THE LASER

FROM YESTERDAY (1960) TO TOMORROW

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Fifty years ago, on the 16th of May 1960, the first laser ("Light Amplification by Stimulated Emission of Radiation") emission was obtained by Theodor Maiman with a flash-lamp-pumped ruby crystal. This observation was the product of a long search, which can be dated back to the early twentieth century.

It combined the development of an optical resonator by Charles Fabry and Alfred Pérot (the "Fabry–Pérot interferometer", in 1897, noted F-P) on the one side and the prediction of stimulated emission of light by Albert Einstein in 1916, from thermodynamic considerations about radiation processes in the blackbody emission, on the other. The rapid advances in high-frequency electronics and radar technology during World War II accelerated the post-war research in microwaves and quantum electronics. It led to the development of optical pumping by Alfred Kastler in 1950, and then to the first demonstration of a MASER ("Microwave Amplification by Stimulated Emission of Radiation"): The first ammonia beam maser was operated by Charles Townes and co-workers in 1954, quickly followed by Alexander Prokhorov and Nicolai Basov. That was the start of what has been called Quantum Electronics. Actually, the laser era started in 1958, when Arthur Schawlow and Charles Townes proposed to extend the maser operating principle towards higher frequencies, into the optical range. This required the replacement of the closed microwave cavity by an open Fabry-Pérot resonator. This idea led to the 1st laser observation by Maiman in 1960. Thereafter the development of lasers was exponential and thousands varieties of lasers have been and are still being developed.

This great variety of lasers involves different materials, wavelengths, sizes and powers, continued or pulsed regimes, etc. What is the common feature for a semiconductor laser diode of micrometric dimensions, a gas laser, a free-electron laser occupying a vast hall, or, for example, the "Laser MegaJoule" (in Bordeaux, France) and the "National Ignition Facility", planned for controlled thermonuclear fusion (in Livermore, USA), which needs several huge buildings? It is the oscillator concept: the laser is a *light oscillator*, combining an amplifying medium with an optical resonator (often of the simple ►

▲ Laser fountain made for the '50 years of laser' at Laboratoire de Physique des Lasers (Université Paris XIII and CNRS, FR). It illustrates in a spectacular way the guiding of light by total internal reflection inside a water jet. The same principle is at work in low-loss optical fibres as used in optical communication (picture credit Ph. Lavialle).

F-P type, but not necessarily) providing the resonant light feedback necessary to reach the oscillation threshold. An essential ingredient of laser operation is the population inversion needed to yield light amplification, *i.e.*, to establish negative temperatures, in contrast to the usual thermal equilibrium. The huge variety of lasers comes, first, from the large choice of amplifying media; these can be gases, liquids or solids, crystallized or not, such as semiconductors, doped insulators or fibres, dyes, polymers, etc. The variety also comes from the population inversion, which can be obtained via optical or electronic pumping, via energy-exchanging collision processes, etc. This has led to the realisation of many different lasers among which one remembers the first continuous-wave laser, the famous helium-neon laser, realised by Ali Javan and colleagues in 1960; the high power CO_2 laser used for decades in industrial applications; the multiple semiconductor lasers presently used everywhere; the dye lasers, which were the first wavelength-tuneable emitters (of particular interest in basic research); the fibre lasers, etc. The progress in laser materials, in nonlinear optical techniques and the development of laser technology allows laser sources now to cover a wavelength range extending from the far-infrared to the hard X-UV domain.

The main properties of a laser beam originate from the stimulated emission process. The light is generally propagating in a single mode of the resonant optical cavity. This imposes both spatial and temporal coherence to the laser beam, in stark contrast with the emission of traditional light bulbs. The spatial coherence implies high beam directivity and thus a strong brilliance (and intensity) of the beams. Beam directivity is used for alignment procedure as well as distance measurement. A striking example is the earth-moon distance, which has been measured with a precision up to the cm level, thanks to the retro-reflector installed on the moon by the Apollo missions. The beam intensity is used in industrial lasers for machining/micro-machining of materials as well as in surgery/micro-surgery applications.

The temporal coherence has many applications in fundamental and applied sciences.

Frequency stabilisation and laser metrology developed very quickly from the early days of the laser, and revolutionized time and frequency standards. The use of He-Ne lasers to measure both wavelength and frequency of a CH_4 transition at 3.39 µm by John Hall *et al.* has yielded the most precise of the various light velocity measurements. Based on this measure, the CCDM[1] decided in 1983 to fix the light velocity and to link to it the time and length standards. Length measurements are now controlled by highly accurate frequency measurements. On the other hand, time standards are regularly improved thanks to the progress in laser sources and cold atoms.

The laser has had a fantastic impact on basic research in atomic, molecular and solid-state physics. In a way, it was at the basis of the renewal of old disciplines (electronics, atomic and molecular physics) from the 1970s onwards: nonlinear optics, high-resolution laser spectroscopy, Raman spectroscopy, measurement of fundamental constants at an unprecedented level of accuracy, laser cooling and trapping, ultra-cold quantum gases and Bose-Einstein condensation, quantum information. The progress in all these fields is a direct consequence of the development of lasers. Eight Nobel prizes since 1964, in physics and chemistry, are directly related to lasers and laser applications. As an example, peculiar properties of lasers rely on the photon statistics of the emitted radiation. The analysis and control of these properties form the basis for the field of Quantum Optics. Quantum Optics can be viewed as a case study in Quantum Physics and dynamical systems, and allows the study under ideally suited conditions of such fundamental concepts as wave-particle duality, Heisenberg uncertainty relations, quantum correlation and entanglement, theory of quantum measurement, decoherence, bifurcations and chaos, squeezing etc. Quantum Optics has opened the way to quantum information and quantum cryptography.

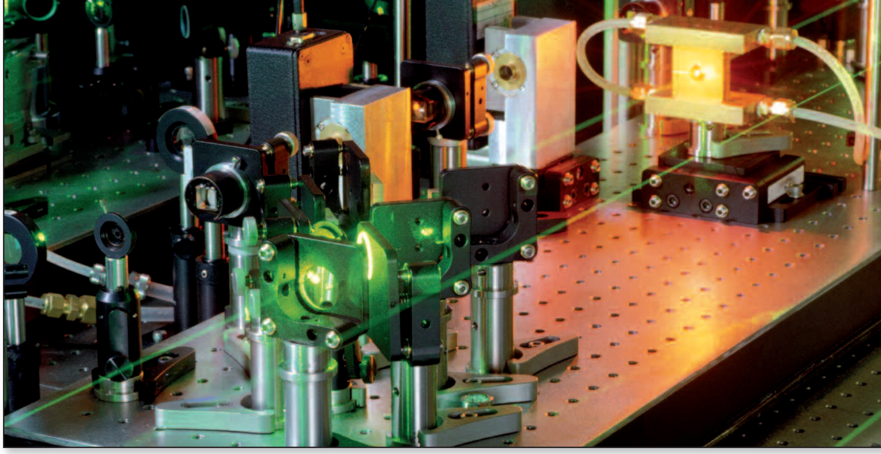
▼ Theodore H. Maiman of Hughes Aircraft Company showing a cube of synthetic ruby crystal, the material at the heart of the first laser.

Note

[1] Comité Consultatif pour la Définition du Mètre, of the "Bureau International des Poids et Mesures" – BIPM - Paris)

In the study of time-dependent phenomena, the development of laser technology has also had a quite impressive impact with the realisation of shorter and shorter laser pulses, lasting now just a few optical cycles. We can now realize pulses below the femtosecond range ($1fs = 10^{-15}s$) and even the hundred attoseconds ($10^{-18}s$). These pulses give access to the domain of fs and sub-fs spectroscopy with its many applications in ultrafast physics, chemistry and biology. For instance, in chemistry, ultra-short laser pulses have been used for the coherent control of physicochemical processes and fs dynamics of molecular reactions, giving access to a stroboscopic picture of atoms and molecules in interaction. Correlated to this shortening in pulse duration, extremely large instantaneous optical powers have been obtained, in the petawatt range ($10^{15}W$) and higher. The corresponding ultra-large electric fields of these lasers are presently investigated to build compact particle accelerators. They may open the door to the observation of nonlinear optics of quantum vacuum (pair creation, etc.). In relation to this, the production of very large energy pulses (higher than the megajoule) is being actively pursued in an attempt to achieve laser thermonuclear fusion by inertial confinement.

The impact of lasers in the socio-economic world and everyday life has been widespread. Technological applications range from communications to aeronautics (like gyro-lasers in airplanes), to medicine and health. For the general public, the most immediate and visible applications are in reading processes: bar codes in supermarkets, the compact disk, DVD, optical disk drives in PC's, etc. In medicine, lasers are used both as a sensitive diagnostic tool and a selective scalpel. Laser micro-dissection is now in common use. From the early laser days, applications in ophthalmology have quickly developed, the principle being to select a wavelength not absorbed by the cornea and able to act inside the eye. Other numerous medical applications include tissue luminescence and DNA decrypting. In a general way, laser spectroscopy allows one to perform selective and accurate *in situ* diagnostics of given species. Such spectroscopy has been applied to remote detection of trace elements in environments as different as upper atmosphere, reaction flames or living tissues. In Earth and atmospheric sciences, LIDAR (Light Detection and Ranging – the laser analogue of RADAR) is commonly used for remote monitoring of pollutants and aerosols. From planes or space, LIDAR is used for 3D scanning of earth surfaces, sea level or archaeological sites. For instance, remote cartography of a Maya site (Caracol, Belize) has been recently performed through the tropical forest, avoiding lengthy terrestrial survey missions. The impact of lasers in long-distance communications has been tremendous. Combined with fibre optics for light guiding (*cf.* Nobel Prize in 2009), lasers



▲ Ultra Fast Laser, UCSD © iStockPhoto

have opened the way to the explosion of both the number and the bandwidth of real-time communications, with a hundred-million-fold increase in communication speed as compared to previous electronic devices.

What is the future? It is clear that the course toward miniaturisation will continue. In the mid-infrared range, quantum cascade lasers have been successfully developed. A field that has been opened up already is nanophotonics, which combines laser and nanotechnologies. New laser sources – nanolasers – have appeared, in which laser emission is obtained in a nanometre-size space, via nanosurface light confinement. Extension of the laser concept from light waves to matter waves has been performed starting from Bose-Einstein Condensates, leading to what has been coined "atom lasers". The future of atom lasers and their eventual everyday use will also depend on their miniaturisation.

The laser is emblematic of a successful revolution. At the beginning, the laser could have been (and was) described as *"a solution looking for a problem"*. Fifty years after its discovery, the number of applications in both fundamental science and the socio-economical world is impressive. In terms of number of patents, the laser ranks third in the 20^{th} century (after engines and computers). The laser era is also an archetype of the way scientific and technological revolutions occur, *i.e.*, by unpredictable jumps. It has been said that it is not by trying "to improve candles", that electric light bulbs were developed in the 19^{th} century. Similarly, laser sources have not been discovered by doing research in view of improving flash lamps. Basic research on radiation emission processes, along with technological advances and interdisciplinary approaches, has opened the way to these novel light sources, with unexpected properties. New fields have been opened: optoelectronics, nanophotonics, etc. The lasers are devices now fully integrated in our technological society through tools considered as part of every day life all over the world. Just suppose that all lasers stop working everywhere: all communications (phones, internet…) would stop, PC's would be out-of-use, all financial transactions (ATM, credit cards…) would be interrupted, etc.

In conclusion, the laser story teaches us that basic, curiosity-driven scientific research is a fundamental element of progress for the society, opening new fields of knowledge and applications, which could have never been predicted from project-oriented research. ■