Research on Maser-Laser Principle Wins Nobel Prize in Physics

On 29 October 1964 the Royal Swedish Academy of Sciences awarded the Nobel prize in physics to Charles H. Townes of Massachusetts Institute of Technology, Cambridge, and to Nikolai G. Basov and Alexandr M. Prokhorov of the Lebedev Institute, Moscow. The award was for "fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle."

The word *maser* is an acronym standing for microwave amplification by stimulated emission of radiation. The word *laser* is a similar acronym, with *light* substituted for *microwave*. The maser-laser principle is, briefly, that the excess energy stored in excited atomic systems can provide coherent amplification of electromagnetic waves. By "coherent amplification" is meant an amplification process wherein not only the strength of an incoming signal is increased but the phase of the signal wave is preserved and, in the case of a beam of light, the direction of the beam is preserved. The maser-laser idea is important for several reasons. First, a (microwave) maser amplifier can be virtually noiseless, hence these amplifiers have found an important use in the very sensitive receivers used for radio astronomy and for communication by artificial satellite. Second, since maser-laser amplification occurs as a bulk property of certain suitable "active" materials, the devices are freed from the necessity of incorporating electrical circuits whose dimensions are comparable to the radiation wavelength. This has made coherent amplification at optical frequencies possible. In a laser, a beam of infrared radiation or visible light is amplified while passing through such an active material.

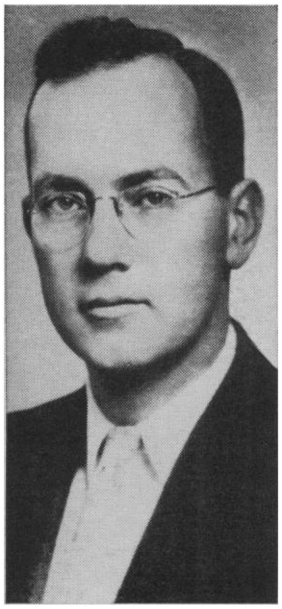
In the early 1950's a number of scientists, including the new Nobel laureates and Joseph Weber of the University of Maryland, conceived the maser idea. The concept came to Townes while he was sitting on a park bench in Washington in 1951, wondering how it might be possible to extend radio and microwave techniques farther toward infrared frequencies. Later that year, Townes, who was then a professor of physics at Columbia University, Herbert J. Zieger, and I made preliminary calculations on a maser proposed by Townes. (The one we actually built, and which first worked late in 1953, was remarkably like this original proposal.)

In 1954, Zieger, Townes, and I published in the *Physical Review* the results of our early successful experiments. Our maser utilized a beam of ammonia molecules to achieve amplification and self-sustained oscillations at a microwave frequency near 24,000 megacycles per second. Individual free ammonia molecules, tetrahedral in shape and consisting of a nitrogen atom and three hydrogen atoms, perform a vibration called the inversion vibration at this frequency.

The nitrogen atom passes back and forth through the plane of the three hydrogen atoms. This vibration is described in quantum mechanics as a transition between two energy states called inversion states. There are actually a number of different pairs of inversion states, each pair associated with a different possible state of rotation of the molecule, but there is no point in going into such added complications. Molecules in the inversion state of lower energy absorb microwaves at the inversion frequency, in the process making transitions to the state of higher energy. Similarly, molecules in the state of higher energy amplify microwaves at the inversion frequency, in the process making transitions to the state of lower energy. Normally, in accordance with Boltzmann's law, more molecules find themselves in states of lower energy than in states of higher energy, and the combination of the two processes results in absorption. Townes and his students were able to make the amplification process dominate the absorption by sending a beam of ammonia molecules into a vacuum chamber and, by means of a strong electric field, keeping in the beam only those molecules which were in the upper inversion states and were therefore capable of amplification. The beam of amplifying molecules was then sent through a microwave cavity resonator tuned to the inversion frequency. It was observed that the molecular beam was indeed amplifying microwave signals sent through the resonator. Also, where the beam was sufficiently strong, so that the power (about a billionth of a watt) necessary to induce the molecular transitions was available from the beam itself, the maser resonator broke into spontaneous oscillation, giving out a microwave signal at 24,000 megacycles per second with no microwave input.

Among my recollections of this work is the day when, in Townes's office, it was decided to go ahead and build something. Characteristically, Townes gave no impression of pushing that decision but, rather, asked Zieger and me if we thought the experiment was worth while. Our early calculations, which later turned out to be based on somewhat pessimistic premises, had shown that the device had just a bare chance of achieving self-sustained oscillations. On the other hand, we had found that even if it did not realize our best hopes, the device could still work as a spectrometer of unusually high resolution, and Townes pointed out that there was some yet unseen hyperfine structure in the ammonia spectrum that we could probably examine. So, happily, we went ahead. Another recollection is of the day shortly after the maser had achieved oscillation, when, at a lunch table in the cafeteria of Teachers College, with about five of us who were involved with the maser, Townes suggested that this new device really ought to have a name. He immediately vetoed any name ending in the suffix *-tron*, and before lunch was over the name *maser* had emerged.

In the meantime, Basov and Prokhorov had, in 1952, independently of the work in the United States, presented a paper at an All-Union (U.S.S.R.) Conference on Radio Spectroscopy in which they discussed the possibility of constructing a "molecular generator"—that is, a maser. Their proposal, first published in 1954, was in many respects similar to



Charles H. Townes

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Townes's. They did not expect to achieve oscillations in the particular example they worked out. However, they were optimistic that better ways could be found of achieving such a device.

In 1955 Basov and Prokhorov discussed, in a short note, a new way to obtain the active atomic systems for a maser—a method which turned out to be of great importance. In this, the so-called three-level method, the atomic systems must be initially distributed among at least three energy states with the fewest atomic systems in the highest state, the most in the lowest state, and an intermediate number in the middle state. This, again, is in accordance with Boltzmann's law. By means of externally supplied radiation near the frequency of the transition between the outer two states, atoms are transferred from the lowest state to the highest by absorption of the radiation. This may, for example, leave the intermediate state with more atoms than are in the lowest state, and so maser action will take place at the frequency corresponding to the transition between the latter two states. Basov and Prokhorov suggested this idea as a way to enhance maser action in a beam of molecules. Nicolaas Bloembergen of Harvard University later came upon the same idea but applied it to paramagnetic crystals, whose resonant frequencies in the microwave range correspond to the precessional motion of the magnetic moments associated with the paramagnetic electrons in the crystal lattice. Bloembergen's idea, first put into effect by G. Feher, H. E. D. Scovil, and H. Seidel at Bell Telephone Laboratories, gave rise to the development of a series of extremely sensitive microwave amplifiers which have proved their usefulness in receivers for radio astronomy and for satellite communications (Telstar).

Perhaps the most important event following the conception of the maser was a paper entitled "Infrared and optical masers," published in the *Physical Review* in 1958 by A. H. Schawlow (then at Bell Telephone Laboratories) and Townes. In this paper were discussed the important ideas necessary for the extension of the maser concept to the short-wavelength infrared and optical regions of the electromagnetic spectrum. Others, notably Basov and Prokhorov and Robert H. Dicke of Princeton University, had discussed the possible extension of maser techniques to frequencies higher than the microwave range, but Schawlow and Townes took the important step of investigating in detail just how far one could expect to go.

A laser consists, in essence, of a relatively long and thin column of amplifying substance. A beam of light of the proper frequency traversing this column is amplified. A laser oscillator can be made by terminating the amplifying column at both ends with reflectors which send the light back and forth through it. If the gain in the active substance exceeds the loss the light beam incurs on reflection from the mirrors, then an intense light beam builds up in the laser. One of the mirrors is made partly transparent so that some of the light comes out that end to form the output beam.

The first observation of laser action was achieved by Theodore H. Maiman of the Hughes Aircraft Corporation, in 1960. The active substance he used was a single crystal of ruby. Ruby is an aluminum oxide crystal in which a small fraction of the aluminum ions have been replaced by chromium ions. These chromium ions absorb green and blue light and hence impart a red color to the ruby. In addition, ruby is fluorescent in the deep red. Much of the absorbed green and blue light is reemitted at a wavelength near 6940 angstroms. The chromium ions are boosted from their ground, or lowest-energy, state into excited electronic states when they absorb green or blue light. From these excited states they drop down into a rather long-lived or metastable state by the emission of heat energy into the crystal lattice. From the metastable state they drop back to the ground state by emission of light of 6940-angstrom wavelength. Thus, ruby exhibits the basic requirements for a three-level laser. Under strong enough illumination, more chromium ions can be lifted into the metastable state than remain in the ground state. Then laser action can occur. In a typical small ruby laser reflectors are applied to the ends of a ruby rod 2.5 or 5 centimeters long and perhaps 0.3 centimeter in diameter. The rod is placed within a helical flash lamp much like those used in high-speed photography. When the lamp is flashed, a bright beam of red light emerges from the partially transmitting end of the ruby rod.

Shortly afterward, A. Javan, William R. Bennett, Jr., and Donald R. Herriott of the Bell Telephone Laboratories demonstrated that laser amplification was obtainable continuously in a low-pressure helium-neon gas discharge, and this has led to the development of a wide variety of gas lasers whose amplification frequencies range from wavelengths longer than 100 microns, in the infrared, on through the visible spectrum and somewhat into the ultraviolet.

The light beam from a laser has extraordinary properties. Its spread as it travels can be as small as is allowed by the basic laws of wave optics. Such a beam can be focused by a good lens to a spot only a few wavelengths in diameter. Its amplitude and frequency are very stable, so it can be modulated to carry broad-band communications, much as microwave beams can. But much work needs to be done before all of the uses of these fascinating devices will be discovered, and before it is known which of its many uses are important.

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Astronomy: Academy Study Urges 10-Year, $224 Million Program Of New Telescope Construction

As financial and political considerations impinge on federal support for science, and as the tools of research become increasingly expensive, the scientific community has developed a literary form to assist its relations with government—namely, the experts' report spelling out the requirements, opportunities, and benefits of federal support for particular fields of research. The distinguishing feature of these reports is careful analysis of the present situation and cautious appraisal of the future, woven through with assertions that the projections of financial needs are conservative, and that the failure of the government to meet them will have unwelcome consequences.

Last year's Ramsey report on high-energy physics, prepared under the joint auspices of the Atomic Energy Commission and the White House Office of Science and Technology, was one of the first fully developed examples of this genre; and though the final word is not yet in on the future of that costly discipline, the quality, thoroughness, and prudence of that report seem to have left little to be said for a long time on what can and should be done in the accelerator field.

Now, just this week, another report has come forth to present the scientists' case for federal support in a costly field, ground-based astronomy.* The report, prepared by a panel of eight astronomers and chaired by A. E. Whitford of the Lick Observatory, in California, is the first of a series planned by the National Academy of Sciences' Committee on Science and Public Policy (*Science*, 23 October). In general it follows the pattern of analysis and advocacy that marked the high-energy physics report, but it adds a new line of argument for support—that the astronomy recommendations, totaling $224 million over a decade, are a pittance compared to the funds going into the space program. The report states that the yearly cost for implementing its recommendations would amount to only one-half of 1 percent of the present annual space budget, and it argues that (i) "our new space capability increases the need for ground-based facilities," and (ii) the National Aeronautics and Space Administration, in its own interest, should start putting substantial funds into earth-bound radio and optical telescopes. NASA's reaction is yet to be heard, but since many disciplines are eyeing the space treasury, and since NASA claims it is close to being financially overdrawn on its commitment to land a man on the moon in this decade, it is difficult to see why the space agency would clutch at a chance to become a major financier for a field that it has heretofore managed virtually to ignore. NASA is, in fact, putting a great deal of money into space-borne astronomical facilities, and the ground-based astronomers praise this space effort and urge its continuation, but they point out that one orbiting observatory costs $60 million and lasts 1 year, whereas "a similar telescope on the ground" costs about $330,000 and can be expected to serve for at least 50 years.

Outside of eyeing the NASA budget as a source of funds, the Astronomy panel sticks to studious analysis of the present and offers what George B. Kistiakowsky, chairman of the parent committee, refers to as "very reasonable" and "definitely conservative" plans for a 10-year program of construction and training.

"Legacy of the Past

"In optical astronomy," it points out, "we are living largely on the legacy of the past, using instruments handed down to us from the era of private financing." The panel acknowledged that many of these can be expected to continue as productive facilities, but it argued that "rapid progress on the unsolved problems" is limited by the "*extremely small number of telescopes of adequate size in dark-sky locations* . . ." (original italics), and it went on to present a dismal picture of the availability of major facilities for the nation's astronomers.

Only the 120-inch Mount Lick and the 200-inch Mount Palomar telescopes, it pointed out, "are adequate for pushing current frontier problems to the observational limit." Experience with these and other facilities, it continued, has shown that they can handle an optimum number of perhaps ten long-term problems at any one time, giving each of them about 35 nights a year. Since, at this rate, 2 to 4 years are often required to complete work on a problem, "this means that 10 to 15 staff astronomers per major telescope is all that can be effective. With only two major frontier telescopes operating," the panel went on, "this means that no more than two or three astronomers in the entire world now have the opportunity to work on the most exciting problems in any given field. Competition and the obviously needed opportunity to check results are lacking. The problem, serious enough from the standpoint of progress, is even more serious in another respect; it squeezes out of research life at the frontier top-notch men who, by accident, are not among the fortunate staff members of the big observatories."

General Inadequacy

But in the optical field it is not only large telescopes that are lacking, the panel found. "The inadequacy . . . is equally critical all along the line" and is producing harmful effects on research as well as on the increasing number of students who have been attracted to astronomy studies.

Continuing its appraisal of optical astronomy, the panel recommended that "first priority" should go to the construction of three large telescopes in the 150- to 200-inch aperture range. Why not two or six large telescopes? The answer appears to be a mixture of scientific judgment, public relations, and financial caution. The panel explained its choice of three as follows: "The decision to recommend three such telescopes was dictated in part by the . . . need for acceleration of research on faint objects, and the fact that the number of large telescopes has not in recent years kept pace with the growth of the astronomical work force in this country. Three more such telescopes would double the number of U.S.-controlled large telescopes in the aperture range 100 to 200 inches. Since . . . the number of astronomers in the United

* *Ground-Based Astronomy, A 10-Year Program*, 105 pp.; $4, Publications Office, National Academy of Sciences, Washington, D.C.