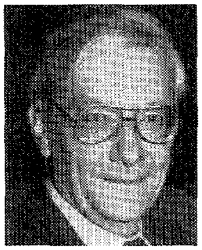

Nicolaas Bloembergen (SM'58–F'64) was born in Dordrecht, The Netherlands, on March 11, 1920. He received the Phil. Cand. and the Phil. Drs. degrees from the University of Utrecht, Utrecht, The Netherlands, in 1941 and 1943, respectively, the Ph.D. degree from the University of Leiden, Leiden, The Netherlands, in 1948, and the A.M. (hon.) degree from Harvard University, Cambridge, MA, in 1951.

From 1942 to 1945 he was a Teaching Fellow at the University of Utrecht. In 1946 he joined Harvard University as a Research Assistant for one year, and from 1947 to 1948 he was with the University of Leiden as a Research Associate. In 1949 he returned to Harvard, where he was in the Society of Fellows during 1949–1951; Associate Professor of Applied Physics during 1951–1957; Gordon McKay Professor of Applied Physics during 1957–1974; and Rumford Professor of Physics during 1974–1980. He is presently Gerhard Gade University Professor at Harvard. He is the author of two books: *Nuclear Magnetic Relaxation* (New York: Benjamin, 1961), and *Nonlinear Optics* (New York: Benjamin, 1965), and over 260 papers in scientific journals on topics in nonlinear optics, quantum electronics, solid-state masers, and magnetic resonance.

Dr. Bloembergen was awarded the Nobel Prize in 1981. He was also the recipient of the National Medal of Science, awarded by the President of the United States, in 1974; the Lorentz Medal, awarded by the Royal Dutch Academy of Science, in 1978; and the IEEE Medal of Honor in 1983. He is a Fellow of the American Academy of Arts and Sciences and the American Physical Society, an honorary member of the Optical Society of America, and a member of the National Academy of Sciences and the American Philosophical Society. He was Associate Editor of the *Physical Review* during 1956–1958; the *Journal of Chemical Physics* during 1960–1962, the *Journal of Applied Physics* during 1964–1967, and the IEEE JOURNAL OF QUANTUM ELECTRONICS during 1965–1970. He has been Advisory Editor of *Optics Communications* since 1969, *Physics* (Amsterdam) since 1975, and *Nuevo Cimento* since 1979.

Lasers in Historical Perspective

ARTHUR L. SCHAWLOW, FELLOW, IEEE

***Abstract*—During the past century, advances in physics have interacted with the needs of technology to permit new devices and opportunities in electronics. A persistent theme through most of this time has been the growth of methods of generating and controlling electromagnetic waves, and the extension of these techniques to shorter wavelengths. The discoveries in quantum physics led up to the use of atoms and molecules as resonators, and eventually as active devices such as lasers, for wavelengths too short for electron tubes. More recently accelerator technology, developed for nuclear physics, has made possible free-electron lasers in the optical wavelength regions.**

IN the nineteenth century, the serious study of electricity was considered a part of physics, or natural philosophy as the science was still often called. The subject owed a great deal to the discoveries of such pure scientists as Ampere, Faraday, Henry, Oersted, and Ohm, as well as to practical men like Edison. By 1884, electrical engineering had become a profession distinct enough to warrant its own society, but not until fifteen years later were scientists who specialized in physics numerous enough to form the American Physical Society. Fortunately, the ties between the two fields have remained close, and each has drawn inspiration, ideas, and techniques from the other.

This close connection between physics and technology has not always been universally accepted. At Oxford University, a professor who taught optics for many years insisted that there was no need for electricity in the light laboratory. Indeed, the profound theoretical discoveries of James Clerk Maxwell were little understood and appreciated a hundred years ago. But two years later, in 1886, Heinrich Hertz demonstrated the reality of electromagnetic waves. Within fifteen years, Guglielmo Marconi succeeded in sending a wireless signal across the Atlantic Ocean, and the radio age had begun.

Meanwhile, gas discharge and vacuum science were making rapid progress, culminating in the discovery of the electron by J. J. Thomson. That opened the way for what may well be the greatest invention of this or any other century, Lee DeForest's triode. The triode amplified electrical signals in a way that we would now call coherent, and made possible the generation of continuous waves of a wide range of frequencies.

When I was a boy, in the 1920's, radio broadcasting was such an exciting development that daily newspapers carried technical columns with simple circuits for the home radio builders. Early in that decade, radio amateurs found that the shortwaves to which they had been restricted could carry signals great distances around the curved earth. Subsequently, it was found that meter wavelengths would not go very far, but they were well suited to broad-band broadcasting, such as for FM radio and television. Centimeter wavelengths were harder to generate in a controlled way, because the familiar lumped circuit elements of coils and capacitors were too big. Nevertheless, transmission line circuits, waveguides, and cavity resonators, combined with new kinds of tubes such as klystrons and magnetrons, provided ways to make microwaves useful for radar and point-to-point communications.

Still shorter wavelengths, in the millimeter, infrared, and visible regions clearly were there to use if they could be generated

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and controlled. Yet that was the domain of quantum systems like atoms and molecules, far smaller than any resonator that seemed practical to construct. And up to the late 1940's, one could have said the same thing about quantum mechanics as about electromagnetic theory in the 1880's. Its existence was known, but it was not really part of electrical or electronic engineering. But radio frequency techniques, particularly in the centimeter wave region, had made it practical to study the absorption resonances of many atoms and molecules, as well as the resonances of electron spins in magnetic fields. Radio frequencies were also used to study the interaction of atomic nuclei with magnetic fields, first in molecular beams and then in solids and liquids. It became evident that atoms and molecules could act as resonators for radio waves, just as could reactance circuits and metal cavities. Moreover, these atomic and molecular resonances were already known to extend far into the infrared, visible, and ultraviolet spectral regions.

But in some important respects, the behavior of these atomic resonances was not at all like that of radio resonators. Each atom could absorb only one quantum of energy, until there was enough time to get rid of that energy by radiating it or converting it into heat. Thus, the resonances of atoms or molecules could be saturated, and this was particularly evident in the radio frequency and microwave region, where the energy quanta are small and numerous. When the radio wave intensity was too high, the absorption was just balanced by stimulated emission, and the medium became transparent to waves of a frequency that it could absorb at low intensity. At intermediate intensities, spectral lines were broadened, since the centers were diminished more than the weaker wings of the lines. This was a nuisance that could be avoided by keeping the incident intensity low enough, at some cost in signal-to-noise ratio. However, it taught an important lesson: populations of quantum states were not always held close to equilibrium values by rapid relaxation. Under suitable conditions, drastic departures from equilibrium could be obtained.

The concept of stimulated emission had been familiar to physicists since Einstein introduced it in 1917, and it had been confirmed by the experiments of Ladenburg and Kopfermann in 1933. But its consequences had not been explored seriously because scientists were so thoroughly trained to think of the world as being in equilibrium, or very close to equilibrium. At equilibrium, no matter how high the temperature, there are always more atoms in every lower state than in any higher state, so that absorption always exceeds the negative absorption from stimulated emission. By the 1950's, experiments in microwave spectroscopy and nuclear resonance had made it evident that this restriction, so universally assumed, was not necessary. Once this obstacle was removed, several scientists began to consider the possibility of actual amplification by stimulated emission. Charles Townes found a way to obtain a microwave population inversion in ammonia. He added a resonator to couple the electromagnetic wave more strongly to the molecules, and to permit the generation of sustained oscillation.

The history of masers and lasers has been described in a recent book by Bertolotti [1], and I have written two accounts of those events as I saw them [2], [3]. A historical study of the origins of quantum electronics has been started, under the direction of Dr. Joan Bromberg, and sponsored by the several professional societies active in this field. There is, therefore, no need to recount the early events here.

The primary aim had been to find ways to generate time-coherent electromagnetic radiation at shorter wavelengths than vacuum tubes could provide. This was not immediately attained, although masers soon found uses in spectroscopy, for frequency standards, and as low-noise receivers for radar, radio-astronomy, and satellite communications. The logical next step might well have been to extend maser techniques to the millimeter and submillimeter region, but that was largely unexplored territory. It proved easier to go directly to the visible and near infrared regions, where much more was known about energy levels and transition strengths. With such a big jump, the resonator had to be drastically different from the microwave single-mode cavity which masers had used. The open resonator, with small parallel mirrors widely separated [4], could select a single mode of oscillation, and that mode would radiate a highly directional beam. That was convenient, but rather incidental since any single wave mode could be transformed into a beam by some kind of a lens. The concept of this kind of mode-selecting resonator came from considering the way that physicists conventionally count the number of modes in a volume, either for electromagnetic waves in space or vibrational modes in a solid or liquid. The different modes are represented as waves of all possible directions and wavelengths that can be resonant in some chosen volume of space. However, the plane wave representation is not unique. When there are so many modes of nearly the same frequency, many equivalent sets can be constructed from superpositions of those wave modes. The laser mode might, for instance, have been a spherically diverging wave.

However, when the first laser, the ruby laser of Theodore Maiman, gave a pulse power output of several kilowatts in a highly directional beam, it was inevitable that the popular press would quickly think of death rays. After all, the idea of an all-destroying light beam is as old as the story of Archimedes setting fire to the sails of enemy ships by reflected sunlight, and has often recurred in science fiction. Whether such weapons may ever be practical, the early lasers were very far from it. Nevertheless, the death ray image did frighten away some people, and retarded the acceptance of lasers as useful tools.

Many of the advances since then have been surprising. Right at the beginning, I was surprised that lasers were so easy to make. Since they had never been made, it seemed likely that the conditions needed might prove to be very special and difficult to attain. It was also surprising that the earliest laser was so powerful. We have come a long way since then with advances too numerous to mention. Lasers are gaining wide acceptance as tools in industry, science, metrology, and surgery. It is sometimes hard to recall how you could possibly have lined up an optical system without a laser.

But some of the things that have not happened have been almost as surprising. The laser eraser for typewriters would use a visible light pulse of about one joule. But such a laser was prohibitively expensive in 1963 when I first discussed that application, and there has been absolutely no progress toward a suitable cheaper laser. We still do not have any kind of efficient visible laser, capable of producing sustained high power, even though many applications await such a device. Of course, we don't know how to make such devices, because we have many kinds of lasers, each tailored to the requirements and capabilities of a particular material, rather than one general laser. Perhaps some broadly adaptable device, such as a free-electron laser, may eventually take over many of the tasks that now require a number of different kinds. But that does not seem close at hand.

We are certainly not at the end of the classic quest for better ways to generate shorter wavelengths. Clearly, the long history of radio, microwaves, and lasers makes it evident that the search for shorter wavelengths will lead to useful devices and applications. No more detailed justification should be needed for such an endeavor. Moreover, many of the most important applications will be those which were not, and could not have been, foreseen. Partly that is because of the cumulative nature of science, quite different from that of the arts. A discovery in one area may overcome a seemingly insuperable obstacle in another. Moreover, applications can be suggested by the capabilities of available devices, when they are made known to people who are aware of the problems of some field of science or industry.

But Hansen's Law does still apply. As cited by E. T. Jaynes [5] and attributed by him to W. W. Hansen, this law states that "given two different ways of accomplishing something, both of which will work in principle, that one will be best which receives the greatest number of man-hours of development work." Conversely, if a system is not worked on, it is unlikely to become useful. Very many kinds of lasers have been discovered and not developed, perhaps because of some difficulty such as fabricating the required materials, or because no immediate application was apparent. There may well be many forgotten treasures among the old reports of laser systems. Such things certainly happened in radio history, as solid state rectifiers and magnetic recording were both tried, used, rejected, and later revived with crucial improvements. So also, vacuum tubes were superseded by lasers, for generation of submillimeter and shorter wavelengths, and then returned in the megavolt traveling wave free-electron lasers. Thus, it seems likely that some of the future advances will be based on discarded ideas of the past, which are made worthwhile by some crucial improvements.

Lasers have already greatly influenced the course of experimental science. In particular, they have provided the tools and the inspiration for searching tests of the processes of radiation and absorption, and of the basic laws of quantum mechanics. While those laws have stood up well to these examinations, the understanding of the relationships between classical and quantum phenomena has been greatly deepened. The study of laser phenomena has been closely related to theories of order, disorder, and chaos in many-body systems. It also has been possible to extend greatly the knowledge of atomic, molecular, and solid energy levels and transitions. Very probably, some of this basic knowledge will affect the course of engineering and technology in the future.

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Arthur L. Schawlow (SM'63–F'64) was born in Mount Vernon, NY. He received the Ph.D. degree from the University of Toronto, Toronto, Ont., Canada, in 1949. He has received honorary doctorates from the University of Ghent, Ghent, Belgium, the University of Toronto, and the University of Bradford, West Yorkshire, England.

After two years as a Postdoctoral Fellow and Research Associate at Columbia University, New York, NY, he became a Research Physicist at Bell Laboratories. In 1960, he was a Visiting Associate Professor at Columbia University. Since 1961 he has been Professor of Physics at Stanford University, Stanford, CA. He was Chairman of the Department of Physics from 1966 to 1970, and in 1978 was appointed J. G. Jackson and C. J. Wood Professor of Physics. His research has been in the field of optical and microwave spectroscopy, nuclear quadrupole resonance, superconductivity, and lasers. With C. H. Townes, he is coauthor of a book, *Microwave Spectroscopy*, and of the first paper describing optical masers, which are now called lasers. For this latter work, Schawlow and Townes have been awarded the Stuart Ballantine Medal by the Franklin Institute (1962), and the Thomas Young Medal and Prize by the Physical Society and Institute of Physics (1963). He gave the A.A.A.S. Holiday Science Lectures in Philadelphia (1965), Salt Lake City (1966), and Durham (1967), and was the Richtmyer Lecturer of the American Association of Physics Teachers (1970). He was the recipient of a Senior Postdoctoral Fellowship from the National Science Foundation for 1970–1971. He was also the Cherwell-Simon Lecturer, Oxford University (England), 1970; the Hoxton Lecturer, University of Virginia (1977); the W. V. Houston Lecturer, Rice University (1978); the recipient of the Geoffrey Frew Fellowship for 1973, Australian Academy of Science; and California Scientist of the Year (1973). In addition, he wrote the introduction for *Scientific American Readings on Lasers and Light*, and three of the articles in that collection. On television, he has appeared on one of the 21st Century programs with Walter Cronkite, and on one of the Experiment Series with Don Herbert, as well as on films for Canadian and British TV networks.

Dr. Schawlow received a Nobel Prize in 1981 for his contributions to the development of laser spectroscopy. He was also awarded the Morris N. Liebmann Memorial Prize by the IEEE in 1964. In 1976, he was awarded the Frederick Ives Medal of the Optical Society of America "in recognition of his pioneering role in the invention of the laser, his continuing originality in the refinement of coherent optical sources, his productive vision in the application of optics to science and technology, his distinguished service to optics education and to the optics community, and his innovative contributions to the public understanding of optical sciences." In 1977, he was awarded the Third Marconi International Fellowship. He also received a Golden Plate Award from the American Academy of Achievement in 1983. In 1982, the Laser Institute of America established the Arthur L. Schawlow medal for laser applications, to be awarded annually. The first medal was awarded to Dr. Schawlow "for distinguished contribution to laser applications in science and education." He is a Fellow of the American Physical Society (Member of Council 1966–1969), the Optical Society of America (Director-At-Large 1966–1968), the Society of Photo-Optical Instrumentation Engineers, the American Association for the Advancement of Science, the American Academy of Arts and Sciences, and the Institute of Physics (Great Britain), and a member of the U.S. National Academy of Science. He was Chairman of the Division of Electron and Atomic Physics of the American Physical Society (1974), President of the Optical Society of America (1975), and Chairman of the Physics Section of A.A.A.S. (1979). He was President of the American Physical Society in 1981. He was Chairman of Commission C.15, Atomic and Molecular Physics and Spectroscopy, of the International Union of Pure and Applied Physics (1978–1981), and Chairman of the U.S. National Committee for the International Union of Pure and Applied Physics (1979–1982). In 1983 he was elected one of six honorary members of the Optical Society of America.

Lasers—Their Development and Applications at AT&T Bell Laboratories

C. KUMAR N. PATEL, FELLOW, IEEE

***Abstract*—AT&T Bell Laboratories has played a crucial role in the invention and further development of lasers. In this paper I give a semihistorical account of the key contributions made by Bell Labs scientists. These contributions include the invention of the laser, optical resonator theory, the helium-neon and other atomic gas lasers, the carbon dioxide and other molecular lasers, solid state lasers, dye lasers, semiconductor lasers, ultrashort pulse mode locked lasers, color center lasers, tunable spin flip Raman lasers, and applications such as two photon absorption, nonlinear optics, etc. This review is by no means all encompassing since even just the listing of only the titles of all the publications in the field of quantum electronics by Bell Labs scientists would more than fill this entire issue of *J-QE*.**

I. INTRODUCTION

THE era of modern quantum electronics began with the invention of the maser by Townes in 1954. While Townes and his colleagues [1] at Columbia University showed a practical implementation of the ideas of stimulated emission of radiation and of population inversion, both of these ideas were well understood much earlier. And, shortly after the invention of the ammonia maser, the race was on to extend the maser principle to higher and higher frequencies, leading ultimately to wavelengths as short as the visible spectrum. Not that one could see a pressing need for an optical frequency maser for the lack of which the technology had ground to a stand still, but this was the thrust of fundamental research in its best tradition. Fundamental research is defined as that part of human endeavor which results in an improved understanding of nature without any predictable, useful application. In the meanwhile, the microwave maser had very quickly found numerous applications as low noise amplifiers of microwave signals. Thus the quest for an optical frequency maser was driven by the need to explore the fundamental limits of a demonstrated phenomenon. During the years immediately following the invention of the microwave maser, Bell Laboratories contributed significantly to the field through the work of Scovil, Feher, and Seidel [2], who constructed the first continuous wave solid state maser, and through the work of DeGrass, Schultz-Dubois, and Scovil [3], who developed a broad band traveling wave maser. However, the real plunge for AT&T Bell Labs into the world of quantum electronics began with the collaboration between Townes at Columbia University and Schawlow at AT&T Bell Labs on the principle of an optical maser.

The seminal paper by Schawlow and Townes [4] spelled out in detail the conditions for obtaining laser oscillation in the visible and the near infrared region with the key recognition that for the success in obtaining a practical laser system was the use of open resonant cavities for mode selection and necessary efficient feedback. Looking back at the events some twenty-five years later, it is remarkable that such a significant departure from the microwave maser cavities was envisioned. The experimental demonstration of the first laser oscillation by Maiman [5] in a ruby crystal occurred in 1960 and the marvelous ride had begun.

In this contribution I would like to recount some of the significant contributions made to the field of quantum electronics by scientists at Bell Laboratories in the twenty-five years since the first paper by Schawlow and Townes. These contributions can be broadly grouped in the following categories: gas lasers including the metal vapor lasers, dye lasers, solid state lasers, color center lasers, short duration laser pulse generation, nonlinear optics including spin flip Raman lasers, optical resonators, and semiconductor (injection) lasers. Also, I will briefly touch upon the subject of applications of the various lasers in science and technology—the latter being a catch all for fields such as laser surgery, use of lasers for industrial applications, and lightwave communications. I will describe each of these categories in no particular chronological order because many of the developments oc-

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