MILESTONES

MILESTONE 1

Let there be light

In the beginning — or, at least, from around the sixth century BCE — the Vaisheshika school of Hindu philosophy held that the world was based on the 'atoms' of earth, air, fire and water. Rays of light were thought to be composed of fast-moving fire atoms or *tejas*, with the characteristics of the light depending on the speed and arrangement of the *tejas*. The nature of light — whether it indeed be some kind of particle or, instead, a wave propagating through a medium — was to become one of the greatest scientific debates of the succeeding centuries: one that was resolved barely a century ago.

Around 300 BCE, Euclid decided that light travelled in straight lines, and described the laws of reflection. In the second century, Ptolemy wrote about refraction. Laws of refraction were formulated by Ibn al-Haytham (also known as Alhazen), who wrote his *Kitab al-Manazir*, or *Book of Optics*, in 1021. Ibn al-Haytham was a prolific experimentalist, notably studying dispersion too. He also thought of light as a stream of minute particles, travelling at finite speed.

René Descartes, however, had other ideas — and many of them, as befitted a Renaissance man. In 1637, alongside his *Discours de la méthode* (with its memorable quote, "I think, therefore I am"), he published three essays, on meteorology, geometry and optics. This last, *La dioptrique*, promoted a concept of light as pulses propagating instantaneously through the contact of 'balls' of some medium (aether). Similar ideas are found in Thomas Hobbes' *Tractatus opticus* of 1644 and Robert Hooke's *Micrographia* of 1665. Although Ignace Gaston Pardies is thought to have taken steps, around 1670, in devising a formal wave theory, the manuscript is lost. However, Christiaan Huygens' *Traité de la lumière* of 1690 survives. In it, he treated light as compressible waves in an elastic medium, analogous to sound; by considering the envelope of secondary wavelets, he showed how to construct reflected, refracted and screened waves; he also explained double refraction.

Huygens' beautiful work did not, however, conquer the idea of light as particles or corpuscles. Isaac Beeckman, who was a mentor of Descartes, and Pierre Gassendi led a revival of Greek atomistic theories, which included the interpretation of colour as a mixture of light and shadow. But it was Isaac Newton who became the great champion of the 'corpuscularists'. In his *Opticks* of 1704, he recognized that colour should correspond to the velocity or mass of the light particles, and thus explained why different colours are refracted by different amounts. He rejected wave theory, because light would be able to stray too far into shadow; diffraction he accounted for as the 'inflection' of light particles by matter. Although Descartes' enduring reputation and Leonhard Euler's 1746 milestone work (including a dispersion law) ensured that wave theory maintained a following in France and Germany, Newtonian corpuscular theory was dominant for the rest of the eighteenth century.

A fresh skirmish began in the early 1800s, with what is often considered to be one of the most beautiful demonstrations in physics: Thomas Young's two-slit experiment, with which he introduced the principle of interference for waves of light. But now the corpuscularists were gaining ground in France: polarization, displays of which were delighting Parisian salons, was considered to be due to some kind of asymmetry among light corpuscles. Augustin Fresnel tipped the balance, with a precise wave theory of diffraction. Having revisited Huygens' work and added interference between secondary waves, he was able to explain, in wave terms, how shadows form. Moreover, in 1821, he showed that polarization could be explained if light were a transverse wave, with no longitudinal vibration. Now, wave theory was all; Newton was supplanted.

But one problem remained. Although Maxwell's seminal equations of 1865 (MILESTONE 2) were gradually and successfully adopted in optics, the aether — to support electromagnetic fields, to yield Fresnel's laws of propagation — was missing. The aether, of course, would never be found. As the twentieth century dawned, a new revolution in physics — led by Max Planck (MILESTONE 3) and Albert Einstein (MILESTONE 4) — would again hinge on the nature of light, be it wave or particle. Or both.

Alison Wright,
Chief Editor, Nature Physics

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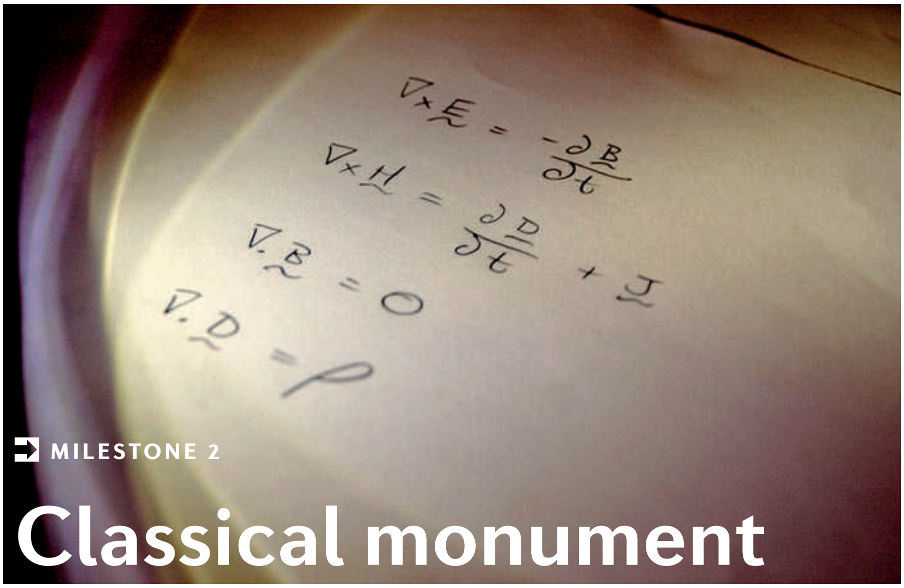
David Pile



MILESTONE 2

Classical monument

By the middle of the nineteenth century, a significant body of experimental and theoretical knowledge about electricity and magnetism had been accumulated. In 1861, James Clerk Maxwell condensed it into 20 equations. Maxwell published various reduced and simplified forms, but Oliver Heaviside is frequently credited with simplifying them into the modern set of four partial differential equations: Faraday's law, Ampère's law, Gauss' law for magnetism and Gauss' law for electricity.

One of the most important contributions made by Maxwell was actually a correction to Ampère's law. He had realized that magnetic fields can be induced by changing electric fields — an insight that was not only necessary for accuracy but also led to a conceptual breakthrough. Maxwell predicted an 'electromagnetic wave', which can self-sustain, even in a vacuum, in the absence of conventional currents. Moreover, he predicted the speed of this wave to be 310,740,000 m s^{-1} — within a few percent of the exact value of the speed of light.

"The agreement of the results seems to show that light and magnetism are affections of the same substance, and light is an electromagnetic disturbance propagated through the field according to electromagnetic laws", wrote Maxwell in 1865. The concept of light was thus unified with electricity and magnetism for the first time.

Maxwell's equations are as important today as ever. They led to the development of special relativity (MILESTONE 4) and, nowadays, almost every optics problem that can be formulated in terms of dielectric permittivity and magnetic permeability (two key constants in Maxwell's equations), ranging from optical-fibre waveguides

MILESTONE 3

The quantum leap

"With the discovery of the principle of energy conservation, the edifice of theoretical physics is fairly complete. There will be a mote to wipe out in a corner here or there, but something fundamentally new you won't find." So spoke Philipp von Jolly when, in 1877, his student Max Planck left Munich for Berlin, to spend his last year of studies there.

Planck, undeterred, went into theoretical physics — not hoping to make new discoveries, but driven by his admiration of its elegance. His main interest was thermodynamics, but works by Otto Lummer and Ernst Pringsheim, and by Heinrich Rubens and Friedrich Kurlbaum, which aimed at constructing a standard for the measurement of illumination intensities, directed him towards heat radiation. He revisited Gustav Kirchhoff's theoretical studies of black-body radiation, which implied that when a substance capable of absorbing and emitting radiation is enclosed in a cavity with perfectly reflecting walls, the spectral distribution of the observed radiation at equilibrium is a function only of temperature and is independent of the substance involved. Intrigued by such an 'absolute' law, Plank devoted himself, from 1896, to finding an explanation for it.

Parallel works on black-body radiation produced confusing results. Lord Rayleigh had found a law (which, with James Jeans, he later refined) that well described the emission spectrum at long wavelengths, but failed at short ones. By contrast, an earlier law by Wilhelm Wien describing the frequency position of the radiation maximum — which had been observed experimentally, but was not reproduced by the Rayleigh–Jeans theory — held for short, but not for long, wavelengths. By October 1900, Planck had found a formula that interpolated between the curve of Rayleigh and Jeans and that of Wien. He sent his result, by postcard, to Heinrich Rubens, who immediately compared it to experimental data. It fitted all observations perfectly. Spurred by the agreement, Planck set about finding the physical character of his empirical formula.

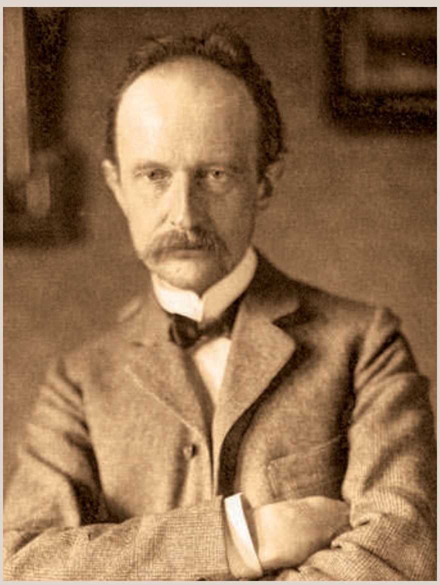


Image courtesy of Rudolf Dührkoop

On 14 December 1900, he presented the outcome in a lecture given to the German Physical Society. Planck had indeed found a sound derivation to explain the behaviours described by his formula, partially guided by the work of Ludwig Boltzmann on entropy. However, there was one revolutionary assumption that he had to make: that light was emitted and absorbed in discrete packets of energy — quanta. These were not a feature of heat radiation alone, but, as Albert Einstein showed in 1905, also of light. Einstein used the term *Lichtquant*, or quantum of light. Only in 1926 was the word 'photon' introduced, by the chemist Gilbert Lewis. His theory of a "hypothetical new atom that is not

(MILESTONE 13) to metamaterials and transformation optics (MILESTONE 21), is treated within the framework of these equations or systems of equations derived from them.

Their actual solution can, however, be challenging for all but the most basic physical geometries. Numerical methods for solving the equations were pioneered by Kane Yee and Allen Taflove, but went unnoticed for many years owing to the limited computing power available at the time. Now, however, these methods can be easily employed for solving electromagnetic problems for structures as complex as aircraft.

David Pile,
Associate Editor, Nature Photonics

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light but plays an essential part in every process of radiation" did not hold up, but the name 'photon' stuck.

Without setting out to do so, Planck had rocked the edifice of physics to its very foundations. "His was, by nature, a conservative mind," wrote Max Born in an obituary of Planck, "he had nothing of the revolutionary and was thoroughly sceptical about speculations. Yet his belief in the compelling force of logical reasoning from facts was so strong that he did not flinch from announcing the most revolutionary idea which ever has shaken physics."

Andreas Trabesinger,
Senior Editor, Nature Physics

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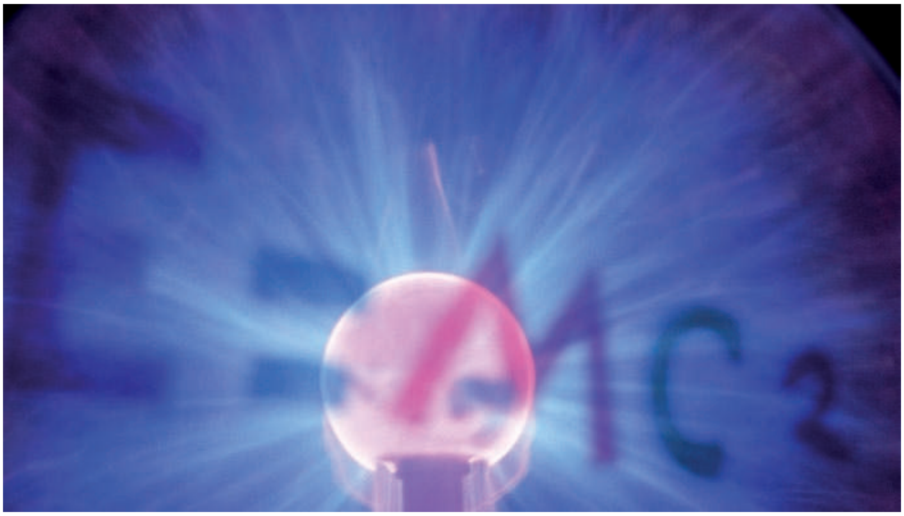

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MILESTONE 4

Light is special

At the dawn of the twentieth century, light was thought to propagate through 'aether', a medium at absolute rest with respect to the fixed stars and transparent to the motion of celestial bodies. "There can be no doubt that the interplanetary and interstellar spaces are not empty but are occupied by a material substance or body, which is certainly the largest, and probably the most uniform", wrote James Clerk Maxwell in 1878. A clear proof of the existence of aether, however, could not be found.

In 1887, Albert Michelson and Edward Morley published the results of arguably the best known attempt to detect aether. Their idea was that if light propagated along the direction of motion of the Earth, its speed would change owing to the velocity of our planet with respect to the aether. They used an interferometer purposely designed by Michelson that had sufficient resolution to detect any expected effect. The result, however, was unequivocally null.

Explanations of the negative result reported by Michelson and Morley would introduce more complications. This bothered, not least, Albert Einstein, who trusted that natural laws obey a universal harmony. From the failure to detect any variation in the speed of light in a vacuum, c, he concluded that this ought to be a constant, regardless of the velocity with which the light source moved. He also assumed that the laws of physics should be the same in reference frames moving with uniform translation with respect to one another. These two postulates were the basis of the theory he published in June 1905, which is now known as special relativity.

Einstein derived the transformations of space and time coordinates between inertial reference frames, and reproduced equations that George FitzGerald and, independently, Joseph Larmor and Hendrik Lorentz had found to make Maxwell's equations consistent with Newtonian mechanics (which governs the laws of dynamics when velocities much lower than c are involved, as in everyday experience). The paper Einstein published in June 1905 was followed by a shorter one in September of the same year, which featured the celebrated equivalence between energy and mass, $E = mc^2$. The speed of light became the upper limit that no body having finite mass at rest can reach, as it would need infinite energy.

As far as aether was concerned, special relativity made it vanish. As Einstein wrote in the opening of his original paper, "The introduction of a 'luminiferous ether' will prove to be superfluous inasmuch as the view here to be developed will not require an 'absolutely stationary space' provided with special properties".

Fabio Pulizzi,
Senior Editor, Nature Materials

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MILESTONE 5

Just a moment

"On the basis of the quantum theory a different hypothesis may be formed", wrote Arthur Holly Compton in 1922, as he worked on interpreting his data on the scattering of X-rays by weakly-bound electrons. He performed his experiments at a time when the boundary between particle and wave representations in physics was starting to blur. This boundary had been firmly established by the mid-nineteenth century, after work by Thomas Young and Augustin Fresnel had put particle theories of light to rest, and atomistic theories of matter consistent with new results in chemical analysis had found widespread acceptance.

But by the beginning of the twentieth century, experiments on the interaction of supposedly wave-like radiation with particle-like matter had begun to challenge this dichotomy (MILESTONE 3), and in 1905 Einstein proposed a completely quantized picture of light. While Compton's X-ray scattering experiments came well afterwards, they represented an important and independent confirmation of Einstein's picture: they delivered the first direct evidence that the momentum of light, as well as its energy, was quantized.

In the experiments, X-rays that were scattered from electrons increased their wavelength to an extent depending on the incident angle, but not on the incident wavelength. According to classical physics, the incoming radiation accelerated many electrons simultaneously and over a finite period of time, and the change in wavelength could result from a Doppler effect. Such an explanation led, however, to unrealistic electron-recoil velocities, and produced the wrong dependence on scattering angle and incident wavelength. The "different hypothesis" of Compton instead postulated an elastic collision between a single photon of light and a single electron to which it instantaneously delivered a single quantum of momentum, leading to a reduction in the energy and wavelength of the photon.

These experiments laid the foundation for the modern quantum theory of light. In 1929, the Compton effect became among the first phenomena to be modelled using quantum electrodynamics, which would develop into one of the most tested and accurate of all physical theories (MILESTONE 6). This model, by Oskar Klein and Yoshio Nishina, applied Paul Dirac's relativistic electron equation, which had been developed only the year before, to reproduce successfully the intensities and energies of Compton-scattered X-rays.

Today, Compton-scattering effects are found in a variety of pure and applied disciplines. In medical radiology,

MILESTONE 6

QED

Much of the groundwork for what would become one of the most successful theories ever devised was laid in the 1920s, particularly in the work of Paul Dirac and the other, usual suspects — Pascual Jordan, Werner Heisenberg and Wolfgang Pauli. As quantum mechanics took shape, Dirac commented, in a 1927 paper, that "hardly anything has been done up to the present on quantum electrodynamics": for instance on how to describe the production of an electromagnetic field by a moving electron and the reaction of that field on the electron; and what happens when force propagates at the speed of light rather than instantaneously.

Dirac devised a workable, non-relativistic theory using a Hamiltonian to describe the dynamical system of an atom amidst "light-quanta". But the devil was in the details: it soon became apparent that attempts at accurate calculation using quantum electrodynamics were beset by divergences. If proper account were taken of all terms in calculating the mass or charge of an electron under the effect of an electromagnetic field, the answer for each was infinite.

Not until 1947 was the solution found. On the opening day of the Shelter Island conference, in June of that year, Willis Lamb presented his data showing the splitting of the $2S_{1/2}$ and $2P_{1/2}$ electron energy levels of the hydrogen atom, predicted by Dirac to be degenerate. On the train home from Shelter Island, Hans Bethe realized the significance of this 'Lamb shift' — that the electron mass calculated in quantum electrodynamics was not the electron mass measured in experiment, and that a procedure of 'renormalization' was necessary to link the two.

By the time of the Pocono conference in March 1948, others had worked out exactly how to accommodate renormalization in a relativistically invariant theory. Julian Schwinger presented, as was his wont, a thorough mathematical formulation that was subsequently found to have been matched, independently in Japan, by Sin-Itiro Tomonaga. Richard Feynman, too, had his own formulation to offer, although he later grumbled that "renormalization theory is simply a way to sweep the difficulties of the divergences of electrodynamics under the rug."

"the most stringently tested, most successful theory in all of physics"

Freeman Dyson soon proved the equivalence of all three approaches, and Schwinger, Tomonaga and Feynman shared the Nobel Prize in Physics in 1965 "for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles". Accurate calculation was at last possible, and was aided greatly by the illustrative tool that Feynman had presented at Pocono: the Feynman diagram. One of the first ever published Feynman diagrams appeared in his 1949 paper, showing the

Willis Lamb, Abraham Pais, John Wheeler, Richard Feynman, Herman Feshbach and Julian Schwinger (left to right) at Shelter Island in 1947. Courtesy of AIP Emilio Segrè Visual Archives

Compton scattering can describe the interaction of X-rays both with tissue and with a detector. Cosmic γ-ray detectors similarly exploit the effect, as do remote probes of extreme states of matter such as accelerator beams and high-density plasmas. Inverse Compton scattering, which increases the energy of incident photons, has been used to make bright and fast X-ray sources, and the Compton formalism has been extended to the scattering of other objects, including neutrons and subatomic particles.

Michael Segal, Associate Editor, Nature Nanotechnology

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now-familiar spacetime representation, as straight and wavy lines, of electrons exchanging a photon.

Quantum electrodynamics is now recognized as an Abelian gauge theory with the symmetry group U(1). Its calculations, using renormalization, have been shown to match experiment to the level, so far, of 1 in 10^{12}. What began with Maxwell's equations for the electromagnetic field (MILESTONE 2) has become the most stringently tested, most successful theory in all of physics. QED.

Alison Wright, Chief Editor, Nature Physics

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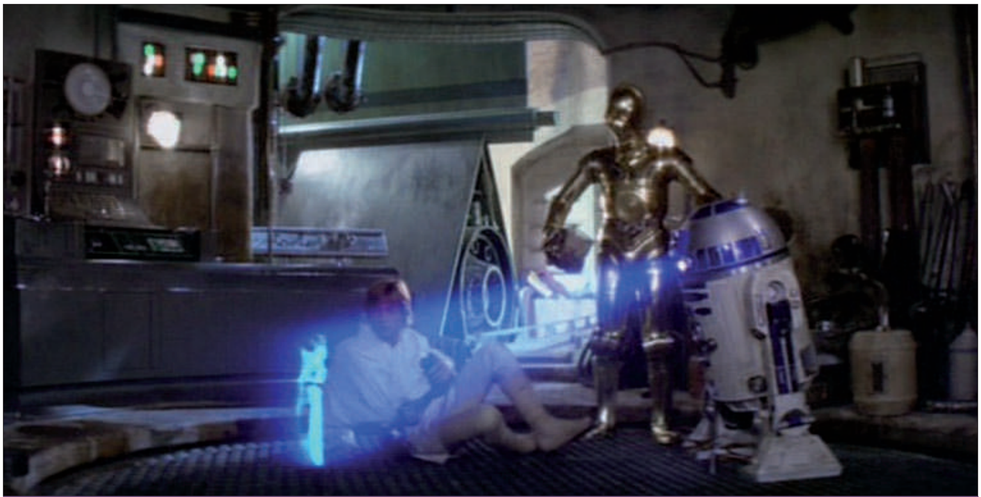

Courtesy of LUCASFILM Ltd.

MILESTONE 7

Ghosts of images past

Holograms have become familiar, common even. They appear on credit cards and money, in fashion shows, television programmes and works of art, and beyond. Originally, the inventor Dennis Gabor simply wanted to improve the electron microscope — itself a great improvement on the resolving power of the light microscope — in order to image an atomic lattice.

In 1947, electron microscopy was limited to a resolution of 12 Å, although the theoretical limit was 5 Å. To get around the limiting factor, which was the electron lens, Gabor thought about the wave nature of light. Photographs record light intensity. Suppose, however, that the phases of light were also recorded? For that there would have to be a reference phase with which to compare the phase of the wave originating from an object. Interference of the reference and object waves would create fringes, with maxima recorded on a photographic film where the two waves are in phase. When this image is illuminated by the same reference wave, it will transmit light only from the reference wave if it is identical to the original object wave. Therefore, the original object appears as a reconstructed image, as if it were there. Using a mercury arc lamp, with the reference source and the object on the same axis, Gabor was able to reproduce a grainy two-dimensional image.

Unfortunately, Gabor was ahead of his time. His proposed holographic electron microscope suffered from insufficient coherence of the electron wave, which led to poor reconstructions. Little wonder that holography did not become popular until after the invention of the laser in 1960 (MILESTONE 9), which provided a supply of highly focused monochromatic light. Within 2 years, holograms experienced a step change, literally gaining an extra dimension. Emmett Leith and Juris Upatnieks used a laser and an off-axis configuration to produce a three-dimensional hologram, while Yuri Denisyuk created three-dimensional holograms using white light as a source.

The shimmering futuristic-looking images soon spilled into science fiction, most notably in the 1977 film Star Wars. Some 30 years later, technology has caught up. Companies market systems that create three-dimensional holographic images that walk and talk, without the audience having to wear special glasses. This technique is also used in teleconference systems, where people can 'beam in' from multiple locations.

One of the most promising technological applications, however, uses three-dimensional holograms for data storage. Simply by varying the reference beam, 'pages' of data can be written and then read from the same volume of material, with storage capacity in the terabyte range. That is equivalent to 100 films on a single disc. With the ever increasing amount of digital data available, such as from the Large Hadron Collider (set to produce 15 PB of data per year), we are going to need higher density recording media to store them all.

May Chiao, Senior Editor, Nature Physics

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MILESTONE 8

Sun power

The conversion of sunlight into electricity is one of the most natural pathways to extract energy from the world around us, and has been studied since at least 1839 when Alexandre-Edmond Becquerel observed the photoelectric effect in rudimentary electrochemical cells. The development of modern solar cells began in earnest in 1939, with the accidental discovery made by Russell Ohl of the p–n junction at Bell Laboratories. While measuring the electrical properties of a silicon crystal containing a crack, he noticed a marked change in electric voltage depending on the illumination of the crystal.

The game changer, however, was the development in 1954 by Daryl Chapin, Calvin Fuller and Gerald Pearson, also at Bell Laboratories, of the first practical solar cell. Having developed a method to dope silicon, they were able to fabricate high-quality p–n junctions that, owing to their purity, were particularly efficient in separating the electrical charges created by the absorbed light. Their first solar cells achieved an efficiency of 6%, which was an improvement by more than an order of magnitude compared with alternative designs.

A fundamental understanding of solar-cell performance was consequently reached in 1961 by William Shockley and Hans Queisser, who determined the maximum theoretical light-conversion efficiency of semiconductor solar cells. Over the next decades, efficiencies in light conversion improved slowly as purer materials could be grown. However, an optimum coupling of light into the cells and an efficient extraction of electrical carriers out of the device are also essential factors. Improving the former, Martin Green at the University of New South Wales in Australia developed solar-cell designs that use inverted pyramids on the surface to direct light into the silicon more effectively.

A way of circumventing the limitations of the Shockley–Queisser limit is to use multi-junction solar cells, in which several layers of semiconductors with different bandgaps maximize the absorption of solar light. Each layer in such cells is optimized for a specific spectral region. These cells achieve efficiencies of >40%, yet they remain expensive and are typically used only in space applications.

Gerald Pearson, Daryl Chapin and Calvin Fuller (from left to right), the inventors of the modern solar cell. Reprinted with permission of Alcatel-Lucent USA Inc.

Meanwhile, solar-cell technologies have emerged that do not use p–n junctions. In 1991, Michael Grätzel developed dye-sensitized solar cells, which work by using an electrolyte in contact with a photosensitized

MILESTONE 9

All together now

Courtesy of HRL Laboratories, LLC

There are only very few occasions when discoveries are made that start an entire new research field and at the same time revolutionize our everyday life. The transistor is one example — it led to modern electronics. At least as important is the invention of the laser, which heralded the field of photonics.

The foundations of laser operation were laid in 1917, when Albert Einstein studied the interaction of electromagnetic radiation with electrons that can occupy two energy levels. In the presence of an incident photon equal to the energy separating the two states, an electron in the higher state can be stimulated to relax, emitting a photon of the same energy as the incident one. The photons are coherent, that is, they have not only the same wavelength but also the same phase.

However, the fact that stimulated emission can amplify light fields to generate coherent light beams was not realized until the 1950s. Then, Nikolay Basov and Alexander Prokhorov developed the principle of the maser — which stands for 'microwave amplification by stimulated emission' — along with James Gordon, Herbert Zeiger and Charles Townes, who independently built the first maser in 1954. Their maser used a microwave transition between two energetic states of ammonia molecules. They sent a beam of ammonia molecules past an electric field to focus excited molecules into a microwave cavity, while defocusing the others. This provides an amplifier and oscillator that emits coherent radiation.

An extension of the maser concept to optical light waves was developed in 1958 by Arthur Schawlow and Townes. Gordon Gould, who coined the term laser, is also credited with independent contributions to the laser scheme, and after a prolonged court battle was granted a subsidiary patent on the laser. For their work that led to the concept of masers and lasers, Townes, Basov and Prokhorov were awarded the 1964 Nobel Prize in Physics.

After the first demonstration of the maser, a deluge of similar research papers flooded the office of *Physical Review*, the editors of which consequently decided to stop accepting any further papers on the topic. So it came that they also turned down the paper on the first working laser, which was demonstrated on 16 May 1960 by the 32-year-old physicist Theodore Maiman from Hughes Research Laboratories (pictured). Instead, Maiman anode. Their performance remains inferior to that of silicon cells but they represent a cost-efficient alternative, although organic solar cells made from semiconducting polymers and fullerenes, which were pioneered at around the same time by Fred Wudl and colleagues, vie for the same market.

With an increasing relevance of solar energy in renewable electricity generation, the development of novel and more efficient solar-cell designs will continue. For example, some emerging solar cells make use of nanostructured architectures, such as nanowires, in which photogenerated charge carriers can be more efficiently collected.

Stefano Tonzani, Associate Editor, Nature Communications

ORIGINAL RESEARCH PAPERS Ohl, R. S. Light-sensitive electric device. US patent 2,402,662 (filed 27 May 1941; granted 25 June 1946) | Chapin, D. M., Fuller, C. S. & Pearson, G. L. A new silicon p-n junction photocell for converting solar radiation into electrical power. *J. Appl. Phys.* **25**, 676–677 (1954) | Shockley, W. & Queisser, H. J. Detailed balance limit of efficiency of p-n junction solar cells. *J. Appl. Phys.* **32**, 510–519 (1961) | Blakers, A. W., Wang, A., Milne, A. M., Zhao, J. & Green, M. A. 22.8% efficient silicon solar cell. *Appl. Phys. Lett.* **55**, 1363–1365 (1989) | Grätzel, M. & O'Regan, B. A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO$_2$ films. *Nature* **353**, 737–740 (1991) | Sariciftci, N. S., Smilowitz, L., Heeger, A. J. & Wudl, F. Photoinduced electron transfer from a conducting polymer to buckminsterfullerene. *Science* **258**, 1474–1476 (1992)

sent his manuscript to *Nature*, where it was published in August 1960.

The Maiman laser was based on a ruby crystal doped with chromium atoms to provide the energy levels for the laser process. In order to excite a sufficient number of electrons to pass the laser threshold, Maiman came up with the idea to use a bright flashlight as a pump source. It worked brilliantly.

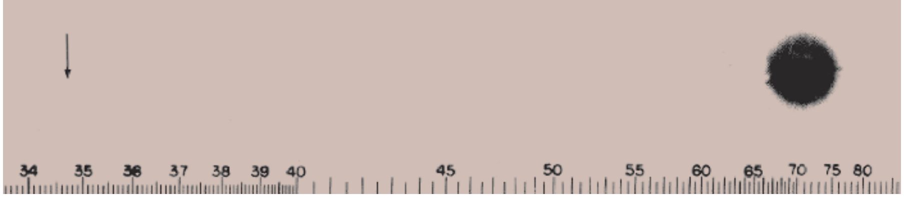
The importance of lasers cannot be overstated. Among a plethora of applications, lasers are used in nonlinear optics (MILESTONES 7 and 10), telecommunications (MILESTONE 13), optical disks (MILESTONE 15) and spectroscopy (MILESTONES 16 and 22). With the help of the laser, photons have become a commodity the properties of which can be designed almost at will. This makes the laser one of the lasting achievements of modern science.

Joerg Heber, Senior Editor, Nature Materials

ORIGINAL RESEARCH PAPERS Einstein, A. Zur Quantentheorie der Strahlung. *Physik. Zeitschr.* **18**, 121–128 (1917) | Basov, N. G. & Prokhorov, A. M. Application of molecular clusters to radiospectroscopic study of rotational spectra of molecules. *Zh. Eksperim. i Teor. Fiz.* **27**, 431–438 (1954) | Gordon, J. P., Zeiger, H. J. & Townes, C. H. Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of NH$_3$. *Phys. Rev.* **95**, 282–284 (1954) | Schawlow, A. L. & Townes, C. H. Infrared and optical masers. *Phys. Rev.* **112**, 1940–1949 (1958) | Maiman, T. H. Stimulated optical radiation in ruby. *Nature* **187**, 493–494 (1960)

MILESTONE 10

Optics in harmony



Reprinted figure with permission from Franken, P.A. *et al.* © (1961) American Physical Society.

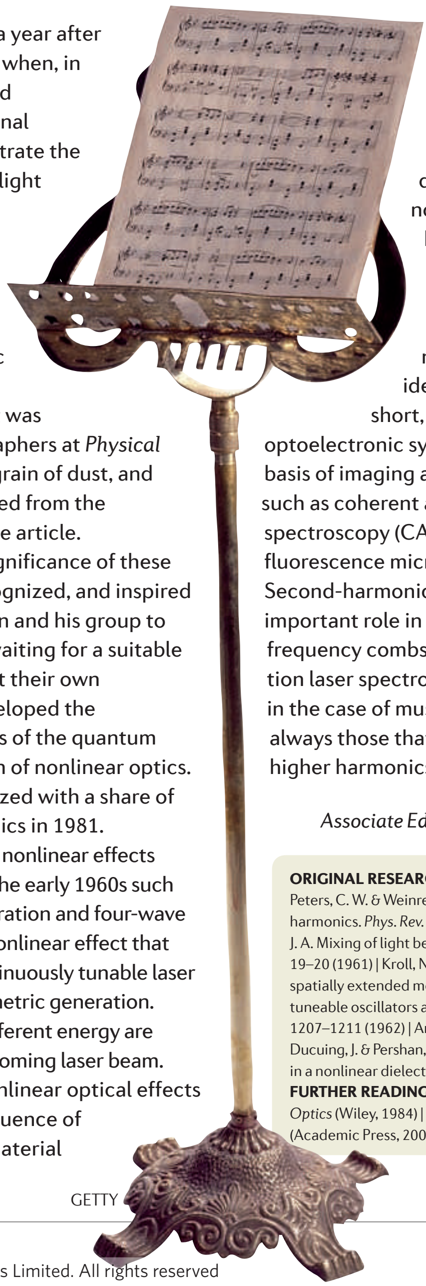
The development of the laser (MILESTONE 9) meant that, for the first time, the interaction of huge electric fields with matter could be studied, particularly in the regime where the electrical polarization created by the laser is no longer linearly proportional to the light field. Then, higher-order effects occur, similar to the excitation of higher harmonics in musical instruments.

Indeed, it was only a year after the first laser was built when, in 1961, Peter Franken and colleagues used a seminal experiment to demonstrate the frequency doubling of light from a ruby laser beam focused into a quartz crystal. This second harmonic signal was imaged as a small spot on a photographic plate. Unfortunately, however, that tiny spot was thought by the lithographers at *Physical Review Letters* to be a grain of dust, and was therefore eliminated from the published version of the article.

Nonetheless, the significance of these results was widely recognized, and inspired Nicholaas Bloembergen and his group to enter the field; while waiting for a suitable laser source to conduct their own experiments, they developed the theoretical foundations of the quantum mechanical description of nonlinear optics. This effort was recognized with a share of the Nobel Prize in Physics in 1981.

Subsequently, other nonlinear effects were demonstrated in the early 1960s such as sum-frequency generation and four-wave mixing. An important nonlinear effect that forms the basis for continuously tunable laser sources is optical parametric generation. There, two beams of different energy are generated from one incoming laser beam.

Another class of nonlinear optical effects occurs through the influence of strong light fields on material properties themselves. Since the nineteenth century, the effects of electric fields on the refractive index of a material — the Kerr and Pockels effects — have been known. High-intensity optical fields can achieve a similar effect, which is known as self-phase modulation. In laser pulses this leads to chirp, which is a variation in the frequency spectrum of the pulse, and is therefore an important detrimental effect to consider in many optical systems.



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Ever since those early discoveries in the 1960s, nonlinear optical effects have been widely used in applications. Apart from telecommunication applications in which nonlinear effects are an ideal tool to manipulate the short, intense laser pulses in optoelectronic systems, they also form the basis of imaging and sensing applications such as coherent anti-Stokes Raman spectroscopy (CARS) and multiphoton fluorescence microscopes. Second-harmonic generation also plays an important role in the femtosecond frequency combs used for ultrahigh-resolution laser spectroscopy (MILESTONE 20). As in the case of music, the best works are always those that make perfect use of higher harmonics.

Stefano Tonzani, Associate Editor, Nature Communications

ORIGINAL RESEARCH PAPERS Franken, P. A., Hill, A. E., Peters, C. W. & Weinreich, G. Generation of optical harmonics. *Phys. Rev. Lett.* **7**, 118–119 (1961) | Giordmaine, J. A. Mixing of light beams in crystals. *Phys. Rev. Lett.* **8**, 19–20 (1961) | Kroll, N. M. Parametric amplification in spatially extended media and application to the design of tuneable oscillators at optical frequencies. *Phys. Rev.* **127**, 1207–1211 (1962) | Armstrong, J. A., Bloembergen, N., Ducuing, J. & Pershan, P. S. Interactions between light waves in a nonlinear dielectric. *Phys. Rev.* **127**, 1918–1939 (1962)
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MILESTONE 11

Quantum light

The revolutionary insight by James Clerk Maxwell that light is an electromagnetic wave, and the equations he set up to describe it formally (MILESTONE 2), still serve "as the basis for the discussion and analysis of virtually all the optical instrumentation we have ever developed", as Roy Glauber put it in his 2005 Nobel lecture. "That overwhelming and continuing success may eventually have led to a certain complacency."

This Nobel Prize came exactly 100 years after Albert Einstein had introduced the concept of light quanta, following Max Planck's work on black-body radiation (MILESTONE 3). Still, by the middle of the past century, the granular nature of light did not seem to play a significant role in optics. Even today, when we talk about lasers, holography and photonic bandgaps, these are phenomena that do not demand the quantization of light. Beginning in the 1960s, however, there has been a growing appreciation of a distinct non-classical variety of light, which gave rise to an entire new field of research: quantum optics.

It began with experiments aimed at determining the angular diameter of radio stars. Robert Hanbury Brown and Richard Twiss had measured the radio-frequency signals of these celestial objects using two spatially separated aerials; by correlating the low-frequency outputs of the detectors, the diameter of the star could be estimated. In these experiments, it was exclusively a correlation in signal intensity that was measured, making this kind of interferometer fundamentally different from the Michelson interferometer, in which the correlation in signal amplitude is crucial. The Hanbury Brown–Twiss experiment is understood when considering the radio signals as classical waves, and the method proved useful for its intended purpose. The question then was whether the same approach could be used to measure the diameter of visible stars — whether the concept could be extended to optical wavelengths was far from obvious. So, Hanbury Brown and Twiss did a laboratory experiment: they passed light from a mercury arc lamp through a beam splitter and looked at correlations between the signals of the photomultipliers terminating the two beams. Sure enough, they saw a clear tendency of the photodetectors to register photons simultaneously.

Why should the photons arrive in a correlated manner? The results stirred up controversy, and it was Glauber, in 1963, who presented a full framework to explain higher-order correlations in multiple-photon coincidence measurements. From his quantum theory of optical coherence it followed that there are cases for which the classical description of light is inadequate; only in such non-classical intensity correlations are the signatures of light quantization revealed.

In the years that followed, a number of researchers demonstrated 'strictly quantum' behaviour of light. First came the observation by John Clauser, in 1974, of non-classical correlations between two photons emitted in cascade by a three-level atom. In 1977, Jeff Kimble, Mario Dagenais and Leonard Mandel demonstrated that photons emitted by a single sodium atom

MILESTONE 12

Distant relations

Hard on the heels of the struggle to understand wave–particle duality was the confrontation of something just as bizarre and foreign: non-locality. Is all of the information that is relevant to a physical object or interaction contained at the point in space and time where that object or interaction is located? The same quantum formalism that produced wave–particle duality answered 'no'. Like duality, non-locality had a history stretching back at least to Sir Isaac Newton, whose theory of gravity implied instantaneous communication over arbitrary distances and drew accusations of mysticism. And, like duality, clear answers started to emerge in the early twentieth century.

Quantum mechanics described reality as inherently non-local. To some physicists, this simply meant that quantum mechanics was incomplete. The most famous incompleteness argument was developed by Albert Einstein, Boris Podolsky and Nathan Rosen, and then refined by David Bohm. It pointed out that the measurement of the spin of two widely-separated atoms must be correlated if they originated from a molecule with a known total spin. A spin measurement along one axis of one atom meant that the spin along the same axis was known for the other atom.

Quantum mechanics, however, also stated that the spin of an atom could be known along only a single axis. Therefore, the atom that was second to be measured had an indeterminate (unknowable) spin along x and y if the first atom was measured along z, but it had an indeterminate spin along y and z if the first atom was measured along x. How could that second atom instantaneously 'know' to assume a particular spin along a particular axis, (and an 'unknowable' spin along the others), unless it carried with it all of the relevant information for every axis? Einstein, Podolsky and Rosen concluded that it could not, given that instantaneous communication between the atoms violated Einstein's own theory of relativity. As quantum mechanics did not account for such local information (indeed, it explicitly denied it), it must originate from 'hidden variables', and posed a serious challenge to the emerging quantum picture.

Einstein, Podolsky and Rosen published their argument in the *Physical Review* in 1935, and a reply was published in the same year and the same journal by that famous opponent to Einstein's point of view, Niels Bohr. However, it was not until John Bell tackled the problem in 1964 that a clear, quantitative and testable opposition between hidden variables and quantum mechanics was established. His argument, and subsequent experiments, have fallen strongly, if not decisively, on the side of quantum mechanics.

At the core of Bell's treatment are Bell's inequalities. These place an upper limit on the correlations between measurements of remote

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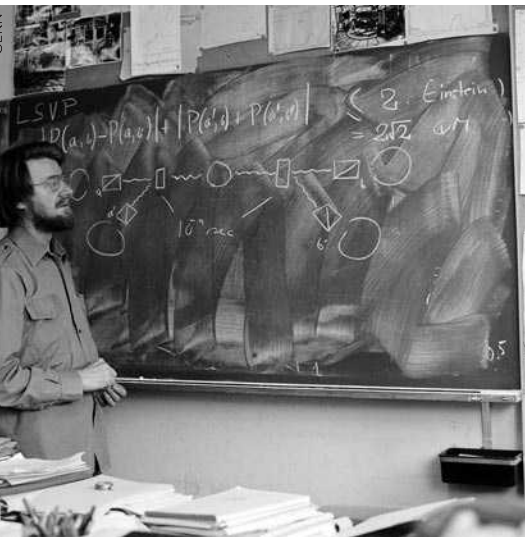

John Bell with a sketch of Alain Aspect's experimental set-up.

particles in the case that those correlations are determined by hidden local variables. Bell showed that these limits are broken by the predictions of standard quantum mechanics. Whereas Bell considered measurements on electrons, the strongest tests of his inequalities — by John Clauser and Stuart Freedman, and later by Alain Aspect — have used photons passed through optical polarizers the directions of which are set after the photons have left their source. This restricts the effect of any hidden variables in the system to be local to the travelling photons. Although no airtight test has been performed as yet, Bell's theorem and are separated in time, which is a phenomenon that is known as antibunching. In 1986, Philippe Grangier, Gérard Roger and Alain Aspect used the same cascade as Clauser to build the first source of single photons, and observed the opposite of the Hanbury Brown–Twiss effect: anticorrelations in the detection of a single photon on the two sides of a beam splitter.

So light is more than just a wave. There could be no further "complacency".

Andreas Trabesinger,
Senior Editor, Nature Physics

ORIGINAL RESEARCH PAPERS Brown, R. H. & Twiss, R. Q. Correlation between photons in coherent beams of light. *Nature* **177**, 27–29 (1956) | Glauber, R. J. The quantum theory of optical coherence. *Phys. Rev.* **130**, 2529–2539 (1963) | Glauber, R. J. Coherent and incoherent states of the radiation field. *Phys. Rev.* **131**, 2766–2788 (1963) | Clauser, J. F. Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect. *Phys. Rev. D* **9**, 853–860 (1974) | Kimble, H. J., Dagenais, M. & Mandel, L. Photon antibunching in resonance fluorescence. *Phys. Rev. Lett.* **39**, 691–695 (1977) | Grangier, P., Roger, G. & Aspect, A. Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences. *Europhys. Lett.* **1**, 173–179 (1986)

the experiments it has inspired have shown to a high degree of confidence that nature is, at least to some extent, not local.

This framework was later extended to entanglement of more than two particles, most importantly by Daniel Greenberger, Michael Horne and Anton Zeilinger, whose 'GHZ state' became a crucial ingredient to an entirely new field: quantum information science (MILESTONE 17).

Michael Segal,
Associate Editor, Nature Nanotechnology

ORIGINAL RESEARCH PAPERS Einstein, A., Podolsky, B. & Rosen, N. Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* **47**, 777–780 (1935) | Bohr, N. Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* **48**, 696–702 (1935) | Bohr, N. Quantum mechanics and physical reality. *Nature* **136**, 65 (1935) | Bohm, D. *Quantum Theory* Ch. XXII (Prentice-Hall, 1951) | Bohm, D. & Aharonov, Y. Discussion of experimental proof for the paradox of Einstein, Rosen, and Podolsky. *Phys. Rev.* **108**, 1070–1076 (1957) | Bell, J. S. On the Einstein Podolsky Rosen paradox. *Physics* **1**, 195–200 (1964) | Clauser, J. F., Horne, M. A., Shimony, A. & Holt, R. A. Proposed experiment to test local hidden-variable theories. *Phys. Rev. Lett.* **23**, 880–884 (1969) | Freedman, S. J. & Clauser, J. F. Experimental test of local hidden-variable theories. *Phys. Rev. Lett.* **28**, 938–941 (1972) | Aspect, A., Grangier, P. & Roger, G. Experimental realization of Einstein–Podolsky–Rosen–Bohm *Gedankenexperiment*: a new violation of Bell inequalities. *Phys. Rev. Lett.* **49**, 91–94 (1982) | Aspect, A., Dalibard, J. & Roger, G. Experimental test of Bell inequalities using time-varying analyzers. *Phys. Rev. Lett.* **49**, 1804–1807 (1982) | Greenberger, D. M., Horne, M. A. & Zeilinger A. in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe* (ed. Kafatos, M.) 73–76 (Kluwer Academics, 1989)
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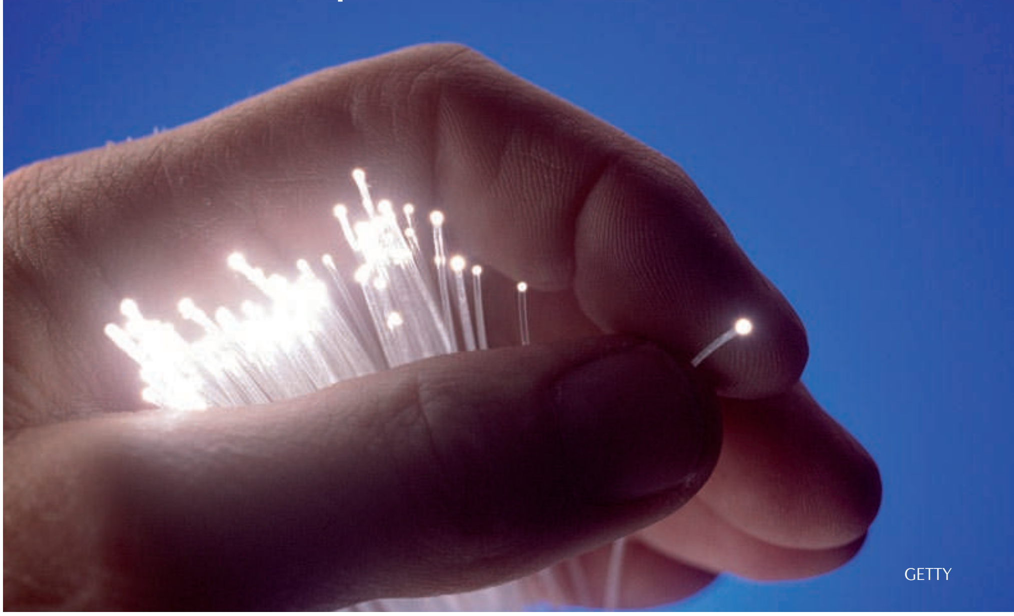
MILESTONE 13

The birth of optical communications



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Without doubt, our world of high-volume data communications would not be possible without the advent of optical fibres. Today, we can send text, images, speech and video files instantly from and to anywhere in the world so conveniently that we have come to take this accessibility for granted.

Optical fibres have been a prerequisite for this extremely rapid development, transporting information over distances of thousands of kilometres. The operation of optical fibres is based on Snell's Law, which states that light can be totally reflected when it travels from a medium with a higher refractive index to one with a lower refractive index — a phenomenon known as total internal reflection. Based on this principle, optical fibres are composed of a high-refractive-index core surrounded by a low-refractive-index cladding layer.

Although the principle of light transmission through optical fibres was known early on, long-distance light transmission was hampered by excessive optical losses during transmission. Then, in 1966, Charles Kao and George Hockham, working for the English company Standard Telephones and Cables, suggested that the attenuation in fibres was caused by impurities in the glass, rather than fundamental physical effects such as scattering. They proposed that, for high-purity silica glass, the attenuation of light could be kept at 20 dB km^{-1}. At the time, optical fibres exhibited losses of 1,000 dB km^{-1}. For this discovery, Kao was awarded the Nobel Prize in Physics in 2009.

However, even at a loss of 20 dB km^{-1}, 99% of the light would be lost over a distance of only 1 km, which is impractical for long-haul transmission. Work on purifying glass began to take place. In 1970, Corning scientists Robert Maurer, Donald Keck and Peter Schultz successfully fabricated a glass fibre with an attenuation of just over 16 dB km^{-1}, exceeding the 20 dB km^{-1} benchmark. It was made of a titanium-doped silica core and a pure fused silica cladding. Two years later, using a germanium-doped core, Corning produced multi-mode glass fibres with a loss of ~4 dB km^{-1}. Subsequent developments reduced the loss to 0.2 dB km^{-1} at a wavelength of 1.55 μm.

In 1988, the world witnessed the first transatlantic optical fibre between the United States and Europe, with a length of 6,000 km. To date, >1 billion km of optical fibres has been laid, capable of carrying >10 Gb s^{-1} of data. Moreover, optical fibres find applications not only in communications but also in imaging, sensing and medicine.

Rachel Won,
Associate Editor, Nature Photonics

ORIGINAL RESEARCH PAPERS Kao, K. C. & Hockham, G. A. Dielectric-fibre surface waveguides for optical frequencies. *Proc. IEE* **113**, 1151–1158 (1966) | Kapron, F. P., Keck, D. B. & Maurer, R. D. Radiation losses in glass optical waveguides. *Appl. Phys. Lett.* **17**, 423–425 (1970)
FURTHER READING Hecht, J. *City of Light. The Story of Fiber Optics* (Oxford Univ. Press, 1999)

MILESTONE 14

Digital photography is born

The CCD inventors, Willard Boyle (left) and George Smith (right). Image courtesy of Alcatel-Lucent/Bell Labs

'Revolutionary' is used too often to describe advances in science. When applied to the invention of the charge-coupled device (CCD) array by Willard Boyle and George Smith, however, it is not far off. Yet, the CCD was not originally intended for applications in digital imaging, for which Boyle and Smith received the 2009 Nobel Prize in Physics, but rather as a potential new form of digital memory.

In the late summer of 1969, Boyle and Smith, who were working at Bell Laboratories, were told to come up with a semiconductor memory that could compete with the so-called 'magnetic bubble' memory that was being developed by a rival group of their division. Bubble memory worked by injecting magnetic domains into garnet patterned with an array of ferromagnetic bars. Applying an alternating magnetic field caused these domains, or bubbles, to hop within the garnet from underneath one bar to the next, like packages on a conveyor belt. By taking the presence or absence of a bubble to represent a 1 or a 0, respectively, such a device could be used to store a series of digital bits.

Boyle and Smith spent barely an hour at the blackboard devising an electronic alternative. Instead of magnetic bubbles, they proposed to use electronic charges injected into metal-oxide-semiconductor (MOS) capacitors grown on silicon. By placing two capacitors close to each other and applying electric voltages they could induce the charge to move from one to the next. In this way, packets of charge could be passed down a linear array of 'charge-coupled' MOS capacitors, mimicking the operation of a bubble array.

Ironically, although the operation of the device was a success, neither it nor bubble memory ever took off as a means of storing digital information. But it did not take long for Boyle and Smith to realize that it might have other uses. At around the same time, Bell Laboratories was working hard to develop the Picturephone, which was a crude videoconferencing system. The commercial cathode-ray-tube cameras used were notoriously unreliable and

MILESTONE 15

Lasers for the masses

Today, the use of lasers is nothing particularly exciting. DVD players, laser pointers, bar-code scanners and telecommunications all use lasers made from semiconductor materials. The situation was different in 1962, when only expensive lasers based on atomic gases existed (MILESTONE 9). Yet, that year, Robert Hall at General Electric realized a first electrically operated solid-state laser, based on the semiconductor gallium arsenide, followed, within 1 month, by similar discoveries by teams lead by Marshall Nathan, Benjamin Lax and Nick Holonyak. However, with high laser thresholds and poor lasing efficiencies even at cryogenic temperatures, prospects for the practical use of these lasers appeared uncertain.

The following year, Herbert Kroemer, as well as Zhores Alferov and Rudy Kazarinov from the Ioffe Physico-Technical Institute of the Russian Academy of Sciences, independently came up with an ingenious suggestion: the concept of double-heterostructure lasers.

Instead of using a bulk semiconductor, they suggested a layered structure made of a thin semiconductor film with a smaller band gap sandwiched between semiconductor layers with a larger band gap. The large gap of the neighbouring layers leads to an efficient confinement of carriers in the central layer, which enhances the performance of the lasers.

It being the time of the cold war, research groups in the West as well as the East began a race to fabricate the first room-temperature semiconductor laser. This important milestone was eventually achieved in 1970, when groups first from the Ioffe Physico-Technical Institute and then from Bell Laboratories realized continuous room-temperature lasing made from gallium arsenide sandwiched between aluminium gallium arsenide.

These and consequent achievements would not have been possible without the parallel drive towards thin film-deposition systems during the late 1960s. Of particular relevance were metallo-organic chemical-vapour deposition originating from the work of Harold Manasevit at the North American Aviation Company, and molecular-beam epitaxy pioneered by Alfred Cho and John Arthur at Bell Laboratories. Despite such advances in fabrication, it was not until 1996 that the first blue semiconductor laser was realized in gallium nitride by Shuji Nakamura (MILESTONE 19).

In addition, more complex laser designs have become possible. An example is vertical-cavity surface-emitting lasers. However, the crowning achievement of such efforts is the quantum-cascade laser developed by Federico Capasso and colleagues at Bell Laboratories in 1994. Quantum-cascade lasers are designed so that during the 'cascading' of electrons through several hundreds

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a more dependable alternative was eagerly sought. The CCD provided the solution.

The simplicity of fabricating large sensor arrays, combined with the linear optical response to even the most faint light sources, has meant that 40 years after their invention they are still used in large-scale optical telescopes, including the Hubble space telescope. It has also allowed them to become cheap enough to be integrated into most modern mobile phones — a fact that news agencies increasingly rely on for important events. So, although the revolution might not be televised, thanks to the CCD it will almost certainly be photographed.

Ed Gerstner, Senior Editor, Nature Physics

ORIGINAL RESEARCH PAPERS Boyle W. S. & Smith, G. E. Charge coupled semiconductor devices. *Bell Syst. Tech. J.* **49**, 587–592 (1970) | Amelio, G. F., Tompsett, M. F. & Smith, G. E. Experimental verification of the charge coupled device concept. *Bell Syst. Tech. J.* **49**, 593–600 (1970)
FURTHER READING Smith, G. E. The invention and early history of the CCD. *Nucl. Instr. Meth. Phys. Res. A* **607**, 16 (2009)

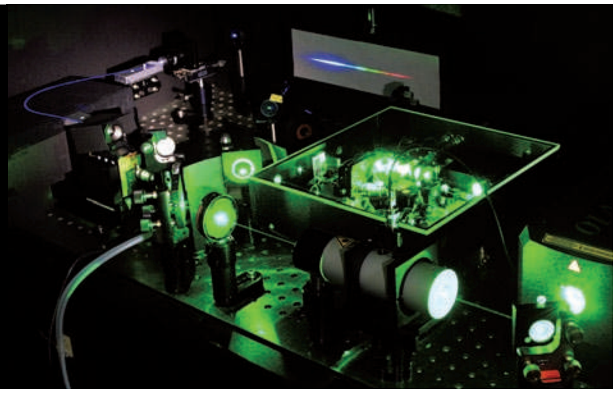
of layers, more than one photon is emitted per electron. Being capable of operating across a broad spectral range, quantum-cascade lasers are a useful source of tunable laser radiation with applications to spectroscopy and chemical sensing.

Noriaki Horiuchi, Associate Editor, Nature Photonics

ORIGINAL RESEARCH PAPERS Hall, R. N. *et al.* Coherent light emission from GaAs junctions. *Phys. Rev. Lett.* **9**, 366–369 (1962) | Nathan, M. I., Dumke, W. P., Burns, G., Dill, F. H. & Lasher, G. Stimulated emission of radiation from GaAs p-n junctions. *Appl. Phys. Lett.* **1**, 62–64 (1962) | Holonyak, N. & Bevacqua, S. F. Coherent (visible) light emission from Ga($As_{1-x}P_x$) junctions. *Appl. Phys. Lett.* **1**, 82–83 (1962) | Quist, T. M. *et al.* Semiconductor maser of GaAs. *Appl. Phys. Lett.* **1**, 91–92 (1962) | Alferov, Zh. I. & Kazarinov, R. F. Semiconductor laser with electric pumping. USSR patent 181737 (application 950840; 30 March 1963) | Kroemer, H. A proposed class of heterojunction injection lasers. *Proc. IEEE* **51**, 1782–1783 (1963) | Alferov, Zh. I. *et al.* Investigation of influence of AlAs–GaAs heterostructure parameters on laser threshold current and realization of continuous emission at room temperature. *Fiz. Tekh. Poluprov.* **4**, 1826–1829 (1970); *Sov. Phys. Semicond.* **4**, 1573–1575 (1971) | Hayashi, I., Panish, M. B., Foy, P. W. & Sumski, S. Junction lasers which operate continuously at room temperature. *Appl. Phys. Lett.* **17**, 109–111 (1970) | Faist, J. *et al.* Quantum cascade laser. *Science* **264**, 553–556 (1994) | Nakamura, S. *et al.* InGaN-based multi-quantum-well-structure laser diodes. *Jpn J. Appl. Phys.* **35**, L74–L76 (1996)

MILESTONE 16

Absolutely accurate



Courtesy of Ted Hänsch and Max-Planck Institut für Quantenoptik

The ability to measure optical frequencies with high precision and stability has led to a plethora of applications, including optical atomic clocks, optical metrology, high-resolution spectroscopy, and even the global positioning systems used in mobile telephones and navigation systems for cars.

Traditionally, precision measurements have been made by comparing the beat frequency between two optical frequencies with a microwave reference, which is a standard based on a specific transition between hyperfine levels of the caesium-133 atom. However, the situation changed when light pulses became available with durations on the scale of femtoseconds. Early approaches to generating such ‘ultrashort’ pulses were plagued by intrinsic instabilities and uncertainty about the underlying mechanisms. A remedy came, in 1981, when Charles Shank and co-workers at Bell Laboratories invented the colliding-pulse mode-locked (CPM) laser, which generated the first coherent photon wave packets in the sub-100-fs regime.

Crucially, the introduction of titanium-doped sapphire (Ti:sapphire) as a broadband gain medium in the near-infrared spectral region revolutionized the generation and amplification of ultrashort pulses. The first broad-bandwidth solid-state laser was demonstrated by Peter Moulton in 1986, and, together with the subsequent demonstration of self-mode locking in Ti:sapphire lasers by Wilson Sibbett and co-workers in 1991, this paved the way to femtosecond pulses with high peak powers and good tunability. Sibbett’s group produced pulses with durations as short as 2.0 ps and, using an intracavity dispersion compensation in a mode-locked Ti:sapphire laser, they managed to achieve pulse durations as short as 60 fs and peak powers of 90 kW. In 1985, Gérard Mourou and co-workers introduced a chirped-pulse amplification scheme that allowed them to push the intensities of femtosecond lasers to $>10^{21}$ W cm^{-2}. In the 1990s, dispersion control was dramatically simplified through the use of chirped multilayer mirrors, which extended the oscillators’ performance into the few-cycle frontier.

The development of reliable high-intensity, sub-100-fs laser technology based on these breakthroughs has stimulated an explosion of activity, leading to fundamental studies into the ways photons and matter interact on very short timescales. Femtosecond lasers have been used as accurate ‘stopwatches’ to observe in real time the energy transfer and storage process, which is at the heart of many chemical processes, resulting in the 1999 Nobel Prize for Chemistry being awarded to Ahmed Zewail. More recently, the broadband coherence of femtosecond pulses has been harnessed in the invention of the femtosecond frequency comb, which is an optical measurement technique that can precisely measure different colours or frequencies of light. John Hall and Theodor Hänsch shared half of the award for the 2005 Nobel Prize in Physics “for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique”.

Their ease of fabrication and simplicity, compared with techniques based on a microwave standard, have helped to establish frequency combs as excellent frequency reference sources and measurement tools. They are nowadays commercially available and widely used for metrological purposes. There should be more to come: optical atomic clocks using frequency combs are expected to have accuracies 100 times better than any other time-keeping systems, making them attractive for use in global satellite-navigation systems.

Rachel Won, Associate Editor, Nature Photonics

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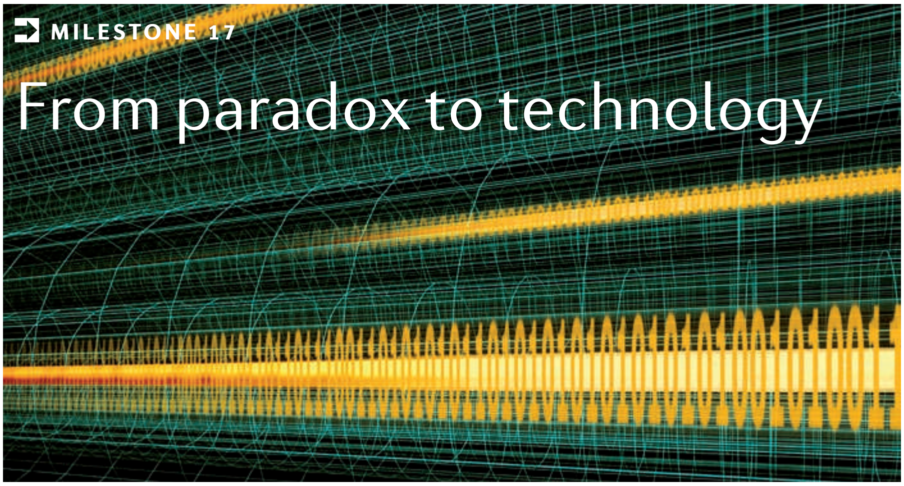

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MILESTONE 17

From paradox to technology

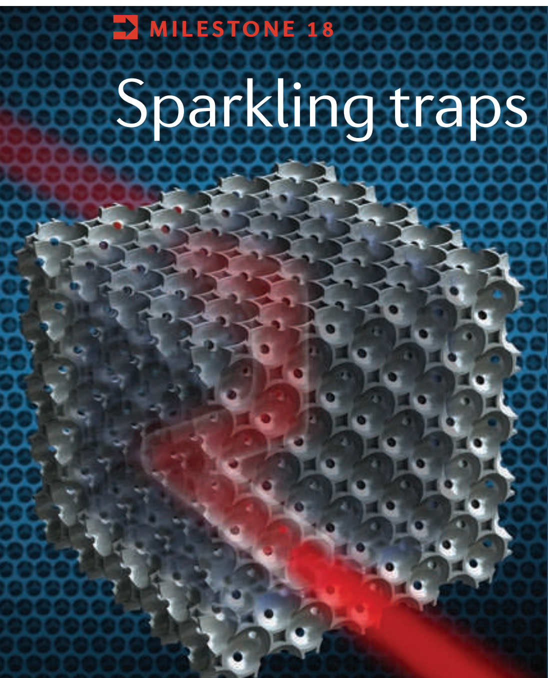
The way we process and communicate information has changed rapidly over the past few decades, but might undergo a fresh revolution with the advent of quantum information technology. The field began in the early 1980s, when laser experiments testing the quantum nature of light matured (MILESTONE 12), and the trend shifted to trying to employ quantum states of light for encoding information. In independent developments, Richard Feynman and David Deutsch introduced the concept of a quantum computer, and Charles Bennett and Gilles Brassard proposed a protocol for quantum cryptography. Bennett and Brassard were inspired by ideas that were formulated by Stephen Wiesner in 1970, and published formally in 1983, about using quantum-mechanical effects to produce banknotes that cannot be counterfeited.

These ideas are based on the quantum principle of superposition, which allows particles to exist in multiple states at once. For example, when a single photon falls onto a half-silvered mirror, there are two possible outcomes: reflection and transmission. Instead of going one particular way, however, the photon is transmitted and reflected at the same time. Only when detectors are put into place will one of the two paths be attributed to the photon. Without detection, the photon effectively goes both ways.

A quantum computer operates in such superposition modes. The basic unit is a quantum bit (or qubit) that, until it is read out, can take on values of both 0 and 1 simultaneously. A qubit can, for example, be an atom in its ground or excited state, or an electron with spin up or down. If we can couple together 10 qubits, they can be collectively in all 1,024 classical states of 10 bits. The power of quantum computing relies on having all superposition states at disposition in parallel during computation.

However, quantum computing is not simply a faster way of information processing; new algorithms are required, tailored to its strengths. Interest in the concept therefore rose sharply in 1994 when Peter Shor found a task to which quantum computers are particularly well suited: factoring large numbers. Using Shor's algorithm, quantum computers could, in principle, factor a 1,000-digit number in a fraction of a second — a problem that classical computers cannot solve within the lifetime of the Universe.

The route to practical applications has always been clear for quantum cryptography. In the protocol of Bennett and Brassard, two parties establish a cryptographic key by exchanging polarized photons that are prepared in superposition states. The essence of the scheme is that they can safely exchange photons because eavesdropping is immediately detected. Any attempt to intercept photons creates errors that legitimate parties can identify by comparing part of the exchanged data; the remaining data are used to build a secret key.



MILESTONE 18

Sparkling traps

Image design by Stephen Eisenmann (University of Illinois at Urbana-Champaign) and Tom Wilson.

In classical physics, whenever a wave encounters a change in density a part of that wave is reflected. In 1887, Lord Rayleigh took this concept further by studying what happens if the wave propagates not through a homogeneous medium but through one with a periodic structure. He showed that rays reflected from the multiple interfaces interfere with one another. For a band of wavelengths of similar value to the periodicity of the stack, the interference is destructive so that this bandgap prevents wave propagation through the structure.

By the 1980s, localization of light in artificial structures was a hot topic. Combining localization with the idea of the Rayleigh bandgap, Sajeev John considered, in 1987, how electromagnetic radiation could be trapped in a periodic three-dimensional dielectric material if randomness is introduced. As an illustration of this, consider altering the periodicity at just one point allows the existence of light at a wavelength within the bandgap; however, this light is trapped in the vicinity of the defect because it is forbidden everywhere else. Applied to chains of imperfections, light can then be guided with little loss. The potential of this approach cannot be understated: just as semiconductors have made possible the miniaturization of electrical devices, so photonic crystals hold the promise of microscale photonic circuitry.

Another landmark was set by Eli Yablonovitch with his paper published earlier in 1987. Following the work of Edward Purcell, scientists had started to think about controlling spontaneous light emission by modifying the photonic environment. This is exactly what a photonic crystal does. A quantum light source surrounded by a photonic bandgap is prevented from decaying because the photon that it needs to emit cannot exist. Conversely, the spontaneous-emission rate can be increased if the emitter is placed inside a defect with which it is in resonance.

The next challenge was fabrication. The first proposed design with a full bandgap comprised dielectric spheres in a configuration similar to atoms in a diamond crystal. However, the eventual structure, which was initially demonstrated in 1991 in the microwave regime, used an approach that was better suited to the material-processing abilities at the time by drilling holes in three different directions.

More proposals for quantum communication schemes and their experimental verification ensued, notably those employing quantum entanglement and demonstrating teleportation. Systems for quantum key distribution are now available commercially. Building a quantum computer, however, remains a formidable task and as yet only a few qubits have been coupled to implement small algorithms. In recent years, various promising new schemes have been explored, using photons as well as material systems such as ions, atoms, molecules, quantum dots and superconducting circuits for processing quantum information. Photons are also employed as 'flying qubits' for transmitting quantum information, thereby ensuring a carrying role of photons in this emerging technology.

Liesbeth Venema,
Senior Editor, Nature

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Of particular relevance to practical applications are two-dimensional photonic-crystal designs, which were first realized in 1996. They represent a compromise between a full bandgap and a simpler fabrication that makes possible the integration of both passive and active optical components on a single photonic chip. With the possibility of a revolution on a par with the development of the semiconductor chip, photonic-crystal research looks set to shine.

David Gevaux, Senior Editor, Nature Physics

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MILESTONE 19

Bright new world

Light-emitting diodes (LEDs) are a ubiquitous part of modern life. Their popularity is evident from their deployment everywhere from car brake lights and giant display boards to traffic lights and indicator lamps on electronic goods. Many also predict that LEDs are poised to play an increasingly important role in interior lighting thanks to their long lifespan and low power consumption.

The origins of the LED can be traced back to the initial research on electroluminescence from semiconductors. In 1907, Henry Round reported a bright glow from a crystal of silicon carbide. This was followed in the 1920s by intensive research by the Russian scientist Oleg Losev, who studied zinc oxide and silicon carbide, observing a threshold behaviour of the light emission and documenting the spectrum of the light emitted.

However, much credit for the invention of a practical LED is widely attributed to scientists in the United States in the early 1960s. In 1961, scientists at Texas Instruments reported that gallium arsenide (GaAs) emitted infrared light when pumped by an electrical current. The following year saw a breakthrough in LED research with various papers on GaAs-based red and infrared light emission, including the report on lasing (MILESTONE 15). Thanks to his pioneering work on red GaAs LEDs, Nick Holonyak is often reported as being 'the father of the LED'.

Although the first versions were dim, LEDs that were much brighter quickly followed, as did yellow emitters. However, for many years scientists struggled to find a suitable material system for emitting bright blue light. This all changed in the 1980s with research on gallium nitride (GaN) and the development by Shuji Nakamura, a scientist at Nichia, of an efficient scheme for positive-type doping (p-doping) of GaN LEDs. His research opened the door to the first commercial high-power blue LEDs in 1993, completing the colour range of LEDs across the visible spectrum. It also led to several important spin-offs including the white LED (a blue LED chip coated with a light-converting phosphor).

In many ways, LEDs can be considered as the first great success of optoelectronics, and improvements in performance have been charted by a law akin to Moore's law in microelectronics. Haitz's law documents that every 10 years the amount of light generated by an LED increases by a factor of 20, whereas the cost per unit of useful light emitted falls by a factor of 10. Today, LED research is flourishing around the world, with scientists attempting to optimize the colour and brightness of white light, push emission deep into the ultraviolet, and explore new efficient material systems based on organic semiconductors as well as quantum dots.

Oliver Graydon,
Chief Editor, Nature Photonics

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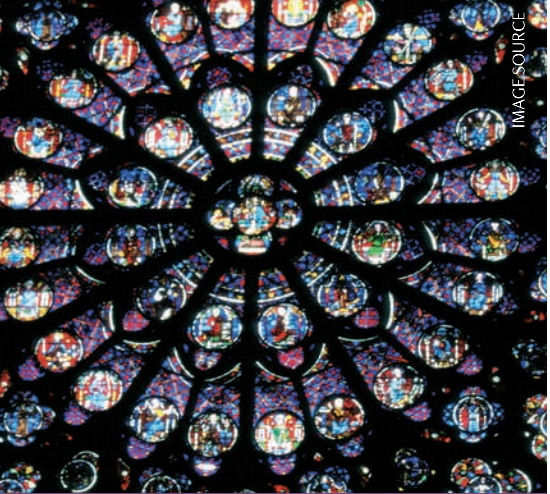

MILESTONE 20

Small and beautiful

The 'diffraction limit' of classical optics does not allow the localization of light into regions that are much smaller than its wavelength. As a result, the level of integration and miniaturization of photonic circuits is not even close to that achievable in electronics. The technology that might close this gap is known as 'plasmonics'. Plasmonic structures have beaten the diffraction limit, and led to advances in spectroscopy and sensing, imaging, cancer therapy, integrated nano-optics and solar cells, to name just a few.

Modern plasmonics started with a publication in 1998 by Thomas Ebbesen and colleagues, who observed a surprisingly efficient light transmission through a thin metal film with holes ten times smaller than the wavelength of light. Additionally, more light was transmitted through the film than was incident onto the area of the holes. Eventually, Ebbesen was able to explain his observations with the properties of surface-plasmon polaritons (SPPs).

SPPs consist of photons that interact with the surface motions of free electrons in metals. Plasmonic effects have inadvertently been exploited by glass makers since at least the fourth century, for example to generate the colours used in stained-glass windows in medieval cathedrals.

The scientific investigation of plasmonic effects began as early as 1899 with theoretical studies by Arnold Sommerfeld and experimental observations of plasmonic effects in light spectra by Robert Wood in 1902. Later that decade, J. C. Maxwell Garnett and Gustav Mie developed theories explaining the scattering effects by metallic nanoparticles. However, it was not until a number of theoretical studies in the 1950s that a more complete understanding of SPPs was reached. The foundation for the systematic experimental study was then laid in 1968 by Erich Kretschmann and Andreas Otto, who devised methods to excite SPPs with prisms attached to metal surfaces.

In the late 1970s, the technological exploitation of plasmons began with the pioneering discovery by Martin Fleischmann and Richard Van Duyne of significant enhancements in the Raman scattering of light by molecules attached to a rough silver surface. This effect is explored for devices that detect molecular concentrations down to the single-molecule level.

For applications in photonic circuits, the Ebbesen discovery has led to efforts aimed at exploiting the highly localized nature of plasmons to guide light on the nanoscale. Furthermore, a plasmon-based analogue to the laser, the spaser, could provide a source of coherent light below the diffraction limit.

In addition, SPPs are exploited in a number of areas, such as metamaterials (MILESTONE 21). Similarly, plasmonic light concentration can not only enhance light absorption in solar cells, but also improve the efficiency of light-emitting devices.

David Pile, Associate Editor, Nature Photonics

MILESTONE 21

The masters of light

The materials parameters of any optical apparatus, such as a lens or a prism, determine how the properties of light can b e controlled. Unfortunately, the range of options available in natural materials is surprisingly limited. Light–matter interactions are described by Maxwell's equations (MILESTONE 2), and the values of the parameters that enter those equations — dielectric permittivity and magnetic permeability — mean that the refractive index of a natural material is always positive, even though the equations allow the possibility of a negative refractive index.

The investigation of negative refractive index, for which permittivity and permeability are both negative, began years ago. Notably, in 1968, Victor Veselago worked out that a planar slab of a material with a negative refractive index would focus light in the same way as would curved lenses made from conventional materials. In the absence of any material that had such properties, however, these early studies largely fell into oblivion.

All this changed in 1999, when John Pendry and colleagues demonstrated a 'swiss roll' structure that had negative permeability. The key was to tailor the structure of the material on a scale smaller than the wavelength of light passing through it, so that the optical waves do not resolve the underlying features. Such devices are now known as metamaterials. Importantly, as negative permittivity occurs in metals close to their plasmon resonance, the realization of a negative refractive index seemed within reach.

Metamaterials then received widespread attention in 2000, when Pendry published his landmark paper on a perfect lens, which was made using a negative-refractive-index material. This work staggered many in the field for its seemingly unbelievable prediction of perfect imaging capability, and was the first concrete step towards metamaterials with functionality that is impossible for natural materials. The following year, the predictions made by Pendry were confirmed when the first negative-refractive-index metamaterial was fabricated by Richard Shelby, Sheldon Schultz and David Smith.

The capabilities of metamaterials are not limited to homogeneous structures. In 2006, Ulf Leonhardt, and independently Pendry, Schurig and Smith, realized that metamaterials with spatially varying properties could be powerful tools for guiding light along almost arbitrary paths. Leonhardt used the ray approximation to make his mapping. Pendry, Schurig and Smith developed a theoretical description that was based on a coordinate transformation of Maxwell's equations, and was hence known as transformation optics. Consequently, transformation optics has broken down many barriers in the field of optics.

In 2006, one of the most widely publicized metamaterial devices was revealed — the optical cloak, using which, for a specific set of parameters, an object can be concealed from an observer. Leonhardt later extended the transformation-optics approach to curved, non-Euclidean coordinate transformations, which allow operation across a broader range of wavelengths. Equipped with the possibility to manipulate the optical properties of matter at will, further exciting designs will undoubtedly emerge.

Joerg Heber, Senior Editor, Nature Materials

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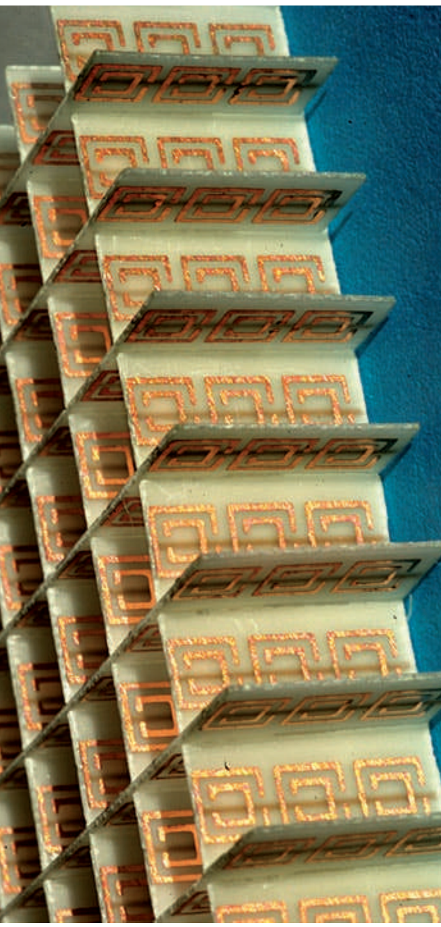


Image courtesy of John Pendry and David Smith

MILESTONE 22

Into the attoworld

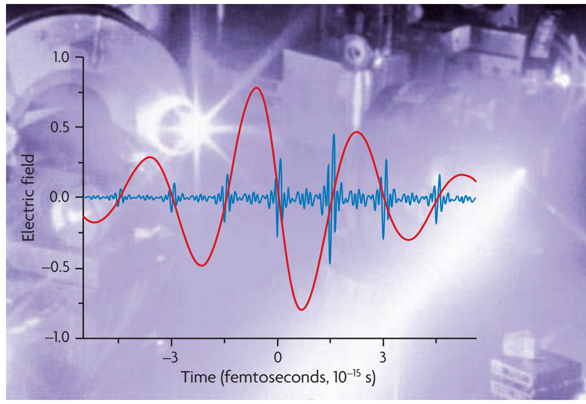
The new millennium has heralded the arrival of attosecond light pulses, and with it the emergence of a radical new technology that is moving time-resolved spectroscopy and control techniques from the molecular (femtosecond) to the electronic (attosecond) timescale.

In fact, attosecond light pulses were created in the early 1990s, when physicists ionized rare-gas atoms with intense laser pulses to generate energetic radiation alongside the original optical pulse. Theory exploring such 'high-harmonic generation', from Kenneth Kulander and co-workers and from Paul Corkum, resulted in 1993 in a simple model for the process: during each half-cycle, the oscillating electric field of an intense laser pulse will tear electrons from atoms in a gas, accelerate them away and then drive them back to re-collide with their parent ion. In each collision, a short burst of extreme ultraviolet (XUV) photons is created.

Theoretical and experimental groundwork — notably by Anne L'Huillier and colleagues — showed that driving high-harmonic generation with a multi-cycle femtosecond laser should produce attosecond light pulses, which are repeated at twice the laser frequency. Rigorous proof of attosecond pulse trains arrived only in 2001, however, when Pierre Agostini and colleagues encoded the properties of the pulses in photo-ionized electrons and then measured the characteristics of these so-called photoelectron replicas.

A few months later, Ferenc Krausz and colleagues reported the first individual attosecond pulses, filtered out of pulse trains. The team then perfected the art of steering re-collision electrons, using the electric fields of intense few-cycle laser pulses, with their waveform judiciously adjusted (MILESTONE 16) so that each pulse generates only one reproducible re-collision event and, hence, one reproducible isolated attosecond pulse. Atomic Auger decay and the photo-ionization of atoms and solids have all been triggered by such isolated attosecond photon pulses, and the ensuing electron dynamics has been probed by the synchronized oscillating electric field of the laser pulse that generated the attosecond trigger.

The ionization process at the heart of high-harmonic generation itself launches electronic and structural changes, with the emitted attosecond electron and photon pulses providing a snapshot of the structure and dynamics of the system at the time of the re-collision. This structural and dynamic information can be retrieved: imaging of molecular structure through re-collision electron diffraction, and the



The initial femtosecond pulse used to ionize atoms is shown in red, and the train of attosecond pulses of higher-frequency light that it produces is shown in blue. The offset between the peak of the initial pulse and the peak of the attosecond pulse corresponds to the length of time the liberated electron is catching a ride in the oscillating electric field of the femtosecond pulse, which moves it away from and then back to its parent ion.

measurement of attosecond proton dynamics and multi-electron dynamics in molecules have all been reported. When more intense attosecond pulses become available, such information could be obtained with ångström spatial resolution and attosecond temporal resolution.

We are only 10 years into the new millennium, but attosecond technology has already established itself. The hope now is that by moving from the mere shaping to the complete engineering of light waves — composed of frequencies from the UV to the infrared — unprecedented control over electron motion will become feasible. This promises access to attosecond pulses of coherent hard X-rays that would revolutionize X-ray laser research. Ultimately, light-wave engeneering should also give access to pulses rivalling the atomic unit of time (~24 as) in duration that would allow us to capture — and even control — the fastest motions outside the atomic core.

Magdalena Helmer, Senior Editor, Nature

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Mirrors in the GEO600 gravitational wave detector. Image courtesy of Wolfgang Filser/Max Planck Society

MILESTONE 23

Mirror finish

> Cavity optomechanics … exploits the interactions between photons and mirrors in table-top experiments that should, one day, be able to shed new light on the boundary between classical and quantum mechanics

Mirrors have a supporting role in most physics and astronomy research. When light strikes a mirror, it is usually reflected to somewhere more interesting — photons from a distant star, for example, might be focused onto a detector, or the beam from a nearby laser might be redirected to cool an atomic gas. But what happens to the mirror? This question is ignored in most research; however, in a small number of fields — such as the detection of gravitational waves and cavity optomechanics — the influence of the photon on the mirror is extremely important.

In an optical cavity or interferometer formed by two highly reflecting mirrors, momentum is transferred from the photons to the mirrors each time a photon is reflected. This 'radiation pressure' is usually insignificant compared with thermal fluctuations and other effects. However, it imposes limits on the performance of the kilometre-scale laser interferometers that have been built to detect gravitational waves, given that these devices have to measure exceedingly small changes in the distances between the mirrors.

Cavity optomechanics, by contrast, exploits the interactions between photons and mirrors in table-top experiments that should, one day, be able to shed new light on the boundary between classical and quantum mechanics. Moreover, cavity optomechanics might allow quantum behaviour to be observed in a macroscopic system, although a number of rival approaches are also closing in on this goal.

A typical cavity-optomechanics experiment consists of an optical cavity in which one of the mirrors is free to move, for example because it is mounted on a cantilever. When a laser beam is shone into the cavity, the light bounces back and forth between the mirrors, and the position of the 'free' mirror changes due to radiation pressure and thermal fluctuations. This changes the length of the cavity and, hence, its resonant frequency, which in turn changes the optical intensity in the cavity. When the frequency of the laser is lower than the nominal resonant frequency of the cavity, the overall effect is to cool the mirror by reducing thermal fluctuations. This process is called dynamical back-action (conversely, when the laser frequency is higher than the resonant frequency, the motion of the mirror is amplified).

In 2006, Markus Aspelmeyer and co-workers and, independently, Pierre-François Cohadon and colleagues used this approach to cool micromirrors mounted on cantilevers from room temperature to ~10 K; a third team, led by Tobias Kippenberg and Kerry Vahala, cooled a toroid microcavity by a similar factor. Reaching the quantum regime will require cooling to sub-Kelvin temperatures, which will necessitate increasing both the optical finesse and the mechanical quality factor of the experiments, whereas actually observing quantum behaviour will involve using photons to measure the position of the mirror while keeping the disturbance caused by radiation pressure to a minimum.

Peter Rodgers,
Chief Editor, Nature Nanotechnology

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