PHYSICAL REVIEW RECORDS THE BIRTH OF THE LASER ERA

The first paper reporting an operating laser was rejected by *Physical Review Letters* in 1960. Now lasers are a huge and growing industry, but the pioneers' chief motivation was the physics.

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The historical development of masers and lasers has been well documented in several books.[1] It is not my purpose here to recapitulate or improve on those accounts, which focus on the roles individual scientists, industry and funding agencies played in the evolution of the laser.

The purpose of this brief article is to point out that the *Physical Review* and *Physical Review Letters*, the offspring of its middle age, published a majority of the early, essential steps in this development. That fact, I contend, provides *prima facie* evidence that the original motivation of the individual scientists who pioneered in the development of lasers and masers was the intellectual challenge of problems presented by atomic, molecular and solid-state physics on one side, and by electronic and optical technology on the other.

In the mid-1950s the funding agencies and industrial management may have had visions of the birth of a multi-billion-dollar industry. But the physicists who did the early work were more intrigued by basic questions of the interaction of molecules and magnetic spins with microwave and millimeter-wave radiation. Could atoms or molecules be used to generate such radiation, they asked themselves, and would this lead to better spectroscopic resolution?

The maser

At Columbia University in 1951, Charles Townes conceived the idea of a microwave oscillator based on stimulated emission by molecules in an excited state. He and his coworkers James Gordon and Herbert Zeiger succeeded in operating the first such molecular oscillator at the frequency corresponding to an inversion-doublet resonance of the ammonia molecule. (See figure 1.)

Their first paper appeared in 1954 as a letter to the editor in the *Physical Review*.[2] There was no separate journal called *Physical Review Letters* until July 1958. The note by Townes and his colleagues was entitled "Molecular Microwave Oscillator and New Hyperfine Structure in the Microwave Spectrum of NH_3." A comprehensive paper soon followed,[3] its title, "The Maser—New Type of Microwave Amplifier, Frequency Standard and Spectrometer," sporting the new acronym for "microwave amplification by stimulated emission of radiation." In those early years, before 1955, there was virtually no known competition from other research groups, although an independent parallel effort had been launched by Nikolai Basov and Alexander Prokhorov in the Soviet Union.

After its demonstration with molecular beams, the maser concept began to attract the attention of the magnetic resonance community. Those physicists had known for many years that a transient state with inverted magnetization, displaying a negative magnetic resonance absorption, could be obtained by three methods: adiabatic rapid passage,[4] instantaneous field reversal[5] or the imposition of a 180° pulse.[6] Because solid-state masers based on population inversion between magnetic-spin levels were now recognized as promising low-noise amplifiers, it became important to devise a scheme that would permit continuous-wave operation in a piece of material at rest. That would obviate

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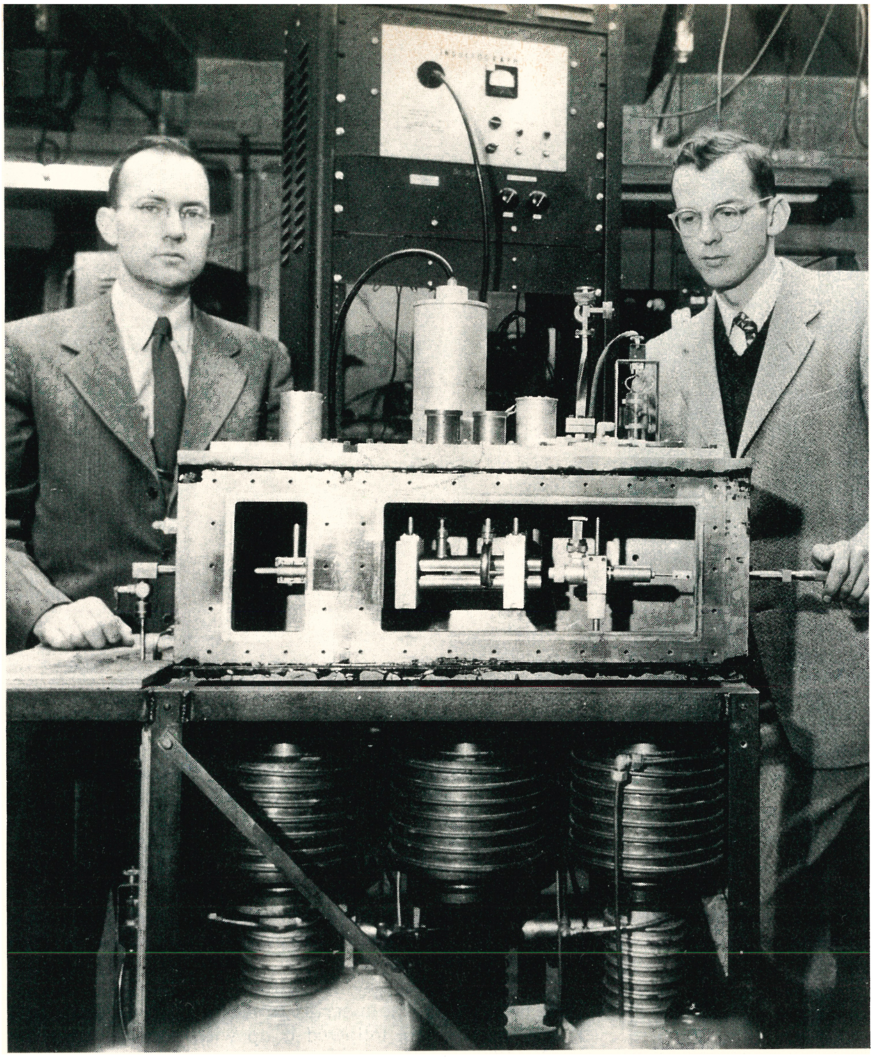


Charles Townes and his student James Gordon (right) in 1954, showing off one of the first masers they built at Columbia University. **Figure 1**

the need for molecular beams.

My proposal for a three-level solid-state maser[7] solved this problem by saturating a resonance between two nonadjacent energy levels. I argued that the interplay of such a pump with the various relaxation mechanisms that seek to restore thermal equilibrium between all levels in a multilevel system would often lead to a steady state in which an inverted population could be maintained indefinitely. This concept was experimentally demonstrated a few months later by Herbert Scovil and coworkers at Bell Labs. They too published their result in the *Physical Review*.[8]

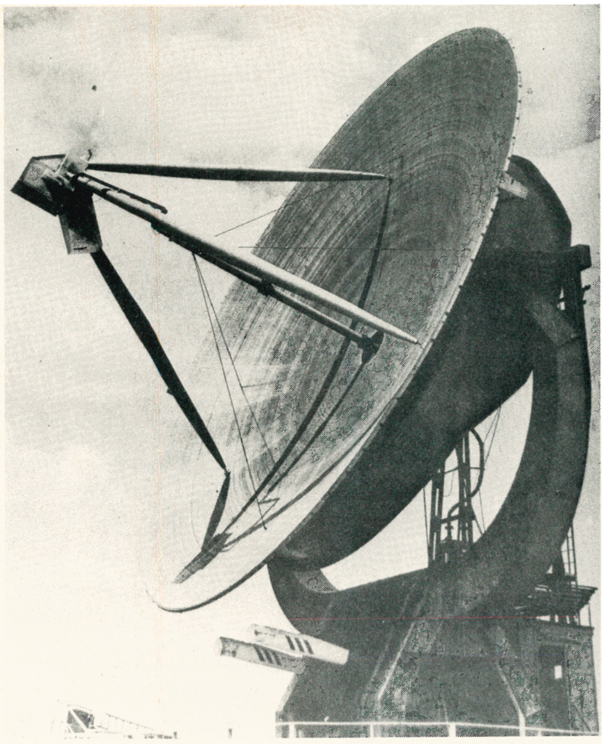
Those papers were followed by an explosion of work on solid-state masers. The devices really did achieve the expected low noise temperature. They were used as low-noise preamplifiers in some radiotelescopes. (See figure 2.) Arno Penzias and Robert Wilson at Bell Labs used a ruby maser amplifier for their celebrated discovery of the 3 K cosmic microwave background. Some solid-state masers were also used in microwave antennas for deep space probes, receiver stations for satellite transmitters and in Distant Early Warning radar systems.

For most practical purposes, however, solid-state masers could not compete with parametric semiconductor heterodyne receivers. The latter are cheaper and easier to build, and they do not require liquid helium cooling to provide good noise characteristics. From a commercial point of view, masers never became significant.

A very different story

With regard to the marketplace, the development of lasers has been a very different story. The laser market has developed along a curve that mimics the development of the market for semiconductor devices and chips, with a time lag of roughly 17 years.[9] The annual laser market now totals about $20 billion; that's where the semiconductor electronics market was in the mid-1970s. The widespread commercial applications of lasers include their use in fiber optic communication systems, surgery and medicine, printing, bar-code readers, recording and playback of compact disks, surveying and alignment instruments, and many techniques for processing materials. Laser processing runs the gamut from sculpting corneas by means of excimer laser pulses to the heat treatment, drilling, cutting and welding of heavy metal parts in the automotive and shipbuilding industries by CO_2 lasers with continuous-wave outputs exceeding 10 kilowatts. The commercial laser market for peaceful applications is now at least three times as big as the military market.

Much of the funding of basic laser research was initially motivated by potential military applications, and the general public was being excited by death-ray stories in newspapers and James Bond movies. But the indi-



Ruby maser mounted in 1957 at the focus of the 50-foot radio antenna on the roof of the Naval Research Lab in Washington, DC. Built by Lee Alsop, Joseph Giordmaine and Townes at Columbia, this was the first maser to be used as an amplifier for radioastronomy. **Figure 2**

vidual scientists responsible for the early laser work were more excited about extending the maser and other concepts of the emerging discipline of quantum electronics to higher frequencies in the electromagnetic spectrum.

The promise of higher resolution in optical spectroscopy and of higher optical irradiances was attractive from a purely scientific point of view. This promise has been amply fulfilled. Lasers have revolutionized spectroscopy, and they have given birth to the new field of nonlinear optics. They are used extensively in many scientific disciplines, including chemistry, biology, astrophysics, geophysics and environmental sciences.

Townes and Arthur Schawlow were the first to present a fundamental discussion that extended maser principles to optical frequencies. Their paper[10] was entitled "Infrared and Optical Masers." It combined the notion of pumping a gas to obtain population inversion between a pair of atomic levels separated in energy by an optical quantum with the idea of an optical resonator in the Fabry–Perot geometry of two parallel mirrors. With small enough mirrors sufficiently far apart, they pointed out, one should be able to get good transverse-mode selection.

The first laser

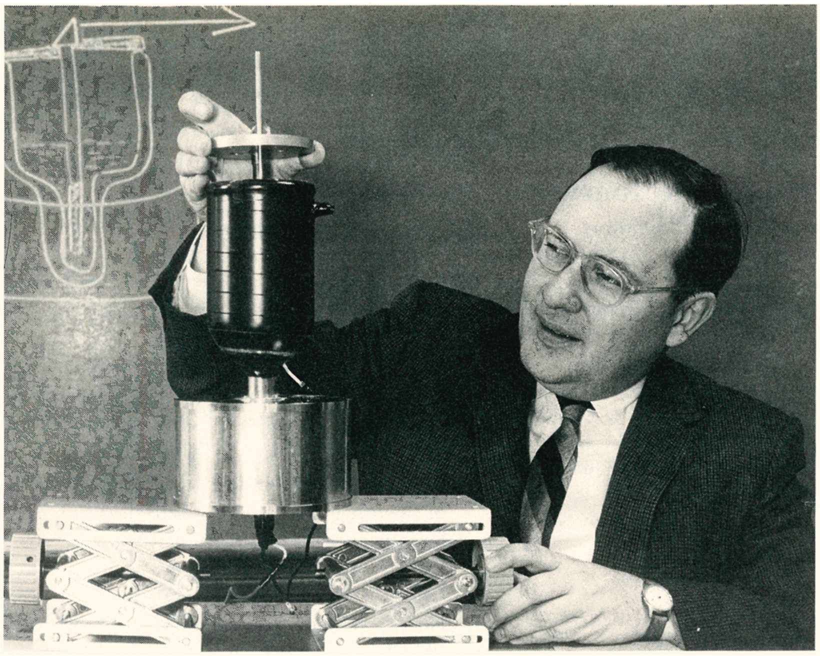
In 1960 Theodore Maiman demonstrated the first operation of a laser. He used the fluorescence of a ruby crystal pumped by a helical xenon discharge flashlamp. He created the optical resonator by putting reflective coatings on the end faces of the ruby cylinder. Maiman submitted a paper to the new *Physical Review Letters*. It was rejected. The probable reason for this unwise rejection was the stated editorial policy of rejecting letters on masers that did not "contain significant contributions to basic physics."[11] There was also the long-standing policy against serial publication; an earlier paper by Maiman on optical fluorescence in ruby had, after all, just been published.[12]

Maiman promptly submitted a somewhat abbreviated form of his manuscript to *Nature*, which published it forthwith.[13] He followed it up with detailed accounts in the *Physical Review*.[14]

Physical Review Letters quickly corrected its policy and published a confirmation of laser action in ruby by Schawlow and coworkers at Stanford.[15] (See figure 3.) It also published the account of the second type of operating laser, based on the fluorescence of U^{3+} ions embedded in a CaF_2 crystal.[16] Soon afterward, the letters journal published the announcement, by Ali Javan and coworkers at MIT, of the first operating gas laser.[17] Javan had already written in 1959 about the possibility of obtaining population inversion in a noble gas discharge.[18] This first continuous-wave He–Ne laser operated at the infrared wavelength of 1.15231 microns. Soon laser action was demonstrated at the visible wavelength of 632.8 nm, and the He–Ne laser became the first mass-produced laser type. It is widely used for alignment and educational purposes.

New fields, new journals

In 1961 *Physical Review Letters* also published a seminal paper[19] by Peter Franken and coworkers at the University of Michigan on the nascent subject of nonlinear optics. It described the generation of the second harmonic when a ruby-laser pulse passes through a quartz crystal. The editorial office carefully removed a little smudge on a photographic recording. That smudge, unfortunately, was precisely the experimental evidence of the second harmonic. No erratum was ever published, because most cognoscenti were willing to believe the result and those who had access to a ruby laser readily reproduced the



Arthur Schawlow in 1961 with a laser built by his Stanford group that employed chromium ions embedded in dark ruby. **Figure 3**

effect. Many new nonlinear optical phenomena were reported during the next few years, both in *Physical Review Letters* and in the *Physical Review*.

The operation of a semiconductor laser was first described in 1962 in *Physical Review Letters*, by Robert Hall and coworkers at General Electric.[20] But three other groups, working independently, announced similiar results on the operation of GaAs injection lasers at nearly the same time in the first volume of *Applied Physics Letters*. This new rapid-publication journal would become a favorite channel for publication in the burgeoning field of lasers and quantum electronics. It was later joined by *Optics Communications*, *Optics Letters* and other rapid-communication journals in the field of optoelectronics. Several other journals devoted to this field were born in the early 1960s. Among these were *Applied Optics* and the *IEEE Journal of Quantum Electronics*.

The laser industry is now served by a long list of journals appearing in many countries. Their contents span the range from physics and applied physics to various engineering specialties and trade communications. The *Physical Review* and *Physical Review Letters* still retain their fair share of articles related to laser physics. On the occasion of the centenary of the *Physical Review* it is appropriate to present evidence of the dominant role that journal has played in revealing the scientific principles that underlie laser technology.

The development time in this field, from initial conception and prototype demonstration to large-scale applications, is measured in decades. During the 1960s, many different basic types of lasers and modes of operation were established, together with a thorough understanding of the physical principles. The 1970s witnessed a proliferation of devices and improved materials. During the 1980s, lasers and laser-based systems became a mature, economically competitive technology. For example, the semiconductor laser, first demonstrated in 1962, became technologically important only in the 1980s.

In 1988, two hundred million semiconductor lasers were produced, by methods borrowed from microelectronic manufacturing. Semiconductor lasers are essential in fiber optic communication systems, in compact disk players and in pointing devices. Semiconductor laser arrays may eventually replace widely used gas lasers such as the He–Ne and argon ion lasers. It is not yet clear what role integrated solid-state optical devices will play in information processing.

In this cursory review, I have tried to trace the roots of the now sturdy trees of laser technology back to the seeds that physics planted almost half a century ago.

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