compressed in this way: $(\Delta\hat{x})^2 < h/2$, accompanied by a corresponding enlargement in the uncertainty of momentum p: $(\Delta\hat{p})^2 > h/2$, and vice-versa; $\hat{x}$ and $\hat{p}$ stands for position and momentum operators, respectively.

Soon after the nonclassical "collapse and revival" effect of atomic inversion was observed in 1987 (Rempe et al. 1987); the effect occurs when an atom interacts with certain types of quantized fields, then it oscillates with decreasing amplitude that tends to zero, keeping this null value during certain time interval and, very surprisingly, it recovers its initial oscillations, as shown in Figure 9. According to many authors, the occurrence of this effect also helped support the particle character of light. However, one could also argue on the contrary, that the collapse and revival effect is due to interference effect; in this case it would support the wave character of the light.

Three years later a new nonclassical effect was observed (Rempe et al. 1990), named "sub-Poissonian statistics"; it occurs when the number variance $\langle(\Delta\hat{n})^2\rangle$ is less than the average number $\langle\hat{n}\rangle$, that is: $\langle(\Delta\hat{n})^2\rangle < \langle\hat{n}\rangle$. It was from this effect that the Optics came to deal with three types of statistics: i) Bose-Einstein statistics, obeyed by thermal and chaotic light (light from cold sources); ii) Poissonian statistics, obeyed by all coherent states of light, represented by the symbol $|\alpha >$ and iii) the sub-Poissonian statistic, that characterizes the photon number states, represented by symbol $|n >$. Afterwards, other nonclassical effects have been discovered and published in the literature.

Thus, from 1977, the year when Quantum Optics emerged as a necessary theory to explain new effects in Physics, several publications appeared in the literature studying various properties of nonclassical states of the light field, including their preparation in laboratories, the search of new nonclassical effects, and their theoretical use and practical applications. In the next section we will discuss some aspects of these effects and, because of being a very technical topic, it will be simplified. Here, everything that is said about the light field can be equally extended to electromagnetic radiation in the near-ultraviolet and infrared regions.

NONCLASSICAL EFFECTS IN THE LIGHT FIELD

LIGHT FIELD SHOWING ANTIBUNCHING EFFECT

Antibunching effect was observed in 1977 and marks the date of birth of Quantum Optics, when this theory gained special importance in theoretical and experimental physics. In the thermal or chaotic state of light, light particles (photons) prefer to group together, closer than what they are in the coherent state (Glauber 1963), in which photons appear equally spaced. In case of antibunching, the spacing between the neighboring photons is greater than it is in the coherent state, as if repelled by one another; also, their distance increases the higher the intensity of antibunching effect. Now, coherent state of light may be exemplified by the type one observes in very good lasers, mainly near the ideal laser, which is very monochromatic (narrow color or frequency) and very coherent (easy to produce interference in the double slit experiment). Antibunching effect occurs in a field state when we measure the 2nd coherence function $g^2(\tau) = \langle\hat{a}^\dagger(0)\hat{a}^\dagger(\tau)\hat{a}(\tau)\hat{a}(0)\rangle/\langle\hat{a}^\dagger\hat{a}\rangle^2$ where $\hat{a}^\dagger$ and $\hat{a}$ are the photon creation and annihilation operators, respectively, used as a mathematical tool to implement the quantized theory (Kimble et al. 1977). These two operators were introduced by P. M. Dirac in 1927 to construct a new version of quantization, named "second quantization", notably developed by Vladimir Fock and Paschoal Jordan.

Antibunching effect is represented in Figure 7, quoted from Refs. (Gerry & Knight 2004; Loudon 2000); in this Figure red line stands for bunching effect $g^{(2)}(\tau) > 1$, the photons behaving as if they were attractive particles; blue line stands for antibunching effect $g^{(2)}(\tau) < 1$, the photons behaving as if they were repulsive particles; dashed line is for zero bunching and zero antibunching when at time $\tau, g^{(2)}(\tau) = 1$; neither attraction nor repulsion. Zero bunching and zero antibunching characterize all coherent states. Calculations show that for light fields exhibiting bunching effect, one has: $g^{(2)}(\tau = 0) = 2$ and also $1 \leq g^{(2)}(\tau) \leq 2$. The expression $g^{(2)}(\tau) = 1 \pm \exp(-2|\tau|/\tau_0)$ stands for bunching $(+)$ and antibunching $(-)$ effects. The variance of the photon number distribution is given by,

$$\langle(\Delta\hat{n})^2\rangle = \langle\hat{n}^2\rangle - \langle\hat{n}\rangle^2 = \langle(\hat{a}^\dagger\hat{a})^2\rangle - \langle\hat{a}^\dagger\hat{a}\rangle^2, \tag{7}$$

and using the commutation relation $[\hat{a}, \hat{a}^\dagger = 1]$ we obtain,

$$\langle(\Delta\hat{n})^2\rangle = \langle(\hat{a}^\dagger)^2\hat{a}^2\rangle + \langle\hat{a}^\dagger\hat{a}\rangle - \langle\hat{a}^\dagger\hat{a}\rangle^2, \tag{8}$$

$$\langle(\Delta\hat{n})^2\rangle - \langle\hat{n}\rangle = \langle(\hat{a}^\dagger)^2\hat{a}^2\rangle - \langle\hat{a}^\dagger\hat{a}\rangle^2. \tag{9}$$

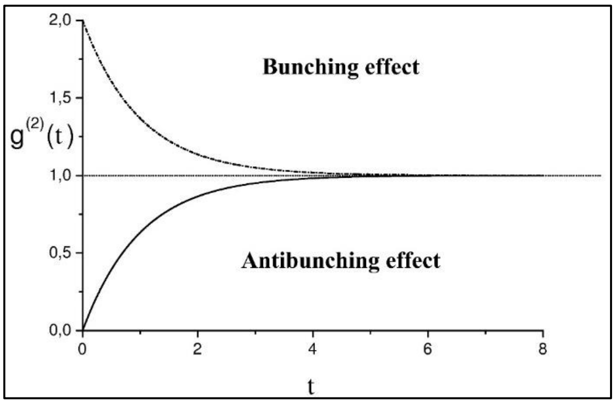
For arbitrary single-mode fields the second-order correlation function is defined as,

$$g^{(2)}(\tau) = \frac{\langle(\hat{a}^\dagger)^2\hat{a}^2\rangle}{\langle\hat{a}^\dagger\hat{a}\rangle^2}, \tag{10}$$

which leads to,

$$g^{(2)}(\tau) = 1 + \frac{\langle(\Delta\hat{n})^2\rangle - \langle\hat{n}\rangle}{\langle\hat{n}\rangle^2}. \tag{11}$$

Figure 7. Plot of second order correlation function for states showing bunching effect (dashed line), antibunching effect (solid line) and coherent states (horizontal line, $\boldsymbol{g^{(2)}(\tau) = 1}$).



Source: Authors.

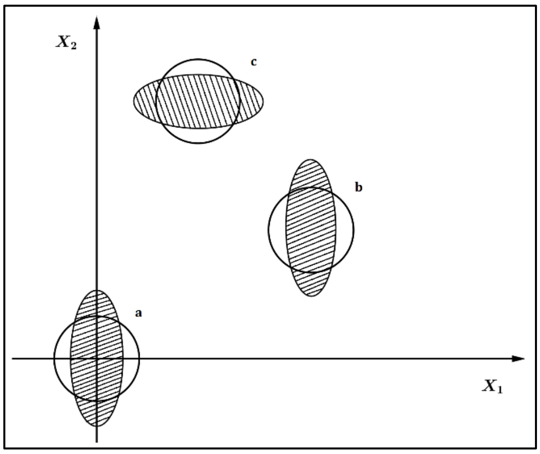
For a field in coherent state, represented by the symbol $|\alpha\rangle$, one obtains $g^{(2)}(\tau) = 1$ as represented by the horizontal line of the Figure 7,

Light Field Showing Squeezed States

Coherent states are those exhibiting minimum position-moment uncertainty. They are also eingenstates of the annihilation operator $\hat{a}$, that is: $\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$. They are represented by circles with diameter $h/2$ in phase space (position-momentum space (x, p)). Now, if these circles are compressed in an arbitrary direction of this space they shrink in the perpendicular direction; in this case we say that both, the quantum vacuum state $|\alpha = 0\rangle$, a circle at the origin, and the arbitrary coherent state $|\alpha\rangle$, any circle outside the origin, are squeezed. It means that we can have the basic relation of quantum mechanics $\Delta\hat{x} \cdot \Delta\hat{p} \geq h/2$ with $\Delta\hat{x}$ squeezed and $\Delta\hat{p}$ enlarged; and vice-versa, in such a way that the relation $\Delta\hat{x} \cdot \Delta\hat{p} \geq h/2$ is maintained; $\hat{x}$ and $\hat{p}$ stands for position and momentum operators, whose values are represented by x and p, respectively.

In the light field, the operators $\hat{x}$ and $\hat{p}$ are substituted by quadrature operators $\hat{X}_1$ and $\hat{X}_2$ such that $\hat{x} = \sqrt{h/2m\omega}(\hat{a} + \hat{a}^{\dagger})/2 \rightarrow \hat{X}_1 = (\hat{a} + \hat{a}^{\dagger})/2$ and $\hat{p} = \sqrt{\frac{hm\omega}{2}}(\hat{a} - \hat{a}^{\dagger})/2 \rightarrow \hat{X}_2 = (\hat{a} - \hat{a}^{\dagger})/2i$; hence, different from operators $\hat{x}$ and $\hat{p}$, $\hat{X}_1$ and $\hat{X}_2$ stand for dimensionless quantities. The quantum vacuum state has no photon, but when squeezed it has and the number of photons increases the greater the squeezing. The circular areas of Figure 8 represent the noise in the vacuum state (a) and in the coherent states (b, c). Elliptical areas represent noise in the squeezed state. It means that if one quadrature, $\hat{X}_1(\hat{X}_2)$, is squeezed, the other, $\hat{X}_2$ $(\hat{X}_1)$ is enlarged to satisfy the Heisenberg uncertainty principle.

Figure 8. Representation of coherent (circles) and squeezed states (ellipses) in the quadrature plane (phase space).



Source: Authors.

LIGHT FIELD CAUSING COLLAPSE- REVIVAL OF ATOMIC INVERSION

This effect occurs when an atom interacts with certain types of quantized fields, which oscillates with decreasing amplitude tending to zero, keeps this null value during certain time interval and, surprisingly, recovers its initial amplitude of oscillation (Jaynes & Cummings 1963). The effect repeats over certain time, with the maximum value of the amplitude decreasing, as displayed in Figure 9 showing atomic inversion when the atom interacts with a field in a coherent state $|\alpha\rangle$ with $|\alpha|^2 = \langle\hat{n}\rangle = \sqrt{5}$ (see Figs II.4 and II.5 of Ref. (Maia & Baseia 1999)). It is worth mentioning that revival effect of atomic inversion does not occur when the atom interacts with a field in a number state, although it is the most quantum of all states of the light field.

The most general expression of atomic inversion for atom-field interaction is given by the equation (proof is omitted for brevity),

$$W(t) = \sum_{n=0}^{\infty} |C_n|^2 \cos(2\lambda t\sqrt{n+1}). \tag{12}$$

For light fields in coherent states the coefficients C_n are given by,

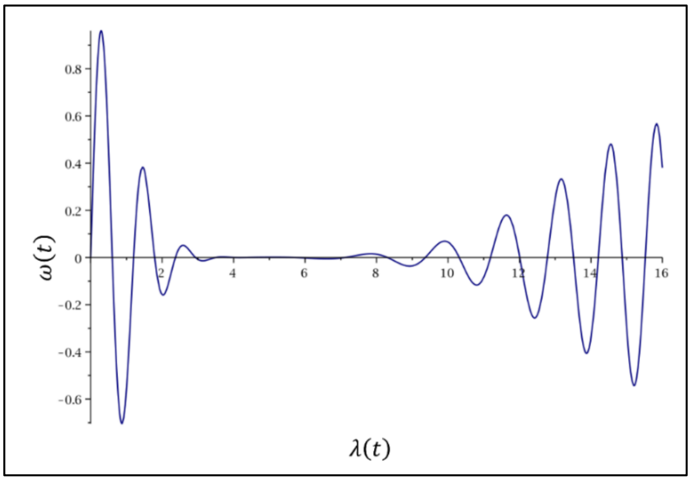
$$C_n = e^{-|\alpha|^2/2}\frac{\alpha^n}{\sqrt{n!}}, \tag{13}$$

and the atomic inversion is mathematically represented by the expression,

$$W(t) = e^{-\langle\hat{n}\rangle}\sum_{n=0}^{\infty}\frac{\langle\hat{n}\rangle^n}{n!}\cos\left(2\lambda t\sqrt{n+1}\right), \tag{14}$$

which shows the collapse-revival effect, displayed below (Figure 9),

Figure 9. Collapse and revival effect of atomic inversion when a two-level atom interacts with a light field prepared in a coherent state $|\boldsymbol{\alpha}\rangle$ with photon number average $\langle\hat{\boldsymbol{n}}\rangle = |\boldsymbol{\alpha}|^2 = \sqrt{\mathbf{5}}$.



Source: Authors.

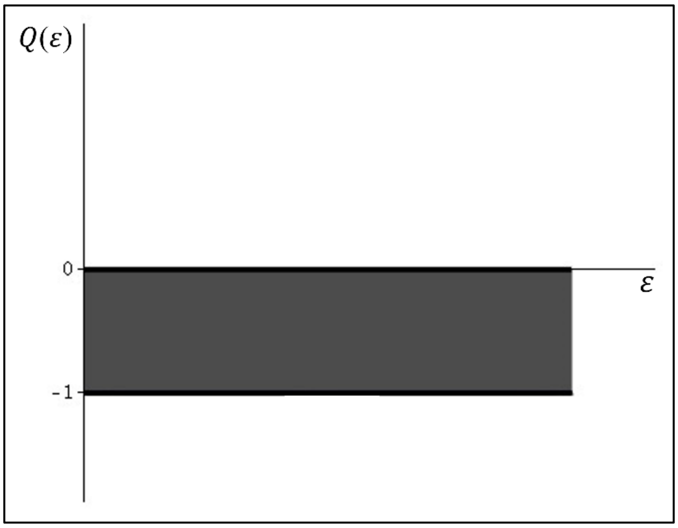
LIGHT FIELD SHOWING SUB-POISSONIAN STATISTICS

Photon statistic of a luminous field state is super-Poissonian when the Mandel parameter $Q > 0$; Poissonian when $Q = 0$, or even sub-Poissonian if $Q < 0$. The latter case cannot be explained within the scope of Classical Optics – but only in Quantum Optics, as occurs with antibunching and squeezing. The Mandel parameter Q is defined by the expression,

$$Q = \frac{\langle(\Delta\hat{n})^2\rangle - \langle\hat{n}\rangle}{\langle\hat{n}\rangle}, \tag{15}$$

so that, in case of arbitrary number states $|n\rangle$, whose variance of the number operator $\langle(\Delta\hat{n})^2\rangle = \langle\hat{n}^2\rangle - \langle\hat{n}\rangle^2 = 0$, one obtains $Q = -1$ the minimum value of Q; this value of Q corresponds to maximum sub-Poissonian effect. Then, with exception of the state $|n = 0\rangle = |0\rangle$, any other component $|n\rangle, e.g., |1\rangle, |2\rangle, |3\rangle$ ..., of the family $\{|n\rangle]\}$ of number states will exhibit maximum sub-Poissonian effect. On the other hand, in case of coherent states $|\alpha\rangle$, where the variance $\langle(\Delta\hat{n})^2\rangle$ equals the average number, namely: $\langle(\Delta\hat{n})^2\rangle = \langle\hat{n}\rangle$, we obtain $Q = 0$. In Figure 10 dark area corresponds to non-classical region. Another example is the case of coherent states distributed over a circle of radius $|\alpha|$, around the origin of the phase space (x, p): it was found that certain superpositions of these states can show sub-Poissonian statistics, similar to the number states $|n = 2^n\rangle$; for examples see Refs (Maia et al. 2004; Malbouisson & Baseia 1999).

Figure 10. Mandel parameter showing nonclassical region $(-1 \leq Q \leq 0)$, dark area.



Source: Authors.

LASER LIGHT

Among all kinds of light, one has those emitted by natural sources, the most important being the sun light, and those emitted by artificial sources, the most important being the laser light. Laser is constituted from excited atoms interacting with electromagnetic radiation in the light domain or around it (near infrared and near ultraviolet); the maser concerns the very distant infrared, the microwave domain. The active atoms in the laser suffer from influences of various sources that cause loss and gain of energy. Laser operation requires inversion of the atomic population that participates in the process of light emission. Population inversion means the number of atoms in excited state being greater than the number of atoms in the lower state (also named ground state). Stimulated emission is the radiation emitted from an excited atom caused by the action of a photon incident on it: the photon emitted has the same characteristics as those of the stimulanting photon: same energy, frequency, direction of propagation, phase, and polarization.

Then, when the laser is turned on any atom of the excited population that spontaneously decays from the excited level to the lower level emits a photon that starts the laser action. This emitted photon also do the same upon another excited atom; the effect repeats many times and an avalanche of photons is formed. This avalanche must stop at some time, on the contrary the laser would blow up due to great energy accumulated in the lamp. Hence, stabilizing the intensity of the laser light is mandatory. Fortunately, when the number of photons becomes too large, the stimulated emission automatically stops growing, because the number of available excited atoms diminishe since the major part of them had fallen into the non-excited state. As can be shown, the cause of this effect is the presence of nonlinearities, as we will see below.

One should not think that this necessary brake on the avalanche of photons ends up zeroing its intensity. There is a compensatory pumping mechanism that keeps the population excited at a certain level where the laser intensity stabilizes. Now, after stabilizing the laser, if we increase the pumping, it can increase the value of the stabilized intensity, or not, according to the type of material that makes up the laser; if this material resists without burning, the laser becomes more potent - the more so as this procedure is allowed. So, in this case the laser can be highly intense, monochromatic, directional, and coherent. Coherence means all photons synchronized in same phase, i.e., like photons walking together as the footsteps of soldiers in a well-trained military march. Verification of the degree of coherence is made by observing whether the laser light produces, or not, interference in the double slit experiment of Thomas Young in 1801.

LASER IN CLASSICAL AND QUANTUM OPTICS

THE LASER VIEWED FROM THE FRAME OF CLASSICAL OPTICS

The first maser was built by the Russians Alex Prokhorov and Nicolai Basov in 1953 while the first laser came in 1960, built by the North American Theodore Maiman. While the master works in the microwave band ~10^{11}Hz, the laser operates in the optical band ~10^{14}Hz. The invention of the laser faced greater difficulties compared to the maser, which explains its invention only seven years after the maser. At the time researchers did not even believe in this possibility, which caused great surprise when the first laser was announced.

The difficulty was due to the fact that lateral modes of vibration in a rectangular optical cavity are very close to the central longitudinal mode, in comparison with the distance between the lateral vibration modes of microwave cavity. The longitudinal mode is one chosen to resonate with certain atomic line; this entails the energy competition by neighboring lateral modes is much greater in the laser than in the maser, making it difficult to concentrate energy in the central mode, as required by operation laser. So, it was as if the laser could never work. However, Maiman circumvented this difficulty simply by opening the sides of the optical cavity, thus getting rid of the (spurious) lateral modes. A misunderstanding on this point led to a refusal to publish the laser discovery in the Physical Review; the discovery was accepted in Nature a month later, in 1960.

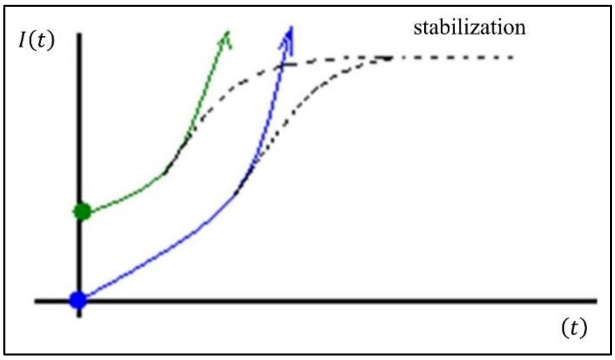
In resume, the laser is constituted from excited atoms interacting with electromagnetic radiation in the light domain. The atoms suffer from influences of various sources causing loss and gain of energy. Its operation requires inversion of the atomic population participating in the process of light emission. Population inversion means the major part of active atoms in their excited state. Stimulated emission occurs when an excited atom emits a photon stimulated by another photon. The photon emitted has the same characteristics of the stimulating photon: energy, frequency, direction of propagation, phase, and polarization.

Lasers can be constructed from solids, liquids (dyes) and gas; one exception being the Free Electron Laser. Solid lasers constitute the major part of them, using crystals or glasses. Among all solid lasers we can mention the (pioneer) Ruby laser (1960), the semiconductor lasers (1970), Nd - Yag lasers and Titanio-Safira (1985) as some examples of them. The liquid lasers (1966) use dyes (rhodamines) in liquid solution enclosed in a glass bottle. Gas lasers can be exemplified by Helium-Neon (He - Ne), CO, CO_2 and N_2 lasers. Chemical lasers when fueled by a chemical reaction can reach high powers in continuous operation. Lasers can be pulsed, as the Ruby laser, or continuous, as the He - Ne laser, but this difference cannot be perceived by us since our eyes cannot distinguish pulses if the distance in time between them is less than 0.1s. Pulsed lasers are the most powerful. Classical and Quantum Optics try to explain the laser operation: the difference between these two theories is that in the former we get only a partial explanation, while in the latter the explanation is complete. In what follows, we begin by focusing the laser in the realm of Classical Optics.

Besides explaining the threshold of operation laser, namely: the minimum value of pumping that starts the laser action, Classical Optics also explains stabilization of the laser intensity. To show the stabilization, we need to use the classical theory in its nonlinear version, that is, we must replace the usual linear approximation $P = kE$ that connects the polarization P of the laser medium to the amplitude E of the laser field via the nonlinear form $P = kE \pm k'E^2$ or $P = kE \pm k''E^3$; the inclusion of the quadratic term $k'E^2$ or the cubic term $k''E^3$ will explain the stabilization of laser intensity at a finite value. Indeed, infinite values of any properties are not allowed in physics. In the laser, infinite intensity would destroy the laser device, then its stabilization is necessary, a requirement that cannot be fulfilled by the linear theory. To give an example, calculations made for the $He - Ne$ gas laser show that $dE/_{dt} = aE - bE^3 = (a - bE^2)E$ and the stationary solution come from $dE/_{dt} = 0$ implies that $E^2 = a/_b$. Note that for $b = 0$ we have $E^2 \rightarrow \infty$. In these expressions, E is the amplitude of the light field, $a = (gain - loss)$ and b is the saturation parameter; the lower the value of b, the greater the stabilization value of the light intensity I, since $I \sim E^2$, see Figure 11.

The cubic form $\sim E^3$ stands for lasers using isotropic media, as in some solids (e.g., NaCl), liquids and gas (e.g., He-Ne gas-laser). But, among others results, even the inclusion of nonlinear terms in classical theory allows one to explain the photon statistics of the laser light, e.g., whether the light obey the Bose-Einstein statistic or another, a task that is only solved in the quantized nonlinear theory. This is so because the photon is not an ingredient of Classical Theory.

Figure 11. Variation of laser light intensity as a function of time: it starts from a non-zero value in the form of a parabola and tilts to the horizontal line stabilizing, caused by nonlinearities as $\boldsymbol{k'E^2}$ or $\boldsymbol{k''E^3}$. The parabola that would follow to infinity (both solid colored lines) does not occur in practice, due to the presence of nonlinear effects.



Source: Authors.

Due to its four spectacular properties mentioned before and its various applications, the laser caused a revolution in theoretical and experimental researches, starting from 1960. For example, it was from the laser that classical nonlinear optics took off: before the laser invention, nonlinear materials were searched with little success; the effect was sometimes observed but exhibiting low nonlinear effects, much less than 0,1% compared with linear effects. The emergence of various types of lasers, having high intensities and operating in different frequencies, stimulated researchers to look for materials having high nonlinearity. Actually, nonlinear effects do not depend only on the material medium, through its parameters k' and k'', usually very small $k'' \ll k' \ll k$; in fact, they depend on the product $k'E^2$ and $k''E^3$. Then, since the amplitude E of the laser field can be very large, we may get large nonlinear effects even if k' and k'' are not too large. For example, we always have $k \gg k'$ but we may have $kE \sim k'E^2$ for large values of E; the same is valid for $kE \sim k''E^3$.

Here, let's give an illustrative example of a kind of nonlinear effect : consider a transparent material in which a luminous field E is incident; if the medium is linear the field that emerges from the material is given by $E' = kE;$ then if we chose $E = \sin(\omega t)$ we obtain $E' = k\sin(\omega t)$; that is, the wave $\sin(\omega t)$ traverses the linear material and the wave $\mathrm{k}\sin(\omega t)$ emerges from the this medium. Next, consider the same field E entering a nonlinear material. In this case the emerging field is given by $E' = kE \pm k'E^2$; then, for the same input $E = \sin(\omega t)$, the emerging field is now given by $E' = k\sin(\omega t) \pm k'\sin^2(\omega t)$. Actually, in practice the major part of the emerging field concerns the linear term, but the nonlinear term can no longer be neglected.

Now, very interesting: if we take the above expression $sin^2(\omega t)$ replaced by the trigonometric identity $\sin^2(\omega t) = (1 - \cos(\omega t))/2$, we notice the appearance of a doubled frequency 2ω, known as "second harmonic" generation, a nonlinear effect also named 'frequency doubling'. Another representative example, if we let two incident fields $E_1\ and\ E_2$ on the nonlinear medium, two intense light beams of different frequencies, ω_1 and ω_2, we will see in the output the same frequencies ω_1 and ω_2, but accompanied by others: $2\omega_1$, $2\omega_2$, $\omega_1 + \omega_2$, and $\omega_1 - \omega_2$. Before the laser invention, the extra nonlinear terms emerging from the medium were very small and difficult to be detected; so they were not even considered.

The scientific advance brought by the invention of the laser, even when treated by Classical Optics, was also due to the discoveries of new materials having large nonlinearities. This also concerned the large intensity of the laser light; on the other hand, since the laser light can be also very monochromatic, it brought fantastic advance in sophisticated spectrometry. However, it happens that light is formed by photons, and photons are ingredients of Quantum Optics, having no place in Classical Optics. So, at the microscopic level Classical Optics began to face several difficulties, many of them insurmountable, as those coming from discoveries of the nonclassical effects, already mentioned in the subsections A – D.

THE LASER VIEWED FROM THE FRAME OF QUANTUM OPTICS

We have already mentioned that Classical Optics does not offer a complete explanation for the laser. This is because, for example, it cannot explain the evolution of laser light from vacuum fluctuations, a purely quantum effect, the laser being initially triggered by spontaneous emission. Also, the Classical Optics does not explain the photon statistics in lasers, because photons have no place in Classical Optics, they are not ingredients of this theory: photons are quanta of excitations of the quantized electromagnetic radiation.

While in Classical Optics the energy ε depends on the field intensity $I \approx |E|^2$, in Quantum Optics the energy ε depends on the frequency f of field oscillations, given in the form $\varepsilon = hf$, where h is the Planck constant. This difference between the two theories - one that explains everything about laser and the other that explains only part of the entire description, not everything. The fail of Classical Optics also happens when we consider other effects, some of them being mentioned above (antibunching, squeezing, sub-Poissonian statistics, collapse and revival of atomic inversion, etc).

Each distinct type of quantum effects entails distinct types of light with different properties. The wealth of novelties brought by Quantum Optics constitutes a “forest” of new light states. For example, in Classical Optics the types of light are basically two: the thermal light and the chaotic light, both having the same statistics. In Quantum Optics there are many types of quantum states, each of them showing different characteristics, as (i) antibunching, (ii) squeezing, iii) collapse and revival effect, iv) subPoissonian statistics, etc. The attributes of a light field depend on its type of quantum state, e.g.: number state $|n\rangle$, coherent state $|\alpha\rangle$, phase state $|\theta\rangle$ and many others, including the superposition of states corresponding to the well known “Schrödinger cat” state; and also the EPR “entangled state”. It is also worth mentioning that in Quantum Optics we can use these states to build new ones. For example, a superposition of two coherent states on a circle centered on the origin of the phase space was used to construct a version of “Schrodinger cat-state” (Malbouisson & Baseia 1999) and this result permitted to prove the Bohr’s hypothesis proposed in 1935 to support quantum mechanics, concerning the rapid decoherence of macroscopic states; another version of such superposition, involving many coherent states, was shown to provide some types of number state $|n\rangle$ (Brune et al. 1992; Maia et al. 2004); the case of phase states (Aragão et al. 2004; 2005) was also obtained when the superposition is distributed on a straight line in phase space; and so on (Gerry & Knight 1997; Monroe et al. 1996; Roy 1998)

For example, a superposition of two coherent states on a circle centered on the origin of the phase space was used to construct an extended version of "Schrodinger cat-state" (Malbouisson & Baseia 1999) and this result is in favor of the Bohr's hypothesis proposed in 1935 to support quantum mechanics: the issue concerns the rapid decoherence of macroscopic states. Another version of such superposition, involving many coherent states, was shown to provide some types of number state $|n\rangle$ (Brune et al. 1992; Maia et al. 2004); the case of phase states (Aragão et al. 2004; 2005) was also obtained when the superposition is distributed on a straight line in phase space; and so on (Gerry & Knight 1997; Monroe et al. 1996; Roy 1998). The Schrödinger "cat state" was proposed in 1935 by Erwin Schrödinger to question Quantum Mechanics, a theory he helped to create. In the same year and with the same goal, Albert Einstein, Boris Podolsky and Nathan Rosen proposed the entanglement of states: also named EPR states; they describe a composite system that cannot be written as a product state, $|\psi\rangle_{AB} = |\psi 1\rangle_A |\psi 2\rangle_B$; instead, entanglement is represented below, constituting a support for the EPR paradox.

Now, while quantum superpositions rejected by E. Schrodinger usually concern the state describing a single system, the entangled state introduced in the EPR paradox concerns the state describing two (or more) systems. E. Schrödinger questioned quantum mechanics when this theory establishes that a particle having two states to occupy with equal probabilities, it occupies both, as a living and dead cat would be. On the other hand, paradox EPR was proposed to question this important rule of quantum mechanics: "the measurement made on the state of a subsystem affects the state of the other one, whenever the whole state describing both sub-systems is entangled; in this example the entangled state is mathematically represented in the form $|\psi\rangle ab = |1_a, 2_b\rangle + |1_b, 2_a\rangle$, where for example $|1_a, 2_b\rangle$ means particle 1 in state a and particle 2 in state b. These two questions, raised by superposition and entanglement of states, were technically refuted by Niels Bohr, both in 1935. Although the Bohr refutations sounded speculations for more than 40 years later, new experiments gave Bohr a reason: one of them was made in 1996 in the domain of Quantum Optics (Brune et al. 1992); the other appeared in the domain of Atomic Physics (Brune et al. 1992), and in 1997 (Bredas et al. 1994).

APPLICATIONS OF THE LASER LIGHT

Laser is a special type of lamp and what we commonly call laser is the beam of light emitted by this lamp, not the lamp itself. Due to its spectacular properties several applications of the laser beam were widely implemented in practice.

LASER LIGHT APPLIED IN INDUSTRY

As some examples of laser light applications in industry one can cite: cuts in straight or curved lines in metal and plastic sheets, thermal treatment of surfaces (laser cleaning, coat removal), welding, use of 3D laser cutter, laser painting and rust removal, fiber optic analyzer, laser ablation, laser surface structuring, laser conservation and restoration of architectural structures, laser engraving machine, laser cutting in different sizes, formats and dimensions, metalworking processes, laser marking serial numbers, chassis, laser fiber mode analyzer, manufacturing dates or algorithms for identification, are some of the applications that laser offers to industry taking advantage of its high intensity, degree of directionality, and monocromaticity.

LASER LIGHT APPLIED AS MILITARY WEAPONS

In addition to the problem of intensity, being high for this purpose, it has been found that electromagnetic radiation beams propagating with high intensity ionizes the atmosphere, making it an absorber plasma that interrupts the own beam that formed itself. Estimates predicted a decay in the intensity, of a factor $1/300$, in each 5km path of the beam. Even in minor courses of 1km, this factor being $1/10$. Thus, powerful lasers installed in the ground would only be efficient when the enemy target (a guided missile) was already very close. Although the speed of photons of a laser beam is 1 million times greater than guided missiles, there was doubt as to whether such a beam would exceed conventional weapons (missiles). The "Star Wars" Project was then thought: a belt of 50 satellites orbiting around the earth, passing continuously over the enemy territory. In this way they would be in an area of rarefied atmosphere (no beam absorption) at high altitudes and equipped with high power chemical lasers. The problems to overcome in this case would be: the weight of satellites, the control of aiming, the focusing system, and even consider the protections that the target missiles could offer.

The use of ground lasers was recalled later when the deuterium fluoride (FH) laser was invented, having radiations with wavelength causing little energy absorption by the atmosphere; in this case it happens as if the laser beam with this wavelength "sees" a window in atmosphere to cross it freely. The problem of the aiming and its control was solved when a beam of light, emitted by a laser in the peak of Hawaii (clear sky), succeeded in accompanying during 2 minutes a guided missile with speed $v = 10.000$km/h (~8 times the speed of sound). To destroy this target it only lacked the laser beam had high enough power. But that was only a follow-up test of missels.

Two years later, in September of 1987, the HF chemical laser "MIRACL", $2.2\,MW$, accompanied and destroyed a test missile, with $v = 10.000$km/h, height 560km (La Recherche, Mars/1988). In this same year, the "blue-green" laser appeared, appropriate in submarine warfare; due to its frequency this beam is little absorbed by the sea water. It is said that salt water "opens a window" for this beam to propagate without absorption. Having solved the laser aiming control, the pursuit of high power lasers was intensified. In this direction the candidates were two: the chemical laser, with frequency in the distant ultra violet, of $ArF, KrF, XeCl$, the first arisen around 1980, and X-Ray lasers, named "Xasers" [see Matthews et al. (1985)], the first appearing in 1980, another in 1985.

However, five years later, with the end of the "cold war" in the late 80's, the subject declined and left the news. Then, little has been written about laser applications for military purposes, disappearing from the headlines of the written and television media. In fact, there are certain types of research whose results are conveniently hidden, in view of strategic reasons (state secrets and military interests), the same also occurs with industrial and commercial conglomerates.

LASER LIGHT APPLIED IN MEDICINE AND ODONTOLOGY

The bad reputation of the laser, coming from its application as a powerful deadly weapon, could be compensated in its application for the good of Humanity. Thus, the "death ray" of Agent 007 James Bond, became the "ray of life" for applications in medicine, ophthalmology, odontology, and similar activities. Due to wide variety of applications in these areas it has become a star in medicine and the "darling" of aesthetics in plastic operations. However, at first, researchers did not know to what practical end this new and formidable beam of light would serve; and initially the laser was a kind of "solution looking for a problem".

The first medical applications of the laser in the 1960s were in ophthalmology: the staff was learning how to use the laser beam and at the beginning its use was disastrous, causing irreparable damage to guinea pigs (e.g., prisoners of war). In 1972 the first photo-coagulating lasers were constructed: the Argon laser, used to correct retinal displacements. With the advance of technique the advantages of its use in ophthalmology and medicine in general was proved fantastic: pain in surgeries, tissue necrosis, and blood loss were minimal; dispensable anesthesia and rapid healing: patient convalescence started to take less than 1h, instead of weeks. Use of laser pulses was intense and offering fast results: in cataract operations, power lasers ranging from kW to MW and pulse duration of less than micro seconds were used.

Usually, for problems affecting the surface of the human body, the $Nd-YAG$ laser is applied. For internal human body problems, the use of CO_2 laser is more commonly used. For specific cases certain frequencies of the laser light is more appropriate than others. Around the years 90, a list of specific lasers was published according the type of disease and the affected part in the human body: for tumors in brain, they recommended use of CO_2-laser; for eye diseases they use Ar and Nd lasers and excimers according to specific case, e.g., strabismus, glaucoma, retinal displacement and cataract. For dental fillings and dental surgeries, $Nd-YAG$ lasers are also used. For prostate cancer and disease in uterus CO_2-lasers are applied. For heart and for disruption of arteries physicians recommend the use of Holm-laser beam adapted to an optical fiber, etc.

LASER LIGHT APPLIED IN COMMUNICATION

As well known, it is very widespread the use of laser light connected to optical fibers. On the other hand, using Optical Laser Communication technology, between command stations on Earth and astronauts in space travel, you can transmit messages or videos via 50 megabits of data per second, 200 times faster than using sources based on radio waves. In 2014 the transmission capacity was of at most 0.4 megabits, 500 times smaller. For example, signals and photos sent by the MRO spacecraft orbiting Mars take 90 minutes to reach Earth and will take 1 minute using the laser technology.

LASER LIGHT APPLIED COMMERCIALLY

In addition, the laser is also used commercially as bar code readers and in every day at our homes: CD, DVD and Blu-Ray players, laser printers, laser pointer used for presentations of publicities and marketing. Laser is also featured in popular Compact Discs, CD-players that allow one to store hours of music on a CD, or thousands megabytes of data on a CD-ROM. The system uses semiconductor lasers, average price less than 10 dollars and size about 5mm.

In summary, the various applications of laser mentioned in IC-A to IV-D, take advantage of the four splendid properties offered by this light beam: high intensity, high monochromaticity, high directionality, and high coherence. However, in practice each of these areas rarely uses these four properties. The use of one or another will depend on the specific purpose. The list of different situations is large and we give here only a few examples of them relating to each other, i.e., the required properties to each application:

1. To measure long distances (e.g., the Earth-Moon distance): monochromaticity (specific frequency) and directionality are required from the laser light;
2. High resolution spectroscopy: requires high monochromaticity and coherence;
3. To destroy enemy missiles (“Star Wars”): very high intensity and directionality;
4. Alignment of instruments to measure great distances: directionality;
5. For optical fiber communications: monochromaticity;
6. For isotopic separation: very high monochromaticity and high intensity;

7. In nuclear fusion control: very high intensity;
8. To produce of highly excited atoms (Rydberg): monochromaticity;
9. In the use of materials with high non-linear effects: intensity and monocromaticity
10. To cut metals and plastics: intensity and directionality;
11. Coolling atoms to near 0K temperatures: directionality and monochromaticity;
12. Medicine & Dentistry: monochromaticity with fast and intense laser pulses,
13. Use in holography: monochromaticity and coherence of the laser light.

Here we will fail to mention interesting information on the dozens of types of lasers used in the modest list above. It is that their applications vary from case to case and from one area to another, which would take up huge space for such sampling

COMMENTS AND CONCLUSION

In the present work we used an easy-to-read language to treat an important part of Physics, the Optics, which may be considered in two very different approaches: Classical and Quantum Optics. The presentation initiates with a historical summary of the first optical effects found since ancient times and the most outstanding founders of them; we considered the evolution of experiments that led to the establishment of the laws monitoring these two theories and also the events where Classical Optics failed, which opened ways to Quantum Optics. We also discussed the reason why, even though Quantum Optics was formulated in 1926, it took so long (50 years!) to be accepted as a necessary theory. The most important quantum effects in Quantum Optics were considered, the first of them found in 1977, the photon anti-bunching; in sequence appeared the vacuum compression (squeezing), collapse and revival effect of atomic inversion, sub-Poissonian statistics, and others. We also mentioned two powerful quantum features explored in Quantum Optics that, although sometimes sounding strange, esoteric, and even bizarre, they work in the practice: a) the polemical proposal raised by E. Schrodinger in 1935 against quantum theory, known as "Schrodinger's cat paradox" , expressed by the principle of superposition of quantum states; b) the controversial "EPR paradox" proposed by A. Einstein, B. Podolsky and N. Rosen also in 1935, giving another hard argument against the quantum theory concerning the use of "entangled states". Nowadays, although proposed to challenge the quantum theory, these two proposals, (a) and (b), have become crucial theoretical tools that opened the possibility for quantum computer, quantum cryptography, and quantum information. Part of this work was dedicated to the various applications of the laser light in many new technologies and devices, with emphasis to those used for the good of society.

As a final remark, it is worth mentioning that, if Isaac Newton came close to understanding the language of the gods, Erwin Schrodinger certainly wrote the first compendium of this language: his alternative invention of quantum theory put into the mathematical formulation the concepts involved in the most intimate behavior of the matter, the light, and the matter-light interactions – their interactions being expressed mathematically as $\lambda(a^{+}S + aS^{+})$, where λ represents the degree of the atom-light interaction, $a^{+}(a)$ stands for creation (annihilation) operators of the light field and $S^{+}(S)$ stands for raising (lowering) atomic operator. It is also worth citing a very important work in Optics developed by the Brazilian physicist Herch Moysés Nussenzveig, where he explained details of the Rainbow and the Glory effects (Nussenzveig 1979); so he received the Max Born Prize in 1986. Max Born is the physicist who proposed the meaning of the wave function of quantum mechanics; so he received the Nobel Prize in 1954.

REFERENCES

Aragão A, Avelar AT, Baseia B 2004. States of the quantized electromagnetic field with highly concentrated phase distribution. *Physics Letters A* 331(6):366–373. https://doi.org/10.1016/j.physleta.2004.09.022.

Aragão A, Monteiro PB, Avelar AT, Baseia B 2005. Superposition of new phase states: Generation and properties. *Physics Letters A* 337(4–6):296–304. https://doi.org/10.1016/j.physleta.2005.02.013.

Baseia B 1995. Sobre a real necessidade de uma teoria quântica para a luz: ótica quântica. *Revista Brasileira de Ensino de Física* 17(1):1–10.

Born M, Heisenberg W, Jordan P 1926. Zur Quantenmechanik. II. *Zeitschrift für Physik* 35(8–9):557–615. https://doi.org/10.1007/BF01379806

Bredas JL, Adant C, Tackx P, Persoons A, Pierce BM 1994. Third-Order Nonlinear Optical Response in Organic Materials: Theoretical and Experimental Aspects. *Chemical Reviews* 94(1):243–278. https://doi.org/10.1021/cr00025a008.

Brune M, Haroche S, Raimond JM, Davidovich L, Zagury N 1992. Manipulation of photons in a cavity by dispersive atom-field coupling: Quantum-nondemolition measurements and generation of "Schrödinger cat" states. *Physical Review A* 45(7):5193-5217. https://doi.org/10.1103/PhysRevA.45.5193.

Einstein A 1905. On a Heuristic Point of View about the Creatidn and Conversion of Light? translated from german by T Haar. *Annalen der Physik* 322(6):132–148. https://doi.org/10.1002/andp.19053220607.

Einstein A 1907. Die Plancksche Theorie der Strahlung und die Theorie der spezifischen Wärme. *Annalen der Physik* 327(1):180–190. https://doi.org/10.1002/andp.19063270110.

Gerry CC, Knight PL 1997. Quantum superpositions and Schrödinger cat states in quantum optics. *American Journal of Physics* 65(10):964–974. https://doi.org/10.1119/1.18698.

Gerry CC, Knight PL 2004. *Introductory Quantum Optics*. Cambridge: Cambrige University Press.

Glauber RJ 1963. Coherent and incoherent states of the radiation field. *Physical Review* 131(6):2766-2788. https://doi.org/10.1103/PhysRev.131.2766.

Jaynes ET, Cummings FW 1963. Comparison of Quantum and Semiclassical Radiation Theories with Application to the Beam Maser. *Proceedings of the IEEE* 51(1):89–109. https://doi.org/10.1109/PROC.1963.1664.

Kimble HJ, Dagenais M, Mandel L 1977. Photon antibunching in resonance fluorescence. *Physical Review Letters* 39(11):691–695. https://doi.org/10.1103/PhysRevLett.39.691.

Loudon R 2000. *The quantum theory of light*. 3rd ed. Oxford University Press, Oxford. 448pp.

Maia LPA, Baseia B 1999. Estados Não-Clássicos do Campo Luminoso. *Revista Brasileira de Ensino de Física* 21(4):476-489.

Maia LPA, Baseia B, Avelar AT, Malbouisson JMC 2004. Sculpturing coherent states to get highly excited Fock states for stationary and travelling fields. *Journal of Optics B: Quantum and Semiclassical Optics* 6(7):351–359. https://doi.org/10.1088/1464-4266/6/7/013.

Malbouisson JMC, Baseia B 1999. Higher-generation Schrödinger cat states in cavity QED. *Journal of Modern Optics* 46(14):2015-2041. https://doi.org/10.1080/09500349908231390.

Matthews DL, Hagelstein PL, Rosen MD, Eckart MJ, Ceglio NM, Hazi AU, Medecki H, MacGowan BJ, Trebes JE, Whitten BL, Campbell EM, Hatcher CW, Hawryluk AM, Kauffman RL, Pleasance LD, Rambach G, Scofield JH, Stone G, Weaver TA 1985. Demonstration of a Soft X-Ray Amplifier. *Physical Review Letters* 54(2):110–114. https://doi.org/10.1103/PhysRevLett.54.110.

Monroe C, Meekhof DM, King BE, Wineland DJ 1996. A "Schrödinger Cat" superposition state of an atom. *Science* 272(5265):1131–1136. https://10.1126/science.272.5265.1131.

Nussenzveig HM 1979. Complex Angular Momentum Theory of the Rainbow and the Glory. *Journal of the Optical Society of America* 69(8):1068-1079. https://doi.org/10.1364/JOSA.69.001068.

Nussenzveig HM 1998. *Curso de Física Básica: ótica, Relatividade, Física Quântica*. Vol. 4. Blucher, São Paulo, 437pp

Planck M 1900. On an Improvement of Wien's Equation for the Spectrum. *Verhandlungen der Deutschen Physikalischen Gesellschaft* 2(202):1–3.

Rempe G, Schmidt-Kaler F, Walther H 1990. Observation of sub-Poissonian photon statistics in a micromaser. *Physical Review Letters* 64(23):2783-2787. https://doi.org/10.1103/PhysRevLett.64.2783.

Rempe G, Walther H, Klein N 1987. Observation of quantum collapse and revival in a one-atom maser. *Physical Review Letters* 58(4):353–356. https://doi.org/10.1103/PhysRevLett.58.353.

Roy B 1998. Nonclassical properties of the real and imaginary nonlinear Schrödinger cat states. *Physics Letters A* 249(1–2):25–29. https://doi.org/10.1016/S0375-9601(98)00642-2.

Schrödinger E 1926. Quantisierung als Eigenwertproblem. *Annalen der Physik* 384(6):489–527. https://doi.org/10.1002/andp.19263840602.

Slusher RE, Hollberg LW, Yurke B, Mertz JC, Valley JF 1986. Observation of squeezed states generated by four-wave mixing in an optical cavity. *Physical Review Letters* 55(22):2409–2414. https://doi.org/10.1103/PhysRevLett.55.2409.

Óptica Clássica e Quântica e suas Influências nas Ciências e na Sociedade

RESUMO

Neste trabalho apresentamos uma breve história da óptica, iniciada a vários séculos antes de Cristo em sua evolução caracterizada como óptica clássica; mais tarde, essa teoria também se caracterizou como Ótica Quântica. A primeira destas duas teorias foi completada na grande obra de J. C. Maxwell, enquanto a segunda começou em 1977 com a descoberta do primeiro efeito quântico na Optica, tendo em Roy Glauber um dos seus maiores representantes. Aqui, um rápido passeio por essas duas teorias foi feito, incluindo as várias aplicações tecnológicas na ciência e na sociedade.

Palavras-Chave: Óptica Clássica e Quântica; Equações de Maxwell; Efeitos não Lineares; Aplicações de Luz Laser.

Submission: 10/09/2018
Acceptance: 27/03/2019