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AMAZING LIGHT

How a handful of scientists and engineers made an arcane phenomenon of quantum physics into a powerful, now commonplace technology—the laser

by Joan Lisa Bromberg

Before the Second World War quantum physics had few technological payoffs. The small group of imaginative scientists who had created the field were driven, like many artists or writers, by aesthetic considerations and the pursuit of truth. During and after the war, however, one after another of the phenomena of quantum physics became the basis for technological innovation—transistors, semiconductors, and nuclear energy, to name but a few. Half a century later their combined effect has revolutionized everything from the most esoteric areas of science to the ordinary details of everyday life.

The laser is a case in point. Its physical basis was laid out by Albert Einstein in 1917 in the course of his research into the quantum theory of light. Einstein showed that in addition to the *spontaneous* emission of light by excited atoms, which we see in an incandescent bulb or the flame of a candle, there also exists *stimulated* emission, in which an excited atom releases radiation of a specific wavelength when it is acted upon by radiation of the same wavelength. Stimulated emission was part of the lore of physics through the 1920s and 1930s. Yet it was only after World War II that it was translated into the laser, a device so versatile that today it is the central component of equipment ranging from compact-disc players and surgical tools to metal-cutting machines and smart bombs.

How did the remote theories of Einstein and his colleagues get translated into late-twentieth-century technology? The invention and development of the laser have features in common with other quantum-physics technologies, such as the transistor and nuclear energy. Wartime research was decisive for all these innovations.

The development of the laser was spurred not by the effort to build an atomic bomb, as with nuclear fission, but by the need to improve military radar. Radar is a system that detects the location and motion of objects by bouncing radiation off them. The shorter the wavelength of the radiation, the greater the resolution and the more compact the equipment. So during and after the war, scientists tried to develop radar equipment that used increasingly shorter wavelengths.

Radar research contributed three essential elements to the development of lasers. It compelled physicists to learn the tools of electrical engineering. It helped convince the U.S. military to keep on funding physicists in peacetime. And it elicited both the scientific questioning and the instrumentation that would invigorate the field of molecular spectroscopy (the measurement of how molecules absorb radiation).

Early in the war British scientists developed radar equipment that operated at a wavelength of 10 centimeters, which is in the middle of the microwave range. U.S. scientists successfully developed 3-centimeter radar. But when they tried to take the next step, to 1.25 centimeters, the range of the emitted beams unexpectedly contracted from 75-100 miles to about 15 miles. Something in the atmosphere was absorbing the waves, and it seemed the likely culprit was water vapor. (The principles behind a modern microwave oven were at work.) It became an urgent military matter to understand the absorption spectrum of water (that is, how much radiation it would absorb at what wavelengths).

As the war ended, the absorption phenomenon that scientists had stumbled over took on a life of its own. Physicists returned to their laboratories eager to get back to basic science and the absorption spectra of water and other molecules—an attractive new field. They had the equipment to do so, because the government was selling war-surplus radar components at bargain-basement prices, and molecular spectroscopy burgeoned. "So far as I know," one pioneer wrote in 1948, "only one paper on microwave spectroscopy exists in prewar literature.... Yet in the brief period since the ending of World War II no less than 100 research papers ... have appeared." But as they mapped molecular spectra, the scientists realized that even waves in the 1.25-centimeter range were too long for their purposes. Most molecules turn out to have their strongest microwave absorption below that, in the millimeter region. In order to perform spectroscopy, scientists needed equipment that could generate useful amounts of microwaves in those smaller wavelengths.

The military was meanwhile interested in millimeter waves for radar to be used in submarines, tanks, and missiles; smaller wavelengths would make it possible to shrink radar devices to the sizes needed for such applications. The outbreak of the Korean War in 1950 made these concerns more pressing. In 1946 the military had established the Joint Services Electronics Program to support former wartime radar laboratories, including those at MIT and Columbia University. Thus, for both military and scientific reasons, U.S. physicists were trying to solve the problem of millimeter-wave generation as the 1950s began.

In 1951 Charles Hard Townes was a professor of physics at Columbia and director of the Columbia Radiation Laboratory. He had been born in Greenville, South Carolina, in 1915 and entered Furman University at age sixteen, after a youth spent devouring each issue of *Popular Mechanics*. He studied Greek, Latin, Old English, French, and German while participating in a wide array of activities, such as the swimming team and the glee club. By the end of his third year he had satisfied the requirements for a B.A. in modern languages, but in his fourth year he switched his major to physics. He went on to get a master's at Duke University in 1937 and a doctorate at Cal Tech in 1939.

Townes, slim, bespectacled, and serious, had designed and tested Air Force radar bombing systems during the war at Bell Laboratories in New York City. After the war he was one of the first to plunge into molecular spectroscopy. He moved to Columbia in 1948, and in 1950, at the behest of the Office of Naval Research, he put together a small group of experts from academia, government, and industry to study the problem of generating millimeter waves.

The group scheduled a meeting in Washington, D.C., for April 26, 1951. Townes, who had arrived in the capital the previous evening, was up early, sitting on a park bench and pondering the meeting's agenda. None of the schemes proposed so far for creating millimeter radiation had panned out. Electron tubes, klystrons, magnetrons, and traveling-wave tubes were the usual devices for generating microwaves, but it was very hard to build them small enough to work in the millimeter range, and even harder to dissipate the heat they created when made so tiny. A radically new idea was needed.

Townes had considered stimulated emission as a source of microwaves, but there were two big problems. First, stimulated emission only works on molecules that are in an excited state. In any kind of ordinary sample, most of the molecules are in the ground state, with only a few excited. This means that any radiation emitted from excited molecules falling back to the ground state will quickly be absorbed by ground-state molecules becoming excited, and there will be a net absorption of radiation. What was needed was a means of creating a "population inversion"—that is, a sample with most of the molecules already excited. That way, the radiation that was emitted would not all simply be reabsorbed.

The other problem was that according to Townes's calculations, even if a population inversion could be achieved, any amplification of microwaves would be quite weak. Excited molecules would emit radiation spontaneously, and that radiation would stimulate other emissions, but the process would not repeat itself enough to make microwaves with the intensity needed to be scientifically useful. So even if the problem of population inversion could be solved, there had to be a way to increase the efficiency of amplification.

Sitting on his park bench among the blooming azaleas, Townes suddenly had an inspiration. He knew that Edward M. Purcell and Robert V. Pound of Harvard University had demonstrated population inversion in a crystal of lithium fluoride the previous year. Their research was mainly concerned with pure physics, however, and they had no intention of putting stimulated emission to technical use. Townes was also familiar, from his radarrelated work, with regenerative oscillators, which use feedback to amplify a signal. Why not employ the feedback principle from electronics to, in effect, "reuse" microwaves, so that each bit of stimulated radiation would in turn stimulate emissions from other molecules?

A cavity of precisely the proper size, Townes realized, would reflect microwaves coherently (i.e., in phase with one another) back into the system, resonating at a certain wavelength the way a kettledrum or a glass of water vibrates at a certain frequency of sound. As microwaves passed back and forth through the cavity, they would stimulate new emissions at the same wavelength, and the small amount of seed radiation from spontaneous emissions would be amplified enormously. The microwave resonator cavity was Townes's key advance. By combining his knowledge of physics with his training in electrical engineering, Townes had come up with a new way to produce microwaves.

In fact, unknown to Townes as he was working out these ideas, a graduate student at Catholic University named Joseph Weber was thinking along the same lines. Weber had been a Navy engineer working on electronic countermeasures to radar before returning to school in 1948, and when he encountered stimulated emission in a quantummechanics class, he immediately realized that it could be used in a microwave amplifier. After hearing about Purcell and Pound's population inversion, he started investigating how such a device might work. Since he was interested only in amplifying radiation, not in generating it, he did not see the need to bottle up waves and get the maximum use out of them. His calculations showed that a stimulated-emission amplifier could work, but it would have only minimal effect, so he did not pursue the idea. Still, his results, revealed at a conference in 1952 and published in 1953, brought the topic to the attention of researchers.

Townes's idea was at first too speculative to bring up at the meeting that had brought him to Washington, but on his return to New York City he enlisted a postdoctoral fellow, Herbert J. Zeiger, to investigate the problem. Shortly thereafter he arranged with James P. Gordon, a graduate student, to make it the subject of his doctoral thesis.

Townes planned to use ammonia as the basis for his device. A molecule of ammonia (NH_3) is arranged like a pyramid, with a nitrogen atom at its apex and three hydrogen atoms forming a triangular base. When the molecule is in its ground state, the nitrogen attracts any negative electric charge away from the hydrogen atoms. Thus, a ground-state ammonia molecule has positive and negative ends, and it can be deflected by a nonuniform electric field.

However, if an ammonia molecule absorbs a certain amount of energy, the nitrogen atom will vibrate through the pyramid's base (the triangle formed by the hydrogen atoms). In this excited state the nitrogen spends an equal amount of time on either side of the base, so the molecule has, on average, no positive or negative end. Townes saw that he could separate excited ammonia molecules from ground-state ones, and thus create a population inversion, by passing a beam of ammonia through a nonuniform electric field. The ground-state molecules would be deflected off to the side while the excited ones would continue on a straight path.

Townes's group started doing detailed calculations in the fall of 1951. Initially he had hoped to use deuterated ammonia, ND_3, which contains deuterium (hydrogen with an extra neutron in its nucleus) in place of the regular hydrogen atoms. The energy needed to excite the vibrational mode in ND_3 corresponds to a wavelength of 0.5 millimeters, which was in the range of radiation that Townes was trying to produce.

Almost immediately, however, a theoretical result mandated a change of direction. Zeiger and another group member, George Dousmanis, calculated that a cavity machined for 0.5-millimeter waves would not retain electromagnetic energy well. Townes decided to shift from the 0.5millimeter transition in ND_3 to the 1.25-centimeter transition in NH_3. That made it possible to build a cavity that would confine the waves much better; moreover, there were good off-the-shelf detectors and wave-guides available at 1.25 centimeters, but not at 0.5 millimeters, so building and calibrating the apparatus would be easier. By the same token, however, there were already good off-the-shelf generators of 1.25-centimeter radiation. Townes's decision to use regular ammonia effectively put aside the original goal of generating millimeter waves in favor of demonstrating the feasibility of using stimulated emission to generate centimeter waves.

Zeiger and Gordon began their experimental work in early 1952. The plan was to direct a beam of excited ammonia molecules through a cylindrical cavity about half an inch in diameter and four and a half inches long. Built with sufficient care, the cavity would retain energy from the stimulated emission of microwaves. These would build up and stimulate further emissions as more ammonia passed through. Eventually a strong beam of coherent microwaves would be created, and it could be released to the outside through a hole in the end of the cavity.

By February 1953, as Zeiger was completing his postdoctoral fellowship, the cavity was ready. With Zeiger gone to MIT, Gordon continued on alone under Townes's direction, debugging and modifying the equipment. At the end of 1953 he demonstrated electromagnetic wave amplification; the apparatus could not yet generate waves on its own ("oscillation"), but it could amplify ones fed in from outside. By April 1954 he had improved the equipment enough to also show oscillation, at a power output of about 0.01 microwatt. In the words of the Columbia Radiation Laboratory's quarterly report, it was "the first time that energy has been obtained continuously from a molecular resonance."

Townes and his team called their device a maser, short for "microwave amplification by stimulated emission of radiation." The word *amplification* in the acronym (rather than, say, *oscillation*) was appropriate, because it was as a highly sensitive amplifier, rather than as a generator of radiation, that the maser found its niche. Even as the maser was being developed for this application, however, other types of amplifiers began to appear in the centimeter region. They were somewhat noisier and less sensitive, but also more rugged; no liquid helium was needed, and they were not as bulky or as complicated to operate. Other sorts of amplifiers could also be tuned to a much wider range of wavelengths than a maser.

Indeed, one scientist was later to remark that the most important application of masers may well have been the stimulus they gave to the invention of more convenient microwave amplifiers. Masers were eventually relegated to those special circumstances in which the utmost sensitivity and freedom from noise was required —radioastronomy, satellite communications, and tests of special relativity, for example.

While masers were evolving, scientists returned to Townes's original goal: generating millimeter waves. It was still far from certain that the step to shorter wavelengths could be made. One problem was the chamber used to confine the radiation. The ammonia maser used a resonant cavity whose diameter was on the order of the emitted radiation's wavelength, about a centimeter and a half. But machining cavities of sub-millimeter dimensions would be a daunting task. Still worse would be the problem of dissipating heat from such small structures.

In September 1957, after a couple of years spent working on refinements and applications of his ammonia maser, Townes sat down to think thróugh the problem of shorter wavelengths systematically. He decided that trying to machine a device of precise sub-millimeter dimensions was hopeless, so he chose to base his calculations on the use of a cavity much larger than the wavelength. Single-frequency operation would have to be enforced by some other means.

He then wrote down an equation for the population inversion that would be needed. The expression revealed something surprising. Under appropriate conditions the required degree of population inversion (that is, the ratio of excited to unexcited molecules needed for a device to work) was largely independent of the wavelength. Theoretically, therefore, it would be feasible to leap over millimeter waves entirely—or even to leap five orders of magnitude from centimeter wavelengths to wavelengths of a few ten-thousandths of a millimeter, into the range of infrared and visible light.

This realization was contrary to prevailing wisdom. There was an unspoken presumption among scientists that the electromagnetic spectrum would be conquered step by step, as it always had been in the past: first radio waves, then ultra-high-frequency waves, then microwaves. Millimeter and submillimeter waves were the logical next step. It took considerable imagination for Townes to conceive of skipping over the region completely and pressing on to much shorter wavelengths.

Townes decided to join forces with Arthur L. Schawlow to conduct a detailed theoretical study. Schawlow was a physicist who had spent 1949-51 as a research associate in Townes's laboratory, and ended by marrying Townes's sister Aurélia in 1951. He was a burly young Canadian with an impish sense of humor; among other pranks, he was to make the "first edible laser" from a solution of Knox gelatin. In 1957 he was working at AT&T's Bell Laboratories, where Townes was a consultant.

Townes and Schawlow decided to use potassium vapor, a fairly simple and well-studied gas, as the active substance of their "optical maser." The biggest hurdle they had to surmount was mode selection: coming up with an analogue for the resonant cavity that would reinforce only waves of the desired frequency. Early in 1958 Schawlow proposed the idea of a long, slim tube whose end walls would reflect infrared and visible radiation but whose side walls would be transparent. Only waves traveling parallel to the long axis of the tube would be reflected; those traveling in other directions would pass out the side walls and be lost. This arrangement would produce a very narrow beam of coherent light (i.e., one having all photons in phase with each other) of several frequencies, which could be separated with a lens. This sort of tube came to be known as a Fabry-Perot resonator, because of its similarity to a device called the Fabry-Perot étalon, used in optical spectroscopy.

When they had completed their calculations, Townes and Schawlow submitted a patent application on behalf of Bell Laboratories. Shortly thereafter, in August 1958, they sent their theoretical paper "Infrared and Optical Masers" to *Physical Review*, the most widely read outlet for physics publications.

As with Joseph Weber and the maser, the idea for an optical maser occurred to others at around the same time. Robert H. Dicke, of Princeton University and RCA, recorded an idea for an infrared maser in his notebook in February 1956 and even patented it, but he never did any work to develop it. Then there was R. Gordon Gould, a graduate student at Columbia. He had also been thinking about transferring the maser principle to visible light. Gould was working on a Ph.D. thesis in molecular beams, but he thought of himself primarily as an inventor. He had received a master's degree in optical spectroscopy at Yale University in 1943, and when the war ended, he set himself up as an independent inventor. He had designed an improved contact lens and had tried to make synthetic diamonds. In the mid-1950s, however, he returned to fulltime graduate work, seeking to acquire a deeper scientific background.

In late October 1957 Townes discussed with Gould ways of exciting thallium vapor, which Gould was using in his thesis experiments. Gould was later to testify that these discussions alarmed him because they suggested that Townes was thinking along similar lines with regard to optical masers. Fearing that he might lose a claim to the priority of his ideas, Gould hastily wrote them up under the heading "Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation." In these notes Gould sketched out apparatus similar to what Townes and Schawlow would describe in their 1958 patent, including a Fabry-Perot-type resonator, and in the last two pages he listed some possible applications. He had the notes notarized on November 13, 1957.

Since the laser could, for the first time, produce visible light with the same coherence that microwaves had, it could do the same sorts of things with visible light that engineers had been doing with microwaves. As visible light is much more energetic, this was an exciting prospect. Gould foresaw optical radar and optical communications. He also pointed out the potential for laser-driven nuclear fusion: "Perhaps the most interesting and exciting possibility lies in focusing the beam into a small volume ... with a tremendous factor of energy concentration. A solid or liquid placed at that focal point would be heated at the rate of [about] 10^{16}°K/sec. If the substance were heavy water, nuclear fusion temperatures could possibly be reached before the particles were dissipated."

It is hard to tell what ideas, if any, Gould took from Townes. As a graduate student at the Columbia Radiation Laboratory, he worked in an atmosphere permeated with knowledge of Townes's pathbreaking maser work. Conscious, unacknowledged, and unscrupulous borrowings are certainly a fact of scientific life, but so are situations in which the same idea occurs independently to several people. Moreover, it is clear that however Gould may have arrived at his conception of the laser, he began to develop it in original ways. For example, Townes and Schawlow would not think of the Fabry-Perot resonator that appears in Gould's November 1957 notes until early the following year.

By the end of 1958, first through preprints of the Schawlow-Townes article and then through its publication in December, the idea of building a laser was widely known. It could hardly have come to the attention of scientists and engineers at a more auspicious time. *Research* was a byword in the 1950s. Corporations were creating campuslike central laboratories and giving their scientists unprecedented freedom to undertake long-range projects. The military, committed to an unceasing revolution in weaponry, was supporting the research and development necessary to achieve it.

In October 1957, against this already favorable background, the Soviet space satellite *Sputnik* burst on the scene, creating fears that the U.S.S.R. was getting dangerously far ahead of the United States in science. The federal government responded by creating new agencies and programs for science and technology and pouring additional money into them. New arrangements and higher funding levels were established at precisely the right time for lasers to flourish. When Townes applied to the Air Force Office of Scientific Research (AFOSR) in July 1958 for a contract to pursue experimental work on the potassium-vapor laser, he had approval in his hands by September. One scientist with the agency recalled this as perhaps "the shortest time between receipt of a proposal and the issuance of a contract in the history of AFOSR."

While Townes, at Columbia, was putting graduate students to work on potassium vapor, Schawlow, at Bell Laboratories, decided to work with crystals. He first considered synthetic pink ruby, a material that had recently been used in masers. Pink ruby is aluminum oxide doped with a little chromium; the stimulated emissions would come from chromium ions embedded in the crystal lattice. It was promising because it was readily available and familiar to scientists, unlike such exotic crystals as gadolinium ethyl sulphate, which had been used in other maser experiments.

However, Schawlow ran into a problem. Since the vast majority of the ions in pink ruby would be in the ground state to begin with, at least half of them would have to be excited in order to achieve a population inversion. Based on experimental work by Irwin Wieder of Westinghouse, Schawlow decided that exciting them would require too much energy. He abandoned pink ruby and turned his attention to different materials.

Meanwhile, others joined the race to build the first operating laser. Ali Javan, an Iranian-born physicist who had been working in Townes's group, first heard of opticalmaser research when he spoke to Schawlow in April 1958 while applying for a position at Bell Laboratories. In their paper Townes and Schawlow were proposing to create a population inversion in potassium vapor by irradiating it with light, a process called optical pumping. Javan saw this as a weak point; he doubted that optical pumping could deliver enough power. Excitement by collision struck him as more promising.

He decided to try an electric discharge tube filled with helium and neon. An electric discharge tube is a gas-filled chamber with positive and negative electrodes inside. At the proper voltage an electric current will pass between the electrodes, ionizing the gas and kicking off electrons. In Javan's scheme, energetic electrons from the discharge would excite helium atoms, which would transfer their energy to the neon atoms by collision. This would leave the neon atoms in excited states, from which they could emit stimulated radiation. Javan started systematic work on this scheme at Bell Laboratories in October 1958.

By that time Gould had left Columbia for the New York City firm of TRG, Inc. Prodded by his new management, he wrote up his laser ideas into a proposal that described various schemes for securing laser action. TRG submitted the proposal to the Department of Defense's Advanced Research Projects Agency (ARPA), one of the organizations that had been created in response to *Sputnik*. TRG requested $300,000 for a contract to try out Gould's ideas one at a time. ARPA, which had its eyes on technologies that could defend the nation against ballistic missiles, instead gave the company $999,000, asking it to pursue all of Gould's suggestions at once. In the spring of 1959 TRG filed a patent application on Gould's laser ideas. Since Bell Laboratories had previously filed a similar application, it led to an interference proceeding, the first of a series of patent litigations on Gould's behalf that would plague the laser industry for decades.

Some of the laser work was aired in September 1959 at a conference on quantum electronics that Townes organized for the U.S. Office of Naval Research. The meeting prompted Peter P. Sorokin and Mirek J. Stevenson of IBM's new Thomas J. Watson Research Center in Yorktown Heights, New York, to drop their other experiments and concentrate on laser research, using calcium fluoride crystals doped with uranium and samarium. It also inspired Theodore H. Maiman, a physicist who had been working with ruby masers at the Hughes Aircraft Company's research laboratories in Malibu, California.

Maiman distrusted the emphasis being placed on gas experiments by the scientists at the conference. He noted that potassium vapor was corrosive and difficult to work with, and that even inert gases such as helium and neon embroiled the experimenter in the complications of vacuum systems and worries about contaminants. Solids struck him as far more promising. They could give higher power, be more rugged, operate under less restrictive temperature conditions, and make smaller devices possible. Gases are easier to perform theoretical calculations on, because each molecule stands alone instead of being embedded in a lattice. But Maiman planned to use a simple solid whose properties were well known. He chose pink ruby. Maiman was aware that Schawlow thought it would require too much energy, but he was suspicious of Wieder's data, upon which Schawlow's opinion was based.

It is one of the ironies of the race to make the first operating laser that two of the earliest pioneers, Townes and Gould, ended up on its periphery. Townes, who had a strong sense of national service, felt compelled by the tensions of the Cold War to take a leave of absence from Columbia and serve as director of research at the Institute for Defense Analyses, the scientific organization that advised ARPA (though he continued to direct his graduate students one day a week). In 1961 he became the provost of MIT.

Gould ended up being legally barred from fully participating in the research that his ideas had helped start. Because of its potential applications to national defense, ARPA classified TRG's entire laser project secret. Gould had belonged to a Marxist study group during World War II, and so he was unable to obtain clearance, though he did serve as a consultant. Despite their increasing distance from the research their work had started in the 1950s, Townes and Gould continued their patent litigation for years, as Gould insisted that Townes had stolen his ideas, which Townes of course denied.

The two men's contributions to laser development took different forms. Townes, trained as a scientist, had built his maser and planned his laser with materials that were well understood and would yield simple, predictable results. His aim had been not so much to develop immediately useful devices as to demonstrate a technique and understand the principles behind it as rigorously as possible. Townes was deeply pious and saw basic science as a means of approaching sacred truths. "There is a tremendous emotional experience [in scientific discovery] which I think is similar to what some people would normally describe as religious experience, a revelation," he said in 1962.

Gould, by contrast, was a practical inventor. Within a year of first conceiving of the laser he had mapped out many different ways one could be built, explored scores of possible media and methods of excitation, and suggested applications by the dozen, some of which would be put into practice years later. He made errors in his analysis, and many of his projected uses were more vague hints or outlines than detailed proposals. Still, the range and depth of his inventive output, for a device that would not even be built for another two years, is startling.

A further irony of the laser story is that success appeared first where the fewest people expected it: from Maiman, with his "unpromising" pink ruby. One major factor in Maiman's victory was his discovery of a new way to "pump" (i.e., excite) the sample. He placed a cylinder of ruby within the spiral element of a photographer's flash lamp. A flash excited chromium ions in the ruby, which emitted coherent light as they returned to the ground state. This technique of "optical pumping" produced a pulse of laser light, instead of a continuous beam. Because of the transient nature of the output, and Hughes Aircraft's haste in publicizing Maiman's accomplishment (it was announced at a press conference in July 1960, a month after Maiman got his first results), many scientists were skeptical that what he had observed was in fact a laser (as optical masers were now commonly being called). Soon afterward, however, a group at Bell Laboratories duplicated Maiman's setup and verified his results rigorously.

Additional lasers soon followed. By November 1960 Sorokin and Stevenson, adopting Maiman's technique of flash lamps, got doped calcium fluoride to "läse" (i.e., undergo laser action). In December Javan, working with William R. Bennett, Jr., and Donald R. Herriott, succeeded in making the helium-neon apparatus work, achieving the first continuously operating laser. At the American Optical Company Elias Snitzer operated the first laser with doped glass as the emitting substance in the fall of 1961, making possible great gains in power output. TRG put a cesium-vapor laser, a near relative of the potassium-vapor laser, into operation in 1962.

By this time great excitement had gripped scientists and the general public. About four hundred companies had some kind of laser research in progress by 1962. Department of Defense spending on extramural laser research rose from about $1.5 million in 1960 to roughly $12 million in 1962 and about $20 million in the fiscal year 1963. Publications soared. Meetings were jammed. At its March 1961conference the Optical Society of America had to open additional rooms, fitted with loudspeakers, to handle the overflow crowds—much as conferences on superconductivity and "buckyball" carbon structures have had to do in recent years. Technical advances outstripped the available scientific vocabulary, and new words and units had to be invented. One scientist measured a laser's power output in "gillettes"—the number of razor blades it could burn a hole through.

Lasers became a staple of the popular press. *Life* ran a photo essay called "The Amazing Laser" in January 1963; *Reader's Digest* published an article called "Light of Hope—or Terror?" in February 1963; *The Saturday Evening Post* weighed in with "The Astounding Laser" in October 1964. One substance after another was being converted into a laser until in 1963 *Fortune* could quote a scientist as saying, "I expect any day now to hear that someone has got a tube of plain air to lase." When Townes and two Soviet pioneers, Nikolai G. Basov and Alexander M. Prokhorov, shared the Nobel Prize in physics in 1964 for their work on masers and lasers, the U.S. public understood as well as it ever has why the honor was being awarded. (Schawlow would get the prize in 1981 for his work in laser spectroscopy.) Then the hoopla abruptly died down. At the same time, the rate of scientific publication increased. The excitement of invention was being replaced by the hard work of developing reliable and cost-effective systems.

Getting lasers out of the laboratory and into the marketplace took the rest of the decade. The first systems produced in sizable quantities were military ones, as has been typical for postwar American high technology. "Smart" bombs and other tactical laser weapons were ready for field use in the early 1970s. Gradually, as the 1970s and 1980s passed, the emphasis in laser applications has shifted from military to civilian uses, which are numerous. Today lasers are used to cut, bore, and etch materials with precision undreamed of a few decades ago; to provide exact, straight-line paths for alignments during construction; for extremely accurate distance measurements; in holography and printing; and for many other tasks.

Three-quarters of a century after Albert Einstein discovered stimulated emission, the technology it spawned has become pervasive. Einstein was a pacifist and would likely have regretted the military applications his research made possible (if his ambivalence about the atom bomb is any guide), but he would have applauded the laser scalpels and laboratory instruments that have followed. And he would certainly have been delighted by compact audio discs for listening to the classical music he so loved.

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