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SUBJECT: Optimization of Lasers

TASK/PROBLEM

1. Explore the production of 0.53 micron (blue-green) laser radiation by harmonic doubling in KDP and ADP crystals.

DISCUSSION

2. The purpose of this program has been the production of a report discussing the investigations and tests accomplished. At the start of the program, the expected emphasis was upon reporting:

a. The knowledge gained regarding the combination of a laser with a harmonic doubling cyrstal element as a source of coherent visible light radiation.

b. Data regarding use of the laser with a variety of photographic sensitized materials.

c. Recommendations regarding the breadboarding and building of prototype equipment to support the photo exploitation community.

3. The production of blue-green laser radiation by harmonic doubling had already been demonstrated at [redacted] and other laboratories. There are many factors to encourage the use of radiation in the 5000A and 6000A region in photographic systems. These are: 25X1

25X1

a. Availability of a wide range of existing sensitized products for which considerable performance data is already available.

b. Many existing optical system designs are corrected for this wavelength range.

c. The possibility of using sensitized materials which may be handled under safelights.

d. The possibility of visual observation of the image as an aid to operation of the system.

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GROUP 1
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There was much activity in progress in the contractor's laboratory on "doped" borate glass lasers which provide high-energy output pulses at 1.06 micron wavelength. Reports in the technical literature, just prior to the time of the project beginning, suggested the possibility of operating a glass laser and a harmonic doubling element at a high-repetition rate using plasma-pinch techniques. Repeated flashing at rates about 20 to 30 cps should provide the visual effect of a continuously operating system for visual observation and equipment adjustment.

THEORETICAL BASIS FOR HARMONIC DOUBLING

4. When a monochromatic beam of light is propagated through a medium, it has associated with it a single or fundamental frequency, ω . For this to remain a "pure" frequency, a linear relationship would have to exist between the induced polarization, P, and the incident electric and magnetic fields E and H. A linear relationship, however, does not exist and P is more accurately expressed by a power series in E and H. In such an expansion, one term is proportional to the square of the electric field. This term leads to the frequency components of P at both 2ω and zero, the 2ω frequency being the second harmonic.

5. To understand the mechanism involved in efficient production of second harmonic radiation, consider an isotropic medium having the same refractive index for both ω and 2ω. Under this condition, both the fundamental and the generated harmonic would be propagated with the same velocity and in the same direction. They would, therefore, continually be in phase and the second harmonic would be propagated without interference. Tn real media, refractive indices are not independent of frequency, and ω and 2ω would not be propagated with the same velocity or in the same direction. As a result, the second harmonic generated at one point along the beam is slightly out of phase with that generated just ahead or behind it. This continually varying phase results in a periodically destructive interference

of the second harmonic with itself. Its intensity, rather than continuing to increase with path in the nonlinear medium will oscillate about some small value. To achieve maximum efficiency in such a situation, the medium must be cut into a thin wafer to select the first peak in harmonic intensity. To overcome this difficulty in producing second harmonic, a birefringent material such as KDP or ADP can be used as a generating medium. In these materials, the refractive indices are dependent on polarization and direction of propagation, in addition to frequency. As a result, a propagation direction exists in some birefringent materials where one polarization of the fundamental frequency has the same refractive index as the other polarization of the second harmonic. This is referred to as index matching and provides one technique for producing second harmonic. This technique was used throughout this program.

EXPERIMENTS IN PRODUCING SECOND HARMONIC RADIATION

6. The goal of the first part of the experimental program was to produce second harmonic radiation from a pulsed neodymium-doped borate glass laser rod. To do this, an experimental breadboard was made using a 12-inch long, 1/2-inch diameter glass laser to produce the fundamental 1.06 micron radiation. The harmonic generating medium was a 1-inch square 5mm thick KDP crystal, and the detector was a white cardboard located about two feet beyond the crystal. When the crystal was correctly oriented, a bright green spot of 0.53 micron radiation (second harmonic) was produced on the screen. The duration of the pulse was approximately one millisecond, the same as that of the fundamental. In addition to the green spot, several bright spots, the order of 0.050 inches, were also observed on the screen. Experimentation showed this to be incandescence, a result of the intense 1.06 micron beam interacting with the cardboard. This was verified by burn marks which became observable after 10 or 15 pulses. These spots were eliminated by putting a filter glass (Pittsburgh 2043 Heat Absorbing) between the crystal

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and the screen. Transmission of the filter was $2 \times 10^{-4}\%$ at 1.06 microns, 80% at 0.53 microns.

7. The next step in the program was to optimize the second harmonic output with the crystal. This was done using a 929 Phototube as a detector and recording the pulsed harmonic output as a function of crystal rotation. A plot of these results is shown in Figure 1. To obtain quantitative measurements of this output, the experimental equipment had to be modified. The laser cavity was enclosed in a "lighttight" wooden box, having only an opening at the output end. This opening was covered with a [redacted] 2540 filter having an average density of 6 throughout the visible, but transmitting 67% at 1.06 microns. Also, a 925 Phototube was added to the system to monitor the intensity of the fundamental beam incident on the crystal. This was done by placing a beam splitter ahead of the crystal and splitting off about 10% of the energy. A schematic view of this setup is shown in Figure 2. 25X1

8. The goal of the effort described in paragraph 7 was to produce second harmonic conversion efficiencies comparable to those obtained by R. W. Terhune[1] using a ruby laser. The initial measurements toward this goal showed that an input of 36 joules of 1.06 micron radiation produced 10^{-4} joules of 0.53 micron radiation -- a conversion efficiency of $3 \times 10^{-4}\%$. By increasing the incident 1.06 micron radiation to 120 joules, 9×10^{-4} joules of the harmonic was produced -- an efficiency of $10^{-3}\%$. This increase in conversion efficiency with increased input results from the second harmonic intensity being a second order effect of the electric field. In other words, the power of the second harmonic varies as the square of the fundamental power. In the data just quoted, for example, the input power was increased by a factor of 3. This increased the harmonic power by a factor of 9 and the conversion efficiency by a factor of 3.

[1] R. W. Terhune, "Non Linear Optics," SOLID STATE DESIGN, Vol. 4, No. 11, p. 38, 1963.

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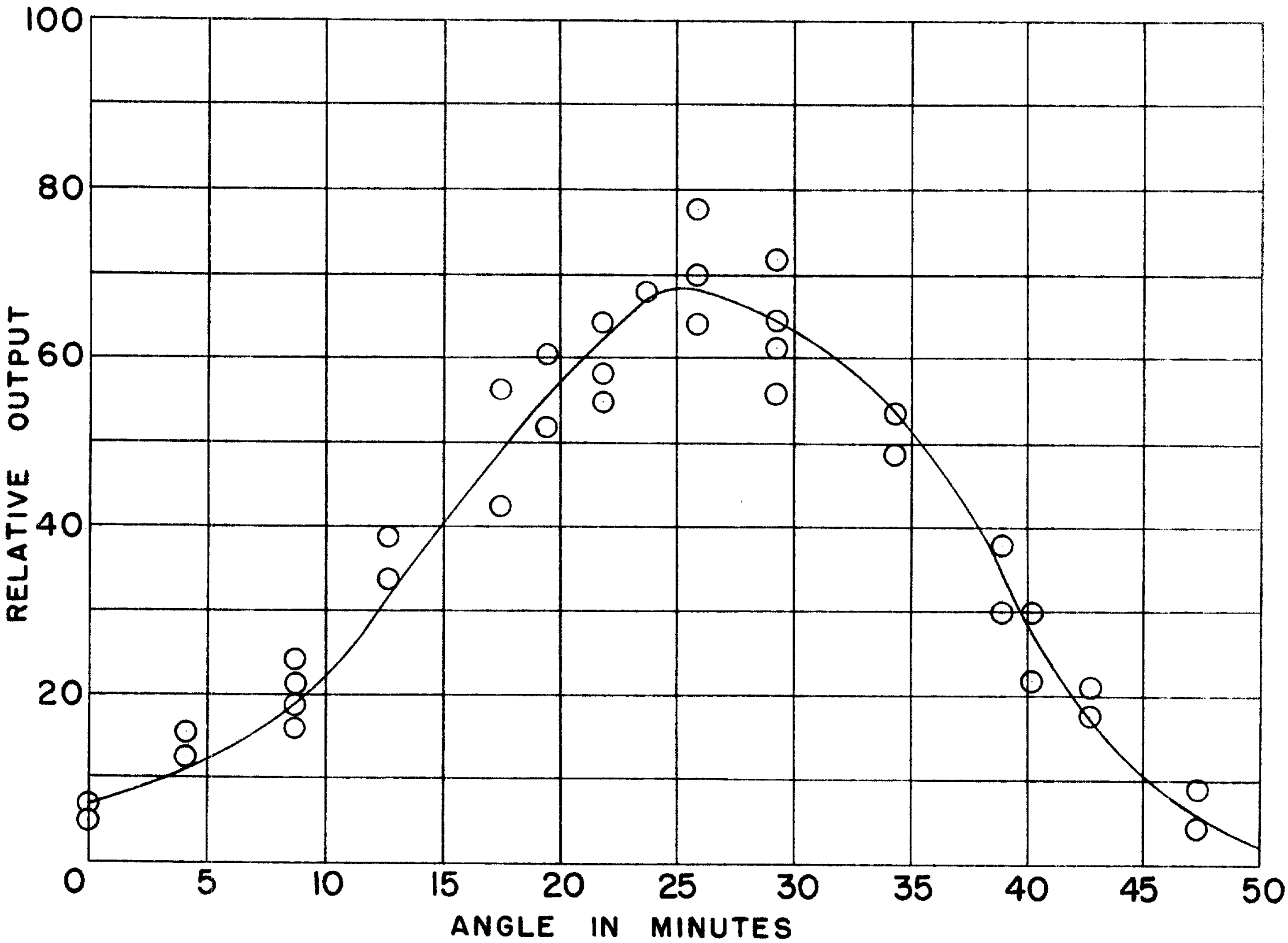

RELATIVE OUTPUT OF 0.53 MICRON
RADIATION FUNCTION OF CRYSTAL
ALIGNMENT TO 1.06 MICRON INPUT BEAM

FIGURE 1

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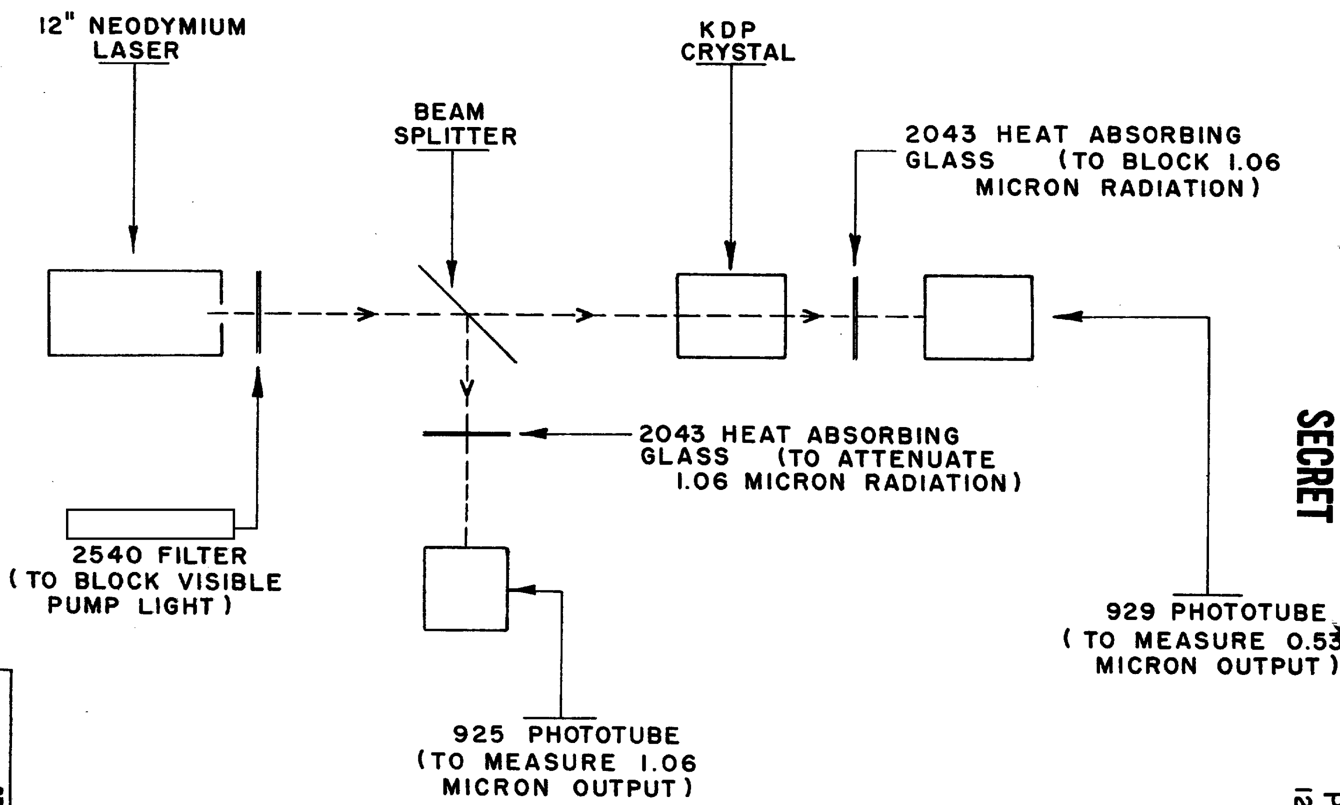

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FIGURE 2 — HARMONIC GENERATING SCHEMATIC

9. Efficiencies of the order of 10^{-3} and 10^{-4}% for the system, however, were below Terhune's results and a reevaluation of the KDP crystal showed this to be partially due to an error in orientation. The correct orientation is shown in Figure 3. The z axis or optical axis is inclined to the surface normal at the index matching angle Ψ, and the x and y axes are symmetrically positioned with respect to the normal. The index matching angle was determined by the equation[2]

$$\Psi = \left[\frac{(V_1^{\circ})^2 - (V_2^{\circ})^2}{(V_2^{E})^2 - (V_2^{\circ})^2} \right]^{1/2}$$

where V_1° is the velocity of the ordinary fundamental ray through the crystal, V_2° the velocity of the ordinary harmonic ray, and V_2^{E} the velocity of the extraordinary harmonic ray. The solution was obtained by using index values[3] of

$$N_1^{\circ} = 1.4940$$

$$N_2^{\circ} = 1.5125$$

$$N_2^{E} = 1.4706$$

The calculated angle was 41°1', and a 1-inch long 1-cm. square crystal having this configuration was ordered.

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[2] J. A. Giordmaine, "Mixing of Light Beams in Crystals," Bell Telephone Technical Memorandum MM 61-115-67, December 27, 1961.

[3] Fritz Zernike, Jr., "Refractive Indices of ADP and KDP Between 2,000 Angstroms and 1.5 Microns," JOURNAL OF THE OPTICAL SOCIETY OF AMERICA, Vol. 53, No. 10, 1964.

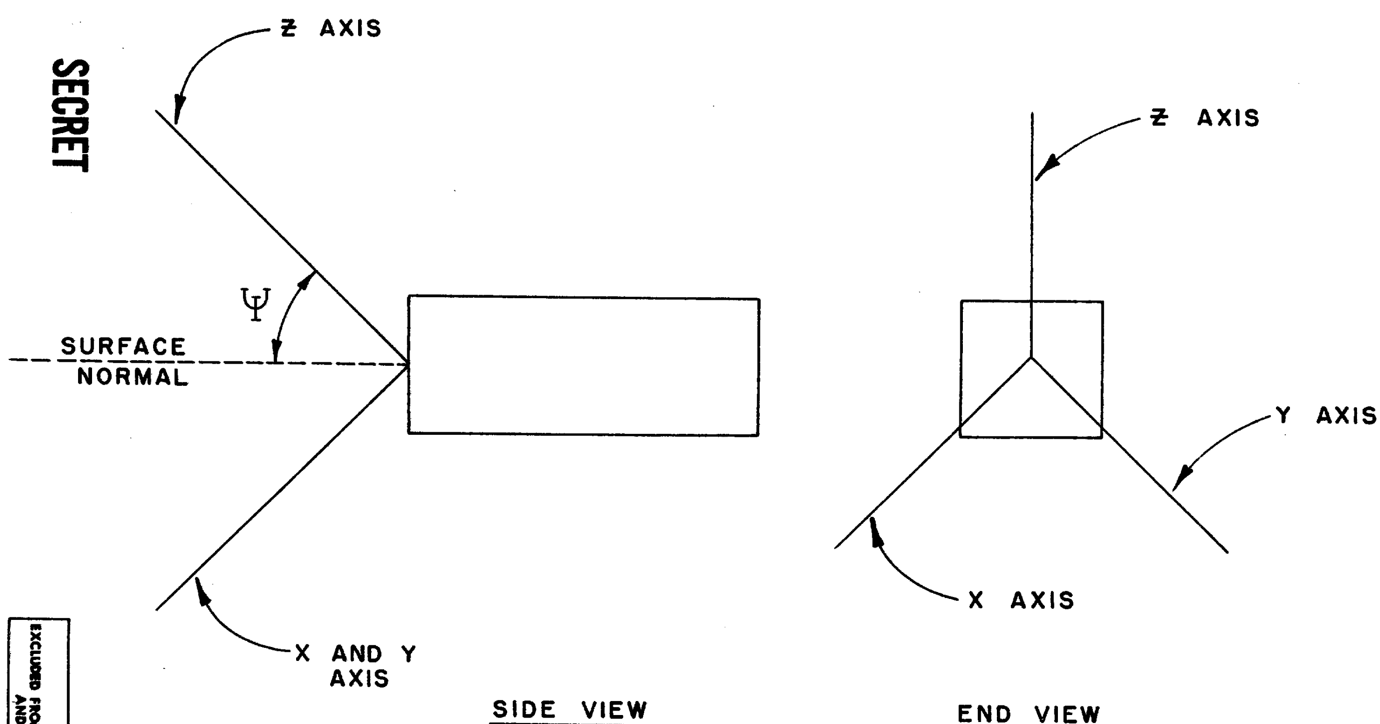

FIGURE 3 - KDP CRYSTAL ORIENTATION

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10. Using this new crystal, most of the experimental work, which had been done with the 5mm long crystal, was repeated. This was done, however, with an effective two-meter long laser cavity instead of the 12-inch cavity. The purpose of increasing the length was to increase the harmonic efficiency by reducing the fundamental beam divergence. The result of this was a reduction in the harmonic beam width from 25 minutes of arc (see Figure 1) to 30 seconds of arc, and an increase in efficiency of approximately 50 percent. The end result of these measurements was that 4×10^{-3} joules of second harmonic was produced with 140 joules of 1.06 micron radiation -- a conversion efficiency of 2.8×10^{-3}%, a percentage nearly that achieved by Terhune with ruby.

11. Having developed an extremely bright spot of green light, a preliminary qualitative study was begun on the beam uniformity. To do this, a short focal length lens was used to diverge the harmonic beam and the resulting enlargement was displayed on a white matte screen. A photograph of the resulting pattern is shown in Figure 4. The appearance of the lattice-like structure in the beam suggested a diffraction pattern formed by the 1-cm. square KDP crystal. This was quite probable considering the crystal was the limiting aperture of the system and the only element in the system having a straight line periphery. Before this could be verified, experimental effort on the program was stopped. During some of the final observations, however, it appeared visually that structure other than the lattice work pattern was present in the beam.

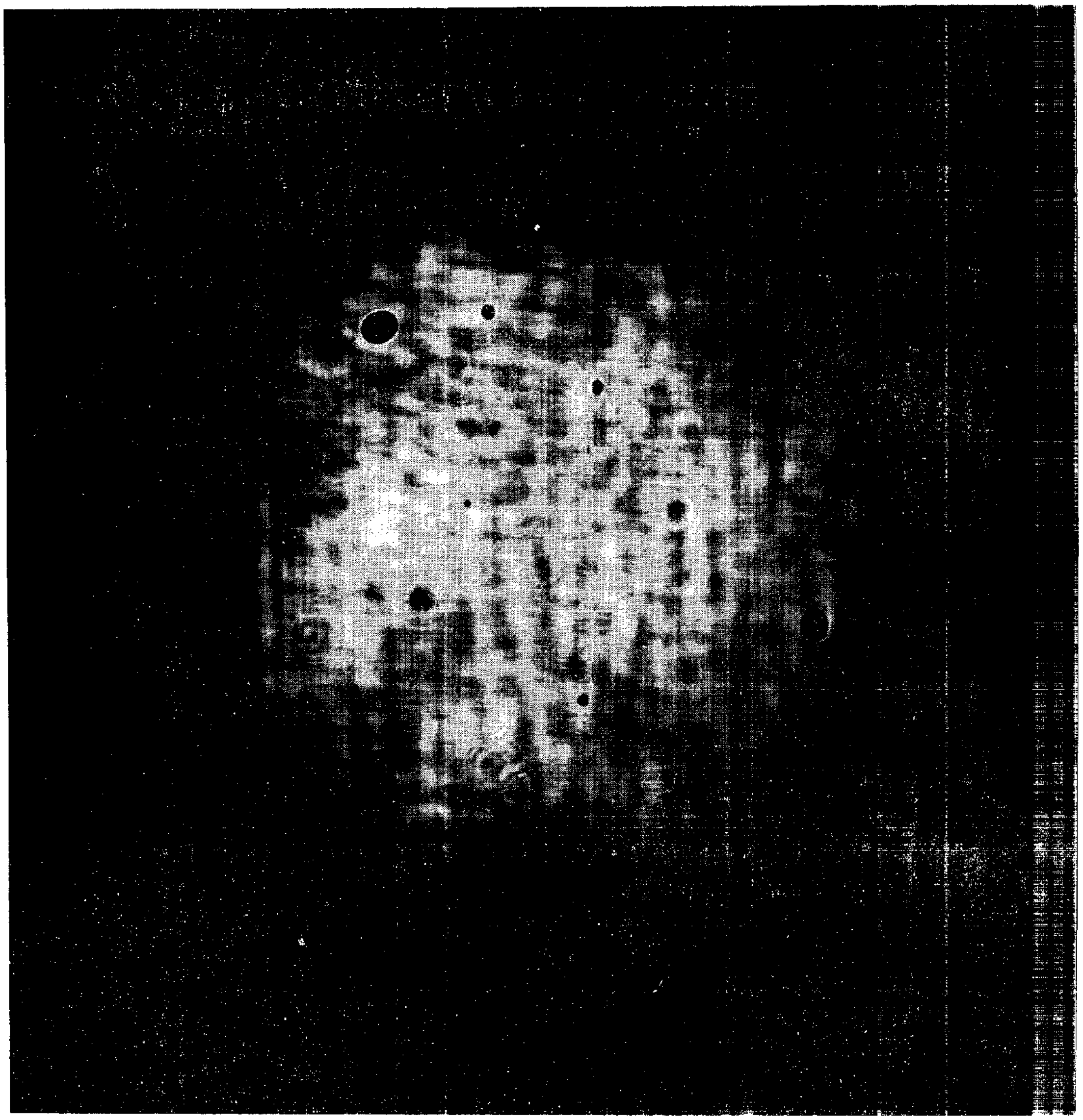

Figure 4. Expanded Beam of 0.53 Micron Radiation

REEXAMINATION OF PROJECT GOALS

12. The activity described above took place between the project authorization in March 1964 and December 1964. The findings on this project and on PAR 216, "Exposure of Photographic Material with Lasers,"[4] together with developments of new visible light lasers in other laboratories made it evident that the goals of this project should be reexamined.

13. In the PAR 216, Final Report, it was condlued that "No experimental evidence or theoretical prediction was found that a photographic emulsion (acting as a detector) reacts any differently to coherent than to non-coherent radiation, provided they are of the same approximate wavelength and energy level. Photographic materials for the detection of laser-generated radiation may be chosen by the same criteria as for the detector of other radiation of the same wavelength and energy level." No further effort toward providing data specifically on the use of the harmonic doubling laser with photographic sensitized materials was required.

14. Technical reports on the "theta-pinch" source for laser activation after the time of the preparation of the Project Authorization Request indicated it was an inefficient technique. An early minor effort on this project indicated that the equipment available in our laboratory was not adequate for high-repetitive-rate operation of the theta-pinch source and several thousand dollars worth of additional equipment would be required to make it adequate. In view of the discouraging reports in the literature, tests on this manner of operation were abandoned.

15. During 1964, there was information appearing in the technical literature on the development of new visible-light lasers. It appeared desirable to make an orderly study of this information to attempt theoretical comparisons of those lasers with the harmonic doubling green light system.

[4] Final Report, PAR 216, 15 February 1965

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16. A "Restatement of Project Goals" was prepared and submitted to the customer as an attachment to the Monthly Report of 22 January 1965. Approval of the indicated redirection of effort was given. The new goals were summarized as:

a. Attempt to learn the causes of the nonuniformity in the beam and to discover means to make the beam from the harmonic-doubling laser source uniform in brightness.

b. Conduct a literature and vendor search from June 1963 to the present on visible light lasers and attempt to make a theoretical comparison of their performance with that achieved by the harmonic-doubling system.

BEAM UNIFORMITY STUDY

17. During the period of reexamination of the project goals, the contractor-owned glass laser and power pack were transferred to another project and were not available for the beam uniformity study. This condition continued to exist as late as May 1965, and we were requested by the customer to terminate this portion of the project. No further work on beam uniformity was performed beyond that reported in paragraph 11.

LITERATURE SEARCH ON VISIBLE LIGHT LASERS

18. The initial phase of the literature search was concerned only with the beam uniformity of visible light lasers. The search was begun by the contractor's "Technical Information Service" group (library). The material collected by this group covered most of the laser articles in the technical journals from June 1963 to early 1965. The sources and journals surveyed are shown in Appendix I. Although a large number of articles and letters have been published on visible lasers, none contained any specific information on beam structure.

19. In May 1965, the approach toward the literature search was reviewed, and it was decided that before any additional searching was done a list of existing laser materials should be compiled. This was done with the list being divided into two sections: gas lasers and solid material lasers, both including operational wavelengths. These lists, shown in Figure 5 and 6, do not contain all the operational and experimental laser materials as of May 1965. They do, however, contain a representative majority.

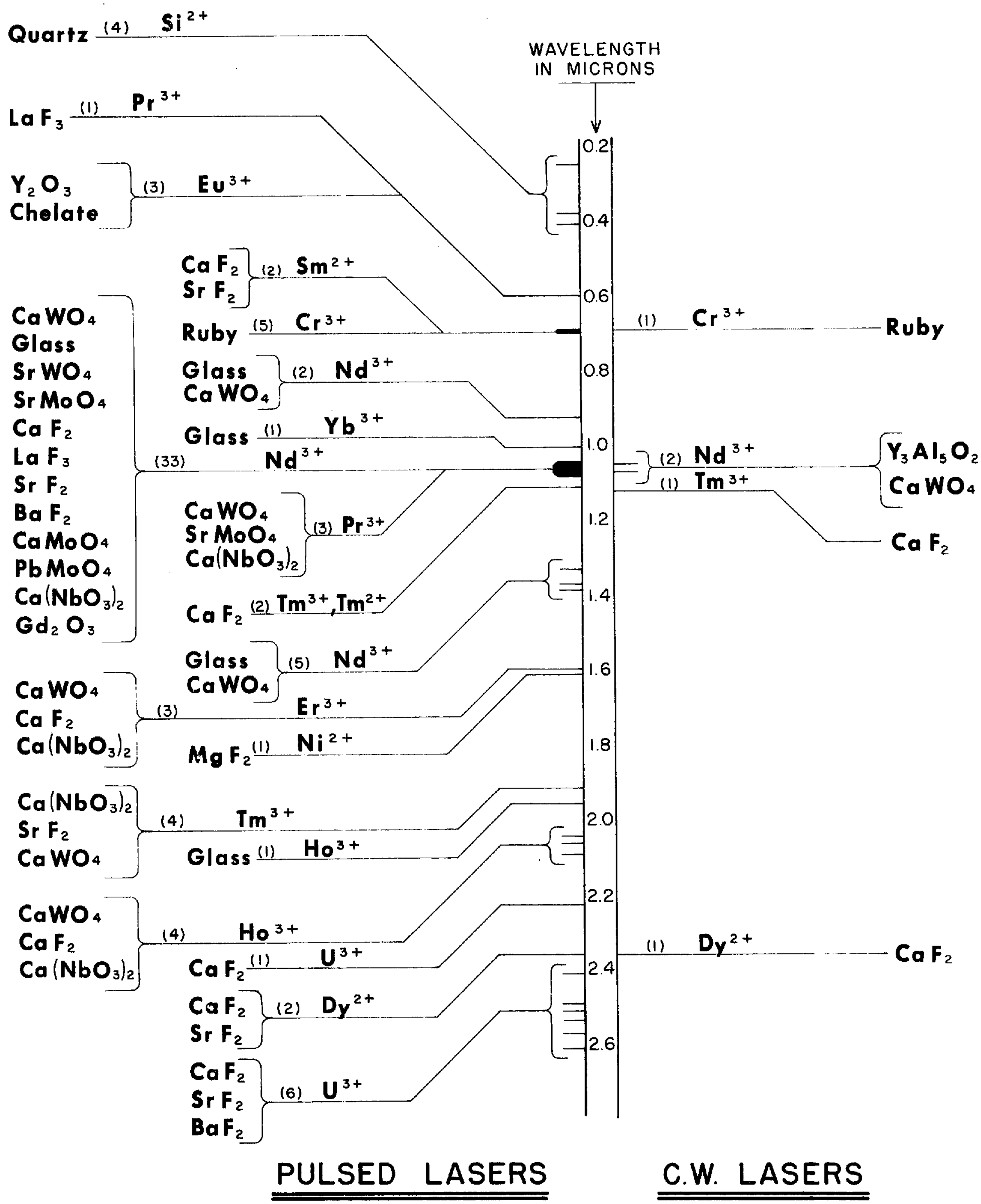
20. The power output of various laser types can vary with a variety of design parameters, therefore, a meaningful comparison of the output of various visible light lasers must be obtained from manufacturer's data. However, at the customer's request, the project activity was terminated without making a vendor search for this type of information.

CONCLUSIONS

21. A high power pulsed source of 0.53 micron wavelength (blue-green) coherent radiation has been achieved. The beam produced has a characteristic lattice-like pattern (nonuniform brightness) which makes it unsatisfactory as an exposing source in many potential photographic applications.

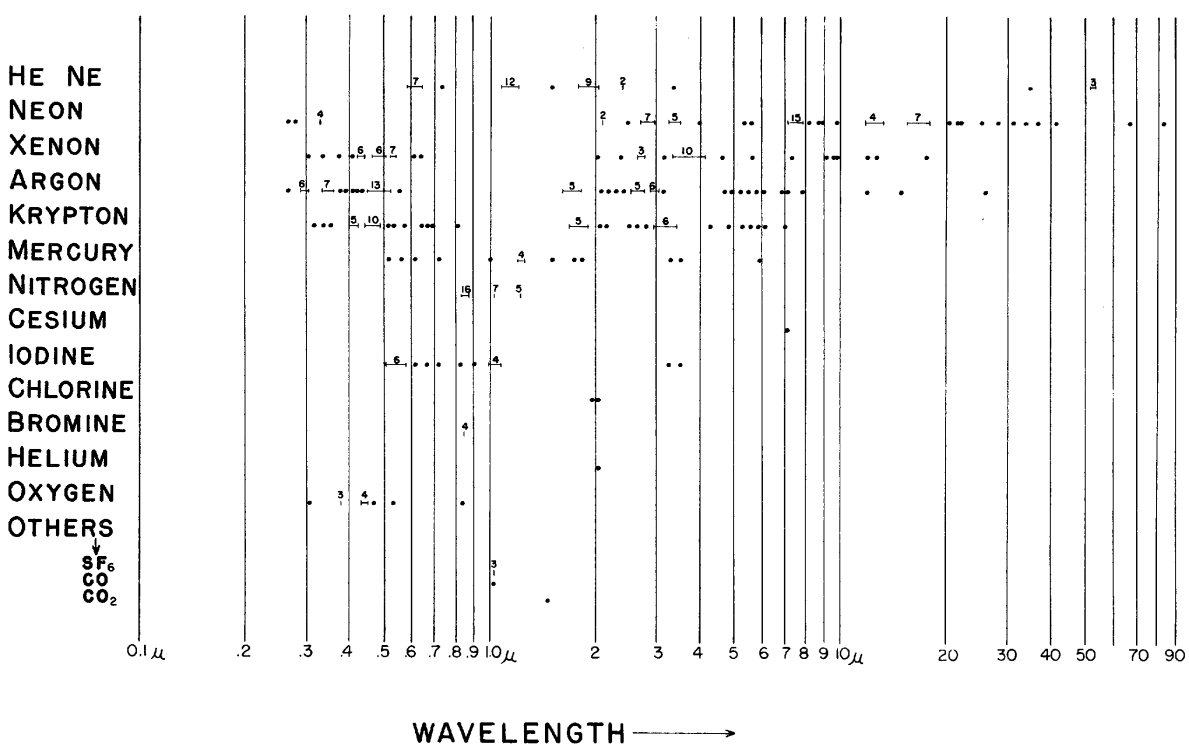
22. With a one-inch long KDP crystal having optimum orientation of the crystal axes 4×10^{-3} joules of second harmonic (0.53 micron wavelength) radiation was produced from 140 joules of 1.06 micron wavelength primary radiation input. The conversion efficiency was $2.8 \times 10^{-3}\%$, nearly equal to that achieved by Terhune with a ruby laser primary source. The pulse time in these experiments was about 1 millisecond, therefore, the average power output of 0.53 micron radiation was about 4 watts.

23. As a basis for comparison, consider the performance of several He-Ne continuous operating gas lasers offered for sale by several manufacturers. Their power output at 0.6328 micron wavelength ranges from about 3 milliwatts to 50 milliwatts in various models. This output level is



SOLID MATERIAL LASERS

FIGURE 5



GAS LASER WAVELENGTHS

FIGURE 6

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less than the peak from the second harmonic system, but in only one second of operation the smallest units can deliver as much energy as the second harmonic pulse achieved in our experiments.

24. The efficiency of the second harmonic technique for the generation of visible coherent radiation increases with the power level of the input radiation. Its use appears practical only with a high energy pulsed laser as the input source.

RECOMMENDATIONS

25. It appears likely that convenient, moderate-priced laboratory laser units for continuous operation with blue-green and green light output will soon be available as commercial units comparable to the present He-Ne units. The possible availability of such equipment should be explored with potential suppliers.

26. Photographic materials for the detection of visible coherent radiation should be selected by the same criteria as for detection of noncoherent radiation of the same wavelength and power level.

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APPENDIX I

LITERATURE SEARCH ON VISIBLE LIGHT LASERS

SOURCES CONSULTED

- ENGINEERING INDEX
- INSTRUMENTATION ABSTRACTS
- PHYSICS ABSTRACTS
- IEEE INDEX
- NASA BIBLIOGRAPHIES
- STA REPORTS (Scientific and Technical Aerospace Reports)

JOURNALS

- BRITISH JOURNAL OF APPLIED PHYSICS
- JOURNAL OF THE OPTICAL SOCIETY OF AMERICA
- INDUSTRIAL RESEARCH MAGAZINE
- ELECTRONICS
- ELECTRONIC INDUSTRIES
- APPLIED OPTICS
- JAPANESE JOURNAL OF APPLIED PHYSICS
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- BRITISH COMMUNICATIONS AND ELECTRONICS
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- PHYSICS LETTERS
- NATURE
- PHYSICAL REVIEW
- PROCEEDINGS OF THE IEEE
- MICROWAVES
- LASER - Abstracts [redacted] 25X1