.: A History of the Laser: 1960 - 2019

MELINDA ROSE AND HANK HOGAN

In 2020, the laser will celebrate its 60th anniversary. Here Photonics Media presents a timeline of some of the more notable scientific accomplishments related to light amplification by stimulated emission of radiation (laser). An interactive version of the laser timeline is also available, as well as a primer on laser basics detailing how lasers work.

A trip through the light fantastic

The laser would not have been possible without an understanding that light is a form of electromagnetic radiation. Max Planck received the Nobel Prize in physics in 1918 for his discovery of elementary energy quanta. Planck was working in thermodynamics, trying to explain why "blackbody" radiation, something that absorbs all wavelengths of light, didn't radiate all frequencies of light equally when heated.

Max Planck (AP Photo)

In his most important work, published in 1900, Planck deduced the relationship between energy and the frequency of radiation, essentially saying that energy could be emitted or absorbed only in discrete chunks — which he called quanta — even if the chunks were very small. His theory marked a turning point in physics and inspired up-and-coming physicists such as Albert Einstein. In 1905, Einstein released his paper on the photoelectric effect, which proposed that light also delivers its energy in chunks, in this case discrete quantum particles now called photons.

*Physicists John L. Emmett (**left**) and John H. Nuckolls were the key Lawrence Livermore National Laboratory pioneers in laser and fusion science and technology. Emmett co-invented the multipass laser architecture still in use today. (Lawrence Livermore National Laboratory)*

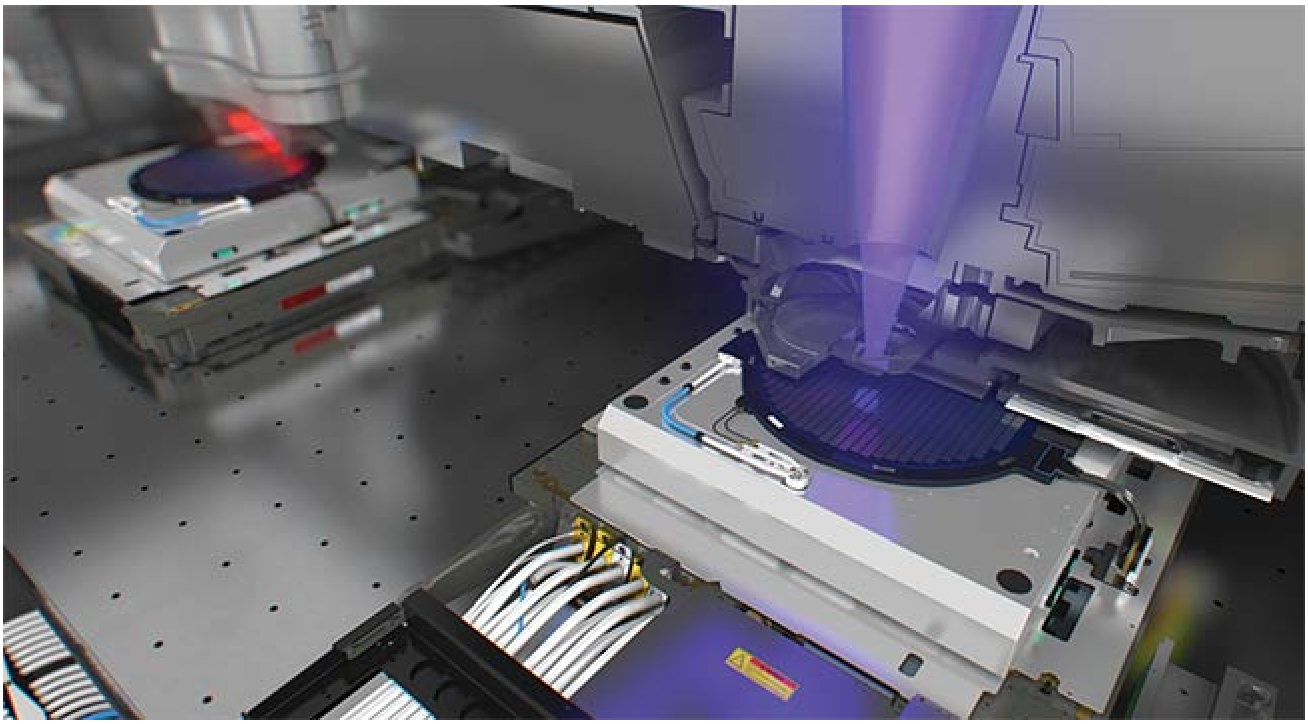
In 1917, Einstein proposed the process that makes lasers possible, called stimulated emission. He theorized that, besides absorbing and emitting light spontaneously, electrons could be stimulated to emit light of a particular wavelength (for more on the pioneers of the laser, see “On the Shoulders of Giants”). But it would take nearly 40 years before scientists would be able to amplify those emissions, proving Einstein correct and putting lasers on the path to becoming the powerful and ubiquitous tools they are today.

The trip continues

Over the past decade, lasers have become both bigger and smaller in size, as well as more powerful and less expensive. The technology has expanded in number of wavelengths and in the range of materials used. Lasers have worked their way into everyday life and otherworldly applications. By the end of 2018, the laser market stands at more than $12.9 billion, according to a December 2018 study by MarketsandMarkets.

A self-driving car equipped with radar, lidar, and other sensors for navigation. Courtesy of Waymo.

Lasers have become essential to many applications and industries, magnifying the impact of the light fantastic. Laser-powered lithography today plays a key role in the making of semiconductors, for instance — revenues of which totaled $477 billion in 2018, according to research and analysis firm Gartner. Laser-based ranging systems provide the information needed for safe navigation in autonomous vehicles. The market today is small for such vehicles, but projections by Allied Market Research (AMR) indicate the market could top $550 billion by 2026. The medical laser market — which includes solid-state and gas laser systems, dye laser systems, and diode laser systems — could total between $12 and $13 billion by 2023, according to AMR. Popular medical applications include cardiovascular, dermatological, and eye-related treatments. Finally, the market for data centers and long-haul fiber, where lasers and optical connections carry data traffic, is forecast by networking giant Cisco to increase an average of 26% every year through 2022.



A critical step in manufacturing, semiconductor lithography uses lasers, as shown in this rendering of the exposure and printing of EUV (extreme ultraviolet) lithography of a semiconductor wafer on a stage. Courtesy of ASML.

HISTORY OF THE LASER TIMELINE

April 26, 1951: Charles Hard Townes of Columbia University in New York conceives his **maser** (microwave amplification by stimulated emission of radiation) idea while sitting on a park bench in Washington.

Charles Hard Townes (National Institute of Biomedical Imaging and Bioengineering, NBIB)

1954: Working with Herbert J. Zeiger and graduate student James P. Gordon, Townes demonstrates the first maser at Columbia University. The ammonia maser, the first device based on Einstein's predictions, obtains the first amplification and generation of electromagnetic waves by stimulated emission. The maser radiates at a wavelength of a little more than 1 cm and generates approximately 10 nW of power.

Nikolai G. Basov (Wikimedia Commons)

1955: At P.N. Lebedev Physical Institute in Moscow, Nikolai G. Basov and Alexander M. Prokhorov attempt to design and build oscillators. They propose a method for the production of a negative absorption that was called the pumping method.

1956: Nicolaas Bloembergen of Harvard University develops the microwave solid-state maser.


Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation.

Conceive a tube terminated by optically flat [illegible] partially reflecting parallel mirrors. The mirrors might be silvered or multilayer interference reflectors. The latter are lossless and may have an arbitrarily high reflectance depending on the number of layers. A practical achievement is [illegible] in the visible for a 7-layer [illegible] reflector. Flats with closer tolerance than 1/100 λ are not available so if a resonant system is desired, higher reflectance would not be useful. However for a nonresonant system, the 99.9% reflectors which are possible might be useful.

Consider a plane standing wave in the tube. There is the effect of a closed cavity, since the [illegible] wavelength is small the diffraction and hence the lateral loss is negligible.

O.S. Heavens, "Optical Properties of Thin Solid Films" (Butterworths Scientific Publications, London, 1955), [illegible]

This is the first page of Gordon Gould's famous notebook, in which he coined the acronym LASER and described the essential elements for constructing one. This notebook was the focus of a 30-year court battle for the patent rights to the laser. Notable is the notary's stamp in the upper left corner of the page, dated Nov. 13, 1957. This date stamp established Gould's priority as the first to conceive many of the technologies described in the book. (Wikimedia Commons)

September 14, 1957: Townes sketches an early optical maser in his lab notebook.

November 13, 1957: Columbia University graduate student Gordon Gould jots his ideas for building a laser in his notebook and has it notarized at a candy store in the Bronx. It is considered the first use of the acronym laser. Gould leaves the university a few months later to join private research company TRG (Technical Research Group).

1958: Townes, a consultant for Bell Labs, and his brother-in-law, Bell Labs researcher Arthur L. Schawlow, in a joint paper published in *Physical Review Letters*, show that masers could be made to operate in the optical and infrared regions and propose how it could be accomplished. At

Lebedev Institute, Basov and Prokhorov also are exploring the possibilities of applying maser principles in the optical region.

Alexander M. Prokhorov (Wikimedia Commons)

April 1959: Gould and TRG apply for laser-related patents stemming from Gould's ideas.

March 22, 1960: Townes and Schawlow, under Bell Labs, are granted US patent number 2,929,922 for the optical maser, now called a laser. With their application denied, Gould and TRG launch what would become a 30-year patent dispute related to laser invention.

US patent number 2,929,922 (Bell Labs)

May 16, 1960: Theodore H. Maiman, a physicist at Hughes Research Laboratories in Malibu, Calif., constructs the first laser using a cylinder of synthetic ruby measuring 1 cm in diameter and 2 cm long, with the ends silver-coated to make them reflective and able to serve as a Fabry-Perot resonator. Maiman uses photographic flashlamps as the laser's pump source.

July 7, 1960: Hughes holds a press conference to announce Maiman's achievement.

November 1960: Peter P. Sorokin and Mirek J. Stevenson of the IBM Thomas J. Watson Research Center demonstrate the uranium laser, a four-stage solid-state device.

December 1960: Ali Javan, William Bennett Jr. and Donald Herriott of Bell Labs develop the helium-neon (HeNe) laser, the first to generate a continuous beam of light at 1.15 µm.

Theodore H. Maiman (HRL Laboratories LLC)

1961: Lasers begin appearing on the commercial market through companies such as Trion Instruments Inc., Perkin-Elmer, and Spectra-Physics.

March 1961: At the second International Quantum Electronics meeting, Robert W. Hellwarth of Hughes Research Labs presents theoretical work suggesting that a dramatic improvement in the ruby laser could be made by making its pulse more predictable and controllable. He predicts that a single spike of great power could be created if the reflectivity of the laser's end mirrors were suddenly switched from a value too low to permit lasing to a value that could.

October 1961: American Optical Co.'s Elias Snitzer reports the first operation of a neodymium glass (Nd:glass) laser.

December 1961: The first medical treatment using a laser on a human patient is performed by Dr. Charles J. Campbell of the Institute of Ophthalmology at Columbia-Presbyterian Medical Center and Charles J. Koester of the American Optical Co. at Columbia-Presbyterian Hospital in Manhattan. An American Optical ruby laser is used to destroy a retinal tumor.

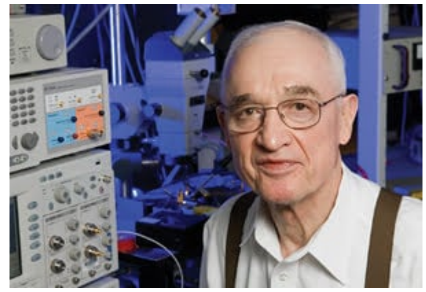
1962: With Fred J. McClung, Hellwarth proves his laser theory, generating peak powers 100× that of ordinary ruby lasers by using electrically switched Kerr cell shutters. The giant pulse formation technique is dubbed Q-switching. Important first applications include the welding of springs for watches.

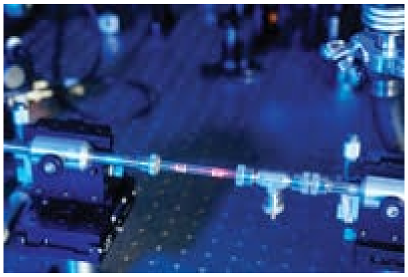
1962: Groups at GE, IBM, and MIT's Lincoln Laboratory simultaneously develop a gallium-arsenide laser, a semiconductor device that converts electrical energy directly into infrared light but which must be cryogenically cooled, even for pulsed operation.

Nick Holonyak Jr. (L. Brian Stauffer/University of Illinois)

June 1962: Bell Labs reports the first yttrium aluminum garnet (YAG) laser.

October 1962: Nick Holonyak Jr., a consulting scientist at a General Electric Co. lab in Syracuse, N.Y., publishes his work on the "visible red" GaAsP (gallium arsenide phosphide) laser diode, a compact, efficient source of visible coherent light that is the basis for today's red LEDs used in consumer products such as CDs, DVD players, and cell phones.





Extreme nonlinear optical techniques have succeeded in upconverting visible laser light into x-rays, making a tabletop source of coherent soft x-rays possible. (University of Colorado)

Early 1963: *Barron's* magazine estimates annual sales for the commercial laser market at $1 million.

1963: Logan E. Hargrove, Richard L. Fork and M.A. Pollack report the first demonstration of a mode-locked laser; i.e., a helium-neon laser with an acousto-optic modulator. Mode locking is fundamental for laser communication and is the basis for femtosecond lasers.

1963: Herbert Kroemer of the University of California, Santa Barbara, and the team of Rudolf Kazarinov and Zhores Alferov of A.F. Ioffe Physico-Technical Institute in St. Petersburg, Russia, independently propose ideas to build semiconductor lasers from heterostructure devices. The work leads to Kroemer and Alferov winning the 2000 Nobel Prize in physics.

March 1964: After two years working on HeNe and xenon lasers, William B. Bridges of Hughes Research Labs discovers the pulsed argon-ion laser, which, although bulky and inefficient, could produce output at several visible and UV wavelengths.

1964: Townes, Basov, and Prokhorov are awarded the Nobel Prize in physics for their "fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle."

*A laser in operation at the Electronics Research Center's Space Optics Laboratory is checked by Lowell Rosen (**left**) and Dr. Norman Knable. They investigated energy levels of atoms in very excited states as a step to improving the laser's efficiency in space. The ERC opened in September 1964, taking over the administration of contracts, grants and other NASA business in New England from the antecedent North Eastern Operations Office (created in July 1962), and closed in June 1970. It served to develop the space agency's in-house expertise in electronics during the Apollo era. A second key function was to serve as a graduate and postgraduate training center within the framework of a regional government-industry-university alliance.*

Research at the ERC was conducted in 10 different laboratories: space guidance, systems, computers, instrumentation research, space optics, power conditioning and distribution, microwave radiation, electronics components, qualifications and standards, and control and information systems. Researchers investigated such areas as microwave and laser communications; the miniaturization and radiation resistance of electronic components; guidance and control systems; photovoltaic energy conversion; information display devices; instrumentation; and computers and data processing. Although the only NASA center ever closed, the ERC actually grew while NASA eliminated major programs and cut staff in other areas. Between 1967 and 1970, NASA cut permanent civil service workers at all centers with one exception, the ERC, whose personnel grew annually until its closure in June 1970. (NASA Archives)

1964: The carbon dioxide laser is invented by Kumar Patel at Bell Labs. The most powerful continuously operating laser of its time, it is now used worldwide as a cutting tool in surgery and industry.

1964: The Nd:YAG (neodymium-doped YAG) laser is invented by Joseph E. Geusic and Richard G. Smith at Bell Labs. The laser later proves ideal for cosmetic applications, such as laser-assisted in situ keratomileusis (lasik) vision correction and skin resurfacing.

1965: Two lasers are phase-locked for the first time at Bell Labs, an important step toward optical communications.

1965: Jerome V.V. Kasper and George C. Pimentel demonstrate the first chemical laser, a 3.7-µm hydrogen chloride instrument, at the University of California, Berkeley.

1966: Mary L. Spaeth of Hughes Research Labs invents the tunable dye laser pumped by a ruby laser.

1966: Charles K. Kao, working with George Hockham at Standard Telecommunication Laboratories in Harlow, UK, makes a discovery that leads to a breakthrough in **fiber optics**. He calculates how to transmit light over long distances via optical glass fibers, deciding that, with a fiber of purest glass, it would be possible to transmit light signals over a distance of 100 km, compared with only 20 m for the fibers available in the 1960s. Kao receives a 2009 Nobel Prize in physics for his work.

1966: French physicist Alfred Kastler wins the Nobel Prize in physics for his method of stimulating atoms to higher energy states, which he developed between 1949 and 1951. The technique, known as optical pumping, was an important step toward the creation of the maser and the laser.

March 1967: Bernard Soffer and Bill McFarland invent the tunable dye laser at Korad Corp. in Santa Monica, Calif.

February 1968: In California, Maiman and other laser pioneers found the laser advocacy group Laser Industry Association, which becomes the Laser Institute of America in 1972.

1970: Gould buys back his patent rights for $1 plus 10 percent of future profits when TRG is sold.

1970: Basov, V.A. Danilychev, and Yu. M. Popov develop the excimer laser at P.N. Lebedev Physical Institute.

Spring 1970: Alferov's group at Ioffe Physico-Technical Institute and Mort Panish and Izuo Hayashi at Bell Labs produce the first continuous-wave room-temperature semiconductor lasers, paving the way toward commercialization of fiber optic communications.

1970: Arthur Ashkin of Bell Labs invents optical trapping, the process by which atoms are trapped by laser light. His work pioneers the field of optical tweezing and trapping, and leads to significant advances in physics and biology.

1971: Izuo Hayashi and Morton B. Panish of Bell Labs design the first semiconductor laser that operates continuously at room temperature.

1972: Charles H. Henry invents the quantum well laser, which requires much less current to reach lasing threshold than conventional diode lasers, and which is exceedingly more efficient. Holonyak and students at the University of Illinois at Urbana-Champaign first demonstrate the quantum well laser in 1977.

1972: A laser beam is used at Bell Labs to form electronic circuit patterns on ceramic.

June 26, 1974: A pack of Wrigley's chewing gum is the first product read by a barcode scanner in a grocery store.

1975: Engineers at Laser Diode Labs Inc. in Metuchen, N.J., develop the first commercial continuous-wave semiconductor laser operating at room temperature. Continuous-wave operation enables transmission of telephone conversations.

1975: The first quantum well laser operation is made by Jan P. Van der Ziel, R. Dingle, Robert C.

Miller, William Wiegmann, and W.A. Nordland Jr. The lasers actually are developed in 1994.

1976: A semiconductor laser is first demonstrated at Bell Labs, operating continuously at room temperature, at a wavelength beyond 1 µm. It's the forerunner of sources for long-wavelength lightwave systems.

1976: John M.J. Madey and his group at Stanford University in California demonstrate the first free-electron laser (FEL). Instead of a gain medium, FELs use a beam of electrons that are accelerated to near light speed, then passed through a periodic transverse magnetic field to produce coherent radiation. Because the lasing medium consists only of electrons in a vacuum, FELs do not have the material damage or thermal lensing problems that plague ordinary lasers and can achieve very high peak powers.

Gordon Gould (AP Photo)

1977: The first commercial installation of a Bell Labs fiber optic lightwave communications system is completed under the streets of Chicago.

October 11, 1977: Gould is issued a patent for optical pumping, then used in about 80% of lasers.

1978: The LaserDisc hits the home video market, with little impact. The earliest players use HeNe laser tubes to read the media, while later players use IR laser diodes.

LaserDisc vs. CD (Wikimedia Commons)

1978: Following the failure of its videodisc technology, Philips announces the compact disc (CD) project.

1979: Gould receives a patent covering a broad range of laser applications.

Professor Arthur Schawlow (AP Photo/Paul Sakuma)

1981: Schawlow and Bloembergen receive the Nobel Prize in physics for their contributions to the development of laser spectroscopy.

1982: Peter F. Moulton of MIT's Lincoln Laboratory develops the titanium-sapphire laser, used to generate short pulses in the picosecond and femtosecond ranges. The Ti:sapphire laser replaces the dye laser for tunable and ultrafast laser applications.

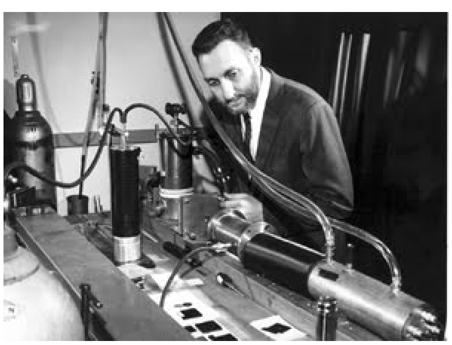
October 1982: The audio CD, a spinoff of LaserDisc video technology, debuts. Billy Joel fans rejoice, as his 1978 album "52nd Street" is the first to be released on CD.

Former Energy Secretary Steven Chu (US Department of Energy)

1985: Bell Labs' Steven Chu (U.S. secretary of energy, 2009-13) and his colleagues use laser light to slow and manipulate atoms. Their laser cooling technique, also called "optical molasses," is used to investigate the behavior of atoms, providing an insight into quantum mechanics. Chu, Claude N. Cohen-Tannoudji, and William D. Phillips win a Nobel Prize for this work in 1997.

1987: David Payne at the University of Southampton in the U.K. and his team introduce erbium-doped fiber amplifiers. These new optical amplifiers boost light signals without first having to convert them into electrical signals and then back into light, reducing the cost of long distance fiber optic systems.

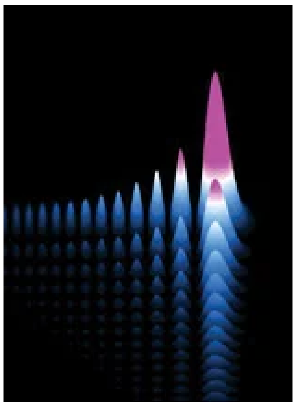
1988: Gould begins receiving royalties from his patents.



This Electronics Research Center study of the molecular properties of liquids was conducted using laser technology. ERC opened in September 1964 and has the particular distinction of being the only NASA Center to close, shutting down in June 1970. Its mission was to develop new electronics and training new graduates as well as NASA employees. The ERC actually grew while NASA eliminated major programs and cut staff in other areas. Between 1967 and 1970, NASA cut permanent civil service workers at all Centers with one exception, the ERC, whose personnel grew annually until its closure. (NASA Archives)

1994: The first semiconductor laser that can simultaneously emit light at multiple widely separated wavelengths — the quantum cascade (QC) laser — is invented at Bell Labs by Jérôme Faist, Federico Capasso, Deborah L. Sivco, Carlo Sirtori, Albert L. Hutchinson, and Alfred Y. Cho. The laser is unique in that its entire structure is manufactured a layer of atoms at a time by the crystal growth technique called molecular beam epitaxy. Simply changing the thickness of the semiconductor layers can change the laser's wavelength. With its room-temperature operation and power and tuning ranges, the QC laser is ideal for remote sensing of gases in the atmosphere.

1994: The first demonstration of a quantum dot laser with high threshold density is reported by Nikolai N. Ledentsov of A.F. Ioffe Physico-Technical Institute.



An ideal finite-energy Airy Beam is a light beam that can bend and propagate without spreading. (Dr. Georgios Siviloglou, Center for Research and Education in Optics and Lasers, University of Central Florida)

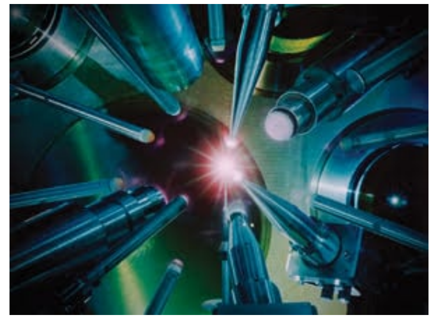
November 1996: The first pulsed atom laser, which uses matter instead of light, is demonstrated at MIT by Wolfgang Ketterle.

January 1997: Shuji Nakamura, Steven P. DenBaars, and James S. Speck at the University of California, Santa Barbara announce the development of a gallium-nitride (GaN) laser that emits bright blue-violet light in pulsed operation.

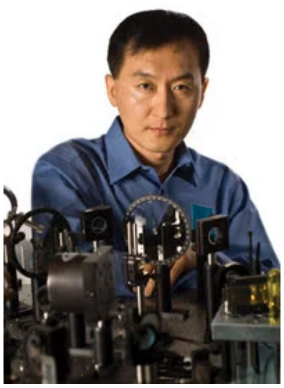
In 1997, an engineer at the Marshall Space Flight Center (MSFC) Wind Tunnel Facility uses lasers to measure the velocity and gradient distortion across an 8-in. curved pipe with joints and turning valves during a cold-flow propulsion research test, simulating the conditions found in the X-33's hydrogen feedline. Lasers are used because they are nonintrusive and do not disturb the flow like a probe would. The feedline supplies propellants to the turbo pump. The purpose of this project was to design the feedline to provide uniform flow into the turbo pump. (NASA Archives)

September 2003: A team of researchers — from NASA's Marshall Space Flight Center in Huntsville, Ala., from NASA's Dryden Flight Research Center at Edwards Air Force Base in California, and from the University of Alabama in Huntsville — successfully flies the first laser-powered aircraft. The plane, its frame made of balsa wood, has a 1.5-m wingspan and weighs only 311 g. Its power is delivered by an invisible ground-based laser that tracks the aircraft in flight, directing its energy beam at specially designed photovoltaic cells carried onboard to power the plane's propeller.

The international inertial confinement fusion community, including LLNL researchers, uses the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics to conduct experiments and test target designs and diagnostics. The 60-beam OMEGA laser at the University of Rochester has been operational since 1995. (Lawrence Livermore National Laboratory)



2004: Electronic switching in a Raman laser is demonstrated for the first time by Ozdal Boyraz and Bahram Jalali of the University of California, Los Angeles. The first silicon Raman laser operates at room temperature with 2.5-W peak output power. In contrast to traditional Raman lasers, the pure-silicon Raman laser can be directly modulated to transmit data.



Chunlei Guo of the University of Rochester stands in front of his femtosecond laser. (Walter Colley Studio)

September 2006: John Bowers and colleagues at the University of California, Santa Barbara, and Mario Paniccia, director of Intel Corp.'s Photonics Technology Lab in Santa Clara, Calif., announce they have built the first electrically powered hybrid silicon laser using standard silicon manufacturing processes. The breakthrough could lead to low-cost, terabit-level optical data pipes inside future computers, Paniccia said.

August 2007: Bowers and his doctoral student Brian Koch announce they have built the first mode-locked silicon evanescent laser, providing a new way to integrate optical and electronic functions on a single chip and enabling new types of integrated circuits.

May 2009: At the University of Rochester in N.Y., researcher Chunlei Guo announces a new process that uses femtosecond laser pulses to make regular incandescent light bulbs superefficient. The laser pulse, trained on the bulb's filament, forces the surface of the metal to form nanostructures that make the tungsten become far more effective at radiating light. The process could make a 100-W bulb consume less electricity than a 60-W bulb, Guo said.

A National Ignition Facility (NIF) hohlraum. The hohlraum cylinder, which contains the fusion fuel capsule, is just a few millimeters wide, about the size of a pencil eraser, with beam entrance holes at either end. The fuel capsule is the size of a small pea. Credit is given to Lawrence Livermore

National Security LLC, Lawrence Livermore National Laboratory and the U.S. Department of Energy, under whose auspices this work was performed. (NIF/LLNL)

May 29, 2009: The largest and highest-energy laser in the world, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in Livermore, Calif., is dedicated. In a few weeks, the system begins firing all 192 of its laser beams onto targets.

While orbiting the moon, the Lunar Reconnaissance Orbiter will take pictures and gather information about the moon's surface. (NASA)

June 2009: NASA launches the Lunar Reconnaissance Orbiter (LRO). The Lunar Orbiter Laser Altimeter on the LRO will use a laser to gather data about the high and low points on the moon. NASA will use that information to create 3D maps that could help determine lunar ice locations and safe landing sites for future spacecraft.

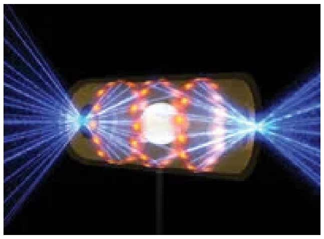
Light Peak module close-up with laser light added for illustration (actual infrared light is invisible to the eye). (Jeffrey Tseng/Intel)

September 2009: Lasers get ready to enter household PCs with Intel's announcement of its Light Peak optical fiber technology at the Intel Developer Forum. Light Peak contains vertical-cavity surface-emitting lasers (VCSELs) and can send and receive 10 billion bits of data per second, meaning it could transfer the entire Library of Congress in 17 minutes. The product is expected to ship to manufacturers in 2010.

Remote laser cutting. (Fraunhofer ILT)

November 2009: An international team of applied scientists demonstrates compact, multibeam, and multiwavelength lasers emitting in the IR. Typically, lasers emit a single light beam of a well-defined wavelength; with their multibeam abilities, the new lasers have potential uses in chemical detection, climate monitoring, and communications. The research is led by Nanfang Yu and Federico Capasso of the Harvard School of Engineering and Applied Sciences (SEAS), Hirofumi Kan of the Laser Group at Hamamatsu Photonics, and Jérôme Faist of ETH Zürich. In one of the team's prototypes, the new laser emits several highly directional beams with the same wavelength near 8 μm, a function useful for interferometry.

December 2009: Industry analysts predict the laser market globally for 2010 will grow about 11%, with total revenue hitting $5.9 billion.



This artist's rendering shows an NIF target pellet inside a hohlraum capsule with laser beams entering through openings on either end. The beams compress and heat the target to the necessary conditions for nuclear fusion to occur. Ignition experiments on NIF will be the culmination of more than 30 years of inertial confinement fusion research and development, opening the door to exploration of previously inaccessible physical regimes. Credit is given to Lawrence Livermore National Security LLC, Lawrence Livermore National Laboratory and the US Department of Energy, under whose auspices this work was performed. (NIF/LLNL)

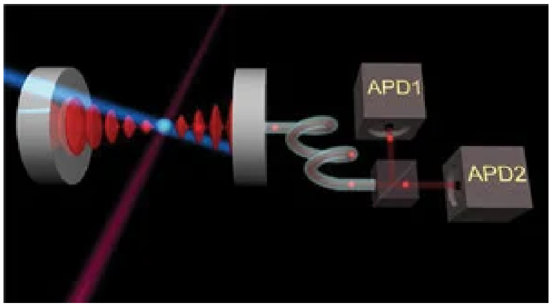
The following chronology covers the developments in lasers between 2010 and 2019. The list isn't intended to be complete or exhaustive. Rather, it provides an indication of how lasers have advanced along various dimensions: size, power, pulse width, wavelength, methods, and materials.

2010

As reported in the January issue of *Nature Photonics*, scientists at the University of Konstanz generated a 4.3-fs single-cycle pulse of light at 1.5-μm wavelength from an erbium-doped fiber laser. Such short laser pulses could benefit frequency metrology, ultrafast optical imaging, and other applications, they said.

In January 2010 The National Nuclear Security Administration announces that NIF has successfully delivered a historic level of laser energy — more than 1 MJ — to a target in a few billionths of a second and demonstrated the target drive conditions required to achieve fusion ignition, a project scheduled for the summer of 2010. The peak power of the laser light is about 500× that used by the U.S. at any given time.

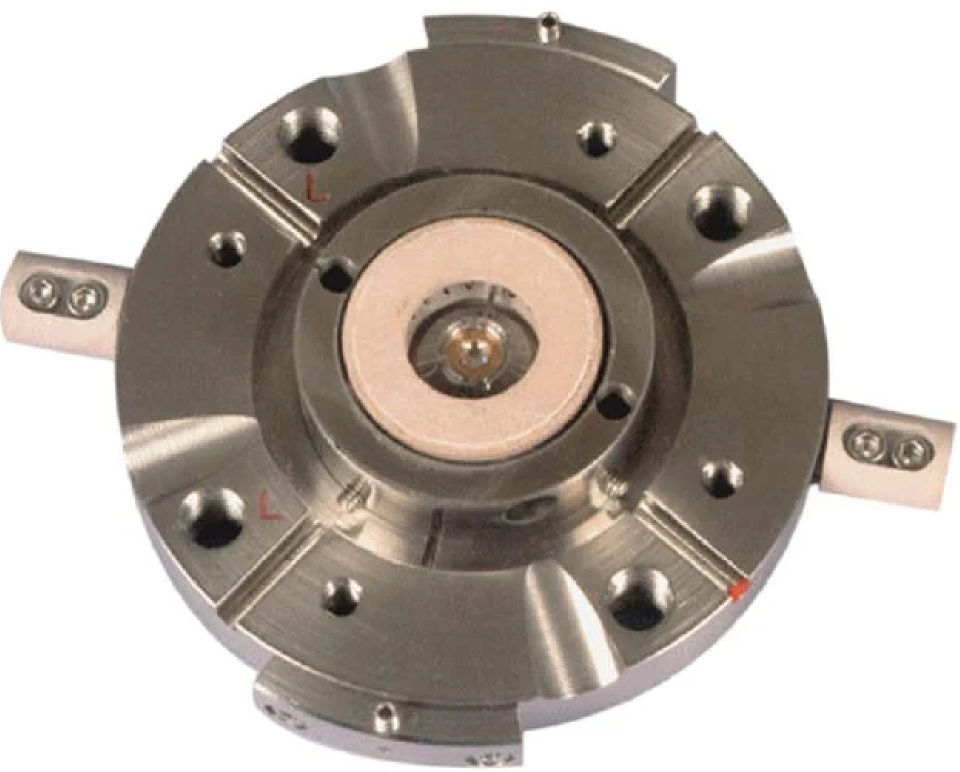
Also in January, Northwestern University researchers led by professor Manijeh Razeghi reported a breakthrough in quantum cascade laser efficiency, hitting 53% as compared to the previous best of less than 40%. This efficiency figure, Razeghi said, meant the device produced more light than heat. The lasers emitted at 4.85 μm, in the mid-IR region (3 to 5 μm), which is useful for remote sensing.



A high-finesse optical cavity consisting of two mirrors traps and accumulates the photons emitted by the ion into a mode. The ion is excited cyclically by an external laser and at each cycle a photon is added to the cavity mode, which amplifies the light. (University of Innsbruck © Piet Schmidt)

On March 31, 2010 Rainer Blatt and Piet O. Schmidt and their team at the University of Innsbruck in Austria demonstrate a single-atom laser with and without threshold behavior by tuning the strength of atom-light field coupling.

A paper in the July 15 issue of the *Journal of Applied Physics* reported that Lawrence Livermore National Laboratory physicists used ultrafast laser pulses to probe basic material properties. With the laser pulses, the researchers generated shock waves in a diamond anvil cell, which pushed the pressure in argon and other gases up to 280,000 atmospheres.



Researchers studied matter under extreme pressure using lasers to shock the material in a diamond anvil. Courtesy of Lawrence Livermore National Laboratory.

2011

Under the direction of Hans Zogg, investigators at ETH Zürich (part of the Swiss Federal Institute of Technology) produced, for the first time, a vertical external cavity surface-emitting laser (VECSEL) that operated in the mid-IR at about 5 µm. This wavelength range is useful for spectroscopic applications. The potential of VECSELs motivated members of the research team to found a company called Phocone to commercialize the technology.

Harvard University researchers Malte Gather and Seok Hyun Yun demonstrated a living laser and reported on the advancement in the June issue of *Nature Photonics*. They genetically engineered cells to produce a novel material — green fluorescent protein (GFP), the substance that makes jellyfish bioluminescent. They then placed a 15- to 20-µm-diameter cell in an optical resonator and pumped the cell with blue light pulses. The cell lased without being harmed, thus opening the door to medical and biophotonic applications.

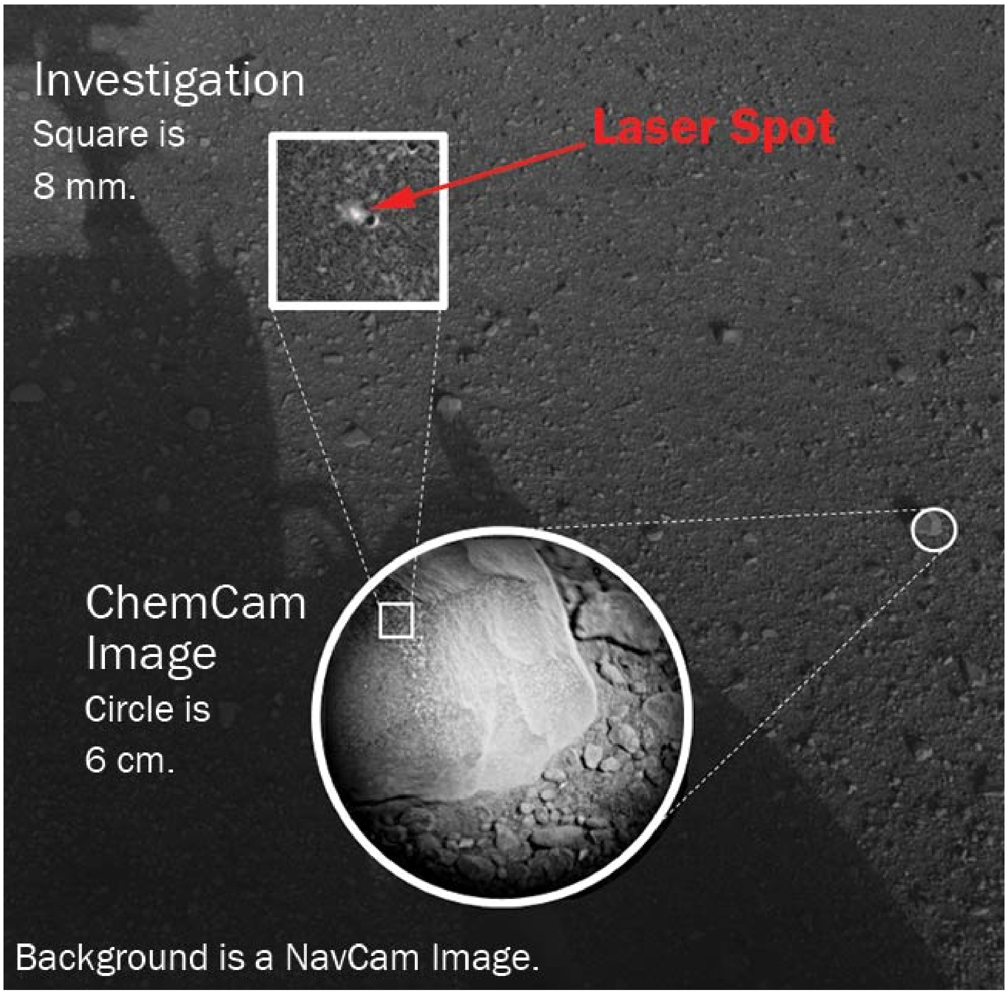
Scientists at the University of California, Riverside, led by professor Jianlin Liu, produced zinc oxide nanowire waveguide lasers. Their findings appeared in the July issue of *Nature Nanotechnology*. By devising a way to create *p*-type material, the team was able to form a *p-n* junction diode. When powered by a battery, this diode made the nanowires lase from their ends. Nanowire lasers could be smaller and lower cost, with higher power and shorter wavelength than other ultraviolet semiconductor diode lasers.

2012

A team from Yale University created a random laser. While as bright as a traditional laser, these sources are made from disordered materials and produce emission with low spatial coherence. Because this characteristic eliminates noise, or speckle, a random laser could benefit full-field microscopy and digital light projection, said researchers Brandon Redding, Michael Choma, and Hui Cao in an April *Nature Photonics* paper.

In July, a new record was set: peak power in excess of 500 trillion watts. Delivered by 192 UV laser beams at Lawrence Livermore National Laboratory’s National Ignition Facility, the 1.85 MJ of energy struck a target that was just 2 mm in diameter. The energy level enabled the study of states of matter such as those found in the centers of planets and stars, and allowed the investigation of hydrogen fusion as a potential power source. The brief burst of energy also duplicated conditions inside a modern nuclear device, providing a way to verify simulations without actual testing. The energy level was 85% higher than that achieved at the facility in March 2009.

In August, a laser zapped a rock on Mars. It was NASA's Curiosity rover getting to work. In September, the rover started on what was to be a two-year mission. The Curiosity's instrumentation used an Nd:KGW crystal to produce light at 1.067 μm. The light then traveled through a telescope and focused on a spot 1 to 7 meters distant. Repeated pulses of light generated a plume from the rock, allowing the use of laser-induced breakdown spectroscopy and a determination of the rock's composition.



The Mars rover Curiosity zapped a rock with a laser, enabling spectroscopy to determine the rock's composition. Courtesy of NASA.

2013

While random lasers offer advantages, they also have drawbacks. They have an irregular and chaotic spatial emission pattern, for instance. A team led by professor Stefan Rotter of the Vienna University of Technology came up with a control scheme. The layout of the granular material in a given laser determines the emission direction, the researchers noted, because the light bounces back and forth among the particles as it undergoes amplification. Pumping the material in a nonuniform way that matches this layout can therefore be used to set the emission direction, making the random laser more useful, the researchers reported in *Physical Review Letters* in July.

Laser pulses traveling down fiber optic cables carry the world's information — everything from financial transactions to cat videos. In a December paper in *Nature Communications*, researchers Camille Brès and Luc Thévenaz from Ecole Polytechnique Fédérale de Lausanne (EPFL) showed how to fit as many as 10× more pulses into a fiber. By modulating the lasers, the scientists produced pulses with frequencies of equal intensity, making the pulses rectangular and able to fit together with little or no wasted space.

A team including Benedikt Mayer and others from the Technical University of Munich demonstrated room-temperature laser nanowires that emitted in the near-IR. Constructed in a core-shell configuration, the nanowires both produced light and acted as waveguides, the researchers reported in *Nature Communications* in December. The nanowires, they noted, could be grown directly on silicon chips, a plus, but also required optical pumping — a minus, as applications are likely to require electrically injected devices.

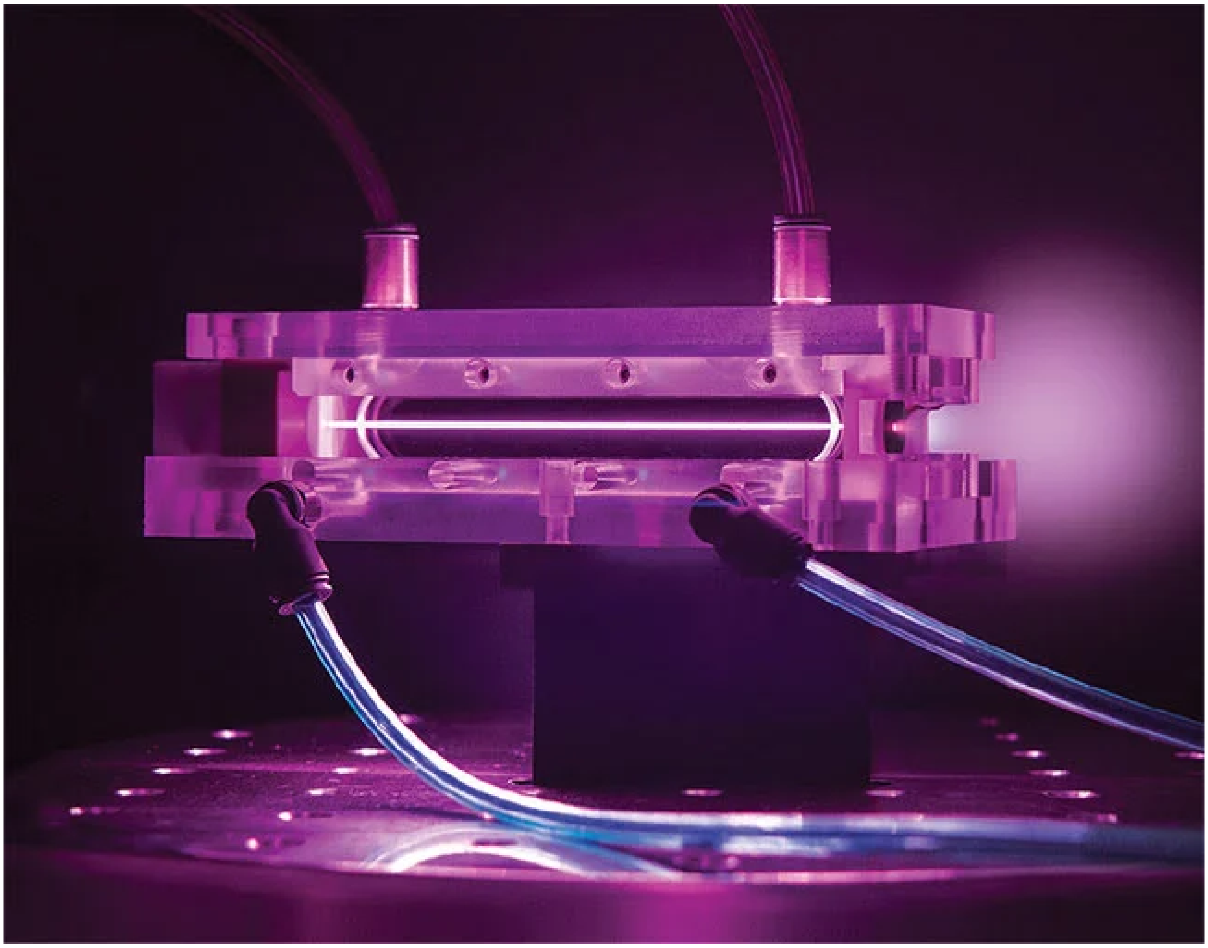
2014

Physicists Yuri Rezunkov and Alexander Schmidt reported in an October *Applied Optics* paper that rockets could get a boost from lasers. Laser ablation has long been proposed for rocket propulsion. In this method, a laser strikes a surface and creates a plasma plume that generates thrust as it exits. Integrating laser ablation with a gas steering system so the plume flows near the interior walls of a space- craft's nozzles increases the speed at which the plume exits, thereby increasing thrust and making the technique more practical.

In November, it was one giant leap for data. The European Space Agency and partner organizations used lasers to create a gigabit transmission between a satellite in low Earth orbit and one in geosyn- chronous orbit — a distance of about 45,000 km. They said the design could scale to 7.2 Gb/s in the future. Because the link was faster than what was available before, data could flow between satellites and ultimately to the ground at a quicker clip. The system in place previously could only transmit to designated ground stations when the satellite was in range. Linking to geosynchronous satellites eliminated these gaps.

A laser from Tenerife, Spain, connects with a satellite in orbit, providing an optical data path. Courtesy of European Space Agency.

A team from Lawrence Berkeley National Lab reported in the December issue of *Physical Review Letters* on a new world record for a compact or “tabletop” particle accelerator: 4.25 GeV. This was accomplished in a 9-cm-long tube, meaning the energy gradient that accelerated the electrons was 1000× greater than traditional particle accelerators. The scientists fired subpetawatt laser pulses into the plasma. Approaching a quadrillion (1015 or a million billion) watts, the pulses of light energy pushed the electrons along like a surfer riding a wave, so they came well within 0.01% of the speed of light.



Experiments with a 9 cm-long capillary-discharge waveguide used in BELLA (the Berkeley Lab Laser Accelerator) generate multi-GeV electron beams. The plasma plume is made more prominent with HDR photography. Courtesy of Roy Kaltschmidt and Lawrence Berkeley National Laboratory/2010 The Regents of the University of California, through the Lawrence Berkeley National Laboratory.

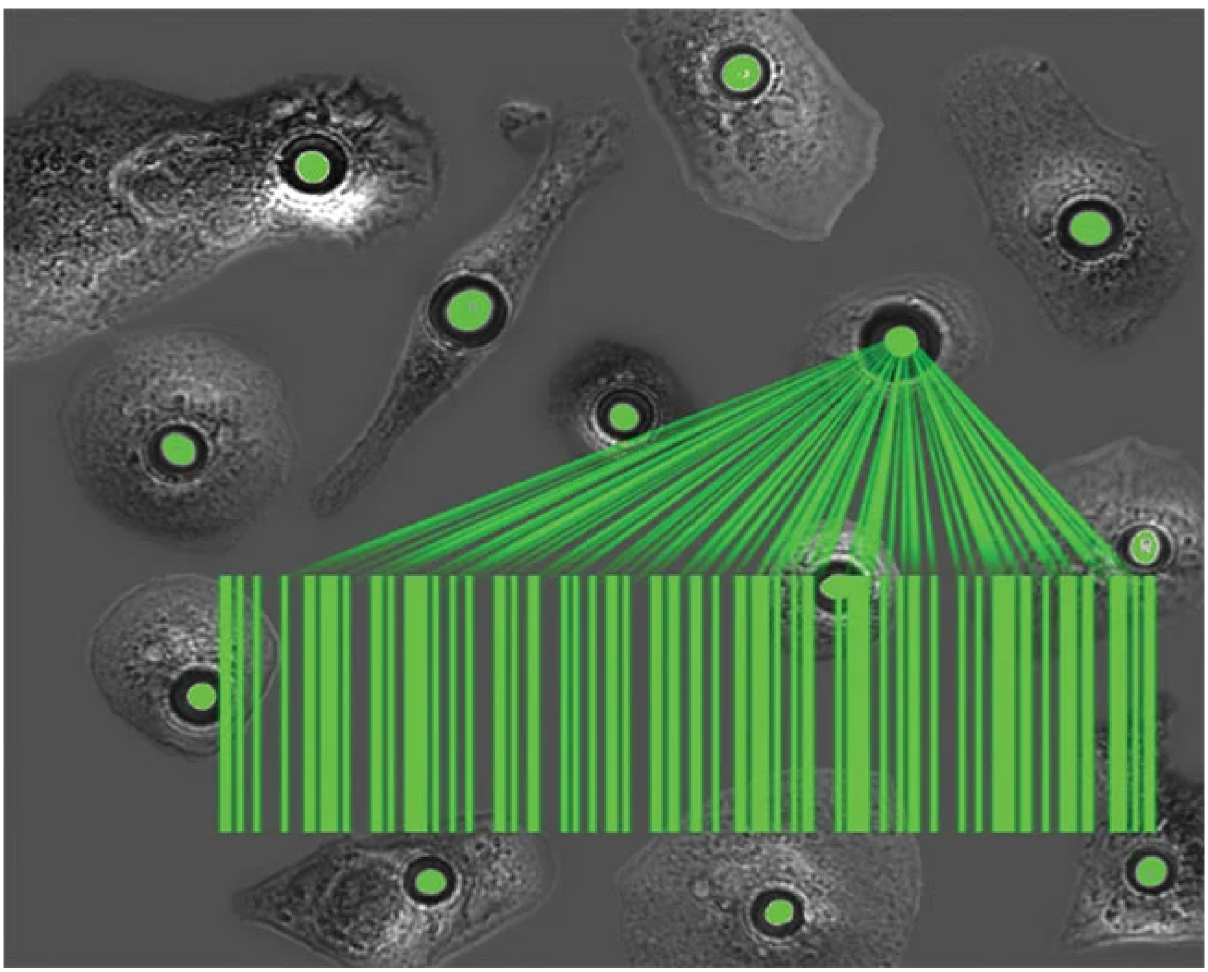
On January 27, 2014, Dr. Charles Hard Townes, whose work on stimulated emission led to the creation of lasers and enabled the photonics industry, died at age 99.

2015

In May, a team led by Texas A&M University physicist Brett Hokr added another bit of randomness to the light fantastic toolbox. In a presentation at CLEO 2015, the researchers reported on a random Raman laser capable of producing a wide-field, speckle-free image with a strobe time of about a nanosecond. The random Raman laser pulse, tests showed, lasted a few nanoseconds and had a spectral width of about 0.1 nm. Using these pulses, the researchers produced a full-frame, speckle-free microscopic image showing the formation of a cavitation bubble from melanosomes, organelles found in animal cells that are the site for synthesis, storage, and transport of the light-absorbing pigment melanin.

Researchers Anders Kristensen and others from the Technical University of Denmark reported in a December *Nature Nanotechnology* paper that laser printing too small to be seen by the unaided eye could be used to encode data. They used laser beams to deform 100-nm-diameter columns, causing the columns to produce colors when illuminated. The scientists exploited this to create a 50-µm-wide reproduction of the "Mona Lisa," about 10,000× smaller than the original. Potential uses included creating small serial numbers or barcodes and other information, said the researchers.

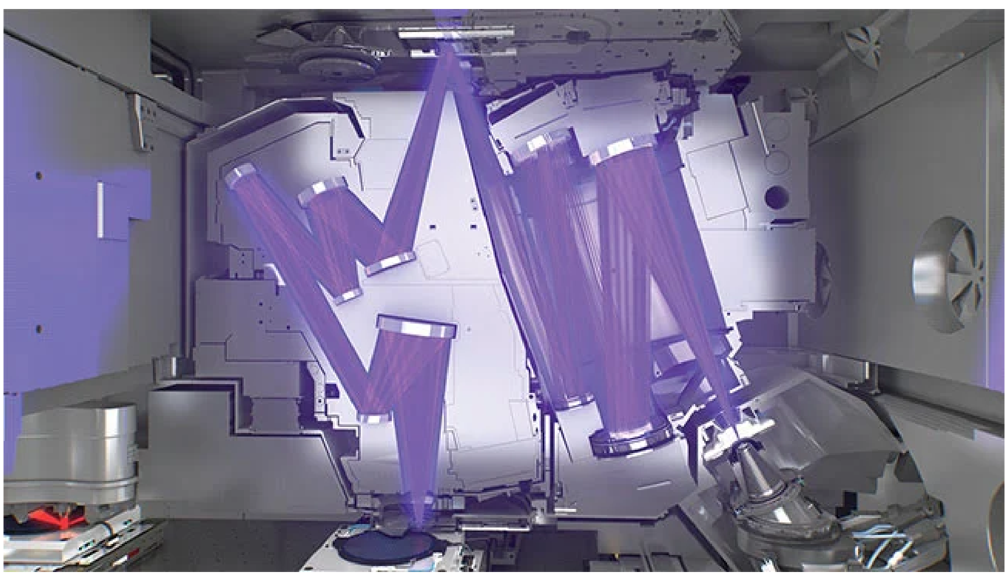
Two groups simultaneously published work in *Nano Letters* (University of St Andrews) and *Nature Photonics* (Harvard Medical School) about research involving cells swallowing microresonators. These microscopic plastic beads trap light by forcing it into a circular path along their circumference. When optically pumped by nanojoule light sources, the resonators lase without damaging the cell. The spectral composition of the microlaser is different for each cell. This, the researchers noted, could enable new forms of cell tracking, intracellular sensing, and adaptive imaging for thousands, millions, and potentially billions of cells.

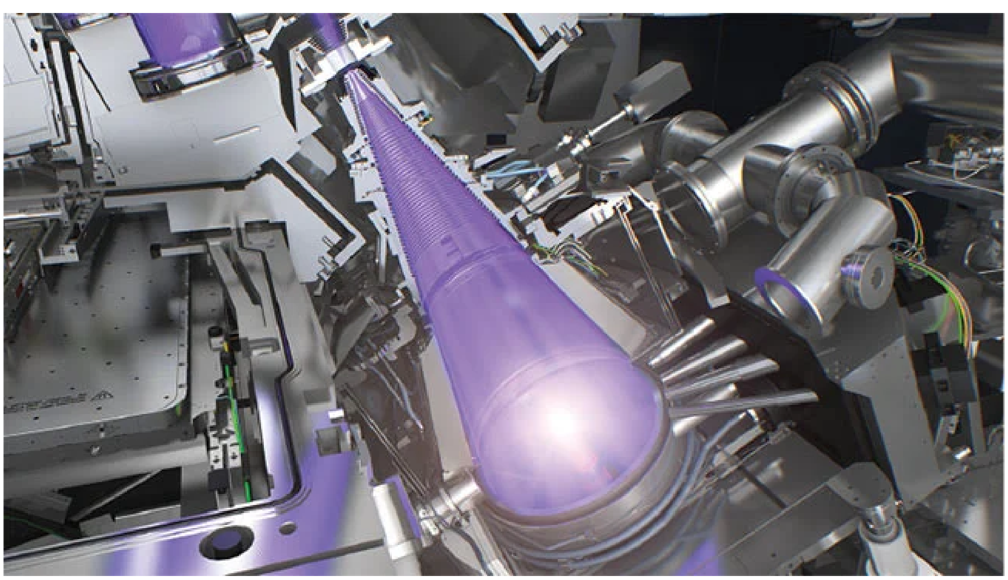


Artist's impression of a group of cells that have been turned into tiny lasers, which differ by cell and provide a barcode-type tag for noncontact optical tracking of a large number of cells over prolonged periods of time. Courtesy of Gather and Schubert/University of St Andrews.

2016

At the SPIE Advanced Lithography Symposium in San Jose, Calif., in February, semiconductor lithography toolmaker ASML announced that EUV (extreme ultraviolet) lithography technology finally appeared to be ready. After years of development in which progress lagged because the light source was not bright enough, ASML threw its weight behind the laser-produced plasma approach. With this method, an infrared CO2 laser fires a concentrated pulse at a microscopic droplet of molten tin. After filtering the resulting emission burst, the result was a 13.5-nm, or EUV, pulse of light. This technology and its resultant wavelength, much shorter than the 193-nm-deep UV lasers used in semiconductor production, are key to continuing advancements in semiconductor manufacturing.

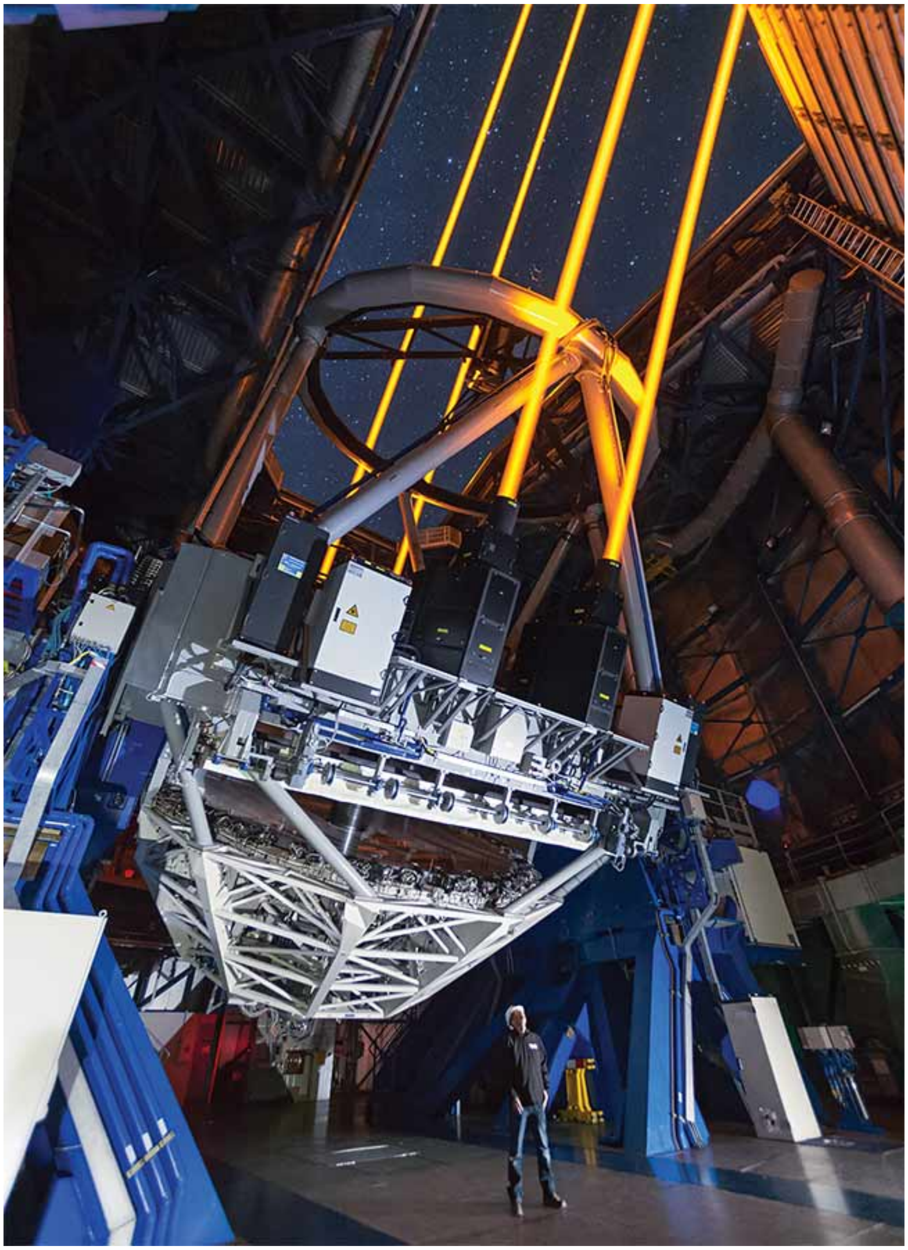




Artist's rendering of the full optical path of an EUV scanner, which uses 13.5-nm wavelength light for semiconductor lithography ***(top)****. Artist's rendering of an EUV source, which at 13.5-nm wavelength is invisible to the eye but crucial to production of advanced semiconductors* ***(bottom)****. Courtesy of ASML.*

Researchers from Cardiff University, University College London, and the University of Sheffield reported in the March issue of *Nature Photonics* that they grew quantum dot lasers on silicon. The lasers were electrically pumped, emitted at 1300 nm, and were shown to operate at temperatures of up to 120 °C for up to 100,000 hours. The goal, according to the team, was ultimately to integrate photonics with silicon electronics.

In September, the Laser Guide Star Alliance won third place for the 2016 Berthold Leibinger Innovation Prize. Modern telescopes use optical wavefront correction to get rid of the atmospheric oscillations that make stars twinkle. The result leads to the ability to see as well as anything achievable in space. The achievement requires guide stars, however, that are sufficiently bright so the correction can be made. If no guide stars are visible, then astronomers create artificial ones by exciting a sodium layer at an altitude of about 90 km. For the Very Large Telescope based in the Atacama Desert in Chile, the Laser Guide Star Alliance used Raman amplification to generate the required wavelength at significantly higher than 20 W, a record power level. The team used diode and fiber lasers in an eight-year development effort.



Four lasers excite sodium atoms and create artificial stars, 90 km up in the atmosphere, for the European Southern Observatory's Very Large Telescope's adaptive optics systems. Courtesy of European Southern Observatory.

2017

In a February release, NASA's Jet Propulsion Laboratory in Pasadena, Calif., noted that lasers could give space communications a "broadband" moment. Since the dawn of the Space Age, radio has been the standard way to communicate. It translates, at best, to connections that run a few megabits per second. A spacecraft orbiting Mars, for example, maxes out at a 6-Mb/s radio transmission rate. A laser could increase the rate to an estimated 250 Mb/s. However, lasers are subject to interference from clouds, they require more precise pointing, and they need a ground-based infrastructure in place to support them. Missions set to launch in 2019 and 2023 will test the technology, helping to determine whether lasers have a future in space communications.

Since their debut commercially in 1990 or so, rugged fiber lasers have grown increasingly powerful and have been showing up in more applications — one example being in a weapon developed by Lockheed Martin for the U.S. military. During testing in March, the system produced a single beam of 58 kW, a world record for a laser of this type. In tests in 2015, a laser half this strength disabled a truck a mile away. The laser gets to the 60-kW threshold by combining several beams and operating near the diffraction limit, according to published reports. The laser system is also said to be efficient, translating more than 43% of electricity consumed into light.

An artist's rendering of a truck-mounted 60-kW laser weapon system for tactical U.S. Army vehicles. Courtesy of Lockheed Martin.

By taking a page — and borrowing a molecule — from nature, researchers from the University of St Andrews, the University of Wurzburg, and the Technical University of Dresden created a fluorescent protein polariton laser. Previous polariton lasers had to be cooled to cryogenic temperatures, but these new lasers were based on green fluorescent protein, the stuff that makes jellyfish emit bright green light. The molecule, the scientists said, was just the right size to strike the optimal balance between not losing energy and quenching and being able to squeeze as many molecules as possible into the light-emitting cells of the jellyfish. The new laser could be a biocompatible, bioimplantable light source, they said. The researchers reported on their work in the August 16 issue of *Science Advances*.

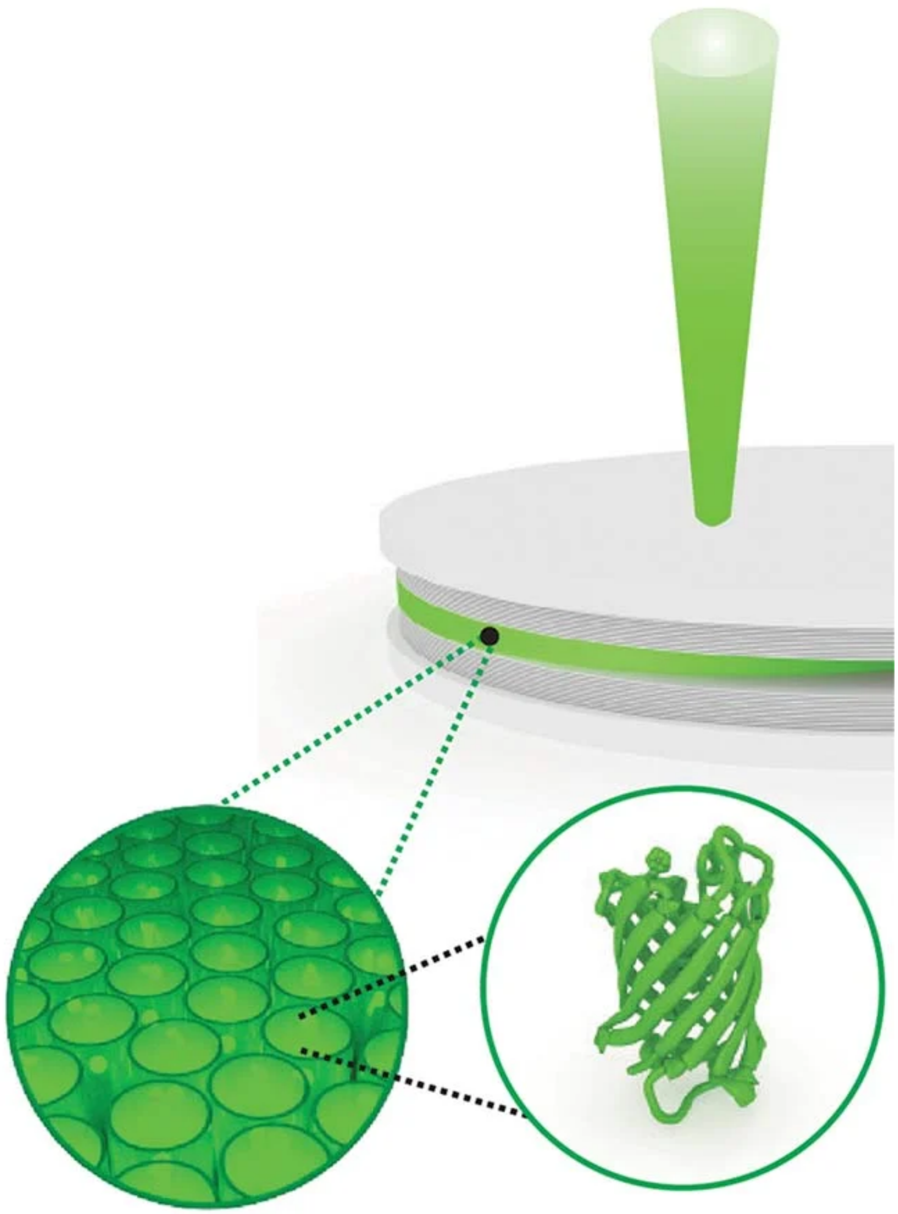
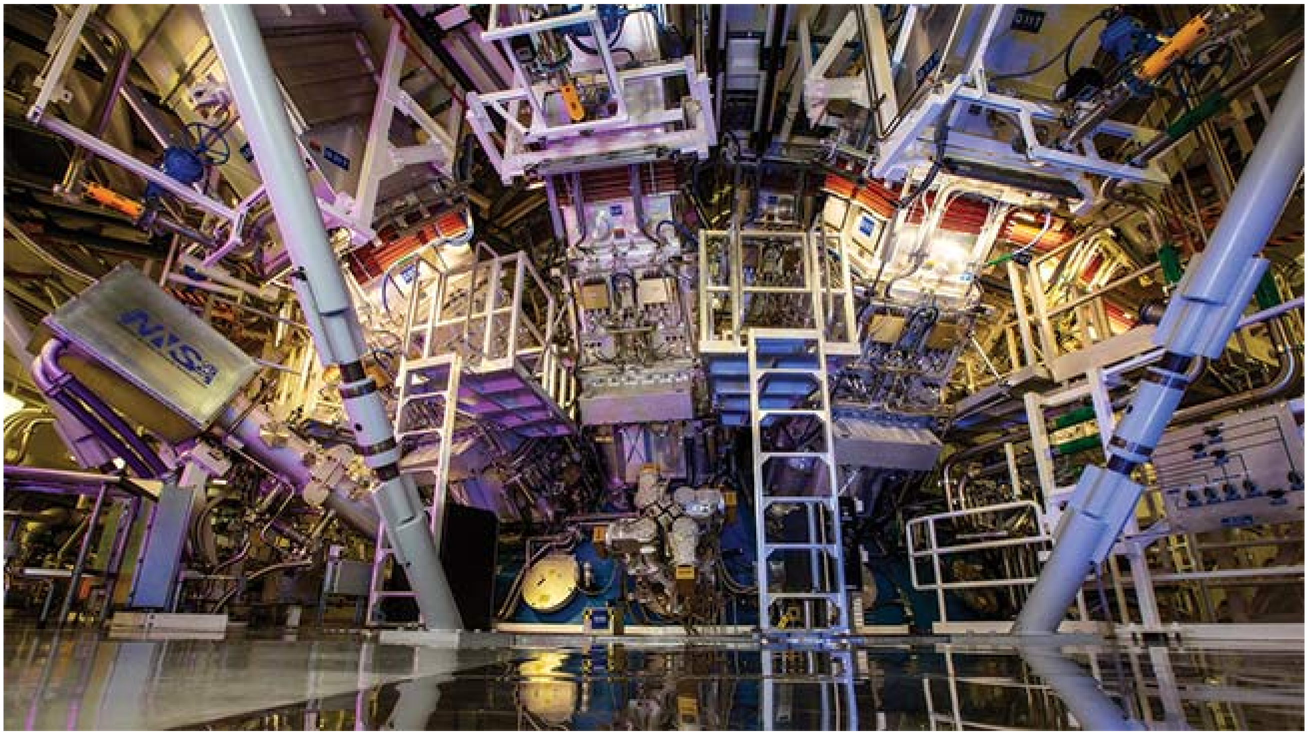


Illustration of a fluorescent protein polariton laser in action. Courtesy of Malte Gather/University of St Andrews.

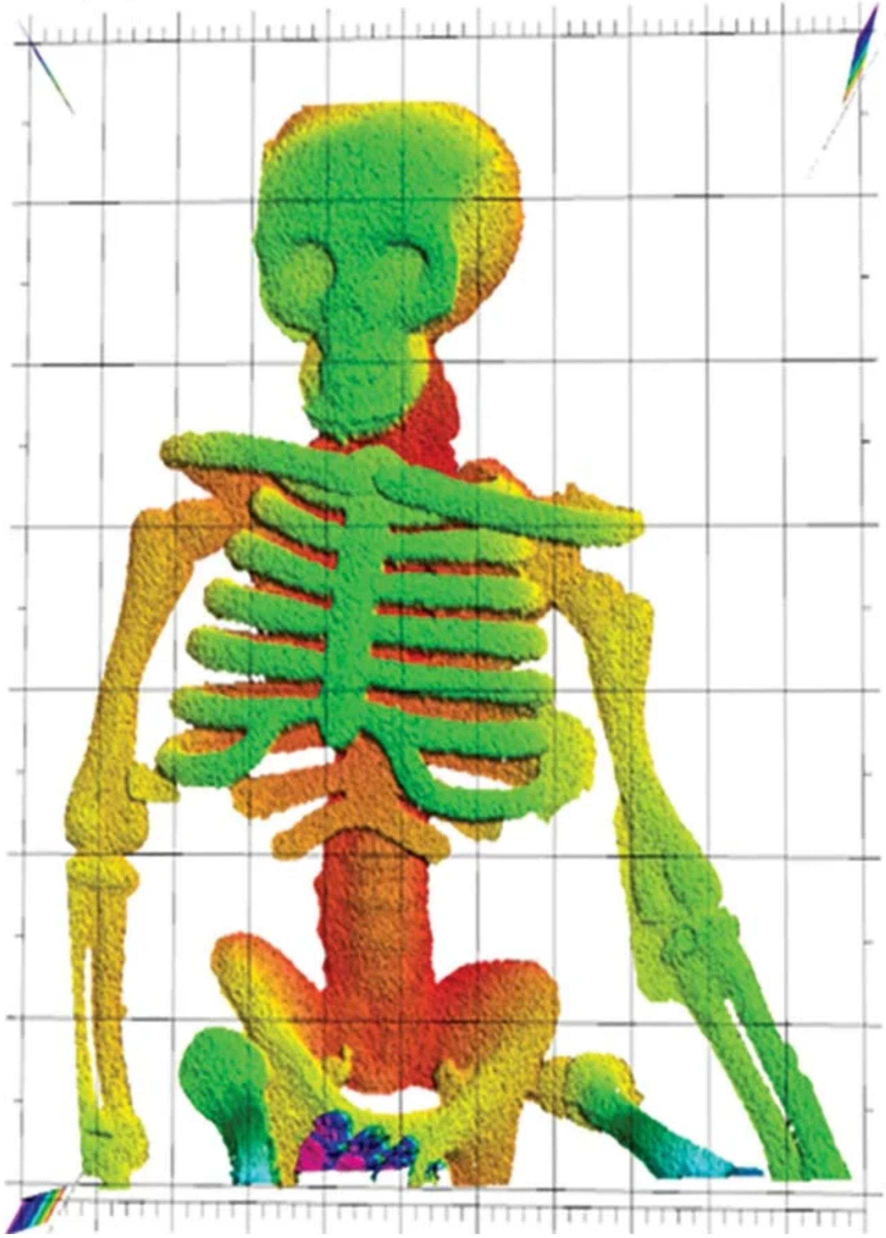
2018

In July, the Lawrence Livermore National Laboratory's National Ignition Facility laser system set a new record: 2.15 MJ. This was more than 10% higher than the previous record set in March 2012.



The National Ignition Facility's 192-laser system set a record shot: 2.15 MJ. Courtesy of Lawrence Livermore National Laboratory.

In an August *Optica* paper, researchers at NIST (the National Institute of Standards and Technology) showed that commercial laser ranging could provide 3D images of objects as they melted in a fire. The NIST team measured 3D surfaces on pieces of chocolate and a plastic toy with 30-µm precision from two meters. The potential to precisely and safely measure burning structures as they collapse could be useful in understanding the process of destruction and in later reconstructing what happened.



NIST researchers demonstrated that laser ranging could "see through flames" to make this image of a plastic skeleton toy. Laser ranging captured the skeleton's complex 3D shape, with depth indicated by false color. The plastic did not melt or deform in the fire, unlike pieces of chocolate. Courtesy of Baumann/NIST.

Random lasers could be less random in the future because of a nanoscale manipulation technique outlined in a September paper published in *Nature Communications*. A team from Finland's Tampere University of Technology, Case Western Reserve in Ohio, and others showed that the output from a random laser based on a liquid-crystal medium could be steered with an electrical signal. This control capability, the researchers noted, brought random lasers closer to practical applications.

Scientists at the Shanghai Superintense Ultrafast Laser Facility have their sights set on a 10-petawatt shot, almost doubling their own record of 5.3 petawatts (PW) (5.3 million billion watts). In a paper published in the November issue of Optics Letters, researcher Wenqi Li and others reported significant progress toward that threshold, with a nearly 340-J output centered at 800 nm. When compressed to a 21-fs pulse, they estimated the peak power would be 10.3 PW. The goal is to hit the 100-PW mark, perhaps by 2023. This power level would be high enough to create matter out of empty space.

2019

MIT researchers outlined a way to use lasers to deliver whispers to listeners. Scientists used a 1.9-μm wavelength thulium laser to excite water molecules near a microphone, which transmitted an audible signal. The signal sounded about as loud as normal conversation. The technique could allow the sending of secret messages, with potential applications in the military and advertising. A paper appeared in January *Optics Letters*.

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GLOSSARY

maser
An acronym for microwave amplification by stimulated emission of radiation. Predecessor to the laser, the maser or 'microwave laser' was the first device to produce coherent electromagnetic waves, and was done at microwave frequencies through amplification by stimulated emission. A laser (light amplification by stimulated emission of radiation) is a maser that works over a broader range of higher frequency photons in the ultraviolet and visible portion of the electromagnetic spectrum.