Amplification by Stimulated Emission of Radiation

A conference report by ***Henry Levinstein***

THE Spring Meeting of the New York State Section of the American Physical Society was held at LeMoyne College in Syracuse on April 14 and 15, 1961. More than 250 persons attended, mainly from the New York state area, although a few came from as far as California. This was the fourth in a series of highly successful semiannual meetings, each devoted to a selected current topic in physics. In contrast to Physical Society meetings on a national scale and topical conferences where research workers exchange ideas with others in the same field, each of these meetings is designed to bring to physicists the latest developments in an important and rapidly growing area of physics not generally their speciality. Meetings are held at various locations in the state, frequently upon invitation by a company or university. Previous meetings of the current series have been held at Rochester on fuel cells, at Hamilton on radio astronomy, and at Binghamton on computers.

The topic chosen for the LeMoyne meeting was "A Survey of Amplification by Stimulated Emission of Radiation". This symposium was organized by Donald Morey of the Eastman Kodak Company, as were the three preceding meetings. The local committee consisted of Father Brennan (chairman), Mr. and Mrs. C. E. McCain, and Mr. and Mrs. J. Welter, all representing LeMoyne, J. Stevens from Carrier, J. W. Brouillette from General Electric, and H. Levinstein from Syracuse University. The meeting was opened by Ted Renzema, chairman of the Section, who presented Father Grewen, president of LeMoyne College. After brief welcoming remarks by Father Grewen, the technical sessions began with four talks summarizing activities in physics in the Syracuse area. Father Brennen, chairman of the LeMoyne Physics Department, discussed the physics facilities and the undergraduate curriculum at LeMoyne. W. R. Fredrickson, chairman of the Physics Department at Syracuse University, outlined both graduate and undergraduate physics programs at Syracuse as well as the current research programs in solid state, high-energy physics, spectroscopy, molecular beams, and field theory. John Burlew, director of research at the Carrier Corporation, illustrated the function of the Research Laboratory at Carrier by giving various examples of research being carried on there. The physics research activities at General Electric's Electronics Park, which are mainly in the electronic-materials areas, were summarized by Harris Sullivan, manager of the Advanced Semiconductor Laboratory.

The second part of the morning session, under the chairmanship of Joseph Weber of the University of Maryland, was devoted to an introduction of the central conference theme. Beginning with a discussion of blackbody radiation and Einstein's contribution to radiation theory, Thomas R. Carver, of Princeton University, introduced the concepts of absorption, stimulated emission, and spontaneous radiation, all of which he demonstrated with the aid of the simplest kind of maser, the water maser. Carroll Alley of the University of Rochester offered a brief historical review and a detailed treatment of the basic concepts involving the interaction of radiation with matter, thereby setting the stage for more specific papers which were to follow. In the discussion of the two papers, Dr. Weber pointed out some of the misconceptions about masers, especially the idea that the use of stimulated emission in amplification is new. Every vacuum-tube amplifier, he emphasized, operates on the basis of stimulated emission of radiation. The new concept in devices which amplify and oscillate is the use of bound state of atoms and molecules, rather than free state.

Applications and new techniques for using masers in the microwave region were discussed in the afternoon session. Patrick Thaddeus of Columbia University reviewed maser development, starting with the ammonia beam maser which was developed by Townes and his group in 1954, and traced the advances of microwave spectroscopy from its beginning, when microwave radiation was passed through a randomly moving gas in a cavity, to the employment of molecular beams. Line widths, which were limited to 50 kc because of the Doppler shift produced by randomly moving gas molecules, were reduced to 10 kc by the use of molecular beams. However, the signal-to-noise ratio, even for the strong lines, was so low that many interactions could

Henry Levinstein is professor of physics at Syracuse University.

not be studied. It was not until the development of the maser principle, the separation of lower and upper states, and subsequent removal of the lower states, that narrow line width coupled with high signal-to-noise ratio made possible a study of a large number of molecules. This opened new areas in the field of microwave spectroscopy. Dr. Thaddeus then went on to describe the solid-state maser conceived by Bloembergen and its inherent advantages for use as an amplifier in radio astronomy. Ruby masers have now been constructed, which, in contrast to the ammonia maser, are tunable, have wider bandwidth, and, when operated at liquid-helium temperature, have an actual noise temperature of 18°K, thereby approaching the theoretical limit of less than 1°K. He gave some examples of the use of masers in radio astronomy for a study of Venus and Jupiter and for communications in conjunction with the Echo satellite.

The second talk of the afternoon session was given by Hendrick Gerritsen of RCA on new developments in maser materials. After summarizing briefly the older developments up to November 1959, he spelled out the requirements for good maser action: namely, the signal frequency cannot generally be more than one half the pump frequency, and the larger the pump frequency the better the inversion ratio with greater gain. High frequencies, in turn, require materials with larger zero-field splitting. He pointed out, however, that going to higher frequencies involves disadvantages in terms of the cost and availability of klystrons at these frequencies. Various sophisticated techniques, such as harmonic pumping, are used to try to get around the pump-to-signal-frequency ratio. Dr. Gerritsen continued with a discussion of current maser materials, such as rutile (TiO_2), cassiterite (SnO_2), calcium tungstate ($CaWO_4$), corundum, and ruby (Al_2O_3), giving their characteristics and the properties of the masers constructed from them. Many of these materials have been selected because they are available, he pointed out, and because of shortcomings in theory it is not yet possible to predict which materials will make good masers and should therefore be synthesized. The direction of effort in the future will probably be toward higher gain-bandwidth products and higher operation frequency (present limit is 72 kMc) with a continuously narrowing gap between microwave and optical masers. This will certainly require hard work on existing materials and the development of new materials.

A survey of methods for precise time and frequency standards given by Peter Bender of the National Bureau of Standards, followed the historical development of time standards, beginning with the crystal oscillator. He then discussed the advantages and limitations of the cesium-beam standard, the ammonia-beam maser, the gas-cell frequency standard, and the hydrogen maser. The first cesium-beam standard, constructed in 1955, had serious limitations in that its line width was too great—and it was too sensitive to magnetic field changes. The more recent devices have greater length and better shielding and lead to a reproducibility of 2 parts in 10^{11}. The use of thallium is expected to result in even higher precision. Many of the early limitations of the ammonia maser have been solved by better engineering and the use of nitrogen-15 instead of nitrogen-14 in ammonia. The most serious difficulty remaining results from the nonuniform population density of atoms along the cavity. Thus, since radiation is stronger in some regions than in others, traveling waves are set up which will produce a Doppler shift. Despite this, reproducibility of 3 parts in 10^{11} has been obtained. Dr. Bender then discussed the hydrogen maser, which combines some of the features of atomic-beam devices and masers, and may, when fully developed, become the main competitor of atomic-beam devices for defining a frequency scale. He ended his talk with a description of methods for comparing standards, including high-frequency transmission from WWV, low-frequency transmission from stations located at the Canal Zone, or, what may yet turn out to be the simplest method, the actual carrying of frequency standards from one location to another.

Daniel Kleppner of Harvard University began his talk on the hydrogen maser as a research tool by describing its operation and comparing it with the other types of masers. He pointed out that for the hydrogen maser, atoms need to be stored in a cavity for about $\frac{1}{3}$ second since their magnetic-dipole interaction with the radiation field is considerably less than the electric-dipole interaction of other atoms. This has required a careful selection of cavity-wall coatings so that atoms are not disturbed when colliding with the walls. He then went on to discuss the various limitations of the original hydrogen maser and the techniques, such as better magnetic shielding and better temperature control, which have been used in the design of the latest model. Experiments which are planned or under way include measurements of the ratios of the hyperfine splitting of hydrogen, deuterium, and tritium, the measurement of the spin-exchange cross section of atomic H, and the measurement of the "g" factor for the free electron. A spirited discussion followed the talk, with much interest centered around the type of cavity-wall coatings which might be used and their effects on the impinging hydrogen atoms.

A short business meeting followed this last paper of the day. The group then adjourned to the LeMoyne College Penthouse for the conventional social hour which has become such a desirable part of so many meetings. Under relaxed conditions, with a beautiful view of Syracuse still partially covered by snow, some conversation centered around the papers presented earlier, some about future meetings and past reminiscences. The dinner was followed by a presentation of past officers: Ted Renzema (chairman), Don Morey (vice chairman), and O. E. Miller (secretary-treasurer). The new officers are Don Morey (chairman), Kenneth Moore (vice chairman), and A. F. Turner (secretary-treasurer). The day was rounded out with an illustrated lecture on recent expeditions to the Antarctic by Father Daniel Linahan of Boston College. Beautiful slides of landscapes, members of the expedition, and wild life, accompanied by highly exciting comments, were presented in such a way that the audience seemed to make the visit to the South Pole, not only with the speaker, but also with many of the pioneers who had preceded him.

THE first two talks of the Saturday session, presided over by Carroll Alley, were on optical masers. D. F. Nelson of the Bell Telephone Laboratories began his talk on solid-state optical masers by comparing them to microwave masers discussed the previous day. He stressed some of the differences between the two: In optical masers the main loss occurs through spontaneous emission which is relatively unimportant for microwave masers. The noise temperature of optical masers is very large (of the order of 30 000°K), thereby making them unsuitable for quantum detectors. Their short wavelength requires at present a multimode structure as compared with microwave masers, where the cavity size is of the order of a wavelength, and the tunability is much smaller than that of microwave masers (only up to 1%). He then went on to discuss the criterion for determining the amount of inversion required for maser operation. After mentioning time and space coherence and citing a few experiments which have been used to determine the degree of coherence, he summarized latest developments in optical masers: The pink-ruby maser contains about 10^{18} chromium atoms per cc; the red-ruby maser contains a higher density of chromium impurities, which then form pairs and produce a modified energy-level system. Both types produce visible radiation. Samarium, when added to CaF_2, produces visible radiation, but uranium in CaF_2 produces radiation at 2.5 μ. All of these devices are at present operated with pulsed light. In conclusion, Dr. Nelson gave some indication of the maximum power output obtained to date (10 kw) and stressed the great importance these devices will have in many areas, especially in communications.

The second paper of the morning session was presented by W. R. Bennett, also of the Bell Telephone Laboratory, on vapor-phase masers in the optical region. He pointed out the greater difficulty in obtaining inversion in gases as compared with the solid-state optical masers and then listed the three basic methods for obtaining inversion in gases: optical pumping, electron impact, and the use of collisions of the second kind. Only the latter technique, as first described by Javan, Bennett, and Herriott, has been successful. Here, an atom in the excited state collides with an atom in the ground state and excites it, while the original atom returns to the ground state. He also described the helium-neon maser and the difficulties which had been encountered in aligning the two Fabry-Perrot mirrors, placed at a distance of 1 meter, which act to reflect the energy back and forth in the gaseous amplifying medium. The talk ended with a description of the properties of the beam. It was especially noteworthy that line widths probably less than 1 kc have been obtained.

Following a coffee break with many stimulating hallway discussions, some of which were so lively that the beginning of the next session had to be delayed, Joseph Weber gave a review paper on noise limitations in masers. He defined some of the basic concepts such as spontaneous emission temperature (T_E), which provides the fundamental limitations of all amplifiers operating by stimulated emission, and the noise figure (F) of a complete system, which represents the signal-to-noise-power ratio at the input of a receiver divided by the signal-to-noise-power ratio at the receiver output. He showed how receiver performance might also be described in terms of its noise temperature T_n, where $T_n = (F-1)\,T_s$; T_s, representing the source temperature. For quiet receivers, the concept of noise number might be a better figure of merit. It represents the number of photons received over the receiver averaging time, which will double its noise output. He applied these concepts to maser systems and concluded that since the spontaneous emission temperature, $T_E = (h\nu/k)\ln 2$, limits maser performance, optical masers will probably serve mainly as coherent sources rather than amplifiers, while microwave masers will be used for low-noise amplifier and frequency standards.

In the final talk of the morning session, Gordon Gould, of the Technical Research Group, looked into the future and showed how a heterodyne system, employing an optical maser as the local oscillator, may eventually replace all other communications systems.

After lunch, the last paper of the meeting was presented by Tittel, von Willisen, and Wessel of GE. The talk included technical details on the construction of an optical maser and a detailed discussion of various types of maser materials available, the design of the cavity, the polishing and plating of the parallel sides of the ruby cylinder, and the various types of pulsed xenon light sources which can be used in the ruby optical maser. The demonstrations given at the end of the talk were spectacular. When the maser was operated below threshold, only the usual incoherent radiation produced by spontaneous emission was obtained. Above threshold, when sufficient population inversion was reached, the coherence of radiation was demonstrated by means of a diffraction pattern produced by placing a fine wire mesh directly in front of the maser.

Carroll Alley temporarily interrupted the demonstrations, which were to continue much of the afternoon, by giving a short summary of the meeting. He pointed out that the development of masers has been the culmination of the research of several generations of physicists working on the interaction of radiation with matter. He objected to the idea, expressed in a recent technical journal, that quantum electronics is concerned mainly with engineering developments with a short-range objective: the evolution of an operating device from a basic concept. These sessions have demonstrated that much fundamental physics is being done and needs to be done, and that, perhaps through much of this work, one will arrive at a better understanding of one of the most fundamental concepts, the photon.