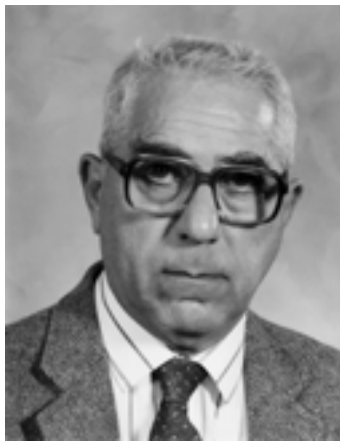
Essay

THE INVENTION OF THE LASER



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The laser had its conceptual beginnings in the early 1950s, when many scientists were engaged in radio frequency and microwave spectroscopy. This field evolved vigorously after World War II, due in part to wartime breakthroughs in radio frequency and microwave technology. These breakthroughs did much to tip the scales of warfare in favor of the Western Allies, principally in their air and naval defense efforts, and contributed measurably to successes in air warfare over Great Britain and antisubmarine warfare in the North Atlantic. The principal centers for radio and microwave research were in Great Britain and the United States.

EARLY MICROWAVE SPECTROSCOPY

The first report of spectroscopy conducted at microwave frequencies was that of Cleeton and Williams at the University of Michigan in 1934.[1] The object of their study was the ammonia gas molecule, NH_3. Through spectroscopic studies, fine structure had been observed in ammonia's infrared rotational bands. This structure was interpreted as being due to the tunneling of the nitrogen atom through the plane of the three hydrogen atoms (see Section 8.2). Theoretical studies of the ammonia molecule's infrared spectrum had suggested that its doublet's wavenumber separation would be of the order of 1 wavenumber, cm^{-1}, which falls outside the infrared but within the microwave region.[2]

To obtain a source of radiation of this energy, magnetrons were borrowed from the Westinghouse Corporation's research laboratory, but they generated radiation of much lower frequencies than those required for the proposed work on ammonia. Using the Westinghouse magnetrons as models, Cleeton and Williams constructed several magnetrons by scaling down the dimensions. To measure wavelength, they constructed a device similar in operation to an echelon (a diffraction grating consisting of a series of plates of equal thickness, stacked like a staircase). They succeeded in observing the inversion at a wavelength of approximately 1 centimeter, just where the ammonia infrared data had suggested.

After this early beginning, microwave spectroscopy remained dormant until the end of World War II, largely because microwave technology had not yet developed to the point where spectroscopy in the centimeter wavelength range could be performed. While working on a project for the war effort, some scientists at the MIT Radiation Laboratory observed an unexplained attenuation in test microwave signals directed across the Charles River from Cambridge to Boston. The phenomenon was most prominent at a time when a local garbage scow released waste products into that river. Later, after the advent of microwave spectroscopy, the cause of this microwave signal attenuation was found to be the effluence of ammonia gas from waste discharge!

Microwave spectroscopy is a consequence of transitions between energy levels, which usually generate spectra in the microwave region. Radio frequency spectroscopy, by contrast, is the result of the fact that nuclear electric quadrupole moment and nuclear-magnetic dipole moment energy separations lie in the radio frequency region of the electromagnetic spectrum. In the case of nuclear electric quadrupole moment transitions, an interaction between nuclear electric quadrupole moments and local electric field gradients causes the partial removal of nuclear-spin angular momentum

[1]C. E. Cleeton and N. H. Williams, *Phys. Rev.* 46:235, 1934.

[2]D. M. Dennison and J. D. Hardy, *Phys. Rev.* 39:938, 1932.

degeneracy. Nuclear magnetic resonance, on the other hand, is due to the removal of nuclear-spin angular momentum degeneracy by an external magnetic field.

By the mid-1950s, the physical science and engineering journals were filled with research papers dealing with radio frequency and microwave spectroscopy. During this decade, significant research in either of these fields might be conceived, executed, and submitted for publication within a single month. Toward the end of the 1950s, microwave spectroscopy was headed for a crisis of sorts, because the supply of unstudied and relatively uncomplicated gas molecules with spectra in the centimeter wavelength region was being depleted. One way to open up new areas of investigation was to extend the wavelength range of microwave spectroscopy to the millimeter and submillimeter region, thereby including molecules of greater moment of inertia. However, there seemed to be no way to obtain monochromatic radiation of constant amplitude from vacuum tubes at wavelengths significantly below 3 mm.[3]

The development of coherent sources of radiation in the centimeter, millimeter, and submillimeter wavelength region took place in two steps, both of which involved the ammonia molecule. The first occurred in 1952 with a report by H. Lyons of the Central Radio Propagation Laboratory of the National Bureau of Standards in Washington, D.C.[4] Lyons described the performance of a clock—a quartz-crystal-controlled oscillator slaved to the peak absorption of the (3, 3) rotation inversion line of the ammonia molecule. The notation (3, 3) signifies the $J = 3$ and $K = 3$ angular momentum states of a symmetric top rotor, with J representing the angular-momentum quantum number of the molecule's rotation about its principal axis and K describing rotation about an axis perpendicular to the principal axis.[5] To first order of approximation, the ammonia molecule does not exhibit an electric dipole moment because the nitrogen atom tunnels through the plane of the three hydrogen atoms, thereby causing its electric dipole moment to reverse its direction relative to the molecule's principal axis of symmetry (see Section 7.2). In second order, however, its electric dipole moment is nonvanishing so that, in fact, it exhibits a robust absorption at 23 870.127 MHz in the microwave region. This clock became known as the ammonia clock. When compared with the primary standard quartz-crystal-controlled oscillator clocks at the National Bureau of Standards, the ammonia clock proved to have a stability of the order of a few parts in 10^9. The ammonia clock used the molecule's rotation inversion absorption line as a reference for its own quartz crystal-controlled oscillator, thereby providing an oscillator of hitherto unprecedented stability.

The second step was a noteworthy advance in 1953, when J. Weber of the University of Maryland provided, for the first time, a theoretical strategy for obtaining coherent amplification of electromagnetic radiation by stimulated emission.[6] The first step, he said, is to create a thermodynamical nonequilibrium distribution of energy levels in a crystalline or gaseous substance. Using the Einstein coefficients for spontaneous and induced transitions,[7] Weber demonstrated the necessary conditions for the coherent amplification of radiation. Oscillations could be sustained if proper control of feedback and gain were provided to compensate for radiation losses. In his paper, Weber estimated the performance of a gas at low pressure. As a choice of an active species, he suggested the gaseous ammonia (3, 3) rotation inversion line, whose absorption is one of the strongest in the microwave region. For a gas pressure of 10^{-2} torr and a frequency of 30 GHz, he estimated that gains of the order of 0.02 dB per meter of

[3]W. Gordy, *Annals of the New York Academy of Sciences* 55:774, 1952.

[4]H. Lyons, *Annals of the New York Academy of Sciences* 55:831, 1952.

[5]C. H. Townes and A. L. Schawlow, *Microwave Spectroscopy*, New York, McGraw-Hill Book Co., 1955. See p. 312.

[6]J. Weber, *Trans. IRE Prof. Grp. Electronic Devices, PGED-3*, vol. 1, 1953.

[7]A. Einstein, *Mitt. Phys. Ges. Zurich* 16(18):47, 1916; Z. *Für Phys.* 18:121, 1917.

ammonia could be achieved, resulting in power levels of 2 mW per 100 cm^3 of ammonia. He pointed out that amplification would die out within a period of the order of the molecule's relaxation time unless the system were maintained in a nonequilibrium thermodynamic condition.

THE FIRST MASERS

Within a year or so of Weber's publication, two molecular devices for generating microwave radiation were reported by N. G. Basov and A. M. Prokhorov of the Lebedev Institute in Moscow[8] and by J. P. Gordon, H. J. Zeiger, and C. H. Townes of Columbia University in New York.[9] Both devices used the ammonia molecule as the active species. The acronym *maser* was coined to stand for "**m**icrowave **a**mplification by **s**timulated **e**mission of **r**adiation." In particular, the Columbia University maser made use of molecular beam technology.

As described in Section 7.2, the ammonia molecule can be represented by one of two configurations (see Fig. 7.14). In one (the right-handed molecule), the nitrogen lies above the plane of the hydrogen atoms. In the other (the left-handed molecule), nitrogen lies below the plane of hydrogen atoms. Note that no rotation can make these two molecules identical, since inversion through center-of-mass coordinates is not a proper rotation. Both right-handed and left-handed descriptions are valid for the ammonia molecule, so an acceptable description of the ground state of ammonia must be a linear combination of the right-handed and left-handed configurations. There are two such linear combinations. If these two combinations are chosen to be of equal amplitude and orthogonal to each other, then one will be a symmetric representation (the σ state) and the other will be an antisymmetric representation (the α state). These two states behave differently when subjected to a gradient electric field.

In the ammonia maser at Columbia University, molecules were introduced into a high-vacuum chamber and then collimated into a beam. The beam of molecules then traversed an electric field that spatially separated the molecules of the two states. Molecules in the lower-energy state were rejected, while molecules in the excited state were sent to the exit beam. These excited molecules were permitted to drift into a region of stimulating electromagnetic radiation, where amplification took place.

Shortly afterward, the Central Radio Propagation Laboratory of the National Bureau of Standards used the ammonia maser amplifier, a self-sustained oscillator, as a standard clock. Its power output was of the order of 1 microwatt, and its stability was estimated at a few parts in 10^{10}, an order of magnitude better than that of the crystal-controlled oscillator locked to the ammonia (3, 3) inversion line. The improvement was due to the maser's much narrower line width, since collision broadening of the energy levels is virtually eliminated in the unidirectional, focused molecular beam. Furthermore, Doppler broadening of energy levels is greatly reduced through the use of molecular velocity selection.

Following the development of the ammonia maser, G. Makov, C. Kikuchi, J. Lambe, and R. W. Terhune reported another device.[10] This was the solid-state ruby maser, which used three of the chromium ion's four electronic spin levels of its ground electronic state. Ruby is the mineralogical name for crystalline corundum (Al_2O_3) having trivalent chromium ions as principal impurities. The maser achieved continuous electron-spin population inversion by applying a strategy—suggested by Bloembergen and similar to that known as optical pumping—that achieves preferential population

[8]N. G. Basov and A. M. Prokhorov, *Zh. Eksp. Theo. Fiz.* 27:431, 1954.

[9]J. P. Gordon, H. J. Zeiger, and C. H. Townes, *Phys. Rev.* 99:1264, 1955.

[10]G. Makov, C. Kikuchi, J. Lambe, and R. Terhune, *Phys. Rev.* 109:1399, 1958.

of excited optical states.[11] Since the electronic spin states' energy levels of the trivalent chromium ion in ruby depend on the strength of an applied magnetic field, the ruby maser proved to be tunable. It quickly gained use as a high-gain, low-noise amplifier, a boon to radio astronomy. The ruby crystal used by Kikuchi and his associates as the active element in their maser was donated by the University of Michigan to the Smithsonian Institution in Washington, D.C., and today resides there as a permanent exhibit.

Another important milestone in maser history came in 1960 when H. M. Goldenberg, D. Kleppner, and N. F. Ramsey reported on the development and operation of a hydrogen maser having the astonishing stability of 1 part in 30×10^{12} at a frequency of 1 420 405 751.786 Hz.[12] Since there are about 31 million seconds in a year, this maser will neither gain nor lose more than a few seconds in 100 000 years. The Michelson–Morley experiment was repeated to ever-increasing accuracy with this very precise clock, thereby verifying the conclusion of the original experiment—that the speed of light when measured in an inertial reference frame is invariant and is a universal constant.

FROM MASERS TO LASERS

Almost immediately upon the development of the ammonia maser, A. L. Schawlow and C. H. Townes suggested that the concept be extended to optical wavelengths.[13] The acronym *laser,* by analogy with *maser,* was coined to stand for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. The rush to invent was on, and the first laser to be reported was T. H. Maiman's ruby laser at the Hughes Corporation Research Laboratories.[14] The ruby laser consisted of a single crystal rod of synthetic corundum with chromium ions substituted for aluminum ions to the extent of a few parts per thousand. The ends of the rod were polished to be planar and parallel to each other and then metallized to form a radiation cavity resonator. The rod was surrounded by a helical flash lamp (Fig. 1). When a bank of capacitors in the flash lamp discharged, they caused the ruby rod to emit a single pulse of coherent and monochromatic radiation of wavelength 694.3 nm. The pulse duration was of the order of 10^{-8} seconds, and the laser had a power output of some 10^7 W/pulse. Due perhaps to media publicity, *laser* became a household word almost overnight, and the verb *to lase* was coined to stand for the action of a laser.

The laser has evolved into an indispensable tool in both research and engineering. Its numbers, varieties, and applications have experienced astonishing growth. Lasers are used in medicine as precision scalpels. Researchers have focused intense laser beams on targets in attempts to initiate controlled thermonuclear fusion (see Chapter 14). Scientists bounce laser light off of total internal reflectors on the Moon's surface to measure moonquakes. Lasers are used for precision machining and for such mundane tasks as reading bar codes on railroad rolling stock and on grocery-store items.

Nature has produced her own masers. Radio astronomers have observed interesting radiations emanating from extraterrestrial space, believed to be associated with interstellar H_2O molecules, electrically neutral OH and SiO free radicals, and perhaps other species. On the basis of the directions in space from which these radiations emanate, their narrow spectral bandwidths, and their radiation intensities, physicists have deduced that the radiations originate in naturally occurring masers. Although some

[11]N. Bloembergen, *Phys. Rev*. 104:324, 1956.

[12]H. M. Goldenberg, D. Kleppner, and N. F. Ramsey, *Phys. Rev. Lett.* 5:361, 1960; *Phys. Rev.* 126:603, 1962.

[13]A. L. Schawlow and C. H. Townes, *Phys. Rev*. 112:1940, 1958.

[14]T. H. Maiman, *Nature* 187:493, 1960.

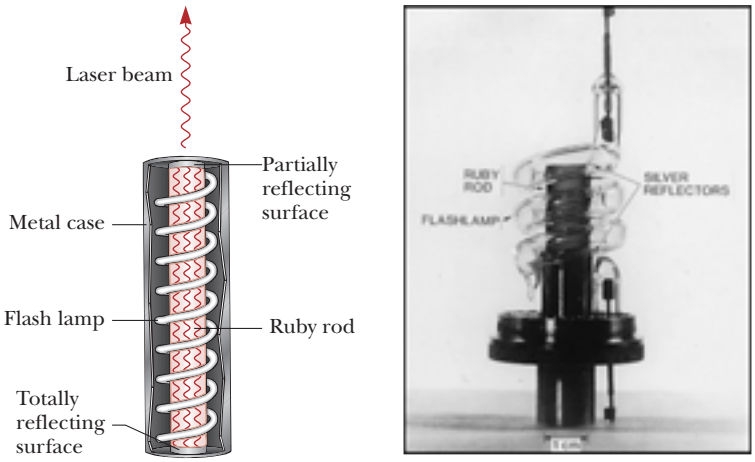

Figure 12.1.1 (a) A flash lamp surrounds a ruby rod. Chromium ions in the rod absorb light from the flash lamp, which pumps electrons to an excited state. A spontaneous emission from the excited state stimulates other ions to emit. The stimulated emission at 694.3 nm bounces back and forth between the reflecting ends of the rod, building up a coherent laser beam. (Adapted from D. Ebbing, *General Chemistry*, 5th ed., Boston, Houghton Mifflin Co., 1996) (b) A photograph of the first ruby laser. (Courtesy of HRL Laboratories, LLC)

maser-burst radiations are known to issue from the Sun, many cosmic masers are most likely either galactic or extragalactic in origin.[15,16]

Acknowledgments The authors would like to express indebtedness to Prof. J. Weber of the University of Maryland for his critical reading of the manuscript and to Mary Beth Riedner of Roosevelt University for providing valuable assistance.

Suggestions for Further Reading

N. F. Ramsey, *Science* 248:1612, 1990. A review of the hydrogen atom maser.

[15]M. Miyoshi, *Nature* 371:395, 1994.

[16]M. Elitzur, *Scientific American* 272:78, 1995.