NOBEL PRIZE IN PHYSICS 2018 AWARDED “FOR GROUND-BREAKING INVENTIONS IN THE FIELD OF LASER PHYSICS”

PREMIO NOBEL DE FÍSICA 2018 OTORGADO “POR INVENCIONES INNOVADORAS EN EL CAMPO DE LA FÍSICA LÁSER”

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After a brief presentation of the Physics Nobel Prize 2018 and its winners, the paper is divided into two main parts. In the first one, the foundations of the optical tweezers are described, and a few of its applications are reviewed in some detail. The second part of the article discusses the physics beyond the technique for obtaining ultrashort, powerful laser pulses, and some of its applications are mentioned.

Después de una breve presentación del Premio Nobel de Física 2018 y sus ganadores, el artículo se divide en dos partes principales. En la primera, se describen los fundamentos de las pinzas ópticas, y se revisan con cierto nivel de detalle algunas de sus aplicaciones. En la segunda parte, se discute la física que sustenta la técnica para obtener pulsos láseres ultra-cortos y muy potentes, y se mencionan algunas de sus aplicaciones.

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The Nobel committee has selected this year two important areas in laser physics which have contributed and continue contributing to the development of remarkable applications concerning the fields of physics and chemistry, biology, biophysics and medicine. The prize has been divided in two parts. One half awarded to Prof. Arthur Ashkin (96 years old!) from USA for all his work on radiation pressure, the invention of the optical tweezers and their remarkable use for the study of biological systems. The second half awarded to Prof. Gérard Mourou (74 years old) from France, shared with his former student Donna Strickland (59 years old) from Canada, for their method to produce ultra short light pulses with high intensities.

As the possibilities for selecting every year the best possible candidates are very restricted, one can guess that the choice made this year is a relatively good compromise: two different continents, a woman among the selected researchers (Donna Strickland being the third one in Physics after Marie Skłodowska-Curie in 1903, and Maria Goeppert-Mayer in 1963), and the recognition of important developments in fundamental physics with broad applications notably in biology and medicine, especially eye surgery.

I. FROM LIGHT PRESSURE TO THE OPTICAL TWEEZERS

Suspected as early as the 17^{th} century based on Kepler’s observations of the comet tails always facing the sun (Fig. 1), and then on Maxwell’s electromagnetic theory, the fact that light exerts forces on objects was experimentally demonstrated by Lebedev in the 19th century. However, being considered too weak to be exploitable, these forces remained a mere curiosity until the invention of the laser in the 1960’s.

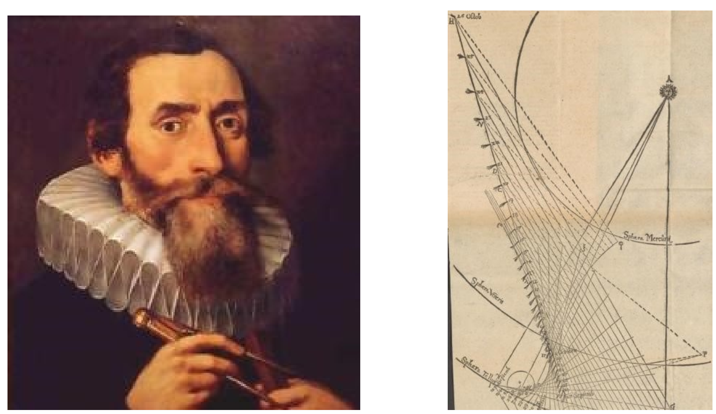

Figure 1. Suspecting the mechanical action of light. **Left**: Johannes Kepler (1571-1630). **Right:** In 1610, Kepler’s observations suggest for first time the idea that light could have a mechanical action on matter. (Image extracted from “De cometis” published in 1619 reporting Kepler’s observations between 1607 until 1618)

From then on, the evolution was rapid and continuous thanks to the works around which Arthur Ashkin’s (Fig. 2) name has been often cited: the first realizations in the 1970s of optical traps using two counter-propagating beams [1], first experiments on the optical levitation of micro spheres [2], first trapping of atoms by resonance radiation pressure [3], first observation of optically trapped atoms [4] and the first stable optical tweezers in 1986 using a single laser beam strongly focused by a high numerical aperture microscope objective, which created an optical gradient force [5]. So 1986 can be taken as the birthday of the optical tweezers.

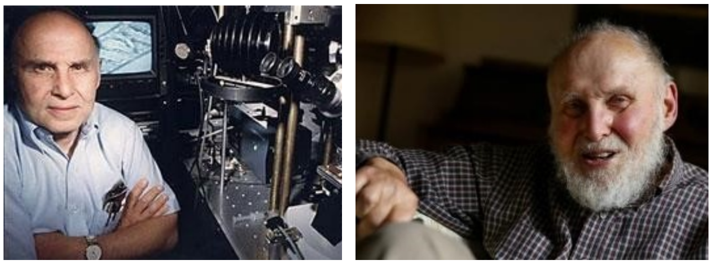

Figure 2. A long quest for optical tweezers. **Left:** Arthur Ashkin at the time of his discovery. **Right:** When he was 90 years old.

I.1. *Optical tweezers in Biology and Medicine*

The use of a laser beam focused through a microscope objective to manipulate tiny objects therefore suggested many potential applications to biology. It was again Ashkin who started to innovate in this field by performing the first manipulations of viruses and bacteria or organelles inside the cell cytoplasm. Also, Arthur Ashkin developed the first applications in the field of medicine, including the problem of sterility and human fertility [6].

On the one hand, optical tweezers allow the precise manipulation of objects without any mechanical contact, so the object may remain in a perfectly sterile environment during its manipulation. On the other hand, the forces generated by the optical tweezers are typically equivalent to those involved in a large number of cellular processes (adhesion, cytoskeleton mechanics, molecular motors, etc.). This is why the development of optical tweezers has been and continues to be very dominant in the field of biological applications. However, it is also applied in other fields of photochemistry or physics, such as the study and control of colloidal particles, polymerization or crystalline growth, or the setting in motion and control of micro motors or micro pumps.

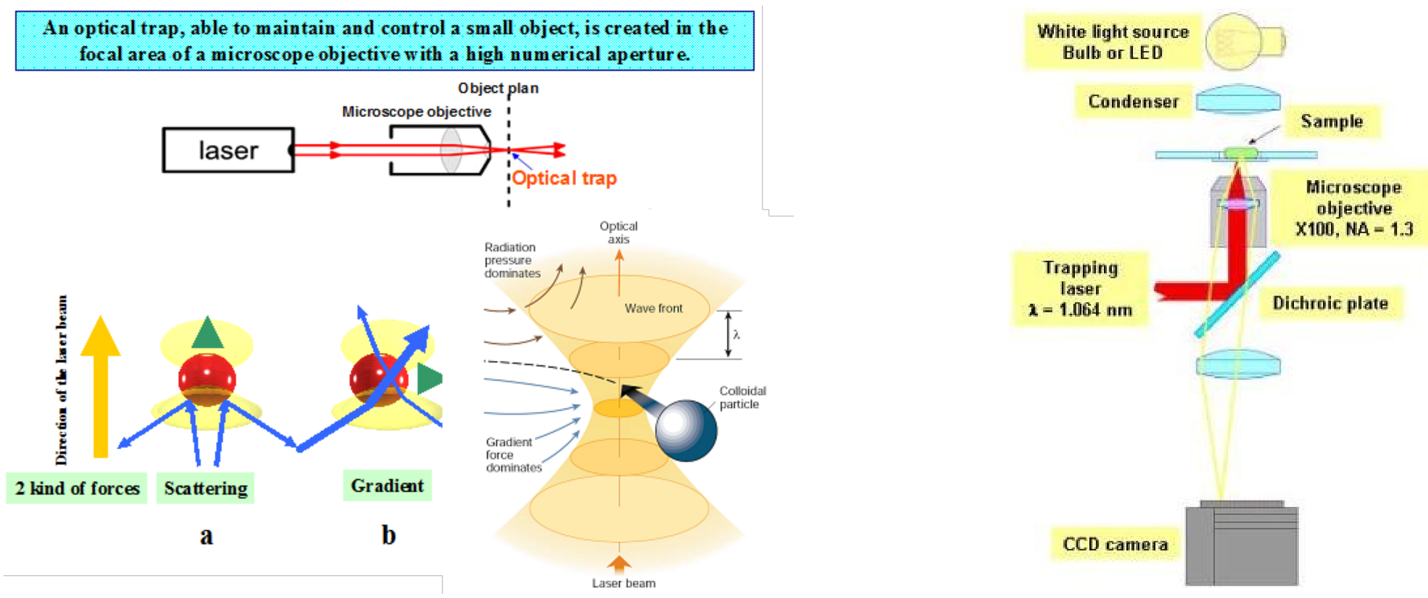

Figure 3. The working principle of the optical tweezers. **Left**: A laser beam is directed at the rear back side of a high numerical aperture microscope objective, and as the beam converges to a diffraction limited spot, mesoscopic dielectric particles in the light path are confined near the focal point. (a) The light exerts an upward force on the sphere (radiation pressure). (b) The light exerts a lateral force to the right on a sphere with refraction index higher that the surrounding. The resulting force pushes the particle towards the region of maximum light intensity, i.e., the particle is trapped into that regions close to the focal point of the objective. **Right**: A complete scheme of an optical tweezers experiment based on the use of an inverted optical microscope commonly used by biologists.

I.2. *Applications on individual DNA and RNA molecules*

The dynamic studies at the level of single DNA or RNA molecules have progressed significantly thanks to manipulations using optical tweezers. Thanks to them, it is possible today to measure the force applied to a DNA molecule which is fixed at one of its ends to the surface of a sample holder and at its other end to a latex ball that is held by an optical clamp (optical tweezers). Also, single DNA can be attached to two balls clamped in optical tweezers [7]. Then, it is possible to directly measure the elasticity of the DNA molecule (Fig. 4a).

Other application has been the study of RNA polymerase molecules responsible for the transcription of the content of the DNA into messenger RNA [8, 9]. During transcription, the RNA polymerase molecule moves along the DNA strand to form the messenger RNA step by step and it is possible to detect this movement with angstrom precision by binding a latex sphere to the RNA polymerase molecule (Fig. 4b), since the displacement of this molecule affects the position of the ball in the optical trap. The separation of the double helix from the DNA is achievable through the action of a mechanical force exerted with an optical clamp. It has thus been possible to determine the force with which the base pairs are bound and it has been established that these forces vary according to the sequence of base pairs.

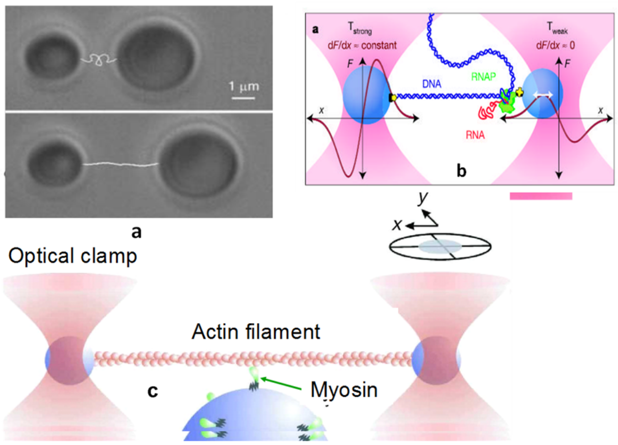

Figure 4. Manipulation of individual molecules (a) Principle of measuring the elasticity of the DNA molecule [7]. (b) A RNA polymerase molecule is bound to a latex microsphere trapped in an optical clamp. [8, 9] (c) A single actin filament is suspended between two latex beads held in position by two optical traps. A molecule of myosin interacts with the filament along which it can move, allowing the study of the forces involved in muscle contraction [10]

Many biological processes involve the transformation of chemical energy into mechanical energy through the so-called molecular motors. Processes such as intracellular transport, bacterial motion, DNA replication or muscle contraction involve different types of molecular motors. Biological motors [10] are excellent model systems for studying protein motions or their conformational changes. In particular, many studies concern the problem of the action of muscle fibers where molecules such as kinesin or myosin act. A prototype system often studied consists of an actin filament attached at its ends to latex beads, themselves held in position by two optical traps (Fig. 4c).

I.3. *Cell manipulations*

This is an area where many experiences have being done since the very beginning of the optical tweezers. Due to the fact that light beams easily cross cell membranes, chromosomes, mitochondria and other intracellular organelles can be manipulated by optical tweezers. Cellular functioning has been the subject of many studies. In particular, one can note the studies on the influence of a stress caused to a cell that has been trapped by latex beads which are collectively controlled by several laser beams to exert a pressure around it and therefore acting on its metabolism. Other studies on cells combine optical tweezers with microsurgical or micro-scalpel microsurgery, or with the use of fluorescent probes that are positioned in specific areas of the cell. An interesting application is the study of gametes and spermatozoa and the action that optical tweezers can provide to help human or animal fertility [6] (Fig. 5 top).

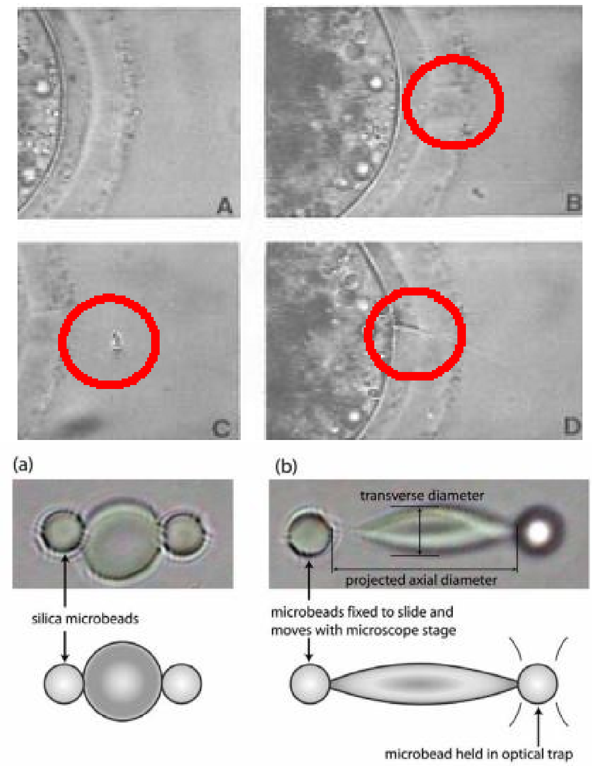

Figure 5. Manipulation of individual cells. **Top:** Helping fertilization with optical tweezers. (a) The optical manipulation of mobile cells such as spermatozoa for the measurement of their flagellar propulsion force is a diagnostic tool for certain types of sterility. Details of the left figure: Laser zona drilling and sperm insertion. (A) Cattle oocyte with intact zona pellucida. (B) Oocyte after drilling a hole into the zona pellucida; note the sharp edges of the channel. (C) Trapped sperm before insertion into the perivitelline space of the oocyte (sperm head in and sperm tail out of focus). (D) Inserted sperm in close contact to the oocyte membrane [6]. **Bottom**: Viscoelastic properties of stretched cells: a red globule with two balls in diametrically opposite positions is deformed by increasing the distance between the traps. The optical image shows an example of large deformation of a cell at 193 pN of force [11].

By providing precise control of the forces exerted on the cell membranes, optical tweezers contributed to a better knowledge of their viscoelastic properties (Fig. 5 bottom). Examples include the study of the elasticity of the red blood cell membrane to understand how the absence or the abnormality of some membrane proteins can lead to a persistent deformation of a globule likely to favor its premature destruction [11].

I.4. *Non-biological applications: nano- and micro-motors*

Another major area of applications of optical tweezers is the study and realization of nano- or micro-motors (Fig. 6), a research topic where much work is focused on the different possibilities to use light for set in rotation small objects, controlling their speed and their direction of rotation. The various applications are strongly related to micro-fluidics: circulation engines, agitators, valves, local viscometers, etc. The driving idea of this research in micro-fluidics often combined with the use of optical tweezers is the production of micro-laboratories or ”lab-on-a-chip”. In the understanding of colloidal systems, this technique has already demonstrated its great utility for studying their dynamical behavior and the interactions between colloidal particles.

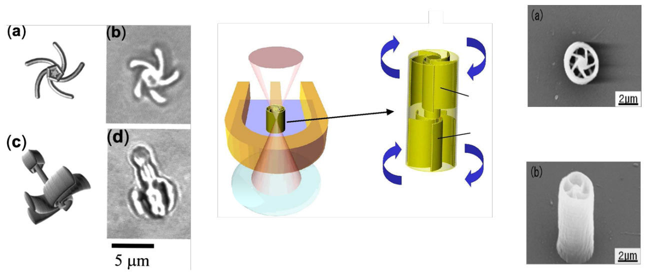

Figure 6. Laser-animated nano-devices. Left: realization of nano-motors animated by the laser beam of an optical tweezers. The rotor starts rotating in the vicinity of the focus of the microscope objective and the direction of rotation changes depending on whether the rotor is above or below the focus [12]. Center: illustration of a U-shaped micro channel in which it is placed a micro pump whose practical realization is shown on the right [13].

The action of light is not limited to the ability to capture an object. Other situations are explored as the possibility of ”making fly.ªn object with the shape of an airplane wing, the flow of photons providing the required lift. Other situations are achieved like those using some particular configurations of beams that according to the size or the refractive index of the micro objects, some are attracted when others are repelled by the light, realizing then an automatic and effective sorting within a mixture of different objects.

All in all, it is difficult to end up this section with any conclusions, since the research and technology based on radiation pressure and optical tweezers is a still extremely active field of research.

II. ULTRASHORT AND POWERFUL OPTICAL PULSES

As pointed out before, Gérard Mourou (Fig. 7 left), professor and member of the Haut-collège of the École Polytechnique in Palaiseau (France) receives the second half of the Nobel Prize in Physics 2018. He shares this award with the Canadian Donna Strickland (Fig. 7 right) for jointly developing a method for the generation of ultrashort optical pulses with extreme high intensity [14, 15].

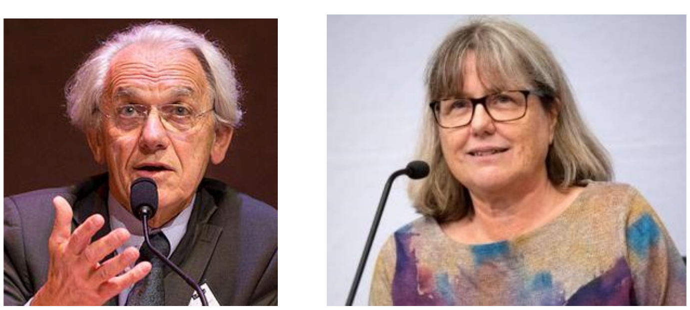

Figure 7. The creators of the “Chirped Pulse Amplification”technique. **Left:** Gérard Mourou. **Right:** Donna Strickland.

Gérard Mourou spent a large part of his career in the United States, and in particular at the University of Michigan where he is now an emeritus professor. Upon his return to France in 2005, he led the Laboratory of Applied Optics belonging to ENSTA ParisTech/CNRS/École polytechnique) until 2008.

It is at the origin of three major initiatives concerning high power lasers: the launch of the XCAN project at the Ecole Polytechnique, the Apollon laser on the Saclay plateau and the great European infrastructure ELI (Extreme Light Infrastructure) which will house the most powerful lasers of the world in Hungary, Romania and the Czech Republic. He is also director of the International Zetta-Exawatt Science and Technology (IZEST), which associates 27 laboratories around the world to anticipate the future of high-power lasers.

II.1. *Chirped Pulse Amplification*

Chirped Pulse Amplification is one of those extremely clever tricks which are easier to say than to do in the laboratory, so it is impressive that Gérard Mourou and Donna Strickland were able to make it work. After demonstrating it, many other researchers started imitating and refining the technique, which has found applications all over physics, and even in medicine.

The Chirped Pulse Amplification principle (CPA) works as follows: an oscillator produces short pulses at low intensity. Firstly, the ultrashort pulses are temporally spread by using an optical stretcher (about 10,000) consisting of two gratings to reduce their instantaneous intensity. Such long pulses are now safe for amplification in an amplifier material without damaging it. The pulse is then recompressed to reach intensities that classic amplification techniques would not achieve. The CPA technique allowed very quickly gaining 10 orders of magnitude in laser power. This discovery has contributed to the advancement of science in several fields, in particular, by making it possible to manufacture increasingly intense lasers to probe matter. Adapted to the medical field, the CPA technique has also allowed advances in the field of refractive surgery of the eye and the treatment of cataract.

II.2. *Understanding the cleverness of Mourou and Strickland invention*

The technique, Gérard Mourou and Donna Strickland invented was a part of Strickland’s thesis research, and is nowadays universally known as CPA. It is founded on one of the central facts of wave physics, namely that making pulses with a short duration in time requires a wide spread in frequency. Mourou and Strickland exploited this frequency spread in a clever way to circumvent the limits imposed by the fact that too high intensities can damage the crystals used to amplify laser pulses.

An important point to understand is why the generation of short pulses needs a wide range of frequencies. First one can look at what happens when adding pulses of light with slightly different frequencies. Fig. 8 (top panel) shows a single frequency wave at the bottom, with combinations of 2, 3, and 5 slightly different frequencies above it [16].

When adding a second frequency, the single smooth wave breaks up into a series of beats regions where there is some wave behaviour separated by regions where the two different frequencies cancel each other out.

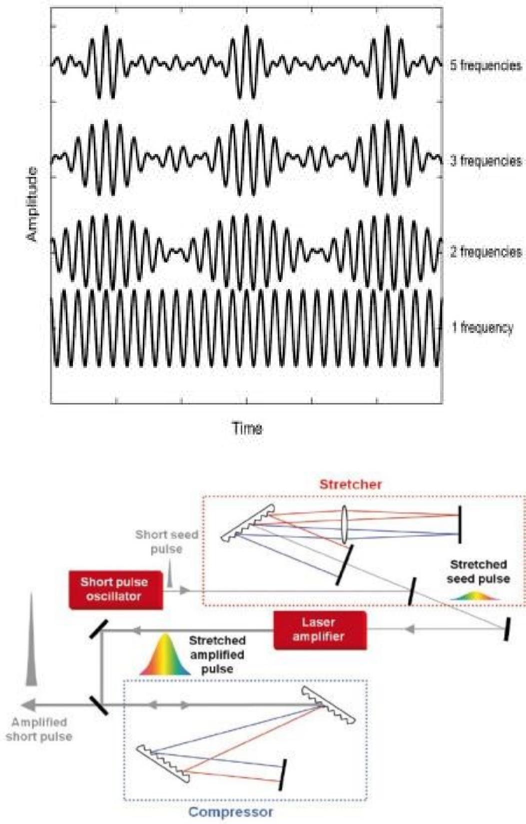

Figure 8. How chirped-pulse amplification works. **Top**: Creating narrow pulses of light by addition of waves with slightly different frequencies [16]. **Bottom**: Conceptual scheme of a chirped-pulse amplification based on a conventional laser system at 800 nm [17].

As more frequencies are added, the general beat structure remains, but the width of the region with obvious wave behaviour gets smaller. This is a very general phenomenon relating to waves, and applies to anything with wave nature: sound waves, light waves, even the matter waves associated with quantum-mechanical particles. When adding together lots of waves with slightly different frequencies, you end up with a series of narrow pulses where you see intense wave activity, separated by wide regions where not much is happening. This process is known as "mode locking".

Based on these physics, a gain medium that will amplify light over a broad range of frequencies is needed to make a pulsed laser. One common such medium is titanium atoms embedded in a sapphire crystal, which will let you amplify light over a range extending from the visible spectrum across a huge band in the near infrared. With a Ti-sapphire crystal placed inside an optical cavity in between two mirrors and pumping it with a high power CW Nd-YAG laser, the non linear properties of the Ti-sapphire crystal allows to get a "self mode-locked"laser in which the presence of a bunch of different frequencies of light leads to the generation of short pulses of light in the femtosecond range with each pulse containing a wide range of frequencies.

You can look at it in two complementary ways: one measurement you can make is to look at the overall intensity as a function of time, in which case you see a very short pulse. The other way is to look at the intensity as a function of frequency, in which case you see a wide spread of different frequencies, each with a little bit of intensity.

If you want to make a really intense ultrashort laser pulse, you quickly run into the problem of how much power an amplifier crystal can support. When the intensity of light becomes excessive, the material can be damaged, and that limits what you can do with one of these lasers.

This problem seemed insurmountable if you think of the pulse only in the intensity-versus-time domain, when the amplifier is getting all the frequencies at once. But if you look at it in intensity-versus-frequency domain, you can think that none of the individual frequencies contributing to the pulse have enough intensity to pose a problem on their own. So, the trick Gérard Mourou and Donna Strickland figured out was to separate those out, so the amplifier had to deal with only a few frequencies at a time.

There are several ways of doing this: one is with a pair of diffraction gratings to spread out the different frequencies so that some follow longer paths than others. It is also possible to stretch the pulse sending it through the length of an optical fibre, in which some frequencies of light travel faster than others. Either way, you end up with a longer laser pulse in which the high-frequency light arrives first while the lower-frequency light straggles in some time later. This is referred to as a "chirped pulse"because the chirp of a bird has the same sort of frequency structure: high frequency at the start, low at the end (or vice versa).

The chirped pulse gets you a longer duration, but more importantly, it spreads out the intensity so that it is always below the damage threshold for the amplifier. Then you can safely boost the intensity of each of the individual frequencies in the pulse, which leaves you with a more intense but longer pulse. Then you just reverse the chirping process, using another pair of diffraction gratings to make the high-frequency light on the leading edge travel a slightly longer path than the low-frequency light on the trailing edge, in such a way that all the frequencies arrive at the same time, but now with many times the intensity.

III. APPLYING THE CHIRPED PULSE AMPLIFICATION TECHNIQUE

What Gérard Mourou and Donna Strickland did was to develop a method for boosting the intensity and reducing the duration of pulses from a pulsed laser. This plays a key role in most techniques that need really high intensity light, from eye surgery to laser-based acceleration of charged particles (sometimes considered as a tool for next-generation particle accelerators), or the need of intense fast pulses of light such as those needed in recent experiments looking at how long it takes to ionise an electron out of a molecule. This kind of enabling of other science is exactly the kind of thing that the Nobel Committee ought to recognize and support, fully justifying the choice for a prize.

III.1. Medicine: for eye surgery and vision correction

Femtosecond laser for myopia and hyperopia correction

When femtosecond laser was first developed, it did not gain tremendous notoriety until researchers determined that it could be used to cut corneal flaps as well as cutting tunnels for the implantation of intra-corneal ring segments for the treatment of keratoconus. Such field of applications needed the development of specific femtosecond sources using a hybrid Chirped-Pulse Amplification system based on erbium (Er)-doped fibres, operating at 1.6 μm [18] (Fig. 9).

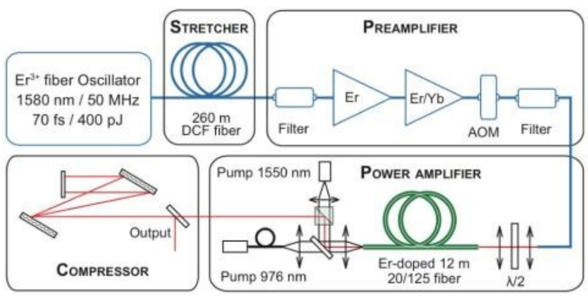

Figure 9. An example of an hybrid Chirped-Pulse Amplification system based on erbium (Er)-doped fibers, operating at 1.6 μm for applications in eye surgery and vision corrections. DCF: Dispersion-compensating fiber. AOM: Acousto-optical modulator. Yb: Ytterbium. $\lambda/2$: Half-wave plate. [18]

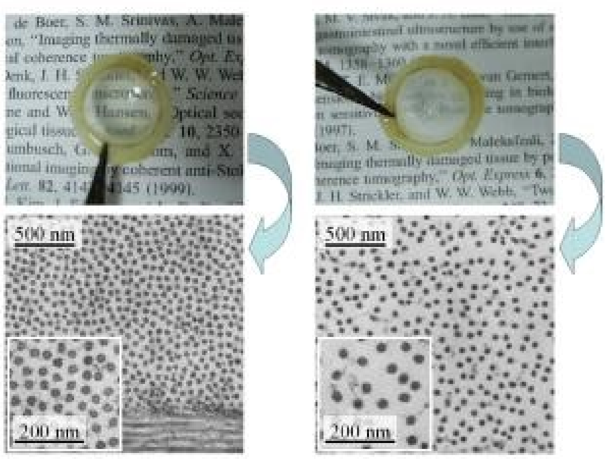

Figure 10. Fixing the cornea using lasers. **Left**: The regular arrangement of the collagen fibrils in the volume of healthy cornea is responsible for its transparency. **Right**: Most reasons for corneal grafting involve edema which perturbs the regular fibril structure and leads to strong optical scattering. [18].

Other treatments concern the corneal refractive surgery with femtosecond lasers. When compared to longer pulse width nanosecond or picosecond laser pulses, femtosecond laser-tissue interactions are characterized by significantly smaller and more deterministic photo disruptive energy thresholds, as well as reduced shock waves and smaller cavitations bubbles. Superior dissection and surface quality results were obtained for lamellar procedures (corneal flap cutting and keratornileusis). A conclusion is that femtosecond laser technology may be able to perform a variety of corneal refractive procedures with high precision, offering advantages over current mechanical and laser devices and techniques [19].

The incision quality achieved with femtosecond pulses can be analyzed by transmission electron microscopy (Fig. 11).

III.2. Laser technology: towards petawatts and attosecond pulses

Application of ultra-broadband attosecond pulses

Strickland and Mourou breakthrough with the CPA amplification scheme opened the way to the extreme limits in laser technologies for application in basics physics and intimate matter studies [21]. For instance, isolated attosecond pulses hold great potential for time-resolved measurements on unprecedented timescales which will only be realized with the development of high-energy attosecond light sources having ultrabroad bandwidths [22].

Bound-state wave-packet dynamics

The spectrum of a broadband isolated attosecond pulse can simultaneously cover bound (or quasi-bound) and continuum states of an atom or molecule, resulting in the formation of a wave packet consisting of both bound and continuum states, which naturally evolves on attosecond timescales. A delayed NIR laser can then transfer population between bound states or ionize the excited states, promoting bound electrons to the continuum. The wave-packet dynamics can be probed using attosecond electron interferometry or attosecond transient absorption spectroscopy. The full complex amplitude, including the lifetime and phase, of each excited state in the bound wave packet can be extracted. Such a measurement was recently performed in singly excited states of helium atoms, but it is applicable to more general systems as well.

Correlated electron motion

In general, attosecond transient absorption appears to be a promising tool for the application of ultra-broadband attosecond pulses for studying the electron correlation in atoms and more complex systems. Recently, attosecond transient absorption has been applied to study field-induced insulating-to-conducting state transitions in SiO2 glass exposed to a strong laser field. Experiments revealed instantaneous and reversible field-induced modification of the insulating material, by probing changes in the transmission of the glass in the vicinity of the L-shell excitonic transition (~100 eV) of silicon. The results have tremendous implications for the development of light wave electronics, and indicate that transient absorption spectroscopy may allow the first access to time-resolved processes and ultrafast switching in high-Tc superconductors or semiconductor solar cells with ultra-broadband isolated attosecond pulses that can cover the absorption edges of all the constituent atoms.

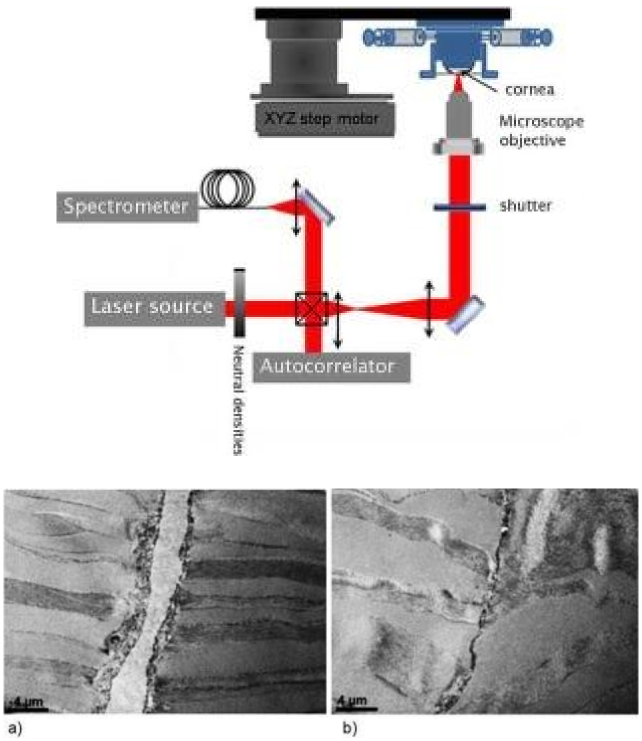

Figure 11. Laser incisions. **Top**: Experimental setup to perform incisions. **Bottom**: Typical transmission electron micrographs of incisions performed in the volume of the stroma at wavelengths of (a) 1030 nm and (b) 1650 nm. [20]

By extending such attosecond sources and spectroscopic techniques to kiloelectronvolt photon energies, the potential of attosecond technology for studying electron correlation in complex materials can be realized. Finally, combining the techniques used to generate broadband attosecond pulses with those for generating high-energy isolated attosecond pulses will allow for the generation of single-cycle pulses with gigawatt peak powers and petawatt per square centimetre peak intensities at the target, which can be applied in true attosecond pump/attosecond probe experiments.

The limits are not achieved still, and the competition continues up to zettawatt-exawatt lasers [23].

IV. SUMMARY

It is worth noticing that both the contributions of Arthur Ashkin or Gérard Mourou and Donna Stricland are very creative, technologically-oriented findings in the field of Physics. Their ideas have been rapidly applied around the globe to shed light on the foundations of laser physics, but have also revolutionized important areas of medicine such as ophthalmology. This ability of expanding the horizons of other fields of science in exactly what the Nobel Committee ought to recognize and support, fully justifying the choice for the attributed Physics prizes in 2018.

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