FINAL REPORT

for Research Grant NGR-07-004-035

on the

"INVESTIGATION OF THE BASIC FOUNDATIONS OF MASERS AND LASERS"

given by the

National Aeronautics and Space Administration

to Yale University

for the period

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to

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I. INTRODUCTION

This Final Report describes research on the theory of Masers and Lasers. The Principal Investigator, Willis E. Lamb, Jr., has been given support under NASA Research Grant NGR-07-004-035 from January 1, 1965 through June 30, 1974 for his studies in the above field at Yale University. On July 1, 1974 he transfers to The University of Arizona in Tucson, where he will be Professor of Physics and Optical Sciences. As a consequence of this move, the Grant to Yale University will terminate. It is hoped that an application for a new Grant will support continuation of the research in Arizona.

The following sections contain a summary of researches carried out under the Grant.

II. HISTORY OF RESEARCH UNDER NASA GRANT 07-004-035

A. Statement by W.E. Lamb, Jr. on His Activity Prior to 1965.

During the Second World War, I was engaged in research on centimeter wavelength magnetron oscillators. A magnetron oscillator has a tendency to operate in one or more unwanted modes. One of my assignments at that time was to give a theoretical guide for the design of oscillators which were free of this shortcoming. The complexity of the electronic trajectories in the combined electric, magnetic and electromagnetic fields of the magnetron oscillator made the problem too difficult for me. In later years, I was to find that laser theory offered me a very satisfactory opportunity to get an understanding of a similar but more manageable problem of oscillator theory.

After the war, in order to apply what I had learned of radar to problems of physics, I turned to the new and exciting field of microwave spectroscopy. For some years, I was concerned with a determination of the fine structure of hydrogen-like atoms, which led in 1955 to the award of a Nobel Prize in Physics. Until 1951, I worked at Columbia University. In that year, one of my colleagues, Professor C.H. Townes, conceived the idea which three years later led to the first successful operating maser oscillator. At first, I did not think that Townes' very clever idea had much chance of practical realization, but in 1954, stimulated by the successful outcome of Townes' work, I turned to a theoretical investigation of the operating mechanism of the ammonia beam maser. This led to a quite satisfactory theory, incorporated in his doctoral thesis (University Microfilms, Ann Arbor, Michigan.) by John C. Helmer at Stanford University in 1956. An account of this theory is also given in my 1959 Summer Session lecture notes on "Quantum Mechanical Amplifiers" at Boulder, Colorado. (Wiley, Intersciences.)

The basic paper (Phys. Rev. 112, 1940 (1958).) leading to the development of the optical maser (or laser) was that by Schawlow and Townes in 1958. This article had some novel, then even strange, ideas in it, and again I did not take it very seriously. In 1960, however, T.H. Maiman made the first optical maser, using a ruby crystal pumped with a flash lamp. (Maiman had been one of my Ph.D. students at Stanford, where his Ph.D. thesis of 1955 dealt with atomic helium fine structure, using a combined microwave-optical method.) I spent the years between 1956 and 1962 at the University of Oxford, where I was the Professor of Theoretical Physics. In 1962 I moved to a position at Yale University.

In 1961, Javan, Bennett and Herriott constructed the first gas laser, using a mixture of neon and helium. I looked for ways to modify my previous treatment of the maser to give a theory of this form of optical maser. This theory evolved during the years 1961 to 1963. Results of the theory, especially those dealing with the single mode tuning dip, were communicated to both Javan and Bennett in February of 1962. The first public presentation of the work was an invited paper at the Third International Conference on Quantum Electronics, Paris in February, 1963. A paper based on the work was published in the Physical Review (vol. 134, pp. 1429-1450) in 1964.

In 1964, I was approached by Mr. Paul S. Johnson of the NASA Electrophysics Branch. (I had met Johnson shortly after the war when he was monitoring the Joint Services support of my research at Columbia University which led to a measurement of the hydrogen fine structure. Johnson was then a Navy Commander, later Captain.) He had heard of my work on laser theory, and believed that it would make an important field of research for support by NASA. He encouraged me to submit an application for a grant on the theory of optical masers. This application, dated September 16, 1964, received favorable consideration and I was given a grant of approximately $30,000. This grant has been renewed annually since then. During one year the amount was increased in $35,000. For 1971 and 1972 the grant was cut in half to $15,000. A step-funding feature has somewhat cushioned the reductions. The Grant for 1973 was increased to $20,000. Preparatory to the impending transfer to Arizona, a Grant of $11,667 was made for the first six months of calendar year 1974.

B. Research Supported by NASA Grant NGR-07-004-035

1. Ph.D. Degrees Awarded by Yale University. The following have received Ph.D.'s in connection with work on this grant:

Balazs R. Gyorffy, 1966

Marlan O. Scully, 1966

Murray Sargent III, 1967

Paul R. Berman, 1969

Aslan Icsevgi, 1969

Martin Spencer, 1971

Yaun-Kong Wang, 1971

Matthew Borenstein, 1971

Gyorffy worked on the theory of ring lasers and on the theory of pressure effects on the operation of lasers. He is currently a Lecturer in Theoretical Physics at the University of Bristol in England.

Scully did his thesis work on the quantum theory of the laser. He was formerly Associate Professor of Physics at the Massachusetts Institute of Technology and is now Professor of Physics and Director of an Institute devoted to laser physics at the University of Arizona in Tucson. He has held both a Guggenheim Fellowship and a Sloan Fellowship.

Sargent did his research on the theory of Zeeman lasers in a magnetic field. He is now an Associate Professor in the Optical Sciences Center at the University of Arizona in Tucson.

Berman worked on the theory of the influence of gas collisions on the shape of spectral lines and on the operation of lasers. He is now an Assistant Professor of Physics at New York University.

Icsevgi took his Ph.D. with research on the propagation of pulses in a non-linear medium. He subsequently took a course in Business Administration at Stanford University, and is currently employed in an industrial position.

Spencer's thesis was devoted to a theory of a laser with a window. He treated both the case where the radiation could escape through the window and the case where radiation was sent into the laser from outside. He also developed the theory of two lasers coupled to each other through a window. Spencer has now returned to his native New Zealand where he is associated with the Physics Department at the University of Christchurch.

Wang's thesis dealt with theories of noise and fluctuation in the quantum theory of the laser. Wang is now a post-doctoral fellow working with Professor Elliott Montroll at the University of Rochester.

Borenstein's thesis had two parts. One gave a completely classical theory of a laser, with applications to the electron cyclotron maser. The other dealt with pressure broadening effects on the operation of a gas laser. Borenstein is now teaching science in the New Haven City High School system, and is also an (unpaid) Research Associate at Yale University.

2. Post-Doctoral Fellows. In addition to the eight people who have received Ph.D.'s as a result of work with the NASA Grant, I should mention two post-doctoral fellows who have worked for a time under the Grant.

A Finnish Physicist, Dr. Stig Stenholm, took his D. Phil. at Oxford and spent a year at Yale as a Post-doctoral Fellow. While here, he worked on the theory of a strong signal-mode laser. He has since returned to Finland and now holds a position as Director of Research in Solid State theory at the Helsinki Technical University.

Dr. Lionel Menegozzi came to Yale in 1968 for two years as a Fellow of the Argentine National Research Council, and remained a third year with NASA support. He has worked on the theory of ring lasers. He then returned for a year to his home country where he was an Associate Professor at the Institute of Physics at the National University of Cuyo. Menegozzi has recently come back to Yale as Research Associate. His paper on ring lasers has been published by the Physical Review. He is now working on the theory of amplified spontaneous emission and other incoherent radiation.

3. Papers Published with Support of NASA Grant

1. Quantum Theory of an Optical Maser, M.O. Scully and W.E. Lamb, Jr., Phys. Rev. Letters 16, 853 (1966); Reprinted in "Selected Papers in Coherence and Fluctuations of Light", pp. 896-898, edited by L. Mandel and E. Wolf, (Dover, New York, 1970).
2. Pressure Effects in the Output of a Gas Laser, B.L. Gyorffy and W.E. Lamb, Jr., Physics of Quantum Electronics Conference Proceedings, pp. 602-610, McGraw-Hill (1966).
3. Quantum Theory of an Optical Maser, M.O. Scully, W.E. Lamb, Jr. and M.J. Stephen, Physics of Quantum Electronics Conference Proceedings, pp. 759-768 (1966).
4. Quantum Theory of an Optical Maser. I. General Theory, M.O. Scully and W.E. Lamb, Jr., Phys. Rev. 159, 208-226 (1967); Reprinted in Series of Selected Papers in Physics, (Physical Society of Japan, 1972); and in Laser Theory, pp. 241-259, edited by F.S. Barnes, (I.E.E.E. Press, New York, 1972).

5. Theory of a Zeeman Laser, I. R.L. Fork, M. Sargent III and W.E. Lamb, Jr., Phys. Rev. 164, 436 (1967).

6. Theory of a Zeeman Laser II. R.L. Fork, M. Sargent III and W.E. Lamb, Jr., Phys. Rev. 164, 450 (1967).

7. Quantum Theory of an Optical Maser. II. Spectral Profile, M.O. Scully and W.E. Lamb, Jr., Phys. Rev. 166, 246-249 (1968); Reprinted in Series of Selected Papers in Physics, pp. 101-104 (Physical Society of Japan, 1972).

8. Pressure Broadening Effects on the Output of a Gas Laser, B.L. Gyorffy, M. Borenstein and W.E. Lamb, Jr., Phys. Rev. 169, 340-359 (1968).

9. The Photoelectric Effect without Photons, W.E. Lamb, Jr. and M.O. Scully, Jubilee volume in honor of Alfred Kastler, Presses Universitaires de France, Paris 1969.

10. Quantum Theory of an Optical Maser. III. Theory of Photoelectron Counting Statistics, M.O. Scully and W.E. Lamb, Jr., Phys. Rev. 179, 368-374 (1969); Reprinted in Series of Selected Papers in Physics, pp. 105-111 (Physical Society of Japan, 1972).

11. Semiclassical Theory of a High-Intensity Laser, Stig Stenholm and W.E. Lamb, Jr., Phys. Rev. 181, 618-635 (1969).

12. Propagation of Light Pulses in a Laser Amplifier, A. Icsevgi and W.E. Lamb, Jr., Phys. Rev. 185, 517-545 (1969); Reprinted in Laser Theory, pp. 295-323, edited by F.S. Barnes, (I.E.E.E. Press, New York, 1972).

13. Influence of Resonant and Foreign Gas Collisions on Line Shapes, P.R. Berman and W.E. Lamb, Jr., Phys. Rev. 187, 221-266 (1969).

14. Build-up of Laser Oscillations from Quantum Noise, M. Sargent III, M.O. Scully and W.E. Lamb, Jr., Appl. Opt. 9, 2423-2427 (1970); Reprinted in Series of Selected Papers, pp. 112-116 (Physical Society of Japan, 1972).

15. Quantum Theory of an Optical Maser. IV. Generalization to Include Finite Temperature and Cavity Detuning, D.M. Kim, M.O. Scully and W.E. Lamb, Jr., Phys. Rev. A2, 2529-2533 (1970).

16. Quantum Theory of an Optical Maser. V. Atomic Motion and Recoil, D.M. Kim, M.O. Scully and W.E. Lamb, Jr., Phys. Rev. A2, 2534-2541 (1970).

17. Theory of Collision Effects on Line SHapes using a Quantum Mechanical Description of the Atomic Center of Mass Motion - Application to Lasers, I. P.R. Berman and W.E. Lamb, Jr., Phys. Rev. A2, 2435-2454 (1970).

18. Theory of Collision Effects on Line SHapes using a Quantum Mechanical Description of the Atomic Center of Mass Motion - Applications to Lasers. II. P.R. Berman and W.E. Lamb, Jr., Phys. Rev. A4, 319-343 (1971).

19. Quantum Mechanical Transport Equation for Atomic Systems, P.R. Berman, Phys. Rev. A5, 927 (1972).

20. Laser with a Transmitting Window, M.B. Spencer and W.E. Lamb, Jr., Phys. Rev. A5, 884 (1972).

21. Theory of Two Coupled Lasers, M.B. Spencer and W.E. Lamb, Jr., Phys. Rev. A5, 893 (1972).

22. Classical Laser, M. Borenstein and W.E. Lamb, Jr., Phys. Rev. A5, 1298 (1972).

23. Effect of Velocity-Changing Collisions on the Output of a Gas Laser, M. Borenstein and W.E. Lamb, Jr., Phys. Rev. A5, 1311 (1972).

24. Why is the Laser Line so Narrow? A Theory of Single-Quasimode Laser Operation, R. Lang, M.O. Scully and W.E. Lamb, Jr., Phys. Rev. A7, 1788-1797 (1973).

25. Speed Dependent Collisional Width and Shift Parameters in Spectral Profiles, P.R. Berman, Journal of Qualitative Spectroscopy and Radiative Transfer 12, 1331 (1972).

26. Physical Concepts in the Development of the Maser and Laser, W.E. Lamb, Jr., pp. 59-111, in The Impact of Basic Research on Technology, edited by B. Kursunoglu and A. Perlmutter (Plenum, New York, 1973).

27. Quantum Theory of an Optical Maser VI: Transient Behavior, Y.K. Wang and W.E. Lamb, Jr., Phys. Rev. 8, 866-873 (1973).

28. Theory of Some Laser Noise Effects, Y.K. Wang and W.E. Lamb, Jr., Phys. Rev. A8, 873-880 (1973).

29. Approach to Thermodynamic Equilibrium and Other Stationary States, pp. 165-186, in The Physicist's Conception of Nature, edited by J. Mehra, (D. Reidel, Dordreckt, Holland, 1973).

30. Theory of a Ring Laser, W. E. Lamb, Jr., and L. N. Menegozzi, Phys. Rev. A, 8, 2103 (1973).

4. Abstracts of Papers Presented at Meetings

1. Temporal Development of the Photon Statistical Distribution for Different Values of Atomic Excitation, M.O. Scully, W.E. Lamb, Jr. and M. Sargent III, Bull. Am. Phys. Soc. 12, 89 (1967).
2. Theory of a Zeeman Laser, M. Sargent III, Invited Paper, American Physical Society Meeting, Mexico, D.F. August 29, 1966.
3. Measurement of Atomic Parameters using Magnetic Field Tuned Optical Masers, R.L. Fork, M. Sargent III, and W.E. Lamb, Jr., Bull. Am. Phys. Soc. 12, 89 (1967).
4. Time Variation of the Electric Field in a Zeeman Laser with an x-y Q Anisotropy, M. Sargent III, W.E. Lamb, Jr., W.J. Tomlinson and R.L. Fork, Bull. Am. Phys. Soc. 12, 90 (1967).
5. Theory of Collision Effects on Line SHapes usinga Quantum Mechanical Description of the Atomic Center of Mass Motion, P.R. Berman and W.E. Lamb, Jr., Second International Conference on Atomic Physics, Oxford, England, July 21-24 (1970); also, Bull. Am. Phys. Soc, 15, 1524 (1970).
6. Pressure Effects in Gas Lasers, P.R. Berman and W.E. Lamb, Jr., New York Meeting of the American Physical Society, Feb. 1-4, 1971.
7. Critical Comments on Radiation Theory, W.E. Lamb, Jr., p. 645, in Conference on Coherence and Quantum Optics, edited by L. Mandel and E. Wolf, Plenum Press, New York, 1973
8. Non-linear amplification of incoherent radiation, VIII International Quantum Electronics Conference, San Francisco, June 1974.

C. Technological Applications of Laser Theory Developed Under NASA Grant 07-004-035

The laser theory developed by the writer and his co-workers gives a very good account of the operating characteristics of gas lasers, especially when the effect of gas collisions is taken into account. One of the consequences of the theory is that the power output of a gas laser depends in a surprising way on the tuning of the laser cavity with respect to the resonance frequency of the atomic transition. The power output exhibits a dip when resonance is approached. This phenomenon is often called the "Lamb Dip." It was predicted by early 1962 in the working out of the theory described in the article "Theory of Optical Masers", Phys. Rev. 134, 1429-50 (1964). The phenomenon was looked for following the theoretical prediction, and found as described by MacFarlane, Bennett and Lamb in Applied Physics Letters 2, 189-90 (1963). This dip in the output of the laser has a rather sharp frequency dependence and affords the possibility of stabilizing the frequency of the laser against changes in cavity resonance frequency. Use of this phenomenon is made in commercially available lasers. The later theoretical work of Stenholm and Lamb (Paper #11) extended the theory of tuning dip to the case of high intensity lasers, and it was shown that the dip persists to very high intensities of single-mode operation. In the last few years a further deveopment in the field has taken place, in which absorber cells are placed in the laser cavity. These contain some molecular gas which happens to have a resonance absorption very close to the laser frequency. The non-linear or saturated absorption produces an "inverted Lamb dip". Such a peak can be exceedingly sharp in frequency, and new possibilities of frequency stabilization, and mode control, of lasers have resulted. This technique combined with improved methods of frequency measurement in the optical region has made it possible to measure the velocity of light with previously unobtainable precision. This is important in connection with laser-ranging measurements as well as for the determination of physical constants.

Just recently, very significant applications of this saturation absorption method to spectroscopy have been made. For example, Hänsch and Schawlow have applied it to the fine structure of the hydrogen Balmer and the sodium D lines, and it is clear that a whole new field of ultra-high precision spectroscopy will flow from use of the "inverted Lamb dip". One of the most promising methods for analysis of combustion products of internal combustion engines is high resolution infra-red spectroscopy, and there is a good chance that the new method may play an important role in such work.

While the output of a laser can be highly monochromatic, there is inevitably some noise of quantum mechanical origin as well as that which can be attributed to thermal or mechanical fluctuations in the laser. In addition, there are fluctuations which arise from the medium through which the laser beam travels. The kind of theory supported by the Grant is relevant to a discussion of the noise characteristics of a communication system based on the laser. There is a good deal of confusion about the nature of laser radiation: for instance, whether it is to be described in terms of photons or in terms of classical electromagnetic fields. The work on the quantum theory of the laser provides a basis for a sound discussion of such problems. Papers # 1,3,4, 7,10,14,15,16 (Scully, Lamb et al.) and 27 (Wang and Lamb). Further insight is provided by the work on the fully classical laser by Borenstein and Lamb (Paper #22).

A good deal of experimental research work has been devoted to the possibility of using a ring laser as a rotation-rate sensing device. The rate of rotation is determined by measurement of a low frequency beat note between waves traveling in opposite directions in the ring laser. It has been found experimentally that, below a certain rotation rate, the beat note disappears. The work of Menegozzi and Lamb, (Paper in Process of Publication #1) supplementing the thesis work of Gyorffy, (Ph.D. thesis, Yale, 1966) makes it possible to decide which experimental circumstances are responsible for the disappearance of the beat note. It should therefore be possible to make a more practical rotation rate sensing device, especially for low rotation speeds.

The theory of the Zeeman laser (Sargent, et al., Papers #5 and #6) has been found to provide very close correspondence with observations on the behavior of lasers in a magnetic fields. There are a number of sharply tuned phenomena which offer possibilities for frequency stabilization and laser modulation. These may be expected to find some use in practical communications systems.

Icsevgi and Lamb (Paper #12) have developed a theory for discussion of the propagation of pulses through a laser amplifier. The theory obtained is somewhat more general than previous treatments by Hahn and McCall and by Hopf and Scully.

The simplest theory of a gas laser takes thermal motion of the atoms or molecules into account, but neglects the effects of collisions. Several papers in the List of Publications (#2 and #8 by Gyorffy, et al.; #22 by Borenstein and Lamb; #13, #17, #18 and #19 by Berman and Lamb) have enabled the theory to describe pressure dependent effects. A first improvement is obtained by adding pressure proportional terms to the radiative decay constants such as γ_a, γ_b and γ_{ab} of the basic theory. In cases of major interest and importance, one cay go beyond this quite useful approximation by the numerical solution of certain integral equations.

Problems in physics, applied physics and engineering fall into two categories - linear problems and non-linear problems. For obvious reasons, physics has largely been devoted to linear problems, which are much easier to handle theoretically. Unfortunately, the real world is highly non-linear. Very much of the work with which NASA is concerned involves non-linear problems - for instance in such problems as that of wing flutter, and of all kinds of aerodynamic situations. The theory of the laser is intrinsically a non-linear problem. It has a rather special simplicity, fortunately, in that the theory of the non-linear medium can be given very precisely, using the quantum mechanical theory for relatively simple atomic level schemes. This non-linearity is not introduced in an empirical fashion, as it might be with departures from Hooke's law for an elastic body. Once granted the non-linear properties of the "lasing medium", the problem remains to solve the coupled equations for the interaction between the electromagnetic field and the active non-linear atoms. This work can be carried out with very good control. One then has a testing ground for precedures used in other non-linear problems, for which at present the theoretical foundation is somewhat less secure. I personally have a very great interest in non-linear problems and have greatly enjoyed the work on laser theory because of the firm foundation on which I could base my work.