Optical Scientists Receive the 2018 Nobel Prize in Physics

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ABSTRACT

The Nobel Prize in Physics of 2018 goes to three optical scientists – Arthur Ashkin, Gérard Mourou and Donna Strickland – for groundbreaking inventions in the field of laser physics. Their works on optical tweezers and short laser pulse amplification have had a significant impact on modern physics, biology, and medical applications.

INTRODUCTION

Optics is an exciting research field, rich with topics for both scientific study and practical applications. Lasers are hugely important in modern optics; optics itself can even be categorized by whether or not lasers are involved. 2018 was a very special year for optical scientists and engineers. We celebrated the first International Day of Light (IDL) on May 16, 2018 [1], and the tradition of recognizing IDL will be continued. UNESCO selected May 16 as the IDL in memory of Theodore H. Maiman's first laser operation on May 16, 1960. Before the proclamation of the IDL, the United Nations had designated 2015 as the International Year of Light (IYL) [2]. Sadly, only a few days after a celebration for the IYL at UNESCO headquarters in Paris, Charles H. Townes, one of the inventors of the laser, passed away. In 2000, he noted that 13 scientists had received Nobel prizes based on works intimately related to masers and lasers [3]. Even afterward, Nobel prizes related to lasers have been awarded from time to time. The year 2018 marked another such event.

On October 2, 2018, the Nobel Committee for Physics of the Royal Swedish Academy of Sciences announced the three 2018 Nobel laureates in physics for "groundbreaking inventions in the field of laser physics". One half of the prize was awarded to Arthur Ashkin for "the optical tweezers and their application to biological systems" and the other half was split between Gérard Mourou and Donna Strickland for "their method of generating high-intensity, ultra-short optical pulses" [4]. Although the two fields are hardly related to each other, it is clear that the impact of their works deserves the Nobel Prize.

ASHKIN

Arthur Ashkin's work on the optical tweezer or trap is very well recognized. When Steven Chu, Claude Cohen-Tannoudji and William D. Phillips received the Nobel Prize in Physics in 1997 for "development of methods to cool and trap atoms with laser light", some optical scientists thought that Arthur Ashkin had been overlooked. It is a little surprising that the Nobel Prize was again awarded for the optical trap, but this time the Nobel Committee stressed the biological system applications of optical tweezers.

The radiation pressure of light was a well-known phenomenon. In 1619, Johannes Kepler thought that comet tails point away from the sun due to the radiation pressure of light emitted from the sun [5]. The source of the radiation pressure comes from photon momentum and the law of momentum conservation when particles collide. In 1970, Ashkin published a paper, entitled "Acceleration and trapping of particles by radiation pressure" in *Physical Review Letters* [6]. He showed that a dielectric particle can be attracted to the laser beam axis. Here refracted light, rather than reflected light, passing through the dielectric particle directs the particle toward the highest intensity region of laser light. This is because the photon momentum difference between the incident and refracted photons is delivered to the dielectric particle. Ashkin used two laser beams propagating in opposite directions to move and trap a dielectric particle along the central axis of the Gaussian laser beam. Even in this paper, he pointed out that atoms and molecules could be trapped if the laser wavelength was matched with transitions in atomic or molecular energy levels.

Ashkin continued his research with colleagues and in a paper published in *Optics Letters* in 1986, co-authored by Steven Chu, he proved that the gradient force of a single focused laser beam can trap a dielectric particle near the laser beam waist [7]. Ashkin and his colleagues also developed wave-optics based gradient force analysis for particles smaller than the wavelength of light.

In the following year, he and his colleagues published two papers in *Science* and *Nature* titled “Optical trapping and manipulation of viruses and bacteria” and “Optical trapping and manipulation of single cells using infrared laser beams”, respectively [8, 9]. The Nobel Committee for Physics explained that the use of optical tweezers to capture living bacteria without inflicting damage was an innovation. It is worth noting that he was 64 - 65 years old when he published these papers as the lead author.

Optical tweezers have inspired sensational research in biophysics, such as the probing of individual molecular actions. One breakthrough example highlighted by the Nobel Committee for Physics is the direct observation of the stepping motion of kinesin, which transports cellular cargo along microtubules [10, 11].

MOUROU AND STRICKLAND

Typical methods of generating pulsed lasers include using the Q-switching technique or the mode-locking technique. However, peak power or pulse energy is quite limited in these laser pulses. In 1985, Donna Strickland, then a graduate student at University of Rochester, and her advisor Gérard Mourou published a paper in *Optics Communications* entitled, “Compression of amplified chirped optical pulses” [12]. Their method came to be known as chirped pulse amplification (CPA). The paper was published in the October 15 issue of the journal with a wrong figure [13] and republished in the December 1 issue with the corrected version.

There used to be limitations in amplifying short laser pulses because high peak power damages amplifying material. The key concept of CPA was surprisingly simple, inspired by a radar technique developed 30 years earlier [14]. A short laser pulse is stretched in time, resulting in a wide pulse with low peak power. This pulse is amplified by repeated round trips in the amplifying cavity and then the time width of the resultant pulse is shortened to generate a high peak power (or high energy) short pulse.

This work immediately attracted a great deal of attention, and Mourou and Strickland gave an invited presentation the following year at a conference organized by the Optical Society of America (OSA) [14]. In their original work, Strickland and Mourou used a 1.4-km long single-mode optical fiber to elongate the initial Nd:YAG laser pulse. The elongation was possible due to the combined effects of self-phase modulation and group velocity dispersion. After amplifying the stretched pulse using a Nd:glass regenerative amplifier, the long chirped pulse was compressed by a double grating compressor, resulting in laser pulses each with 2 ps width and 1 mJ energy. Later the use of optical fibers for pulse stretching was replaced with the use of another pair of double gratings, which became the standard technique [15, 16].

The invention of CPA provided the means to develop tabletop terawatt (T^3) lasers, and the first petawatt laser (1.5 PW peak power) was demonstrated in 1999 [17]. Today, many projects are in progress that aim for lasers with ever higher power and intensity. In 2010, there were about 100 laboratories that achieved a 100 terawatt laser peak power. Currently, there are 15 facilities around the world that have reached petawatt peak power, including four in Asia – the Center for Relativistic Laser Science (Gwangju, Korea), Kansai Photon Science Institute (Kyoto, Japan), the Institute of Laser Engineering (Osaka, Japan) and Shanghai Superintense Ultrafast Laser Facility (Shanghai, China). The most distinguished facility is the Extreme Light Infrastructure (ELI) in Europe, which was initiated by Mourou himself [18].

High-power ultra-short pulse lasers with CPA technology have been fruitful and we anticipate that they will open up several new exciting research fields such as strong-field physics, attosecond science, laser-plasma acceleration, relativistic optics, ultra-relativistic optics and nonlinear quantum electrodynamics. In fact, these research fields may also produce Nobel laureates in the future.

Two weeks before the announcement of the 2018 Nobel Prize in Physics, Mourou gave an inspirational plenary talk at a conference named *Frontiers in Optics + Laser Science;* a video recording is available on the conference website [19].

High-intensity, ultra-short laser pulses enabled by the CPA technique have also found many industrial and medical applications. An example presented by the Nobel Committee for Physics is laser eye surgery called laser-assisted in situ keratomileusis (LASIK) using femtosecond laser pulses [11].

Donna Strickland is the third female laureate in the history of Nobel Prize in Physics – after Marie Curie, née Sklodowska (1903) and Maria Goeppert Mayer (1963). Some commentators in the media have raised issues concerning whether academia is appropriately recognizing female scientists [20]. However in the optics community Strickland is a very well-known scientist. She has been actively serving the academic society and she was the president of OSA in 2013.

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