AMERICAN
JOURNAL of PHYSICS

A Journal Devoted to the Instructional and Cultural Aspects of Physical Science

VOLUME 32, NUMBER 8 AUGUST 1964

Resource Letter MOP-1 on Masers (Microwave through Optical) and on Optical Pumping

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Prepared at the request of the AAPT Committee on Resource Letters; supported by a grant from the National Science Foundation.

This is one of a series of Resource Letters on different topics, intended to guide college physicists to some of the literature and other teaching aids that may help them improve course contents in specified fields of physics. No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments and suggestions concerning the content and arrangement of letters as well as suggestions for future topics will be welcomed. Please send such communications to Professor Arnold Arons, Chairman Resource Letter Committee, Department of Physics, Amherst College, Amherst, Massachusetts.

Notation: The letter *E* after an item number indicates *elementary* level, useful principally for freshman liberal arts through sophomore physics courses; the letter *I* indicates *intermediate* (junior, senior) level; and the letter *A* indicates *advanced* material principally suited for senior, graduate study. An asterisk (*) indicates items particularly recommended for introductory study.

Additional copies: Available from American Institute of Physics, 335 East 45 Street, New York, New York 10017. When ordering, request Resource Letter MOP-1 and enclose a stamped return envelope. A small booklet containing reprints of some of the fundamental references will soon be available for purchase from the American Institute of Physics.

I. INTRODUCTION

IN both masers and optical pumping one attempts to change the energy-level population from that of thermal equilibrium. Therefore, much of the physical understanding required in both subjects is similar. For this reason, the subjects are included together.

The term "optical pumping" refers to the nonequilibrium redistribution of atoms among the energy sublevels of the ground state by absorption of light. By this method very precise measurements of energy separations in the ground state may be made. Closely related to this are such techniques as double resonance, which refers to atoms optically oriented in the excited state.

Basically the maser is a device consisting of a material prepared so that the higher of two energy levels has a higher population than the lower, the device being enclosed in a suitable resonator of sufficiently high Q. Such a system oscillates, producing coherent radiation at whatever frequencies the resonator and energy levels have in common. The word MASER is an acronym originally standing for *M*icrowave *A*mplification by *S*timulated *E*mission of *R*adiation. However, with the extension of the frequency range by using similar principles, it has been suggested that the word MOLECULAR be substituted for MICROWAVE. The words LASER and OPTICAL MASER are synonymous, *L* standing for *L*ight in the former.

Since excellent review articles are available on optical pumping, we have limited the number of references cited in this area. Because of the scarcity of pedagogical materials on optical masers, we have to some extent emphasized original paper references on optical over those on microwave masers.

Optical maser research is continuing at a rapid pace, and a rapidly increasing volume of scientific and technological results is to be expected. Our effort here has been to concentrate attention on references dealing with the fundamental physical concepts rather than with technological results and applications.

The nature of the subject is such that an appropriate background in modern physics and quantum theory is necessary at various levels. For example, the intermediate level is taken to be that corresponding to textbooks such as *Fundamentals of Modern Physics* by R. M. Eisberg (John Wiley & Sons, New York, 1961) or *Principles of Modern Physics* by R. B. Leighton (McGraw-Hill Book Company, Inc., New York, 1959). The designation of a reference by the symbols E, I, or A is not so much an evaluation of the difficulty of the material as an indication of the suitability for use at particular levels. Because of the wide range of material contained in many references, the E, I, and A designations should not be interpreted too rigidly.

II. BACKGROUND MATERIAL

Resource Letter QSL-1 on Quantum and Statistical Aspects of Light by P. Carruthers, American Journal of Physics, **31**, 321 (1963), (hereafter referred to as QSL-1) contains many references which overlap with this subject. Most of them are simply listed and the reader is referred to QSL-1 for comment.

*1.I **Light.** R. W. DITCHBURN. (Interscience Publishers, Inc., New York, 1963, 2nd ed.) This textbook covers many topics in optics and light which are of specific interest with respect to optical masers. Much of the material could be used at the sophomore level.

*2.I **Radiation and Optics.** J. M. STONE. (McGraw-Hill Book Company, Inc., New York, 1963.) This text is slightly more advanced than 1.I and also contains a number of useful topics.

3. 26A of QSL-1, **The Quantum Theory of Radiation.** W. HEITLER. (Oxford University Press, London, 1954), 3rd ed.

4. Section IV of QSL-1 especially 44.E **"On Coherence Properties of Light Waves,"** A. T. FORRESTER. Am. J. Phys. **24**, 192 (1956), and 45.A **"Coherence in Spontaneous Radiation Processes,"** R. H. DICKE. Phys. Rev. **93**, 99 (1956). The roots of the entire subject lie in spectroscopy; the following three references offer a relevant background in the theory of atomic spectra:

*5.I **Atomic Spectra.** H. G. K. KUHN. (Longmans Green and Company, London, 1962.) A modern introduction to atomic spectra suitable for the serious undergraduate at the junior–senior level.

*6.A **The Theory of Atomic Spectra.** E. U. CONDON AND G. H. SHORTLEY. (Cambridge University Press, New York, 1951.) This is still the classic work on atomic spectra.

*7.A **Quantum Theory of Atomic Structure.** Vol. I and II. J. C. SLATER. (McGraw-Hill Book Company, Inc., New York, 1960.) A modern reference book with quite a bit of attention given to pedagogical detail.

8.A **Microwave Spectroscopy.** C. H. TOWNES and A. L. SCHAWLOW. (McGraw-Hill Book Company, Inc., New York, 1955.) Comprehensive discussion of microwave spectroscopy of gases. Discusses atomic frequency standards and the molecular beam maser.

*9.A **Principles of Magnetic Resonance.** C. P. SLICHTER. (Harper and Row, New York, 1963.) Chapter 7 is an introduction to electron spin resonance including the effect of crystalline fields.

*10.A **Paramagnetic Resonance.** G. E. PAKE. (W. A. Benjamin, Inc., New York, 1962.) Chapter 3 contains an introduction to crystal field and the effective spin Hamiltonian. This background is useful for solid-state microwave masers.

11.A **Paramagnetic Resonance in Solids.** W. LOW. Supplement 2, *Solid State Physics.* Edited by F. Seitz and D. Turnbull. (Academic Press, Inc., New York, 1960.) A more advanced discussion of the problem.

12.A **Fluorescence and Phosphorescence.** P. PRINGSHEIM. (Interscience Publishers, Inc., New York, 1949.) This book contains a large amount of useful experimental information. Parts of it can be read at the intermediate level.

*13.A **Resonance Radiation and Excited Atoms.** A. G. MITCHELL and M. W. ZEMANSKY. (Cambridge University Press, London, 1961.) Chapter III of this useful book is on absorption lines and lifetimes. It contains much information that can be applied to stimulated emission in optical masers with little more than a change of sign. The whole book is extremely useful to people interested in optical masers and optical pumping.

*14.A **"Electronic Spectra of Molecules and Ions in Crystals: Part II Spectra of Ions in Crystals."** D. S. McClure. In *Solid State Physics*, Vol. 9, p. 399. Edited by F. Seitz and D. Turnbull. (Academic Press Inc., New York, 1959.) Comprehensive discussion of the optical spectra of ions in crystals. These spectra are important for optical masers.

15.A **The Theory of Transition—Metal Ions.** J. S. Griffith. (Cambridge University Press, London, 1961). Comprehensive account of the theory of transition metal ions, emphasizing noncooperative phenomena such as paramagnetism and single optical spectra.

*16.A **Group Theory and Quantum Mechanics.** M. Tinkham. (McGraw-Hill Book Company, Inc., New York, 1964.) The quantum mechanics of atoms, molecules, and solids emphasizing the use of group theory.

*17.A **Introduction to Ligand Field Theory.** C. J. Ballhausen. (McGraw-Hill Book Company, Inc., New York, 1962.) A self complete book giving a very good introduction to crystal-field theory.

*18.A **Nuclear Moments.** H. Kopfermann. (Academic Press Inc., New York, 1958.) Good discussion of both optical and radio frequency methods before introduction of optical pumping. Section 24 discusses double resonance.

*19.A **Molecular Beams.** N. F. Ramsey. (Oxford University Press, London, 1956.) This book, like 18.A is a source of much useful information for anyone interested in optical pumping or atomic-beam masers.

III. HISTORICAL REFERENCES

For the physicist, the maser is a device which puts into practice basic physical principles which have been known for many years. The realization of the import of these principles and how they can be utilized has lain dormant until the last decade, when it was shown that population inversion providing stimulated emission in conjunction with a cavity could produce a molecular oscillator. Lastly, and perhaps most important, it is only in the last decade that workable systems (materials and resonators) have been discovered.

Optical pumping has drawn heavily on two related fields. The first is optical resonance radiation described in Ref. 13.A. The second is magnetic resonance, especially the work on atomic beams. See, for instance, Refs. 18.A and 19.A.

The historical references are not intended to be complete; the emphasis being on references useful and accessible to teachers.

20.I Ref. 14.I of QSL-1, **"Zur Quanten Theorie der Strahlung."** A. Einstein. Physik Z. **18**, 121 (1917).

21.A "Untersuch über die Anomale Dispersion Angeregter Case." R. Ladenburg and H. Kopfermann. Z. Physik **48**, 15, 26, 51, (1928). Showed experimentally the existence of negative dispersion effects due to stimulated emission. See also Ref. 11, pp. 144–145. See also: **"Dispersion in Electrically Excited Gases."** R. Ladenburg. Rev. Mod. Phys. **5**, 243 (1933).

22.A **"The Optical Detection of Radio Frequency Resonance."** F. Bitter. Phys. Rev. **76**, 833 (1949). First suggestion that radio frequency transitions could be detected by optical means. The suggested effect was very small. See M. H. L. Pryce, Phys. Rev. **77**, 136 (1950).

23.A **"La Detection de la Resonance Magnetique des Niveaux Excite: l'Effet de Depolarisation des Radiations de Resonance Optique et de Fluorescence."** J. Brossel and A. Kastler. Compt. Rend. **229**, 1213 (1949). Proposal of double resonance method for detecting rf transitions in excited states.

24.A **"Quelques Suggestions Concernant la Production Optique et la Detection Optique D'une Inegalite de Population des Niveaux de Quantification Spatiale des Atomes. Application a l'Experience de Stern et Gerlach et la Resonance Magnetique."** A. Kastler. J. Phys. Radium **11**, 255 (1950). Proposal of optical pumping.

25.A **"Fine Structure of the Hydrogen Atom. Part I."** W. E. Lamb, Jr. and R. C. Retherford. Phys. Rev. **79**, 549 (1950). In Appendix I, the possibility of population inversion and negative absorption (with an exclamation mark) under suitable discharge conditions was pointed out.

26.I **"Amplification of Microwave Radiation by Substances not in Thermal Equilibrium."** J. Weber. Transactions of I.R.E., PG on Electron Devices **3**, 1 (1953). Discussed possibility of microwave amplification in media with inverted populations.

*27.I **"Molecular Microwave Oscillator and New Hyperfine Structure in the Microwave Spectrum of NH_3."** J. P. Gordon, H. J. Zeiger, and C. H. Townes. Phys. Rev. **95**, 282L (1954). Molecular beam microwave maser. This was the first operating maser, and the first device to combine stimulated emission with a resonator to obtain coherent radiation from incoherently excited molecules.

28.I **"Possible Methods for Obtaining Active Molecules for a Molecular Oscillator."** N. G. Basov and A. M. Prokhorov, Zh. Eksperim. i Teor. Fiz. **28**, 249 (1955) [English transl.: Soviet Physics—JETP 1, 184 (1955)]. Suggested possibility of three level maser in molecular beam.

*29.A **"Proposal for a New Type Solid State Maser."** N. Bloembergen. Phys. Rev. **104**, 324 (1956). This short article on the conditions for a microwave maser using three levels in a paramagnetic solid contains the basic theory of most solid-state microwave masers.

*30.A **"Infrared and Optical Masers."** A. L. Schawlow and C. H. Townes. Phys. Rev. **112**, 1940 (1958).

Showed that by using parallel plate reflectors as a cavity, by pumping with incoherent light radiation, optical maser action could be obtained in gases and solids.

31.I **"Possibility of Negative Temperature in Gas Discharges."** A. JAVAN. Phys. Rev. Letters, **3**, 87 (1959). Discusses possibility of population inversion in a gas discharge.

*32.I **"Stimulated Optical Radiation in Ruby."** T. H. MAIMAN. Nature, **187**, 493 (1960). Reported lifetime shortening and spectral narrowing indicating the stimulated emission of optical radiation in ruby.

*33.I **"Coherence Narrowing, Directionality, and Relaxation Oscillations in the Light Emission from Ruby."** R. J. COLLINS, D. F. NELSON, A. L. SCHAWLOW, W. BOND, C. G. B. GARRETT, AND W. KAISER. Phys. Rev. Letters, **5**, 303 (1960). Verified the spatial coherence and directionality of the output. Observed spiking.

*34.I **"Population Inversion and Continuous Optical Maser Oscillations in a Gas Discharge Containing a He–Ne Mixture."** A. JAVAN, W. R. BENNETT, AND D. R. HERRIOTT. Phys. Rev. Letters **6**, 106 (1961). Optical Maser action in He–Ne gas at 1.15 μ.

*35.A **"Resonant Modes in a Maser Interferometer."** A. G. FOX AND TINGYE LI. Bell Syst. Tech. J. **40**, 453 (1961). Determined the normal mode electric-field distribution at the mirrors of a Fabry–Perot interferometer and the diffraction losses of the normal modes. This was a major advance in understanding the resonant modes of an optical-maser cavity.

36.A **"Stimulated Emission of Radiation from GaAs p–n Juntions."** M. I. NATHAN, W. P. DUMKE, G. BURNS, G. H. DILL, JR., AND G. LASHER. Appl. Phys. Letters **1**, 62 (1962). **"Coherent Light Emission from GaAs Junctions."** R. N. HALL, G. E. FENNER, J. D. KINGSLEY, T. J. SOLTYS, AND R. O. CARLSON. Phys. Rev. Letters **9**, 366 (1962). **"Semiconductor Maser of GaAs."** T. M. QUIST, R. H. REDIKER, R. J. KEYES, W. E. KRAG, B. LAX, A. L. MCWHORTER, AND H. J. ZEIGER. Appl. Phys. Letters, **1**, 91 (1962). Optical maser action due to emission line of forward-biased semiconductor junction.

IV. BOOKS AND COLLECTIONS OF ARTICLES

There are a number of books on microwave masers, some of them suitable as text books. Several books on optical masers are being prepared by various publishing houses. Several compilations of articles are listed. Anyone seriously interested in this area should have access to these.

37.I **Masers.** J. R. SINGER. (John Wiley & Sons, Inc., New York, 1959.) Introduction to microwave masers.

38.A **Elements of Maser Theory.** A. A. VUYLSTEKE. (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1960.) About half the book is devoted to discussion of quantum and statistical mechanics used in maser theory.

*39.I **Microwave Solid State Masers.** A. E. SIEGMAN. (McGraw-Hill Book Company, Inc., New York, 1963.) Contains material on paramagnetic resonance. Introduces and uses quantum-mechanical concepts in descriptive fashion without requiring the ability to perform detailed quantum-mechanical calculations.

40.E **Masers and Lasers.** H. A. KLEIN, (J. B. Lippincott Company, Philadelphia and New York, 1963.) This book, aimed at the layman, presents the basic ideas in an elementary fashion, useful for teaching non-science majors or even on the high-school level.

*41.I **Lasers.** B. A. LENGYEL. (John Wiley & Sons, Inc., New York 1962.) Introduction to the subject through mid 1962.

42.A **Optical Masers.** G. BIRNBAUM. *Supplement 2, Advances in Electronics and Electron Physics.* Edited by L. Marton. (Academic Press, Inc., New York, 1964.) This book should be useful as a reference work.

43.A **Quantum Electronics.** Edited by C. H. TOWNES. (Columbia University Press, New York, 1960.) Papers and discussion of first conference on quantum electronics. Emphasizes microwave masers and optical pumping.

44.A **Advances in Quantum Electronics.** Edited by J. R. SINGER. (Columbia University Press, New York, 1961.) Papers and discussion of second conference on quantum electronics. Emphasizes optical masers.

*45.A **Applied Optics: Supplement On Optical Masers** (1962). A very useful reprint collection of articles on optical masers with two review articles. See Refs. 62.I, 63.A, 64.A and 78.I.

*46.A **"Quantum Electronics Issue."** Proc. IEEE **51**, 1 (1963). This very useful issue contains several review articles in addition to many articles on optical and microwave masers. See Refs. 62.I and 67.A.

REVIEW ARTICLES

There are a number of excellent review articles, and it is probably with these that the novice should start. It would pay to look at more than one in order to find the approach which best suits the readers taste.

47.E **"Optical Pumping."** A. BLOOM. Sci. Am. **203**, No. 4, 72 (Oct. 1960). Elementary introduction to the subject of optical pumping.

*48.I **"Optical Methods of Atomic Orientation and of Magnetic Resonance."** A. KASTLER. J. Opt. Soc. Am. **47**, 460 (1957). A very lucid review of double resonance and optical pumping.

49.A **"Optical Orientation of Atoms and its Applications."** G. V. SKROTSKII AND T. G. IZYUMOVA, Usp. Fiz. Nauk. **73**, 423 (1961) [English transl.: Soviet Physics-Usp. **4**, 177 (1961)]. Translation of a comprehensive review through about 1960.

*50.A "Optical Pumping." T. R. CARVER. Science 141, No. 3581, 599 (August 16, 1963). Brief nonmathematical survey of optical pumping including very recent developments.

51.A "Radio Frequency Spectroscopy of Excited Atoms." G. W. SERIES in *Report on Progress in Physics*, edited by A. C. Strickland, 22, 280 (1959). Discussion of the radio frequency spectroscopy of excited atoms, which is very closely related in basic ideas and in practice to optical pumping.

52.E "The Maser." J. P. GORDON. Sci. Am. 199, No. 6, 42 (Dec. 1958). Elementary introduction to microwave masers.

53.I "Masers." J. WEBER. Rev. Mod. Phys. 31, 681 (1959). Review of microwave masers and applications through 1958.

54.A **The Three Level Solid-State Maser.** E. O. SHULTZ-DU BOIS. In *Progress in Cryogenics*, Vol. II, 175–231. (Heywood and Company, Ltd., London, 1962.) A detailed discussion of the three-level solid-state microwave maser aimed at physicists who are not specialists in the field.

55.A "Masers and other Quantum Mechanical Amplifiers." J. L. SINGER. In *Advances in Electronics and Electron Physics*, Vol. 15, 163 (1961). Edited by I. MARTON. (Academic Press Inc., New York, 1961.) A review of masers through the introduction of optical masers.

56.A "Quantum Mechanical Amplifiers." W. E. LAMB, JR. In *Lectures in Theoretical Physics*. Edited by W. BRITTIN AND B. DOWNS. (Interscience Publishers, Inc., New York, 1960.) Vol. II. Discussion of the theory underlying quantum-mechanical amplifiers.

*57.E "Optical Masers." A. L. SCHAWLOW. Sci. Am. 204, No. 6, 52 (June 1961). Elementary review of optical masers and their principles.

*58.E "Advances in Optical Masers." A. L. SCHAWLOW. Sci. Am. 209, No. 1, 34 (July 1963). Elementary review of the recent progress in this field. Semiconductor lasers and nonlinear effects are among the topics covered.

59.E "Lasers." A. K. LEVINE. Am. Scientist 51, No. 1, p. 14 (March 1963). Elementary nonmathematical review discussing both principles and applications.

60.I "Infrared and Optical Masers." A. L. SCHAWLOW. Solid-State J. 2, 21 (1961). Introductory review through the beginning of 1961.

61.I "Optical and Infrared Masers." A. L. Schawlow. *Contemporary Physics*, Vol. IV, No. 2, p. 81 (December, 1963). Review of optical and infrared masers through July 1963.

*62.I "The Laser." A. YARIV AND J. P. GORDON. In Ref. 46, p. 4. The article is clear and self contained, and may be useful for introducing students to the subject.

63.A "Optical Masers." O. S. HEAVENS. In Ref. 45, p. 1. Review of optical masers to September 1962.

*64.A "Gaseous Optical Masers." W. R. BENNETT, JR. In Ref. 45, p. 24. Detailed review of gaseous optical masers up to September 1962, with emphasis on the physics of these types of discharge.

NONLINEAR OPTICAL PHENOMENA

Because of the high-field strengths obtainable with optical masers, nonlinear phenomena have become an important field of study.

*65.A "Generation of Optical Harmonics." P. A. FRANKEN, A. E. HILL, C. W. PETERS, AND G. WEINREICH. Phys. Rev. Letters 7, 118 (1961). Report of the generation of optical harmonics in quartz.

*66.A "Optical Harmonics and Non-Linear Phenomena." P. A. FRANKEN AND J. F. WARD. Rev. Mod. Phys. 35, 23 (1963). Review to August 1962.

*67.A "Wave Propagation in Non-Linear Electromagnetic Media." N. BLOEMBERGEN. In Ref. 46, p. 124. Brief tutorial review of nonlinear effects through October 1962, giving pertinent references.

68.A "Theory of Stimulated Raman Scattering." R. W. HELLWARTH. Phys. Rev. 130, 1850 (1963). Discusses the *stimulated* Raman scattering of intense light in a Raman-active material.

LEVEL CROSS-OVER SPECTROSCOPY

Level cross-over spectroscopy is an accurate and relatively simple spectroscopic technique which examines the polarization of resonance fluorescence when levels of excited states "cross" in a magnetic field. Pedagogically, it is a very beautiful example of interference phenomena in quantum mechanics. The justification for including it here is historical—the subject has been primarily explored by people working in optical pumping, and it can be considered as a zero-frequency resonance method. It should also be pointed out that interference effects in zero and low fields (a special case of level crossing) has been studied in much detail. See Chap. 5 of Ref. 13.A.

*69.I "Novel Method of Spectroscopy with Application to Precision Fine Structure Measurements." F. D. COLEGROVE, P. A. FRANKEN, R. R. LEWIS, AND R. H. SANDS. Phys. Rev. Letters, 3, 420 (1959). Level crossing in He.

70.A "Interference Effects in the Resonance Fluorescence of Crossed Excited Atomic States." P. A. FRANKEN. Phys. Rev. 121, 508 (1961). Description of the experiment and its physical basis.

71.A "Coherence Effects in Resonance Fluorescence." M. F. ROSE AND R. L. CAROVILLANO. Phys. Rev. 122, 1185 (1961). Detailed theoretical discussion of this type of experiment.

MISCELLANEOUS

72.E "Atomic Clocks." H. LYONS. Sci. Am. 196, No. 2, 71 (Feb. 1957). Discusses frequency standards including masers.

73.I "**Properties of the Hydrogen Maser.**" D. KLEPPNER, H. M. GOLDENBERG, AND N. F. RAMSEY. Appl. Op. 1, 55 (1962). Properties of the hydrogen maser and details of the apparatus. See "**Theory of the Hydrogen Maser,**" Phys. Rev. 126, 603 (1962) by the same authors for a more comprehensive theoretical discussion.

74.I "**Three Level Masers as Heat Engines.**" H. E. D. SCOVIL AND E. O. SCHULZ-DUBOIS. Phys. Rev. Letters 1, 262 (1959). A three-level microwave maser can be regarded as heat engine with a limiting efficiency of a Carnot engine.

75.A "**Geometrical Representation of the Schrodinger Equation for Solving Maser Problems.**" R. P. FEYNMAN, F. L. VERNON, AND R. W. HELLWARTH. J. Appl. Phys. 28, 49 (1957). Geometrical picture of Schrodinger equation similar to that of magnetic resonance. Useful for two-level problems.

76.A "**Maser States in Ammonia-Inversion.**" A. A. VUYLSTEKE. Am. J. Phys. 27, 554 (1959). Discusses the inversion effect responsible for maser action in ammonia in terms of a simple square-well approximation to the potential.

*77.A **Stimulated Optical Emission in Fluorescent Solids I. Theoretical Considerations.**" T. H. MAIMAN. And "**Stimulated Optical Emission in Fluorescent Solids II. Spectroscopy and Stimulated Emission.**" T. H. MAIMAN, R. H. HOSKINS, I. J. D'HAENENS, C. K. ASAWA, AND V. EVTUHOV. Phys. Rev. 123, 1145, 1151 (1961). An example of the interconnection of optical spectroscopy and optical masers. The substance studied was ruby.

78.I "**Giant Optical Pulsations from Ruby.**" F. J. McCLUNG AND R. W. HELLWARTH. J. Appl. Phys. 33, 828 (1962). By temporarily spoiling the Q of the optical-maser cavity, very high population inversions and hence output powers may be obtained. Included in Ref. 45.

79.I "**Thompson Scattering of Optical Radiation from an Electron Beam.**" G. FIOCIO AND E. THOMPSON. Phys. Rev. Letters 10, 89 (1963). The velocity distribution of atoms and electrons may be determined by the Doppler shift of scattered monochromatic light from an optical-maser source. This paper reported the detection of light scattered from an electron beam.

*80.I "**New Experimental Test of Special Relativity.**" J. P. CEDARHOLM, G. F. BLAND, B. L. HAVENS, AND C. H. TOWNES. Phys. Rev. Letters 1, 342 (1958). By a very precise experiment of the Michelson–Morley type, using two microwave-maser oscillators, the maximum ether drift was shown to be less than 1/1000 of the earth's orbital velocity.

*81.I "**Frequency Stability of He–Ne Masers and Measurements of Length.**" T. S. JASEJA, A. JAVAN, AND C. H. TOWNES. Phys. Rev. Letters 10, 165 (1963). Very monochromatic and stable optical masers now make possible precise measurements of length and hence of relativistic effects. See also: "Test of Special Relativity or of the Isotropy of Space by Use of Infrared Masers." T. S. JASEJA, A. JAVAN, J. MURRAY and C. H. TOWNES. Phys. Rev. 133, A1221 (1964).

82.I "**The Granularity of Scattered Optical Maser Light.**" J. D. RIGDEN AND E. I. GORDON. Proc. IRE 50, 2367 (1962), and "**Sparkling Spots and Random Diffraction.**" B. M. OLIVER. In Ref. 46, p. 220. The sparkling appearance of diffuse reflecting surfaces when coherent light is incident should make an interesting topic in an optic course.

EXPERIMENTS AND APPARATUS

The apparatus required for optical pumping is not elaborate. For a description of optical pumping in the alkalis see:

*83.A "**Optical Pumping.**" ROBERT L. DEZAFRA. Am. J. Phys. 28, 646 (1960). Brief review of the basic concepts of optical pumping followed by description of Rb optical-pumping apparatus suitable for advanced undergraduate or graduate laboratory.

Optical pumping can also be performed in the $^3S_1$ metastable state of He^4, with quite simple apparatus.

*84.A "**Optical Pumping of Helium in the $^3S_1$ Metastable State**" F. D. COLEGROVE AND P. A. FRANKEN. Phys. Rev. 119, 680 (1960). Description of the theory and apparatus used in the optical pumping of He^4 in the $n=2$, metastable $^3S_1$ state.

Level crossing experiments may be formed with the apparatus of 84.A if a magnet is available.

The construction of a microwave maser requires a relatively extensive and expensive set of apparatus. However, if an electron paramagnetic resonance apparatus is available, many of the problems would be simplified.

For high power demonstrations the solid-state optical maser is the most useful. Such units may be constructed without too much difficulty, or complete solid state optical maser units may be obtained commercially. Probably the most useful type of maser for teaching is the *cw* gas optical maser. Using the visible output, diffraction and interference effects can easily be displayed for a number of students. Many laboratory experiments and demonstrations which formerly were quite difficult can be performed with an enjoyable ease. Because of the intensity available, a number of diffraction effects should be demonstrable before a class. The usual gas optical maser has external mirrors as described in:

85.I "**Gaseous Optical Maser with External Concave Mirrors.**" W. W. RIGROD, H. KOGELNIK, D. J. BRANGACCIO, AND D. R. HERRIOTT. J. Appl. Phys. 33,

743 (1962). In Ref. 45, p. 125. Describes gas optical maser with Brewster-angle windows on the tube and external concave mirrors.

Both mirrors and tubes are available commerically, or the complete unit may be purchased from a number of firms. Some attention should be paid to the purity of the mode pattern produced. The most typical cross-hatched patterns consisting of the superposition of several modes are amusing to observe but are somewhat of a nuisance when trying to use the equipment for interferometry or diffraction effects.

86.I **"Optical Properties of Lasers as Compared to Conventional Radiators."** R. C. Rempel; and **"Properties of Laser Resonators Giving Uniphase Wave Fronts."** A. Bloom. Laser Technical Bulletins Nos. 1 and 2, Spectra-Physics, Inc., Mountain View, California. These bulletins will prove useful to teachers of optics and optics laboratories.

*87.I **"Some Demonstration Experiments in Optics Using a Gas Laser."** D. Dutton, M. Givens, and R. E. Hopkins. Am. J. Phys. To be published. Several elementary experiments in geometrical and physical optics which can be adapted as classroom demonstrations by using the enhanced intensity of a visible gas laser are described.