

**NRL Progress in
High-Power Laser Research**

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PREFACE

Since January 11, 1965, laser research at the U.S. Naval Research Laboratory has been expanded under the sponsorship of the Advance Research Projects Agency (ARPA). This report presents a summary of the work done under ARPA Order No. 660 of January 11, 1965, and Amendments No. 1 and 2 of April 27, 1965, and December 11, 1965.

Since the inception of this interest and a more vigorous support by ARPA, the materials research has been pursued more intensively and along more basic lines, while still maintaining a capability for responsiveness to routine testing needs. Many innovations have been introduced, e.g., magnetic Q-spoiling and Q-switching by the Faraday effect, as well as other novel techniques employed in the various research areas.

A fast responsiveness to the investigation and exploitation of new ideas is exemplified by the construction and operation of a molecular nitrogen laser system, which was started early in 1966. Some preliminary results from this system are included in the gas laser section of this report.

PROBLEM STATUS

This is an interim report on the problem; work is continuing.

AUTHORIZATION

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LASER MATERIALS RESEARCH

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INTRODUCTION

Laser materials research carried out under ARPA Order 306 (March 1963 to January 1965) and ARPA Order 660 (January 1965 to the present) has been reported in several ways since the work began. Initially, the results appeared in the following U.S. Naval Research Laboratory (NRL) publications:

- a. "Laser Materials Research" J.H. Schulman, et al., NRL Memorandum Rept. 1442, July 1963, and
- b. "Laser Materials Research" J.H. Schulman, et al., NRL Memorandum Rept. 1483, December 1963.

Later, this laser materials research was reported separately in:

- a. "Energy Transfer In Doubly Activated Barium Crown Glass," H.W. Gandy, R.J. Ginther, and J.F. Weller, NRL Memorandum Rept. 1525, May 1964, and
- b. "Energy Transfer In Silicate Glass Coactivated With Cerium and Neodymium" H.W. Gandy, R.J. Ginther, and J.F. Weller, NRL Memorandum Rept. 1546, July 1964.

At that time, partly because of the time delay in the receipt of NRL Memorandum Reports by ARPA personnel, preprints of reportable work were sent informally to ARPA as they were completed. The reason for this was to attempt to keep ARPA apprised as quickly as possible of current materials research here at NRL in this rapidly moving field of research. Nevertheless, since mid-1964, there has been no formal reporting of the ARPA-supported laser materials research at NRL. In the present report, an attempt to rectify this situation will be made.

This summary will outline the accomplishments under the laser materials research program. Appendix A lists all journal publications, NRL reports, and oral presentations covering the period from March 1963 (the start of ARPA support at NRL) to mid-1964, the last formal reporting time; some of this material has been formally reported to ARPA, some has not. Appendix B is a similar listing covering the period from mid-1964 to the present. This latter material has not been formally reported to ARPA. It was considered that inclusion of all published material in the present report was not warranted; hence, only the reference list is provided here. Copies of all published material are being submitted to ARPA under separate cover. However, two very recent and unpublished works are included as Appendix C.

It should be noted that many of the NRL reports listed are essentially duplicates of journal publications, but they are included here inasmuch as this listing is meant to present a complete record of activity under ARPA support. Those NRL reports which are not duplicates or which contain significant additional information over and above their journal counterparts are marked with an asterisk.

Work carried out at NRL in laser materials research from its inception two years prior to the beginning of ARPA support is not listed here.

ACCOMPLISHMENTS

Energy Transfer Studies

For about the last three years, the main effort in laser materials research work has been directed toward the study of energy transfer (sensitized luminescence) in doubly and triply activated glasses, its manifestations in stimulated emission processes, and the development of equipment to carry out these studies. The principal reason for attempting to utilize the principle of energy transfer in laser materials research is to obtain an increase in coupling efficiency between the excitation source and the etalon. Nonradiative energy transfer is more attractive in this application than radiative energy transfer primarily because of higher transfer efficiency and because this quantity does not depend on the optical path length in the luminescent medium.

The field of energy transfer in glasses has been developing rapidly in recent months. It is noteworthy that as little as three years ago there were no proven cases of radiationless energy transfer in any inorganic glass host matrix, even though sensitized luminescence in crystalline matrices had been known since the early 1930's. The first documented case of radiationless energy transfer in any glass matrix was reported by this Laboratory as UO_2^{2+} to Nd^{3+} in barium crown glass. It has been subsequently found at NRL that energy transfer between different activator species in doubly and triply activated glass matrices is a rather common occurrence. This may be due in part to the greater spectral overlap of activator emission and absorption bands found in glasses as compared to crystalline materials. Radiationless energy transfer appears to be the more prevalent transfer mechanism; indeed, of about two dozen different ion-pair transfer systems investigated thus far, only one (Gd^{3+} to Eu^{2+}) is presently believed to be radiative in its transfer characteristic.

Energy transfer has been studied in several triply activated glasses. Sequential two-step radiationless energy transfer occurs in a barium crown glass matrix from UO_2^{2+} to Nd^{3+} to Yb^{3+} . The necessity for the presence of the bridging ion (Nd^{3+}) to affect the transfer from UO_2^{2+} to Yb^{3+} was shown. Here an ion with a longer emission decay time, Yb^{3+} (2100 μsec), was substituted for another with a shorter decay time, Nd^{3+} (450 μsec), as the final emitting activator species. The potential benefits for either continuous laser operation or Q-switched high-power pulse operation is made possible here with increased pumping efficiency because of radiationless energy transfer. In a lithium magnesium aluminosilicate glass, both sequential (Ce^{3+} to Nd^{3+} to Yb^{3+}) and parallel (Ce^{3+} to Yb^{3+} and Nd^{3+} to Yb^{3+}) radiationless energy transfer have been observed.

The Nd^{3+} , Ho^{3+} system is interesting in a negative sort of way. Strong decreases in both the emission decay times and excitation band intensities indicate there is a mutual radiationless energy transfer between these ions. The Nd^{3+} to Ho^{3+} transfer decreases the possibility of Nd^{3+} laser action at a wavelength of 1.06μ , and after about a 5000 cm^{-1} radiationless deexcitation within Ho^{3+} , a back transfer to Nd^{3+} decreases the possibility of Ho^{3+} laser action at 2.1μ . The back transfer mechanism has not been proven, but all our present data are consistent with this interpretation.

Energy Transfer In Laser Action

More recently, increasing effort has been devoted to investigating the manifestations of energy transfer in stimulated emission processes in multiply activated glass etalons. In the Yb^{3+} to Ho^{3+} transfer laser, the expected benefits of radiationless energy transfer

are indeed found. We have observed as much as a tenfold decrease in the Ho^{3+} laser threshold with the incorporation of Yb^{3+} in the etalon glass.

A more complex case is found in the Nd^{3+} , Yb^{3+} transfer system. By controlling the rate and level of excitation of etalons coactivated with these ions, either ion (or both) can be made to exhibit laser oscillations at their own characteristic wavelengths at liquid-nitrogen temperature. Since Nd^{3+} transfers energy to Yb^{3+} , one would expect Yb^{3+} to lase, but not necessarily Nd^{3+} . This primitive type of laser ion switching is possible by (a) exciting the etalon so rapidly that Nd^{3+} lases before it has time to transfer significant amounts of energy to Yb^{3+} , or (b) slowly exciting the etalon to take advantage of energy transfer and obtain only Yb^{3+} laser action. A mathematical discussion of these considerations is given in Appendix C. It seems that this kind of behavior is possible with many energy transfer systems.

Larger bursts of oscillations from glass etalons have been achieved by introducing a recoverable loss in the etalon itself. This self-Q-switching has been observed in the stimulated emission outputs of Er^{3+} , Yb^{3+} , Nd^{3+} , and Ho^{3+} by utilizing a saturable absorption by one of the activators at the respective laser wavelengths.

In glass etalons triply activated with UO_2^{2+} , Nd^{3+} , and Yb^{3+} , it has been possible to selectively self-Q-switch Nd^{3+} , Yb^{3+} , or both ions together by controlling the rate and level of excitation of the etalon. The necessary saturable absorption is provided by absorption from an excited state in UO_2^{2+} situated about 20,000 cm^{-1} above its ground state. It should be noted that UO_2^{2+} plays a dual role in the glass. At low excitation levels, it behaves like the sensitizer ion in a radiationless energy transfer to Nd^{3+} ; at high excitation levels, excited state absorption is the dominant mechanism for the depopulation of the metastable (radiating) level in this ion.

Self-Q-switching of Ho^{3+} has been achieved by two methods. In etalons coactivated with Ho^{3+} and Fe^{2+} , oscillatory bursts of much as 50 times larger than normal Ho^{3+} spiking have been observed in Ho^{3+} stimulated emission. This is believed to be a saturable ground state absorption in Fe^{2+} . By using an external optically pumped UO_2^{2+} containing glass, passive Q-switching has been observed in the Yb^{3+} , Ho^{3+} transfer laser.

Perhaps the simplest type of self-Q-switching has been observed in silicate glass singly activated with Er^{3+} at a temperature of 80°K. Here the ion provides its own saturable absorption at the laser frequency.

Self-Q-switching of Nd^{3+} stimulated emission has been observed in the Ce^{3+} , Nd^{3+} activated etalons at low temperature, but only after the etalon has been exposed to the intense uv radiation of a double-pulsed xenon flashlamp. The origin of the saturable absorption at 1.06μ is not known, but it seems clear that it is involved with ultraviolet radiation damage of this etalon material, and may involve optical absorption of trapped charge in the glass.

FUTURE PLANS

The study of the physical spectroscopy of selected optically active ions will be continued in different glass and crystalline matrices.

The investigation of the temperature and concentration dependence of radiationless energy transfer will be extended in an attempt to understand the detailed nature of interactions between activators.

A long-term study of both transient and permanent uv-induced optical changes in glass has been initiated.

A study of excited state absorption and relaxation phenomena in selected optically active ions in glass is being planned.

A study of self-Q-switching phenomena will be continued in more detail when suitable equipment is assembled.

For all the above studies, there is a need to prepare glass samples of controlled activator valence of better optical quality than has been previously available, and occasionally in larger sizes. Our present limited facilities will soon be augmented by the availability of a glass melting furnace which will permit melting and stirring of glass samples under oxidizing, reducing, or neutral atmospheres, or under vacuum. It will be possible to draw glass rods from the melt under these conditions.

APPENDIX A

ACTIVITY FROM BEGINNING OF ARPA-SUPPORTED NRL LASER MATERIALS RESEARCH TO MID-1964

Journal Publications

1. Gandy, H.W., and Weller, J.F., "Simple Photomultiplier Cooling Apparatus," *Rev Sci Instr* 35:413-414 (1964)
2. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Radiationless Resonance Energy Transfer from UO_2^{2+} to Nd^{3+} in Coactivated Barium Crown Glass," *Appl Phys Letters* 4:188 (1964)
3. Gandy, H.W., Kolb, A.C., Lupton, W.H., and Weller, J.F., "Persistent Enhanced UV Radiation from Double-Pulsed Flash Lamps," *Appl Phys Letters* 4:11 (1964)
4. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Energy Transfer in Silicate Glass Coactivated with Cerium and Neodymium," *Phys Letters* 11:213 (1964)

NRL Reports

- *5. Bradford, J.N., Tucker, J.W., and Gandy, H.W., "Optical Absorption Processes in Ruby," *Report of NRL Progress*, p. 54, July 1963
- *6. Gandy, H.W., and Weller, J.F., "Optical Absorption in Gadolinium-Activated Glass," *Report of NRL Progress*, p. 31, Oct 1963
- *7. Schulman, J.H., "Laser Materials Research," et al., *NRL Memorandum Rept.* 1442, July 1963
8. Gandy, H.W., Kolb, A.C., Lupton, W.H., and Weller, J.F., *Report of NRL Progress*, p. 32, Nov. 1963
- *9. Schulman, J.H., "Laser Materials Research," et al., *NRL Memorandum Rept.* 1483, Dec. 1963
10. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Energy Transfer in Doubly Activated Barium Crown Glass," *NRL Memorandum Rept.* 1525, May 1964

*These reports contain information not covered in the journal publications referenced above.

11. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Energy Transfer in Silicate Glass Coactivated with Cerium and Neodymium," NRL Memorandum Rept. 1546, July 1964

Oral Presentations

1. 1963 Gordon Research Conference on Glass, Tilton, New Hampshire, Aug. 1963; (invited paper) "Stimulated Emission Studies in Silicate Glass," H.W. Gandy
2. First Conference on Laser Technology, San Diego, California, Nov. 12-14, 1963; "Light Sources for Laser Excitation," W.H. Lupton, H.W. Gandy, A.C. Kolb, and R.C. Elton
3. ONR-ARPA Conference on Lasers, U.S. Naval Research Laboratory, Washington, D.C., Mar. 1964; "Energy Transfer in Glass," H.W. Gandy, R.J. Ginther and J.F. Weller
4. Electrochemical Society Laser Symposium, Toronto, Canada, May 6, 1964; Late News Paper: "Energy Transfer in Barium Crown Glass Coactivated with Uranium and Neodymium," H.W. Gandy, R.J. Ginther, and J.F. Weller

APPENDIX B

ACTIVITY UNDER ARPA-SUPPORTED NRL LASER MATERIALS RESEARCH FROM MID-1964 TO PRESENT

Journal Publications

1. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Energy Transfer in Silicate Glass Coactivated with Cerium and Ytterbium," Appl Phys Letters 5:220 (1964)
2. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Energy Transfer in Triply Activated Glasses," Appl Phys Letters 6:46 (1965)
3. Gandy, H.W., Ginther, R.J. and Weller, J.F., "Energy Transfer and Ho^{3+} Laser Action in Silicate Glass Coactivated with Yb^{3+} and Ho^{3+} ," Appl Phys Letters 6:237 (1965)
4. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Laser Oscillations In Erbium Activated Silicate Glass," Phys Letters 16:266 (1965)
5. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Laser Oscillations and Self Q-switching in Triply Activated Glass," Appl Phys Letters 7:233 (1965)

NRL Reports

6. Gandy, H.W., Ginther, R.J. and Weller, J.F., "Energy Transfer in Rare Earth Activated Glasses, I," Report of NRL Progress, p. 45, Nov. 1964
7. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Energy Transfer in Rare Earth Activated Glasses, II," Report of NRL Progress, p. 52, Feb. 1965

- *8. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Laser Action in Holmium-Activated Silicate Glass," Report of NRL Progress, p. 50, June 1965
- *9. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Laser Oscillations in Erbium Activated Silicate Glass," Report of NRL Progress, p. 32, Aug. 1965
- *10. Gandy, H.W., Ginther, R.J., and Weller, J.F., "Laser Oscillations and Self-Q-Switching In Triply Activated Glass," Report of NRL Progress (to be published)
- *11. Gandy, H.W., "Excited State Population Kinetics In Doubly Activated Luminescent Systems," Report of NRL Progress (to be published)
- *12. Etzel, H.W., Gandy, H.W., and Ginther, R.J., "Laser With Ytterbium Activated Glass Sensitive Element," U.S. Patent 3,208,009, issued Sept. 21, 1965

*These reports contain information not covered in the journal publications referenced above.

Oral Presentations

1. Conference on Luminescence, Hull University, England, Sept. 15-17, 1964; "Energy Transfer In Rare Earth Activated Glasses," R.J. Ginther, H.W. Gandy, and J.F. Weller
2. Conference on Luminescence, Hull University, England, Sept. 15-17, 1964; "Optical Properties of Ytterbium Activated Silicate Glass," H.W. Gandy, R.J. Ginther, and J.F. Weller
3. Research Advisory Committee Review, U.S. Naval Research Laboratory (in-house), June 1965; "Glass Laser Materials Research," H.W. Gandy
4. American Physical Society Meeting, Washington, D.C., Apr. 27, 1965; "Energy Transfer in Silicate Glasses Coactivated with Uranium and Europium," H.W. Gandy, R.J. Ginther, and J.F. Weller
5. American Physical Society Meeting, Washington, D.C., Apr. 26, 1965; "Laser Action In Holmium-Activated Silicate Glass," J.F. Weller, H.W. Gandy, and R.J. Ginther
6. Solid State Seminar, U.S. Naval Research Laboratory (in-house), June 21, 1965; "Energy Transfer and Stimulated Emission Processes In Multiply-Activated Glasses," H.W. Gandy
7. ARPA Laser Review, Institute for Defense Analyses, Arlington, Va., Aug. 5, 1965; "Solid State Laser Materials Research," H.W. Gandy
8. Tripartite Laser Meeting, U.S. Naval Ordnance Laboratory, White Oak, Md., Sept. 13, 1965; "Glass Laser Materials Research," H.W. Gandy

APPENDIX C

LASER OSCILLATIONS AND SELF-Q-SWITCHING IN TRIPLY ACTIVATED GLASS

(H.W. Gandy, R.J. Ginther, and J.F. Weller)

Laser oscillations for both Yb^{3+} and Nd^{3+} wavelengths excited during a single flash-lamp pulse were reported several years ago in a doubly activated silicate glass operated at liquid-nitrogen temperature (1). Radiationless energy transfer from Nd^{3+} to Yb^{3+} was subsequently observed in a crystalline tungstate system (2) and later in a borate glass (3)

in which the utilization of this energy transfer in the laser action of Yb^{3+} was demonstrated (4). In this case, laser action for only Yb^{3+} was obtained, in contrast to prior observations (1). One of the purposes of the present work is not only to demonstrate that, in a suitable host matrix, either Yb^{3+} or Nd^{3+} (or both) ions simultaneously can be excited to exhibit laser oscillations, but also to present a physical explanation of how this may be done.

Nonradiative energy transfer from UO_2^{2+} to Nd^{3+} was observed in barium crown glass (5), and it was later shown that energy transfer from UO_2^{2+} to Yb^{3+} can occur in a radiationless manner in this matrix, provided that Nd^{3+} is also present in the glass to effect the transfer (6). It was suggested (7), and later demonstrated (8), that self-Q-switching of the Nd^{3+} stimulated emission could occur in a coactivated system because of a saturable excited-state broadband absorption in UO_2^{2+} which encompasses the Nd^{3+} laser wavelength region. From the foregoing, it is clear that UO_2^{2+} plays the dual role of sensitizer ion for Nd^{3+} and as an excited-state saturable absorber for infrared wavelengths. At high excitation levels, the latter behavior is dominant.

One purpose of using the triply activated glass was to attempt, by substituting Yb^{3+} with a 2100- μ sec decay time for Nd^{3+} with a 450- μ sec decay time, not only to obtain lower thresholds for normal (two-ion) laser action, but also to achieve higher peak power in self-Q-switching experiments, which is theoretically possible for this system. In this appendix, we will describe the results of pulsed flashlamp excitation experiments using confocal etalons of barium crown glass triply activated with UO_2^{2+} , Nd^{3+} , and Yb^{3+} at liquid-nitrogen temperature.

Confocal etalons, 4 mm in diameter and 25 mm long, were fabricated from the experimental silicate glass which was triply activated with UO_2^{2+} , Nd^{3+} and Yb^{3+} at concentration levels of 2×10^{18} , 2×10^{20} , and 2×10^{20} ions/cc, respectively. The etalons were directly immersed in liquid nitrogen in a vacuum chuck arrangement and were excited with a helical xenon flashlamp. The emission output of the etalons was viewed simultaneously at UO_2^{2+} (0.546 μ), Nd^{3+} (1.06 μ), and Yb^{3+} (1.015 μ) emission wavelengths using a double-beam-splitter arrangement; RCA type 6199 and 7102 photomultiplier detectors (2) were used with appropriate narrow-band filters.

By interposing a red filter between the flashlamps and the etalon cryostat, it is possible to prevent UO_2^{2+} from being optically pumped, while allowing both Nd^{3+} and Yb^{3+} to be excited by infrared absorption. This allows the etalon to be operated essentially as a doubly activated glass (Nd^{3+} and Yb^{3+}) even though the principal pump bands of Nd^{3+} are not used.

A series of pulse excitation experiments was performed in which both the potential across the storage capacitors and the series inductance of the flashlamp circuit were varied in order to control the level, as well as the rate, of optical excitation of the etalon. Using an excitation rise time of about 150 μ sec, it has been found that up to capacitor voltages of about 3 kv, laser oscillations occur only at 1.06 μ (Nd^{3+}). If the excitation rise rate is then decreased by a factor of eight with the same capacitor voltage, laser oscillations are observed at both 1.06 μ and 1.015 μ , with the 1.015 μ emission occurring after (700 μ sec) those at 1.06 μ . By using this excitation rise time, but decreasing the flashlamp voltage by several hundred volts, oscillations are detected only in the 1.015 μ channel.

These specific examples serve to illustrate the following general qualitative behavior of the system studied in the present work. With the shorter excitation times used, laser oscillations are first observed at 1.06 μ . With increasing flashlamp excitation energy, oscillations then occur at both 1.06 μ and 1.015 μ during the same pulse, with the 1.06 μ emission preceding the 1.015 μ emission. Using larger excitation rise times, oscillations occur first at 1.015 μ as the flashlamp energy is increased. At higher input energies,

oscillations are again observed at both 1.06μ and 1.015μ in the same sequence as before. In this case, however, the amplitude of the 1.06μ oscillations is less than that obtained when (a) shorter excitation rise rates are used and (b) when oscillations are observed only at 1.06μ .

This series of experiments has indicated that it is possible to control the occurrence of optical oscillations in either or both ions in this glass matrix by varying the rate and level of optical excitation of the etalon, irrespective of the fact that a strong radiationless energy transfer from Nd^{3+} to Yb^{3+} takes place with a characteristic transfer time of 120μ sec. This transfer time is about four times smaller than the Nd^{3+} emission decay time in this glass and about 20 times smaller than the decay time of Yb^{3+} . By using a rapid rate of excitation it would appear that the metastable ${}^4\text{F}_{3/2}$ state in Nd^{3+} can be quickly overpopulated, and then depopulated by stimulated emission processes at a rate large compared to other depopulation processes; i.e. Nd^{3+} lases before it can transfer energy to Yb^{3+} in significant amounts. On the other hand, the possibility of the expected benefits of energy transfer in this glass can be realized by using slow excitation rates and low excitation levels.

A similar set of experiments was performed at about the same excitation level with the red filter removed, thus allowing the UO_2^{2+} of the etalon to be optically pumped. The same general qualitative conclusions are reached now as before, with, however, important detailed differences. Both the Nd^{3+} and Yb^{3+} spikes are larger in amplitude than before, but more significantly they are now more widely separated in time, suggesting that a recoverable loss process within the etalon is modulating its stimulated emission output. In fact, this time separation for Yb^{3+} increases by a factor of 100 for the experimental conditions employed. The general behavior for both Nd^{3+} and Yb^{3+} in this glass is similar to results we have obtained on confocal etalons activated with only UO_2^{2+} and Nd^{3+} and operated at 80°K , in which self-Q-switching of the Nd^{3+} stimulated emission due to a saturable excited state absorption in UO_2^{2+} is believed responsible (8). With the confocal configuration, we have been able to observe at 1.015μ one or two large spikes which are at least ten times larger than any Yb^{3+} stimulated emission pulses observed before in a Fabry-Perot etalon configuration at this Laboratory.

In room temperature excitation of these triply activated glass etalons, it has been possible to observe large pulses only at 1.06μ using the slowest rate of excitation possible with present equipment. Initially it was thought that only Nd^{3+} was being self-Q-switched at room temperature since optical pulses were not observed at 1.015μ . However, Snitzer has recently shown that in this glass matrix doubly activated at a somewhat higher concentration level, Yb^{3+} lases at a wavelength of 1.06μ at room temperature as a four level laser with a terminal level some 850 cm^{-1} above the ground state (9). Hence, it seems very likely that, at room temperature, we have been observing the self-Q-switching of Yb^{3+} at a wavelength of 1.06μ rather than that of Nd^{3+} . When these etalons are excited at about twice threshold level, a peak power density of about 500 watts/cm^{-1} is observed. In these experiments, several of these large spikes occur some 1500 to 2500 μ sec after pulse initiation. A preliminary measurement of the half-intensity width of these pulses indicates an upper limit of 0.3μ sec.

It is believed that the ability to selectively cause a given activator to exhibit stimulated emission in a multiply activated solid, in which radiationless energy transfer occurs, should be possible in many multiply activated systems. However, the excitation levels and rates so required would be expected to differ with different activator pairs, and even for a given pair these quantities should depend markedly upon the strength of the interaction between the activators, which is determined by the host matrix.

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EXCITED STATE POPULATION KINETICS IN
DOUBLY ACTIVATED LUMINESCENT SYSTEMS

(H.W. Gandy)

It has been shown that it is possible to cause either Nd^{3+} or Yb^{3+} (or both) ions to exhibit laser oscillations in barium crown glass etalons operated at a temperature of 80°K (1). This silicate glass is triply activated with UO_2^{2+} , Nd^{3+} , and Yb^{3+} , and laser oscillation of either the self-Q-switched or free-running modes have been observed for Nd^{3+} and Yb^{3+} . Only the latter type of operation will be considered here. The selective excitation of the lasing species was accomplished by varying the rate as well as the level of optical excitation of the etalon. Peterson and Pearson (2) have not been able to observe Nd^{3+} laser action in a borate glass coactivated with Nd^{3+} and Yb^{3+} ; however, these workers did not report varying the rate and level of excitation of their etalons in their work.

It is the purpose of the present work to give a discussion of population kinetics of the metastable radiating states of two interacting activator species between which energy transfer occurs. This will be done in terms of those physical constants which describe the energy transfer between activators, those that characterize the luminescence of either ion individually, and the electrical parameters of the excitation source. Such a description is not necessarily limited to the Nd^{3+} to Yb^{3+} energy transfer but is applicable to other doubly activated systems which exhibit radiationless energy transfer. In the radiationless energy transfer from the sensitizer activator (Nd^{3+}) to the emitter activator (Yb^{3+}), one would expect the emitter to exhibit laser action, but not necessarily the sensitizer even though both are known laser ions. Hence, emphasis will be placed upon describing the buildup of population in the radiating state of the sensitizer ion prior to the threshold for stimulated emission of either ion.

In order to facilitate the discussion of the population of the radiating states in Nd^{3+} and Yb^{3+} , reference is made to the simplified energy level diagrams for these two ions given in Fig. 1. The arrows directed upwards into the shaded areas depict optical absorption from the ground state to the principal excitation levels for the luminescence of either ion; the downward-directed arrows indicate radiative transitions. It will be assumed that the relaxation rates from the excitation levels to the radiating levels are

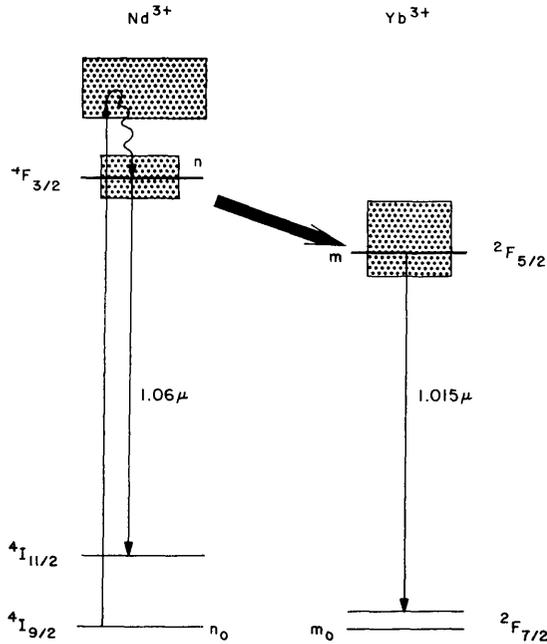


Fig. 1 - Simplified energy level diagrams for Nd^{3+} and Yb^{3+} . Many Nd^{3+} excitation bands are omitted.

large compared to other rates in this system. A similar assumption will be made for the depopulation rate of the terminal energy levels in either ion. With these assumptions the rate of population increase of radiating states in Nd^{3+} and Yb^{3+} , respectively, may be written in the forms

$$\frac{dn}{dt} = E_1(\lambda, t)(n_0 - n) - rn, \quad (1)$$

and

$$\frac{dm}{dt} = E_2(\lambda, t)(m_0 - m) + n/\tau_t - sm \quad (2)$$

where the population of the radiating and ground states of Nd^{3+} and Yb^{3+} are n , n_0 , and m , m_0 , respectively. The direct optical excitation rates of Nd^{3+} and Yb^{3+} as a function of λ and t are denoted by E_1 and E_2 ; r and s are the total depopulation rates of the radiating states for these two ions, and τ_t is the energy transfer time. The probability rate for energy transfer from Nd^{3+} to Yb^{3+} is τ_t^{-1} .

It is a mathematically convenient and physically reasonable approximation to separate $E_1(\lambda, t)$ and $E_2(\lambda, t)$ into the product of a time function and a wavelength function, e.g.,

$$E_1(\lambda, t) = (t/\tau_d) e^{-t/\tau_d} A_1 \quad (3)$$

where

$$A_1 = \int_{\lambda} I(\lambda) F_1(\lambda) \eta_1(\lambda) d\lambda;$$

a corresponding expression may be written for E_2 . $F_1(\lambda)$ is that fraction of the incident radiation intensity $I(\lambda)$ that is absorbed by Nd^{3+} in the solid, and $\eta_1(\lambda)$ is the quantum efficiency for this ion. The integral for A_1 is taken over the excitation spectral region λ for Nd^{3+} . The coefficient of A_1 in Eq. (3) is the function meant to approximate the time dependence of the exciting radiation pulse expressed in terms of those quantities which are determined by the electrical parameters of the flashlamp circuit. The rise time of

the exciting pulse is τ_e and is controlled primarily by the series inductance of the circuit, whereas τ_D is the exciting pulse decay time and is fixed mostly by the value of the storage capacitance used in the flashlamp operation. The level of the incident intensity $I(\lambda)$ (and hence of A_1 and A_2) is principally determined by the flashlamp's capacitor voltage.

If it is assumed that the population of the radiating state of each ion is always small compared to that of its ground state, an assumption which is frequently made for four level lasers, then n_0 and m_0 are equal to the respective activator concentrations in the host, and Eqs. (1) and (2) may be written in the more tractable forms:

$$\frac{dn}{dt} + rn = A_1 n_0 \tau_e^{-1} t e^{-t/\tau_D}, \quad (4)$$

$$\frac{dm}{dt} + sm = A_2 m_0 \tau_e^{-1} t e^{-t/\tau_D} + \tau_t^{-1} n. \quad (5)$$

With the initial conditions that $n=m=0$ at $t=0$ the solutions to these equations are:

$$n = A_1 n_0 (T_1/\tau_e) f_1(t), \quad (6)$$

where

$$f_1(t) = t e^{-t/\tau_D} - T_1 (e^{-t/\tau_D} - e^{-rt}) \text{ and } T_1^{-1} = r - \tau_D^{-1},$$

and

$$m = A_2 m_0 (T_2/\tau_e) f_2(t) + A_1 N_0 \left(\frac{T_1}{\tau_t} \frac{T_2}{\tau_e} \right) g(t), \quad (7)$$

where

$$T_2^{-1} = s - \tau_D^{-1}, \text{ and } f_2(t) = t e^{-t/\tau_D} - T_2 (e^{-t/\tau_D} - e^{-st}),$$

and

$$g(t) = T_2 [e^{-t/\tau_D} (T_2^{-1} t - 1) + e^{-st}] + T_1 (e^{-st} - e^{-t/\tau_D}) + \frac{T_1^2}{T_1 - T_2} (e^{-rt} - e^{-st}).$$

Here T_1^{-1} and T_2^{-1} are the depopulation rates for the radiating states of the sensitizer and emitter activators, respectively, modified by the rate of decrease of the exciting radiation.

The first term on the right in either Eq. (6) or (7) corresponds to the contribution to the population of the radiating states of either activator due to direct optical excitation, whereas the second term in Eq. (7) corresponds to indirect excitation of the emitter due to energy transfer from the coactivating species. The several terms in these solutions are the product of constant coefficients and explicit time functions. The coefficients contain the physical constants of the luminescent system as well as the experimentally controllable parameters used in the pulsed excitation of the system (1). The time functions $f(t)$ and $g(t)$ will not be further considered, partly because of their complicated forms, but mostly because they do not contain all the controllable parameters as do their coefficients. Hence, only the latter will be discussed, and the qualitative conclusions drawn will not be affected by ignoring $f_1(t)$, $f_2(t)$, and $g(t)$.

The modified depopulation rates T_1^{-1} and T_2^{-1} are comprised of several terms corresponding to different depopulation mechanisms, i.e.,

$$T_1^{-1} = r - \tau_D^{-1} = \tau_1^{-1} + \tau_t^{-1} + L_1 + P_1 - \tau_D^{-1} \quad (8)$$

and

$$T_2^{-1} = s - \tau_D^{-1} = \tau_2^{-1} + L_2 + P_2 - \tau_D^{-1}, \quad (9)$$

where τ_1 and τ_2 are the emission decay times of the sensitizer and emitter in the doubly activated solid, τ_t is as previously defined, and L_1, L_2 , and P_1, P_2 are the stimulated emission and radiationless deexcitation (multiphonon emission) rates, respectively, for the sensitizer and emitter.

It is interesting to note that when the sensitizer lases, T_1 becomes small compared to τ_e and τ_1 because L_1 then dominates the expression for T_1^{-1} . When this occurs, η decreases rapidly and the second term in Eq. (7) becomes negligible compared to the first, indicating that radiationless energy transfer from Nd^{3+} no longer significantly contributes to the Yb^{3+} radiating state population. Direct optical excitation is then the dominant population mechanism for the emitter. Above the Nd^{3+} laser threshold, considerable radiative transfer of stimulated emission energy from Nd^{3+} to Yb^{3+} can occur, but this is not included in this prethreshold discussion.

If only the excited state phenomena prior to stimulated emission are now considered, it is instructive to discuss the relative excited state populations of the two activators in order to obtain an indication of the experimental conditions required for the selection of the lasing species. The contributions of L_1 and P_1 to T_1^{-1} and of L_2 and P_2 to T_2^{-1} are now ignored in order to simplify the discussion.

If it is desired to increase n in preference to m , then from Eq. (6) for direct excitation it is desirable to make both $A_1 n_0$ and T_1/τ_e large, and from Eq. (7) $A_2 m_0$ small; to diminish the indirect contribution to m in Eq. (7), one should then make T_1 and T_2 small and τ_t and τ_e large. Apart from varying the relative activator concentrations, the ratio of $A_1 n_0$ to $A_2 m_0$ is fixed by the ratio of the integrated magnitudes of the Nd^{3+} excitation bands to that of the Yb^{3+} excitation bands, assuming an excitation source whose output is wavelength independent. The ratio of A_1 to A_2 , using filtered xenon flashlamp radiation, is estimated to be about 5 to 1, whereas a ratio of about 20 to 1 is estimated without filtering. The threshold values of n and m are believed to be about equal because of high resonator losses; hence, a quantitative comparison of A_1 and A_2 is meaningful. Barring a significant and controllable change in the spectral character of the lamp in the proper wavelength region, this ratio is fixed by the optical properties of the two activators and does not vary greatly in the various glass compositions studied, even though A_1 and A_2 do vary.

Now T_2 can be made small by making τ_D smaller than τ_2 by decreasing the value of the flashlamp storage capacitance. However, τ_D should not be made so small as to make T_1 small compared to practical values of τ_e . The energy transfer time τ_t can be decreased by increasing activator concentration in a given host matrix or, for a given concentration level, it can be changed by selecting different host matrices. For the barium crown glass work reported in the previous section of this appendix, the experimental parameters were chosen such that

$$\tau_e (100 \mu\text{sec}) < \tau_t (120 \mu\text{sec}) < \tau_1 (450 \mu\text{sec}) < \tau_D (1000 \mu\text{sec}) < \tau_2 (2100 \mu\text{sec})$$

for the observation of Nd^{3+} stimulated emission. The storage capacitor voltage was then used as the controllable experimental parameter to observe, first, Nd^{3+} stimulated emission alone, and second, the emission from both ions. Obviously, a number of other combinations of τ_e, τ_D and capacitor voltages are possible for these results.

On the other hand, if it is desired to preferentially increase m with respect to n by radiationless energy transfer processes, it is important to keep n small enough so that Nd^{3+} does not lase. One important way in which this may be achieved is by making τ_e large. In the barium crown glass work reported here (1), the experimental parameters chosen for observation of only Yb^{3+} stimulated emission near threshold were

$$\tau_t(120 \mu\text{sec}) < \tau_1(450 \mu\text{sec}) < \tau_e(800 \mu\text{sec}) < \tau_D(1000 \mu\text{sec}) < \tau_2(2100 \mu\text{sec}),$$

with the capacitor voltage serving as the experimentally controlled parameter. Again a number of other combinations of experimental parameters could be used with this glass for the results reported here.

An important parameter in a doubly activated system is the transfer time τ_t , which depends on the integrated spectral overlap of the sensitizer (Nd^{3+}) emission intensity and the emitter (Yb^{3+}) absorption coefficient (3). The intensities of both of these quantities depend on the symmetry of the ion site in the host matrix (4). Low symmetry increases the intensities of both quantities by mixing optical states of odd parity, thus increasing the coupling between activators and, hence, decreasing τ_t . The opposite trend is true for activator sites of higher symmetry. If one wished to take advantage of the radiationless energy transfer from Nd^{3+} to Yb^{3+} for low threshold and possible cw operation of a Yb^{3+} glass laser, one would ideally like to have a high symmetry site for Yb^{3+} for a long emission decay time τ_2 , and a site of lower symmetry for Nd^{3+} to decrease τ_t . Unfortunately, however, in the glass matrices investigated thus far, both ions tend to go into sites of apparently similar symmetry, as evidenced by the approximately constant ratio of their emission and absorption band intensities; this trend is not surprising from a chemical viewpoint.

There seems to be no good reason why the selection of lasing activator type cannot be, in principle, possible with any interacting activator pair. However, it is clear from Eqs. (6) and (7) that the electrical parameters τ_e , τ_D and capacitor voltage would have to vary appropriately. For example, in the borate glass (2), the 30- μsec transfer time would require smaller values of τ_e and τ_D and higher capacitor potentials than used in the present work.

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LASER MATERIALS EVALUATION PROGRAM

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A materials evaluation center is being put together at NRL for the purpose of monitoring laser materials prepared under the ARPA laser program. This function had previously been carried out in this Laboratory by the Radiometry Branch of the Optics Division. The center is expected to be completed sometime around July 1966. At this time it is intended that we will have the capability of making the following measurements in a more or less routine manner: far-field divergence both in emission and as a passive test, fluorescent line width, static scattering loss, dynamic forward scattering, threshold for lasing, threshold for radiation damage using schlieren, quantum efficiency, and spontaneous lifetime. The necessary space for this equipment has been assigned to be used for just this purpose. As each piece of equipment is set up, it will remain in that condition as long as this center is in existence.

At the present time, in response to a request from Dr. Nicolai of ONR, we are assembling the equipment to measure the static scattering loss of materials that are intended for use as high-powered lasers. Since these materials have low losses and since the size of the samples is of the order of centimeters, we are designing the equipment to have a sensitivity of the order of 0.001 percent per centimeter.

The method that is being used involves placing the sample in an integrating sphere. Light from the source is chopped, and during one half of the cycle a known adjustable portion is fed back into the sphere for comparison with the light that is scattered from the sample. A photomultiplier is used in conjunction with a phase-sensitive detector as a null instrument.

MAGNETIC Q-SPOILING OF COOLED RUBY

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BACKGROUND

Before July 1, 1965, this work was sponsored by ONR under ARPA Order 306-62. The NRL Problem Number was 73N01-09. The present work is supported by NRL Problem No. 73K03-08, ARPA Order No. 660.

The first magnetic Q-spoiling experiments were reported in an NRL memorandum report (1) covering the period from June 30, 1964, to January 1, 1965. These experiments demonstrated that laser action in ruby at 77°K could be appreciably delayed by a magnetic field. This result encouraged a more ambitious experimental program. There is now a broader interest in magnetic Q-spoiling than when this work was begun. A few comments will be made in this section on this result and on the general problem.

In the course of an investigation of cross relaxation between the ²E levels of ruby, attempts were made to operate a ruby laser in the Q-switched mode at 77°K. It was found that normal Q-switched operation could not be obtained because of the high gain of pumped ruby at this temperature. Losses by superadiance and spurious laser action increase so drastically with increasing population inversion that little energy can be stored for Q-switching.

This sensitivity of gain to temperature might have been anticipated by earlier spectral data. At room temperature the R₁ line of ruby is homogeneously broadened to almost 20 times its width at 77°K. Cooling sharpens the R₁ resonance and increases the probability of stimulated emission. It seemed that low-temperature Q-switching would require some form of volume Q-spoiling, such as rapid control of properties of the chromium ion ensemble. A theoretical and experimental investigation (1) indicated that Zeeman splitting of the ground levels by an inhomogeneous magnetic field could be used for gain reduction during the pumping period. Cancellation of this field would restore spectral uniformity throughout the ruby and, hopefully, would result in a short, intense pulse of output radiation.

The sharpness of R₁ fluorescence at 77°K makes low-temperature Q-switching look interesting. It may make it easier to maintain spectral purity at high peak powers. This is important in such laboratory applications as nonlinear phenomena, Raman spectroscopy, plasma physics, etc., and for some operational devices. It is also possible that the high gain of ruby at 77°K will produce a faster buildup of the laser oscillation and a shorter, more intense pulse than can be obtained at room temperature.

Alternative experimental techniques were evaluated theoretically and in the laboratory, and components were designed for a controlled experimental investigation. Orders for major shop work were placed in July of 1965, with completion estimated in August. In the meantime, supporting experiments and component development were carried on in the laboratory.

EXPERIMENTAL PROCEDURE

It was estimated that useful Q-spoiling would require a magnetic field of 30 kG and that generation of this field would require a current of 30,000 A. The prime source of energy for this magnetic field current is a 450- μ F capacitor bank which can be charged to a maximum of 4000 V. An Ignitron discharges the capacitor bank through the primary of a toroidal pulse transformer. The core of this transformer is ribbon wound, and prior to each firing the core is reverse biased so that the full range of its magnetization is available. There are two, parallel-connected, 100-turn primary windings. Each covers one half of the toroid so that, connected together, the winding is uniform and continuous. The secondary is the cylindrical aluminum housing and coaxial inner cylinder. Copper bars carry the output current to the coaxial copper piping which supports the ruby rod, the light pipe, and the field coil. This copper piping carries the field current down into a liquid-nitrogen dewar to the field coil. The field coil consists of two parallel conductors on opposite sides of the ruby rod and is terminated with an annular shorting ring around the ruby rod. The field current reaches its maximum value of 30,000 A in about 3 msec. The sequence of events is so arranged that, by this time, the ruby is well pumped and ready for Q-switching.

Q-switching is initiated by the triggering of a spark gap which discharges a 2- μ F capacitor charged to 20,000 V. This discharge circuit joins the magnetizing current circuit at the junction of the copper bars and the copper piping. Because of the lower inductance of the piping, the bulk of this current flows down the piping and through the magnetizing coil. This fast discharge current opposes the relatively slow magnetizing current so that the net coil current is rapidly brought to zero and reversed in polarity. The magnetic field drops to zero and reverses in less than 1 μ sec after gap triggering. Q-switching should occur as the field goes to zero.

The ruby rod being used at present has flat ends and is uncoated. It is supported in the liquid nitrogen by a steel light pipe filled with dry nitrogen and terminated with a Brewster-angle window. At present, the laser cavity is formed by the ruby faces. For later tests the upper face of the ruby will have an antireflection coating, and an external reflector above the light pipe will form one end of the cavity. This will allow passive Q-switch devices, mode selectors, etc. to be inserted. The ruby is pumped by a 9-kV helical xenon flashlamp which fits around the lower clear portion of the dewar. A window is provided at the end of this cylindrical section for laser output.

PROGRESS

Work on this project in 1965 was directed toward the design, construction, and testing of experimental equipment. Elaboration of details of this preliminary, but necessary, work will be avoided, and progress will be indicated by a chronological outline of the major milestones in equipment development and in experimentation.

1. Shop work was initiated on components of the low-temperature Q-switching assembly. Design of major components continued (July 1965).
2. Began construction of magnetic field generation circuitry (Aug 1965).
3. Started design of energy storage unit for flash tube (Sept. 1965).
4. High-current pulse transformer was completed. Performance tests on it were begun (Sept. 1965).
5. Tests were begun on magnetic field generation assembly (Sept. 1965).

6. Completed assembly of flash tube storage unit (Nov. 1965).
7. Received final components for field cancelling assembly; assembly begun (Nov. 1965).
8. Power supply for flashlamp capacitor bank was received, and safety and performance tests were begun (Dec. 1965).
9. Assembly of Q-switching equipment was completed and performance tests were begun. Because of erratic prefiring of the 10-kV flash tubes, it was decided to use a series Ignitron. An order was placed for the necessary components. In the meantime a magnetic pickup loop was used to monitor the electrical behavior of the field-generating and the field-cancelling circuits. These tests were performed with the appropriate components immersed in liquid nitrogen. Electrical performance was as expected for both circuits but the field-generating conductors and supports could not withstand the mechanical impulse due to the field. These components were redesigned for greater strength and rigidity (Jan. 1966).
10. With a heavily reinforced field coil and series Ignitron circuitry for the flash tube, actual Q-spoiling and switching experiments were tried on Feb. 11, 1966. Very satisfactory Q-spoiling and Q-switching were obtained. With no magnetic field, laser action began 300 μ sec after flash tube firing. With a field of about 20,000 G laser action was suppressed until the cancelling field was applied, some 500 μ sec after flash tube firing. Several oscillograms were made showing the Q-switched output (see Fig. 1). These experiments were terminated by the loss of the dewar and flash tube when an implosion of both components occurred upon firing. It is assumed that there was not enough clearance between the field coil supports and the inner wall of the dewar and that the glass was hit by the magnetic kick of the coil-support retainers. Corrective steps were taken within the constraints imposed by the dimensions of the spare dewar on hand. Work was also started on a dewar of modified design that would relieve the problem (Feb. 1966).
11. The magnetic field sensing and integrating circuits were developed to a satisfactory state. There had been problems with spurious pickup, stray reactances, etc. which were aggravated by the signal loss involved in integrating uniformly from a few cycles per second to 30 Mc/s (Feb. 1966).

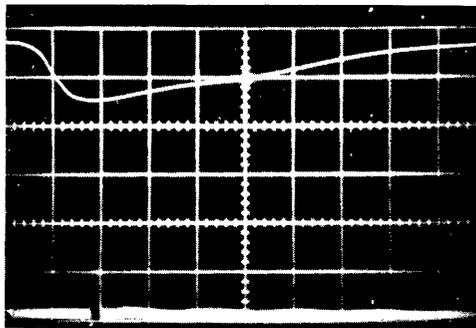


Fig. 1 - Magnetic Q-switching of ruby laser, upper trace - pumplight, 100 μ sec/cm, lower trace - laser output, 2 μ sec/cm. Q-switching is effected by application of the cancelling field 500 μ sec after flashlamp trigger.

PRESENT STATUS AND FUTURE PLANS

Experiments to date have been made with the end faces of the ruby serving as the cavity mirrors. It has been found that a magnetic field will inhibit laser action while energy is being stored and that the application of a cancelling field will result in the release of this energy in a single pulse.

In the next series of experiments an antireflection coating will be placed on one face of the ruby, and a tilted bleachable filter will be between this face and an external mirror. The decreased feedback during pumping should allow heavier pumping, while the increased feedback after bleaching, together with the higher ruby gain, should shorten and intensify the Q-switched output. An investigation will be made of the effect of various parameters on the output pulse, which will be examined by photo-oscillographic, photographic, spectrographic, and interferometric techniques. It is hoped that these techniques can be so applied that characteristics of the output will be resolved in time to within a few nanoseconds. Plane and spherical reflectors will be used with rubies of different chromium concentrations, lengths, and quality and with other laser samples that have sharp fluorescent lines and are subject to Zeeman splitting. The pulse output and the magnetic field will be recorded on synchronized sweeps for various pumping rates, pumping times, and spoiling and cancelling fields.

Results obtained to date will be reported in the monthly Report of NRL Progress and will be submitted as a letter to an appropriate journal. It is expected that the results of the planned experimental program will be submitted for journal publication and will be incorporated in a formal NRL report.

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GAS LASER RESEARCH

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ION LASER EXPERIMENTS

An experimental gas laser system has been set up to study gas lasers at higher currents and current densities than used heretofore. As shown in Fig. 1 the system is designed so that the entire high-voltage part of the circuit is submerged in demineralized water, which is an excellent insulator for the $2\text{-}\mu\text{sec}$ charge times involved in these transient experiments. The system is completely and quickly demountable, using O-ring vacuum seals. The water dielectric capacitor is pulse charged in $\sim 2\ \mu\text{sec}$ through a step-up transformer from a slowly charged bank of commercial capacitors. At 300 kV the $0.06\text{-}\mu\text{F}$ water capacitor stores 2700 joules (J). The total inductance of the circuit is $\sim 0.24\ \mu\text{H}$ and the ringing frequency is $\sim 1.3\ \text{MHz}$. The peak current at 300 kV is 150 kA in both parallel legs, or 75 kA in each leg.

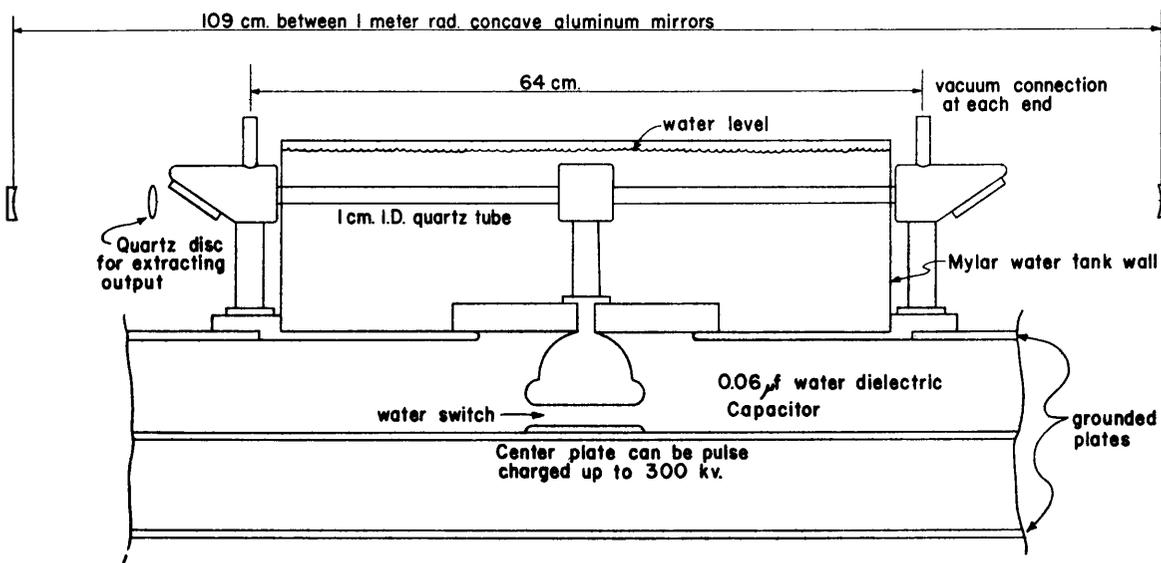


Fig. 1 - Laser portion of the experimental gas laser research facility

Aluminum concave mirrors (1 m radius of curvature) and quartz windows are used so that a wide spectral range can be surveyed at a single shot. The output is extracted by partial reflection from a high-quality fused quartz disc placed within the laser optical

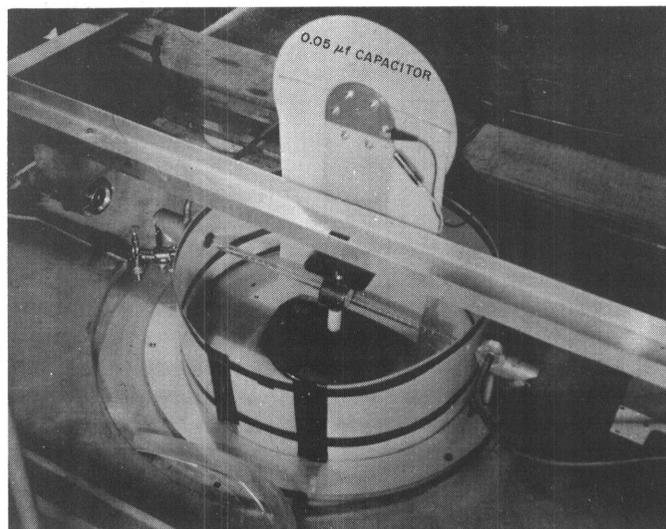


Fig. 2 - Experimental gas laser system atop the water dielectric capacitor

cavity. The following types of diagnostics are employed: Time-integrated spectrographic film records from 1900 to 5400Å are obtained with a grating spectrograph; output pulse waveshapes at specific wavelengths are obtained with a 0.1Å resolution monochromator and photomultiplier detector; power levels are measured with a vacuum photodiode; and instantaneous voltages in the circuit are measured by specially shielded capacitive-resistive voltage dividers and by di/dt techniques. The current is either computed from the voltage and frequency or it is obtained by integrating di/dt signals.

Figure 2 is a photograph of the experimental gas laser system atop the water dielectric capacitor with a small, auxiliary, commercial, 0.05- μ F capacitor connected to the system which is capable of supplying currents up to about 5000 A. It is more convenient to use this auxiliary system at low currents to align the concave mirrors and adjust the other optical and electronic equipment prior to a high-current shot with the large water capacitor.

In addition, the optimum pressure for lasing was determined with this system at 5000 A. The pressure range over which lasing could be obtained was relatively small, e.g., between 0.014 torr and 0.022 torr for argon. A slight gas flow through the tube produced a pressure gradient of typically ± 0.004 torr about the mean values reported here.

Lasing has been observed with argon, neon, and mixtures of argon, neon, and air. About equal parts of argon and dry air at a pressure of ~ 0.02 torr gives the highest output in the visible at 4765Å - about 0.5 watt. Although Bennett et al. (1) reported laser outputs of "hundreds of watts" in argon at 4880Å, the output from this system at 4880Å is very low compared to that at 4765Å.

The greatest output is 5 to 10 W, obtained in the ultraviolet at 3511Å (argon III line). Practically all of the laser output waveshapes are single pulses of 100 to 200 μ sec half-power width, so the dependence of output power on current density is well illustrated by the time-integrated spectrographic records of Fig. 3. At very low currents many lines are recorded in the visible range. As the current increases, lasing commences at 3511Å. The line structure fades from the visible and appears in the ultraviolet. Gradually, a continuum background appears in the ultraviolet and grows stronger as lasing at 3511Å stops. (Such "quenched" has been observed by others (2). The absence of 3511Å

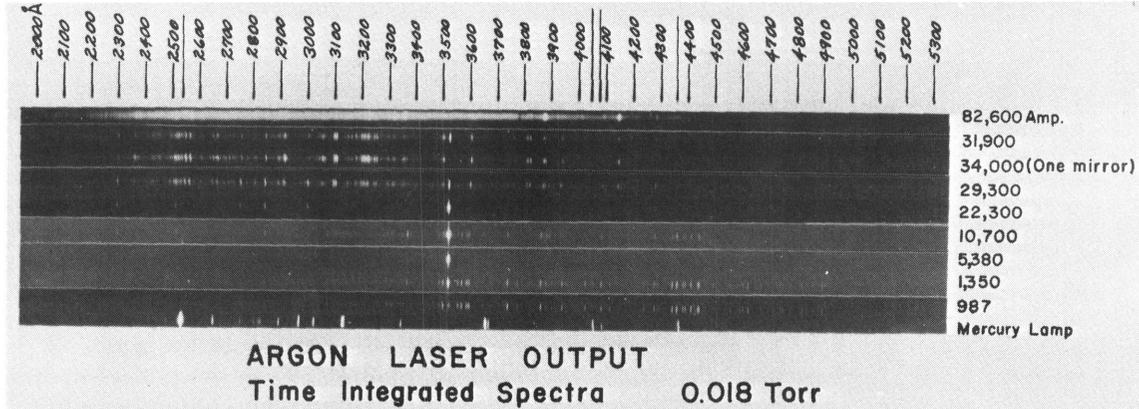
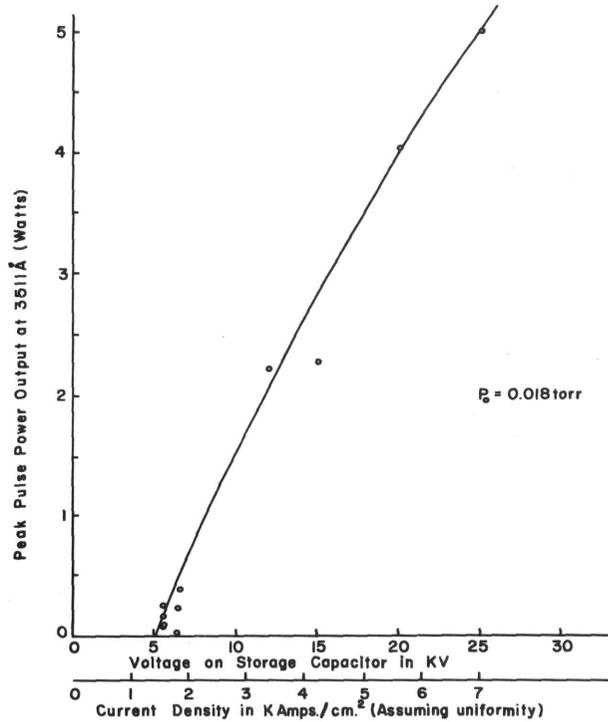


Fig. 3 - Spectrographic film records of several shots at various currents with the laser tube filled with argon

Fig. 4 - Argon III (3511Å) output as a function of peak current density



emission on the spectrogram with one mirror covered shows that it is lasing and not spontaneous emission. Figure 4 shows the argon III (3511Å) output (measured by a photodiode) at 0.018 torr as a function of peak current density.

A low pulse power of 0.5 W was obtained from neon at 0.06 torr in the NeII lines of 3324, 3345, and 3378Å.

MOLECULAR NITROGEN LASER EXPERIMENTS

Laser oscillation in the second positive band system of N_2 was discovered by Heard (3). Gerry and Leonard (4-6) have shown that powers of 200-300 kW at 3371\AA can be produced by a discharge perpendicular to a 200 cm long tube. About 1 J of electrical energy was deposited during the $\sim 20\text{ nsec}$, self-terminating pulse (the lower laser level has a $\sim 10\text{-}\mu\text{sec}$ lifetime). The saturated power density was reported to be 2 kW/cm^3 , and the gain was sufficiently high so that super-radiant emission occurred along the axis without cavity mirrors.

With electron temperatures greater than $\sim 3\text{ eV}$, the rate coefficient for electron-impact excitation of the upper laser level is greater than that for the lower level. At temperatures $\gtrsim 5\text{ eV}$ the ratio is about ten, so that preferential excitation leads to population inversion for times less than the radiative or collisional relaxation time of the laser levels. Thus, to have large power densities, one requires high electron and molecular particle densities, and the electrons should be hot.

We have considered the engineering problems associated with producing excitation conditions required to raise the previously reported saturated power density by at least an order of magnitude. It is calculated that current densities of a few thousand A/cm^2 are needed to produce electron densities of about $10^{15}/\text{cm}^3$ with molecular densities of $\sim 10^{18}/\text{cm}^3$. In the present experiment, the discharge channel has an electrode spacing of 1.7 cm and a 180 cm length. The current flows over $\sim 200\text{ cm}^2$ so that 400 to 500 kA is required to produce the necessary current density. A flat-plate Blumlein transmission line 6 ft wide and 12 ft long was constructed using mylar dielectric and completely submerged under water. The charged line stores 320 J and has an equivalent generator voltage of 150 kV and impedance of $0.3\ \Omega$. Solid dielectric switches are located 1 ft apart at one end of the line and are triggered coincidentally to launch a plane wave in the line toward the discharge gap located across the center of the top plate. Figure 5 shows this line and the laser in operation.

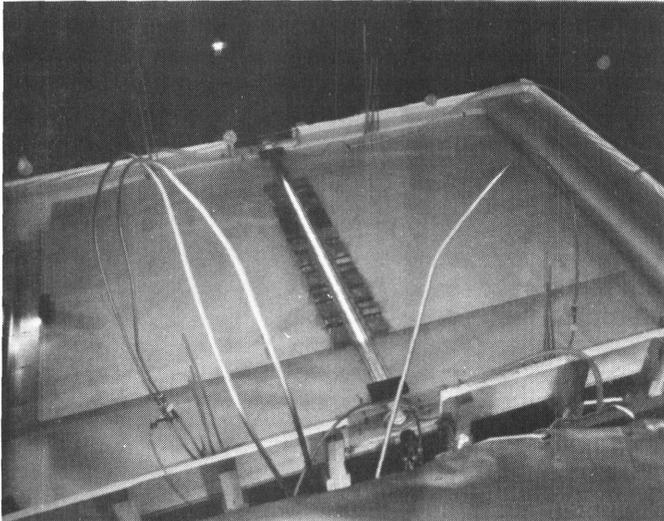


Fig. 5 - Higher-power nitrogen laser

Laser power is optimum at 30 torr. One-half of the 200 cm^3 plasma volume was viewed with an ITT calibrated photodiode and produced the 680-kW output pulse shown in Fig. 6. During the 3-nsec rise time of this pulse, only one-half of the length of the discharge tube can contribute radiation to the pulse. Taking this into account, together with the fact that radiation is emitted from both ends, a saturated power density of 30 kW/cm^3 can be inferred.

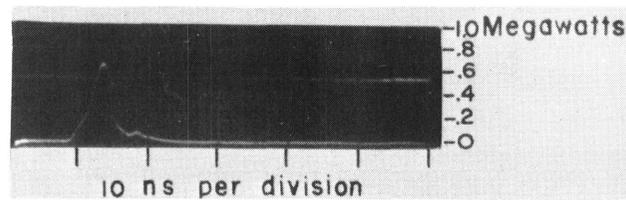


Fig. 6 - Pulse shape of the high-power nitrogen laser

Voltage waveforms indicate that the plasma resistance is small compared to the characteristic impedance of the line. Thus, it is expected that the existing transmission line can accommodate a larger discharge volume and still maintain the present high power densities. Such a modification is planned in the near future with electrode spacings of up to 10 cm.

The output pulse is short compared to the radiation lifetime of the upper laser level, presumably due to cooling of the electron gas by ionization, when the degree of ionization approaches 0.1 percent. Under these conditions, the rate coefficient for ionization is about an order of magnitude larger than the rate coefficient for excitation.

GAS LASER THEORY

In order to understand the limitations and conditions of optimum performance of gas lasers, a computer program has been written for a laser system with up to five energy levels and including all collisional mixing terms. Attention has so far been focused on a three-level system where inversion is accomplished by electron impact. The equations governing the population densities of the upper and lower levels of the lasing line are

$$\frac{dN_3}{dt} = X_{13} N_1 + X_{23} N_2 - N_3 \left(\frac{1}{\tau_{31}} + \frac{1}{\tau_{32}} \right) - (Y_{31} + Y_{32}) N_3$$

and

$$\frac{dN_2}{dt} = X_{12} N_1 - (X_{23} + Y_{21}) N_2 + \left(\frac{1}{\tau_{32}} + Y_{32} \right) N_3 - \frac{N_2}{\tau_{21}},$$

respectively. Here X_{ij} is the collisional excitation rate from level i to level j , Y_{ji} is the collisional de-excitation rate, $(\tau_{ij})^{-1}$ is the radiative decay rate from level i to level j , and N_1 is the ground state population. These equations are equally applicable to ionic, atomic, or molecular lasers where excitation is accomplished by electronic impacts.

With various simplifying assumptions, the above equations can be solved analytically to give some general criteria for inversion. Two noteworthy cases are:

1. The lifetime of the upper level is much shorter than that of the lower level, and the upper level is populated preferentially. This situation is found in the molecular nitrogen laser. In this case, inversion can only be obtained for times t given by

$$t < 2 \tau_{32} / (1 + Y_{32} \tau_{32}).$$

Thus the lasing must terminate at times less than the lifetime τ_{32} , as has been experimentally verified.

2. The lifetime of the upper level is much longer than that of the lower level, and the excitation rates into these two levels are comparable. This situation is found in the argon ion laser. In this instance, the condition for a steady state inversion is given by

$$X_{23} + \frac{1}{2\tau_{21}} > Y_{32} + \frac{1}{\tau_{32}} .$$

This implies that the laser operation is dependent on the lower level being effectively depopulated faster than the upper.

The computer code will be used to predict the optimum conditions (e.g., initial pressure, discharge dimensions, and circuit parameters) required for maximum output power. Following Gerry, the circuit equation for the driving line has been coupled to the rate equations for a three-level laser system. With the parameter values used in the present molecular nitrogen laser, this model predicts a saturated power density of 30 kW/cm³ in agreement with the value deduced from the measurements.

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BEAM SELF-FOCUSING IN LIQUIDS

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(NRL Problem No. 77K03-08A)

In an optical medium with a nonlinear refractive index, an intense light beam may be self-focused down to a thin filament and then propagate without spreading, which would normally occur due to diffraction effects. The intensity of such a beam may be considerably higher than the intensity of the incident beam and, consequently, produce larger amounts of damage (to crystalline materials) or larger amounts of Raman and Brillouin scattering than expected from the incident beam.

These effects were noted by a number of investigators, and Chiao, Garmire, and Townes (1,2), Wang (3), and Kelley (4) have described possible mechanisms that explain this nonlinear behavior. It is generally agreed that increases in the index of refraction are the primary causes for the initial bending of the rays and the eventual trapping of the light rays to form its own optical waveguide.

The goal of the present experiment is to observe the spatial changes in the index of refraction as a function of time when light beams with intensities between 100 and 200 MW are passed through various liquids. Initial attempts to observe the index of refraction changes will be made with water; however, this experiment is also easily adapted to study these effects in nitrobenzene, carbon disulfide, benzene, and other liquids with high Kerr coefficients. A Mach-Zehnder interferometer will be used to measure the changes in the index of refraction, and an image converter camera will be used to record the fringe patterns with a time response of 5 nsec. Such quantitative measurements should be useful in gaining a better understanding of this nonlinear behavior.

At the present time, a Korad K-1Q giant pulse laser (3 J, > 100 MW) and a Mach-Zehnder interferometer (6-in. mirrors), complete with a liquid cell, are ready for use. It will be possible to take our first measurements of the index of refraction changes as soon as the pulse electronic circuits for triggering the image converter camera are ready, which should be sometime in May, 1966.

Time-integrated photographs taken of the giant laser pulse (~150 MW) passing through a water cell have shown evidence of self-focusing and trapping of the light beam; however, this work was very preliminary and it is to be followed by a more careful experiment with the Mach-Zehnder interferometer.

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HIGH-POWER LASER DEVELOPMENT

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MOTIVATION FOR THE DEVELOPMENT OF A FARADAY ROTATION Q-SWITCH

Present Q-switching techniques, such as rotating mirrors, Kerr cells, or saturable filters, fail in one or more ways to meet the three desirable qualities of a Q-switching technique: (a) output reproducibility, (b) synchronization with other systems, and (c) absence of nonlinear effects generated in the Q-switch itself.

The Faraday effect appeared well-suited for use as a switching technique that would satisfy the above criteria since it is a magnetic effect of appreciable size in glasses, with excellent damage resistance. Presumably, the shot-to-shot variations should also be small using this effect.

Two related developments have been reported in the literature; Q-switching at low power with a Faraday rotator switch (1), and a Faraday rotator optical isolator (2).

PRINCIPLE OF FARADAY Q-SWITCH

The Faraday effect is the rotation of the plane of polarization of light passing through a medium in a parallel magnetic field. This rotation is quantitatively given by $\theta = V\ell H$ where

θ is the angle of rotation

V is the specific magnetic rotation (Verdet) constant, which is dependent on the material

ℓ is the length of the material sample

H is the magnetic field.

The light output from a 60-degree-cut ruby (with Brewster-Brewster angle ends) is strongly plane polarized. If a block of fused quartz or other Faraday-active medium is placed inside the laser cavity with no magnetic field applied, no rotation of the plane of polarization will result. If some sort of polarization selector is placed in the beam, this plane of polarization can be reflected out of the resonant cavity, as illustrated in Fig. 1, and no oscillation will result. If a magnetic field strong enough to rotate the plane of polarization 90 degrees is then switched on, the light will pass the polarization selector without loss, and a single giant pulse will result.

EXPERIMENTAL VERIFICATION

A prototype system was constructed as shown in Fig. 2. Fused silica was chosen as the Faraday-active material since preliminary experiments showed that both lead glass (Corning code 8463) and flint glass damaged severely below 50 MW/cm² power levels,

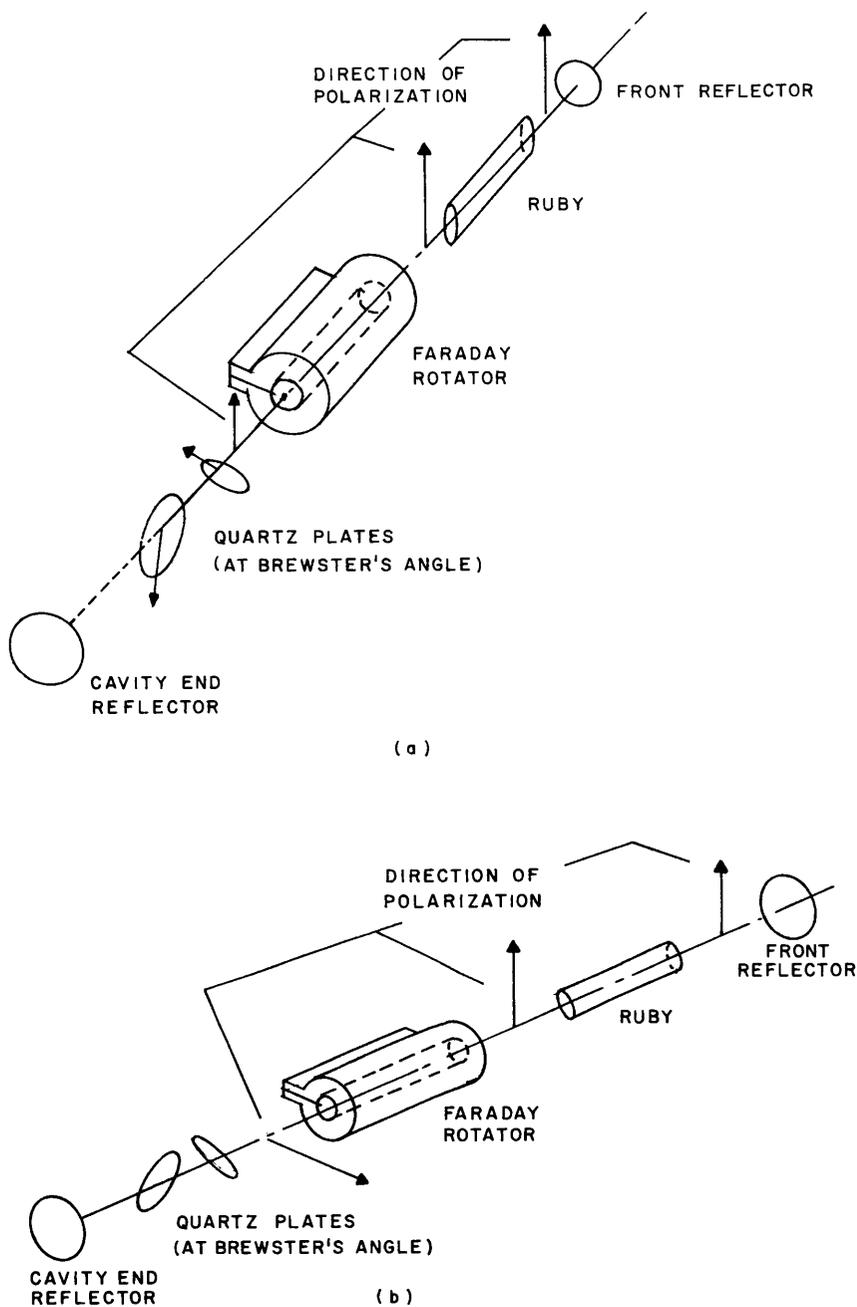


Fig. 1 - (a) Vertically polarized light from the ruby is reflected from the quartz plates at Brewster's angle when there is no magnetic field, and no oscillation results; (b) when the plane of polarization of the light from the ruby is rotated 90 degrees in the Faraday-active material by a pulsed magnetic field, there is no reflection loss in the plates and a giant pulse results

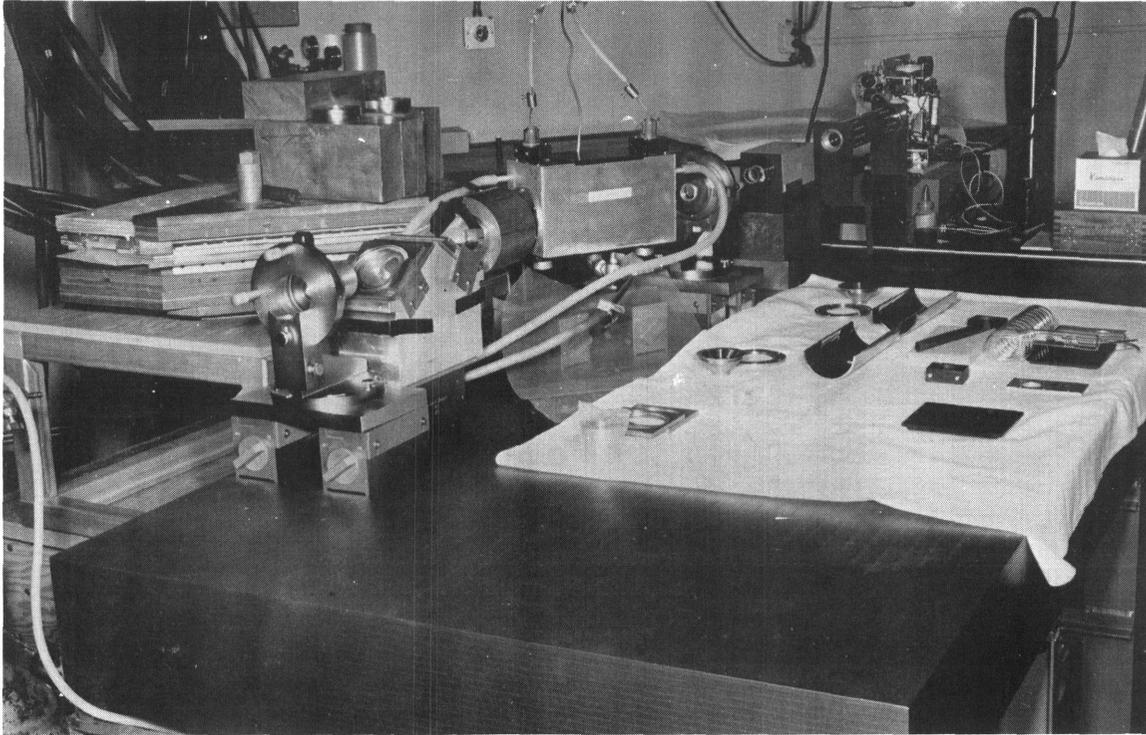


Fig. 2 - Prototype system

and that a German-made lead glass, Schott SF6-SA, damaged internally between 150-300 MW/cm². An 84- μ F capacitor bank was the current source for the Faraday rotator. The measured inductance of the whole circuit was 34 nH, giving a period of 10.5 μ sec. At 18.5 kV a peak field of about 200 kG was produced in the sample. Since a field of about 150 kG gave 90-degree rotation for a fused silica sample of 5 cm length, the laser was Q-switched on the essentially straight-line portion of the rising field.

The relevant experimentally determined parameters are: (a) 20-nsec pulse width between 50-percent power points, (b) 10- μ sec time jitter, (c) 2-3 percent output reproducibility (the experimental error of our measurements), and (d) a range of Q-switched power levels of 10 to 300 MW/cm² (attained by varying input power to flashlamp with all other parameters held constant).

ANCILLARY EQUIPMENT

Our experience in flashlamp cavity design is somewhat limited; however, it appears that the main problems attendant upon successful operation of a cavity for large Brewster-Brewster laser rods have been overcome. The two main features of our cavity design are (a) water-cooling around the flashlamp, ruby, and reflector, and (b) elimination of the usual electrostatic triggering technique with its attendant danger of lamp prefires and corona discharges inside the housing. The water maintains a very even shot-to-shot temperature, damps out shock waves in the cavity, and lowers the spontaneous breakdown voltage of the flashlamp. This last feature is useful in that it enables us to fire the flashlamp by switching its capacitor bank. Our statistics as to lamp life are somewhat incomplete, but lifetimes of over 1000 shots have been realized at input energies of 15,000 to 20,000 J.

FUTURE PLANS

Our future development consists of the following:

1. Test various other glasses to determine their useful operating ranges. Dr. Nicholar Borelli of the Corning Glass Works has suggested several other glasses which may have the requisite damage resistance and larger Verdet constants to permit damage-free operation with simpler banks.

2. Improved versions of the prototype are being designed, and complete drawings will be available should future production of a number of Q-switches be desired.

3. Tests of various other commercial lamps as laser pump sources are continuing to see if any lamp with the long life and reproducibility of the Kemlite 15HH113-42U and higher coupling efficiency can be found.

4. The evaluation and development of a low pressure coaxial lamp operated with the double pulse technique is underway at the present time. It has proved possible to get energy outputs of 2.5 J from a 6-in. ruby rod with the prototype, with the threshold being reached in less than 50 μ sec. Since this time is smaller than the time necessary for longitudinal thermal distortion, it is felt that this approach may offer the hope of a high-power oscillator, free of thermal distortion, in the near future. By this summer, an objective evaluation of the worth of this approach should be possible.

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FLASHLAMP SPECTROSCOPY

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INTRODUCTION

The flashlamp investigation is part of the NRL-ARPA Laser program. The purpose of this phase is to carry out time-resolved spectroscopic studies, on an absolute energy basis, of pulsed flash lamps which may be used as laser pumps. The versatility of the necessary electro-optical instrumentation should be such that a variety of lamp parameters and pulsing techniques can be evaluated. Fast efficient evaluation of these factors from spectroscopic data can only be accomplished with a computer-oriented microphotometer, combined with a comprehensive computerized data-reduction plan. When all instrumentation and film calibrations have been determined, it is estimated that the computer analysis of a time-resolved data spectrogram from a pulse flashlamp can be accomplished in about one-fiftieth the time now required by the exacting and laborious hand reduction of data.

Numerous electronic and optical measurements on a variety of pulse flash tubes have been reported on, either in whole or in part, in the literature on a relative or on an absolute basis. The object of the NRL Flashlamp Program is to produce, in a more concise manner, time-resolved spectral energy profiles with stated accuracy. The accuracy will be based on exacting calibrations of instrumentation and photographic emulsions. From these data such parameters as temperature, electron and ion densities, electrical efficiency, etc., can be determined for the complete time-history of the lamp plasma.

INSTRUMENTATION

A somewhat universal external optical system has been designed and installed as shown in Fig. 1. It is useful for imaging either the flashlamps being studied or the standard calibration lamp onto the slit of the $f/3.5$ Meinel spectrograph*. The spectrograph has a wavelength range from 3350 to 8450Å in the first-order spectrum, a wavelength resolution of 0.5Å, and a first-order reciprocal linear dispersion of 20.7Å/mm.

The spectrograph has been made time-resolving by using a gas-driven rotating plane mirror, positioned ahead of the 20-mm entrance slit, to sweep an image along the slit. The time resolution ranges from 0.2 to 2.5 μsec , with total writing times of 10 μsec to 125 μsec , respectively.

A beam splitter in the external optical system allows the Bausch & Lomb monochromator to observe the photoelectric intensity and time duration of a single monochromator pulse from the flashlamp. Also, it allows the monochromator to observe the spectral radiance N_λ versus wavelength λ for the standard tungsten ribbon-filament lamp. A new MacPherson polychromator will be installed at a later date in order to record more than one wavelength at a time.

*F.D. Harrington, "An $f/3.5$ Medium-Dispersion Grating Spectrograph," NRL Report 5446, Mar. 22, 1960.

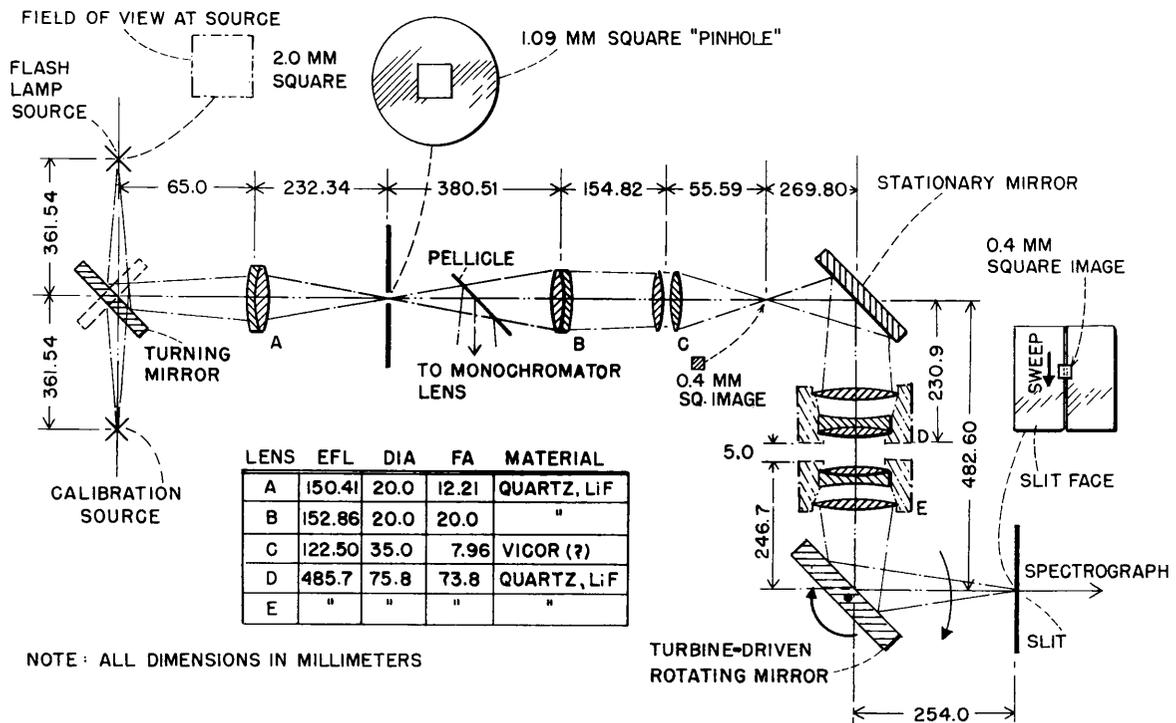


Fig. 1 - External optical system used to image either the flashlamp being studied or the standard calibration lamp onto the slit of a spectrograph

An electronic trigger and timing circuit has been developed and installed as illustrated in Fig. 2. It is used to pulse the flashlamps and at the same time synchronize the rotating mirror so that the image of the lamp is on the slit of the spectrograph during the flash. A calibrated loop has been installed at the condenser in order to measure current (amps/cm²). The current as a function of time is displayed on the oscilloscope, along with the monochromator pulse. Plans call for also measuring the voltage with respect to time at the lamp during discharge because this is one of the parameters required for determining the efficiency of the pulse lamp.

The Jarrell-Ash (JACO) microphotometer shown in Fig. 3 has been computer-oriented with a Datex Corporation digitizing unit equipped with magnetic tape recording. The latter is seen in Fig. 4. Operation and instrumentation checkout procedures have been established for digital recording of data from spectroscopic films on magnetic tape.

In order to test the performance of the Datex unit, a 3650 \AA H&D (density vs log exposure) sensitometric strip of Kodak type 103-0 spectroscopic film, previously processed by the JACO densitometer and Bristol strip recorder, was run through the new data-recording procedure. The resultant H&D curve was identical in shape and form to that previously processed from this sensitometric strip.

The Datex unit records simultaneously two readings on the magnetic tape. The first reading is that of a distance, in microns, over a range of 0 to 200 mm from the data plate. From the spectrograph's dispersion formula, this distance can be converted to wavelength. The second reading is the transmission of the film at a definite position on the film. The transmission is recorded in 1000 bits over a range from 0 to 100 percent. Twenty-five such combination readings are recorded per second. At the maximum scan speed of the densitometer (5mm/min) 312 readings are recorded per millimeter from the data film. Since the Meinel spectrograph used in the program has a reciprocal linear dispersion

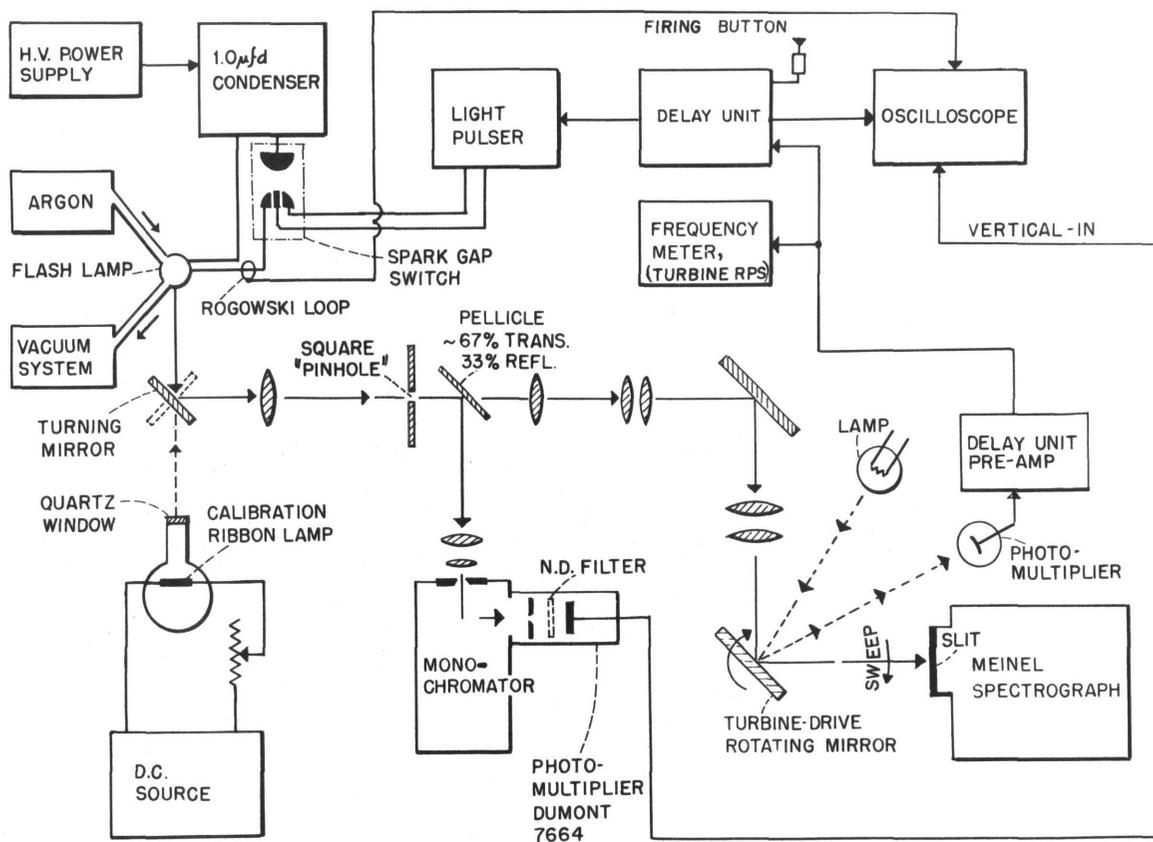


Fig. 2 - Electronic trigger and timing circuit used to pulse the flashlamp and simultaneously synchronize the rotating mirror

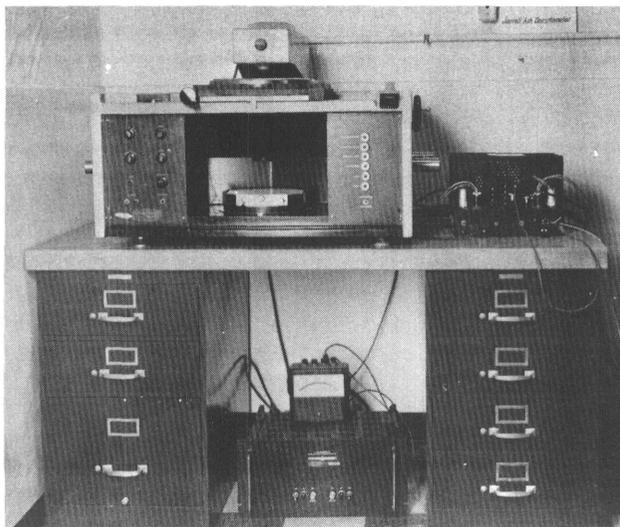


Fig. 3 - The Jarrell-Ash microphotometer used in the flashlamp experiments



Fig. 4 - Datex Corp. digitizing unit used to computer orient the microphotometer shown in Fig. 3

of $20.7\text{\AA}/\text{mm}$, 15 such readings are recorded per angstrom. In order to handle these data properly, computer programs will be required to develop the parameters desired. In essence, the nature of a general program for the reduction of time-resolved spectral profiles (absolute energy vs wavelength) has been designed and displayed in a flow chart (see Fig. 5). This program is being studied by a programmer and will be translated into computer language in the near future.

CALIBRATION PROCEDURES

An attempt to measure the sensitometric precision of the photographic process was completed for a specific wavelength (3650\AA) using 103-0 spectroscopic film. The precision is considered applicable to other wavelengths in the photographic spectrum. An EG&G Mark II flash sensitometer was used with a National Bureau of Standards calibrated gradient tablet which covered a range of 850 to 1 in equivalent exposures. For both the sensitometer's pulse ($\sim 5\ \mu\text{sec}$) and slow pulse ($\sim 1\ \text{msec}$), the accuracies and distributions of the sensitometer's xenon flashlamp beneath the gradient tablet were determined, and corrections were applied to the equivalent exposures applicable to the test set of five film strips obtained for each pulse type. Each film strip was brush developed under controlled conditions. Microdensitometer traces were made for each strip, and the results were plotted as H&D curves. A composite 3650\AA H&D curve was made for each sensitometer pulse, namely $5\ \mu\text{sec}$ and $1\ \text{msec}$. Statistics showed that the photographic reproducibility or precision of both composite curves was ± 5 percent. Another conclusion from these two curves is that the slope (or gamma) is different, thus indicating a difference in reciprocity effect for microsecond and millisecond exposures on the same photographic

emulsion. Other H&D curves were made in the same manner for 5- μ sec exposures for wavelengths of 3950, 4500, 4600, 4850, and 5150 \AA . It was found that a composite H&D curve for the spectral range from 3300 to 5000 \AA could be obtained since the gamma values changed only slightly for the above H&D curves as well as that for 3650 \AA . By adjusting all the curves to a common density of 0.7, the mean composite curve was obtained. The accuracy of the mean curve varied from 0 to ± 5 percent for densities from 0.7 to higher values, and similarly for densities from 0.7 to lower ones. The composite H&D curve for the 103-0 film considerably simplifies the general data-reduction program (shown in Fig. 5) since it eliminates a complicated variable in the film characteristics. In the present hand reduction of data and computer programming this curve will be used. When other recording spectroscopic emulsions are used, and there is a change in gamma with respect to wavelength, the general computer data reduction will have to be used.

In order to establish the calibration of the instrumentation from light source to recording film in the spectrograph, a direct-current, standard, tungsten, ribbon-filament lamp was operated in a steady controlled state at 2400 $^{\circ}$ K. The spectral radiance curve (N_{λ} vs λ) was calculated and used in determining the radiance vs current curve, i.e., N_{λ} vs I . The steady state current I was measured by the B&L monochromator. A quartz, linear, short arc lamp (1-5/8 in. between electrodes) was constructed, and its pulsed light output was found to be repeatable to within ± 10 percent. Time-resolved spectrograms on 103-0 film were obtained from this lamp at a time resolution of 0.8 μ sec. Figure 6 illustrates one of these spectrograms. The lamp was pulsed at 15, 18, and 20 kV using a 1.0- μ F condenser. Wavelengths at 3455, 3685, 3957, 4300, 4515, 4828, and 4946 \AA in the continuum were chosen to be free from line structure. At these wavelengths a series of photomultiplier traces of the light pulse from the quartz lamp was recorded. Density traces at the same wavelengths were correlated in time with the quartz tube pulse current (I_p), and in this way calibration of wavelength density D_{λ} versus pulse current was determined. By relating pulse current to steady-state current from the standard lamp, the relation between spectral radiance N_{λ} and wavelength density D_{λ} at the continuum wavelength positions was derived. Combining this information with the composite H&D curve, the relative exposure of each continuum wavelength was converted to spectral radiance, and from this the energy required to produce a relative exposure of unity was determined. By plotting the above spectral radiance to produce unit relative exposure versus wavelength, a curve was derived which indicated how the energy exposure scale of the composite H&D curve varied with respect to wavelength for similar density changes. The low point, or least energy required, was found to be at 4475 \AA . By normalizing the curve at this point the spectral radiance scale was converted to a multiplication factor (MF) scale with respect to 4475 \AA as unity.

Lines of equal radiance were calculated and plotted on a density versus wavelength graph from 3300 to 5000 \AA . The density and wavelength scales can be made to match those of the microdensitometer traces obtained from the spectrograms. In this way the equal radiance graph could be used as an overlap on any microdensitometer trace of the same scale, and point by point spectral radiance values could be read directly from the overlaid contours.

The wavelength dispersion curve for the f/3.5 Meinel spectrograph has been determined from a mercury calibration spectrum for the spectral range of 3300 to 5200 \AA .

RESULTS

As explained above, a complete study of the characteristics of 103-0 spectroscopic film and instrumentation calibration from 3300 to 5000 \AA has been made. In addition, (a) a means of hand reducing the data from time-resolved pulse lamp spectrographs has been developed, (b) digitization of the JACO microphotometer for rapid recording of basic data

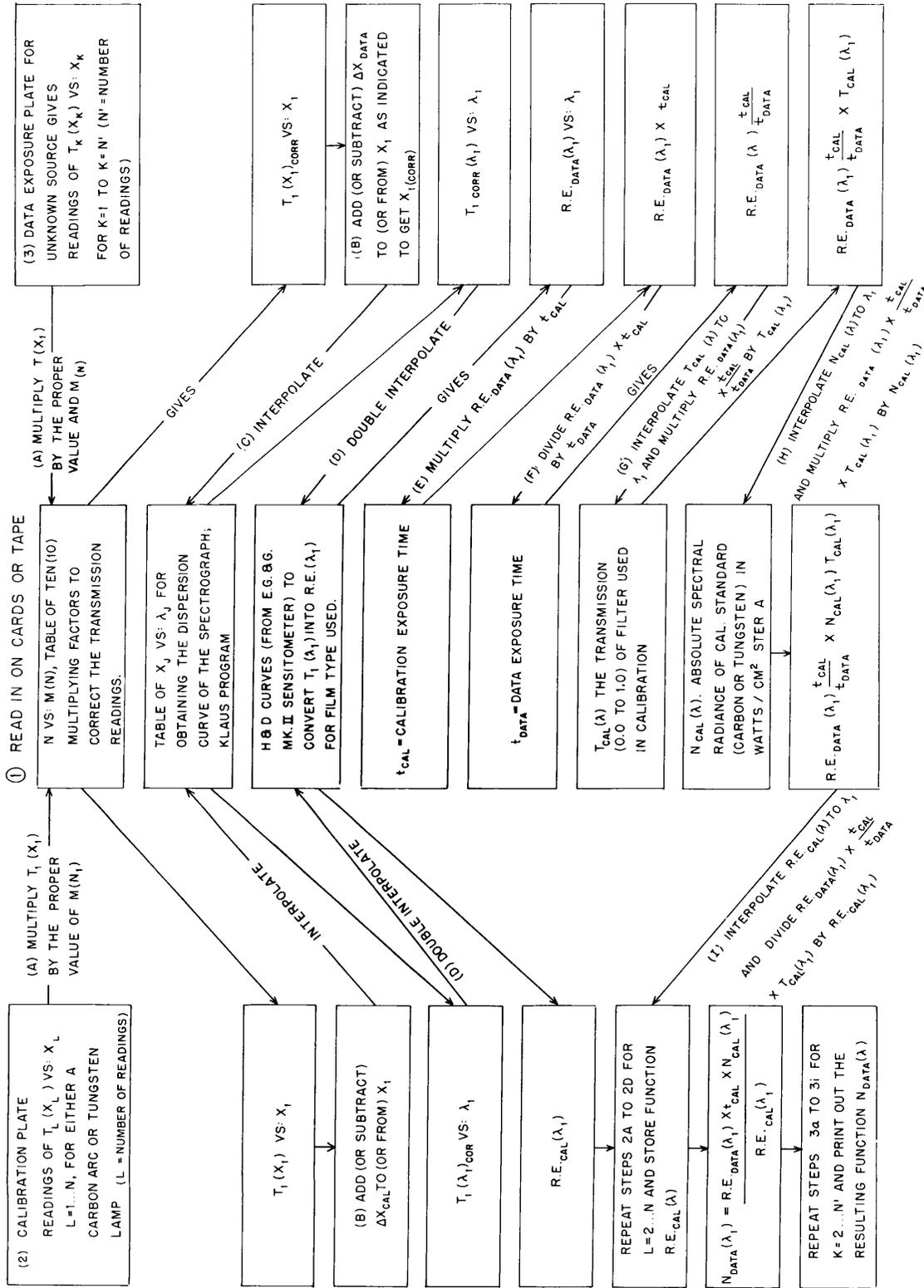


Fig. 5 - Flow chart of general computer program for the reduction of time-resolved spectral profiles of flashlamps. This program allows the determination of the absolute spectral radiance N as a function of wavelength.

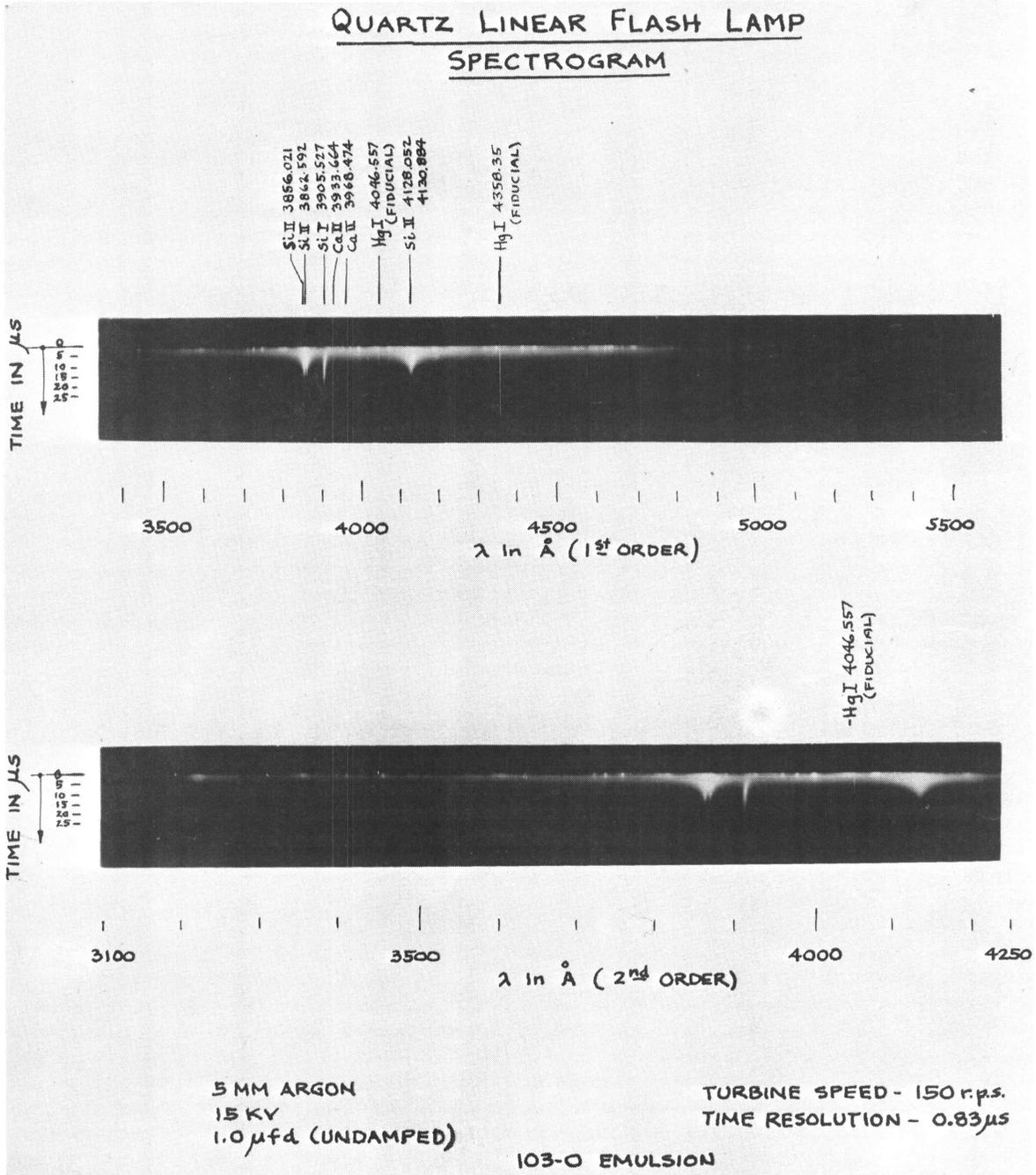


Fig. 6 - Illustration of a time-resolved spectrogram obtained for a quartz, linear, short arc flashlamp

from spectrograms on magnetic tape has been completed, and (c) the program for computer data reduction of parameter studies of pulse flashlamps also has been completed. The completed computer data-reduction program is based on the following three basic calibration relationships:

1. composite H&D curves:
 - a. Density D vs N_{λ} (4475Å, or \circ).
 - b. (Transmission) $^{-1}$ vs N_{λ} (4475Å).
2. multiplication factor (MF) curve for all wavelengths from 3300 to 5000Å. The curve is normalized at 4475Å. All data are reduced from the 4475Å H&D curve and then multiplied by MF_{λ} for the specific λ .
3. Spectrograph dispersion curve (distance d on the spectrogram vs λ) derived from the HgI calibration spectrum. The distance d is equal to zero at 3242.65Å. The fiducial mark in the data spectrogram is for HgI, 4358.35Å, at a distance of 54.279 mm.

A complete time history of one spectrogram (Fig. 6) has been made on the JACO microphotometer from 3350 to 5200Å on some 15 time-spaced traces or profiles (D vs λ). From these traces a variety of parameter studies are planned by hand reduction and computer data processing.

One of the above microdensitometer traces, made at 3.65 μ sec in time, with a time resolution of 0.83 μ sec, was selected for hand reduction in the spectral range of 4100 to 4600Å. The reduction of this spectral range has been completed, and its spectral profile was plotted on an absolute basis in terms of N_{λ} vs λ . This portion of the spectrum contained a well-developed structure of AII and several strong lines of SiII and SiIII. The quartz linear tube which was pulsed for this spectrogram was filled with argon at 5mm pressure. The same spectral region was processed by the computer reduction program. Results from the computer analysis showed that wavelength positions varied by only ± 0.05 Å and the spectral radiances on the average by about ± 3 percent from the same hand-calculated values.

A study of the comparison of the photoelectric and photographic pulse at one wavelength has been made, and these pulses were found to be in close correlation. This comparison will be carried out again for more detailed accuracy.

FUTURE WORK

The following objectives are being considered for future work:

1. to extend the calibration of the spectroscopic instrumentation to a variety of spectroscopic films and over a wide range of time resolutions. A change in time resolution and film, or a combined change of these two factors, requires a completely new individual calibration.
2. a conversion of the f/3.5 Meinel spectrograph to permit observation of the near-ultraviolet to visible region (1800 to 5000Å) with a new uv blazed grating now on hand. Similar calibrations for these conditions will be necessary, as described above.
3. to complete and activate a new condenser bank for single or double pulsing flashlamps (3000 to 25,000 joules for a slow bank, and 6000 joules for a fast bank).
4. to investigate enhanced radiance from double pulsed flashlamps.

5. to experimentally check theoretical changes in parameters and efficiencies of newly designed flashlamps.

6. to devise time resolution of the Meinel spectrograph for slow pulse flashlamps in the millisecond range. It is expected that this will require a change or addition to the present electronic and triggering circuits.

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13. Preface <p>Since January 11, 1965, laser research at the U.S. Naval Research Laboratory has been expanded under the sponsorship of the Advance Research Projects Agency (ARPA). This report presents a summary of the work done under ARPA Order No. 660 of January 11, 1965, and Amendments No. 1 and 2 of April 27, 1965, and December 11, 1965.</p> <p>Since the inception of this interest and a more vigorous support by ARPA, the materials research has been pursued more intensively and along more basic lines, while still maintaining a capability for responsiveness to routine testing needs. Many innovations have been introduced, e.g., magnetic Q-spoiling and Q-switching by the Faraday effect, as well as other novel techniques employed in the various research areas.</p> <p>A fast responsiveness to the investigation and exploitation of new ideas is exemplified by the construction and operation of a molecular nitrogen laser system, which was started early in 1966. Some preliminary results from this system are included in the gas laser section of this report.</p>		

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
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