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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) American Optical Corporation Central Research Laboratory Southbridge, MA 01550	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

NEODYMIUM LASER GLASS IMPROVEMENT PROGRAM

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Summary Report No. 8, 1 January 1966 - 30 June 1966

5. AUTHOR(S) (First name, middle initial, last name)

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6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1971	9	0

8a. CONTRACT OR GRANT NO. Nonr 3835(00) b. PROJECT NO. 7300 c. ARPA Order 306 d.	9a. ORIGINATOR'S REPORT NUMBER(S) TR-598-8 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Distribution of this report is unlimited

11. SUPPLEMENTARY NOTES Project DEFENDER	12. SPONSORING MILITARY ACTIVITY Office of Naval Research Arlington, Virginia

13. ABSTRACT

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The procedure used in the solarization tests is described; results obtained indicate decreased slope efficiencies and increased threshold values are uncorrelated with solarization.

Based on encouraging results obtained from measurements of the change in optical pathlength on a modified athermal glass composition, a second series of 16 athermal glasses was prepared. Finally, efforts to finalize the procedure for measuring stress-optical coefficients are described.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
LASERS						
LASER GLASS						
INTERFEROMETRY						
ATHERMALIZATION						
SOLARIZATION						

II

TR 598-8

This research is part of Project DEFENDER under the joint sponsorship of the Advanced Research Projects Agency, the Office of Naval Research and the Department of Defense.

NEODYMIUM LASER GLASS IMPROVEMENT PROGRAM

Technical Summary Report
Number 8

November 1971

Dr. Richard F. Woodcock

Contract No. Nonr-3835(00)
Project Code No. 7300
ARPA Order No. 306

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FOREWORD

This report has been prepared by the Central Research Laboratory of the American Optical Corporation, Southbridge, Massachusetts under Contract Nonr 3835(00) entitled "Neodymium Laser Glass Improvement Program." The contract is under the sponsorship of the Office of Naval Research and this report covers the six-month period ending 30 June 1966.

Dr. Richard F. Woodcock is project manager and author of this report.

This program is part of project DEFENDER.

This report is unclassified.

CONTENTS

NEODYMIUM LASER GLASS IMPROVEMENT PROGRAM

1. INTRODUCTION

This report is a technical summary covering work performed during the period 1 January - 30 June 1966 on Amendment No. 3 of Contract Nonr-3835(00) entitled "Neodymium Laser Glass Improvement Program." The expiration date of this contract is 30 April 1966. A request has been made to extend the termination date of this contract to 31 July 1966 with no accompanying increase in fundings. A response to this request was not received during this reporting period.

2. SOLARIZATION

During this period the effects of solarization upon laser properties such as slope efficiency and laser threshold were investigated. The first phase of this investigation was carried out on a series of glasses containing various anti-solarization agents as well as a variety of host glass compositions. The laser cavity used in this investigation consisted of a laser rod 6 mm in diameter by 30 cm in length with a TIR roof on one end and a flat on the other. This type of end reflector was chosen instead of the more conventional removed dielectric mirrors in order to minimize possible variations in results which might be introduced by lack of optical homogeneity in the rods. Ten pound melts of glass were made for this study; thus, the laser rods drawn from them will be of fair optical quality but generally not stria-free.

A single linear flashtube with a 25.4 cm arc length was used as a pump source. This was optically coupled to the laser rod with a tight wrap of silver foil. The flashtube was energized from a power supply with a 240 microfarad storage capacitance equipped with a 600 microhenry inductor. The laser cavity, with the exception of the ends of the laser rod, was totally immersed in liquid to provide a thermal bath in all cases and ultraviolet filtration in some cases. The output energy of laser rod was measured with a Model 101 TRG Thermopile. The output end of the laser rod is actually placed inside the input aperture of the thermopile to insure that all the output laser light is collected.

The general procedure for evaluating the effect of solarization was as follows. The laser cavity was filled with a 15 percent solution of sodium nitrite in order to prevent solarization and data were taken for a slope efficiency curve at input energies ranging from approximately laser threshold energy to about three times this value; i.e., 300 to 1000 joules input. Readings were taken at three minute intervals in order that the degree of cooling of the laser rod by the surrounding bath would be approximately the same in each case. The sodium nitrite was then removed from the cavity, the cavity was flushed and then filled with distilled water. The laser was fired 10 times at three minute intervals at an energy input of 1075 joules. Subsequent measurements indicated that this corresponds to a current density of about 1000 amperes per square centimeter in the flashtube. The distilled water was added to provide a thermal bath as previously stated. Since the spacing between the laser rod and the flashlamp is about one millimeter and the two are closely wrapped with silver foil it was not expected that the presence of water would provide any protection against solarization from the flashtubes.

The distilled water was then removed from the cavity and replaced with sodium nitrite solution. The slope efficiency measurement was then repeated. This procedure was followed to prevent solarization from occuring while the slope efficiency measurement was being made. A typical set of slope efficiency curves before and after solarization are shown in Figure 1. Laser threshold values before and after solarization are also obtained from these curves.

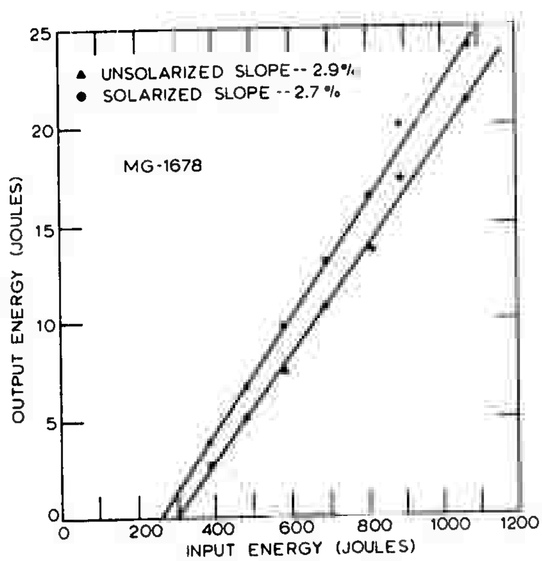

Fig. 1. Change in laser characteristics due to solarization.

The results of the change in slope efficiency and laser threshold, expressed as the ratio of the solarized to unsolarized value, for several different glass compositions are given in Table I. The degree of solarization is indicated by the decrease in transmission at 400 nm produced by our standard solarization test on a 2 mm thick glass sample. (Reference: Semiannual Report No. 3, Contract Nonr-3835(00), January-June 1963). Also included in the table is compositional information on the base glass type plus any ingredients which might effect solarization of the glass. As may be seen from Table I, the values for transmission at 400 nm, slope efficiency and laser threshold change from about 0-10 percent as a result of solarization. However, there appears to be no correlation between the degree of solarization as indicated by the change of transmission at 400 nm and the laser properties of slope efficiency and threshold. As a correlation between the transmission data on 2 mm thick samples at 400 nm and the discoloration of a laser rod made from the same material, the rod made from glass composition 1723 had a distinct reddish discoloration following the testing procedure whereas the laser rod fabricated from glass MG-1681 showed no discoloration when viewed by eye.

Because of the lack of correlation between the degree of solarization as evidenced by transmission changes at 400 nm and the changes which occured in the lasing characteristics of the glass, a more detailed investigation was made of the factors affecting laser characteristics. Glass composition MG-3835 was chosen for this purpose because it was available in good optical quality and showed the largest change in transmission at 400 nm due to solarization.

In order to determine whether the decrease in laser slope efficiency and the increase in laser threshold energy is associated with solarization of the laser rod or with some other deleterious process taking place in the laser cavity, the following test was made. The slope efficiency was determined as described previously using sodium nitrite in the cavity to prevent solarization. This was followed by 60 shots on the laser rod instead of the 10 shots used in the previous procedure and in this case the sodium nitrite solution was left in the cavity to prevent solarization of the rod. Following this the slope efficiency was again determined in the usual manner. No color change was observed in the laser rod following this procedure indicating that no solarization had taken place. The slope efficiency had decreased from 3.1 percent to 2.9 percent and the laser threshold had increased from 320 joules to 340 joules

Table I. EFFECTS OF SOLARIZATION ON LASER CHARACTERISTICS

Glass Number	Solarization[a] at 400 nm	Slope Efficiency (%) [sol./unsol.]	Laser Threshold (J) [sol./unsol.]	Glass Composition: Base Type	PbO	Sb_2O_3	TiO_2	CeO_2	Cr_2O_3
MG-1670	0	3.1/3.1	300/285	3835	-	-	-	1.0	-
MG-1677	0.8	3.0/3.3	300/270	3835	-	-	1.0	1.0	-
MG-1678	1.2	2.7/2.9	300/260	3835	-	1.0	1.0	1.0	-
MG-1681	0.6	3.2/3.1	310/310	Mixed heavy alkali silicate	7.1	1.0	3.0	-	-
MG-1713	0	2.0/2.0	420/410	Simplified 3835	-	-	-	0.6	-
MG-1720	5.0	3.8/3.8	305/290	Mixed heavy alkali silicate	-	1.0	-	-	-
MG-1723	4.5	3.3/3.4	315/300	3835	-	1.0	-	-	0.1
MG-3835	7.0	3.1/3.3	300/310	3835	-	1.0	-	-	-

[a] Decrease in transmission of a 2 mm thick sample due to solarization.

between the initial and final measurements comparable to the results on MG-3835 in Table I. During the "exposure" process in which the laser rod was fired at 1075 joules input, the output energy was measured on every fifth shot and was found to decrease from 23.2 joules output to about 21 joules output. Most of the decrease appeared to occur during the first 40 shots. The temperature of the water bath was maintained at $100^{\circ} \pm 1^{\circ}$F during this test to eliminate the possibility of variations in output due to temperature changes. As a check to be sure that the change in laser characteristics did not occur due to a lack of thermal equilibrium within the laser rod during the initial slope efficiency measurement, the system was allowed to set overnight and slope efficiency was measured again in the morning. The values of slope efficiency and laser threshold remained unchanged at 2.9 percent and 340 joules, respectively.

This laser rod which now had 81 shots on it, including 21 shots acquired during the three efficiency measurements, was now subjected to the normal solarization procedure, namely: (1) the slope efficiency was determined using sodium nitrite solution to prevent solarization, (2) the sodium nitrite solution was replaced with distilled water and the laser was fired 10 times at 1075 joules input, and (3) the water was replaced with sodium nitrite and the slope efficiency was again determined. By visual inspection, the laser rod exhibited a reddish discoloration after the first shot with distilled water in the cavity. This discoloration was noticeably darker after the third shot. The measured slope efficiency changed from 2.9 to 3.0 and the laser threshold remained constant at 325 joules between the initial and final measurements of this last series. The temperature of the bath was monitored but not regulated during this test and was found to be slightly higher at the end of the run. It is not clear whether the slight apparent increase in slope efficiency is due to this temperature change, is in fact a true increase in slope efficiency, or represents the limit of error of the measurement.

These latter tests would strongly suggest that the changes in laser characteristics observed in the initial phase of this study were due to some kind of an aging process since these changes were observed in the latter tests when no visible solarization occured in the rod and furthermore that once this "aging" had taken place, the laser rod could be solarized as determined by a visual reddening of the rod without changing the laser characteristics of the rod.

The final phase of this investigation was to repeat the solarization procedure used in the initial phase of the work, but to increase the degree of solarization. To accomplish this, the 600 microhenry inductance was removed from the flashtube circuit. Measurements made subsequent to this reporting period indicated that under this condition of zero inductance the peak current density in the flashtube exceeded 2500 amperes per square centimeter under these conditions at an input energy of 1075 joules.

As before, the slope efficiency of the rod was measured using sodium nitrite solution in the cavity followed by 10 shots with distilled water in the cavity and a subsequent slope efficiency measurement with sodium nitrite in the cavity. On the last shot of the final slope efficiency measurement, the flashtube failed catastrophically. This treatment resulted in a decrease in slope efficiency from 2.6 percent to 2.2 percent and an increase in laser threshold from 300 to 320 joules. Since the laser rod was already severely discolored from the previous exposures it is difficult to say whether this decrease in laser performance was due to more severe solarization or was due to accelerated deterioration of the flashtube near the end of its life. The lower slope efficiency, 2.6 percent vs 2.9-3.0 percent in the previous test, may be due in part at least to different temporal and spectral characteristics of the flashtube operating with no inductance in the circuit.

3. ATHERMALIZATION STUDIES

As previously reported (Reference: Technical Summary Report No. 7, Contract Nonr-3835(00)), one of the glass compositions with the most promising ratio α_n/α (MG-1204) was slightly modified to improve its laser characteristics (MG-1750) and melted in a one pound size melt. The thermal properties of the modified athermal composition were still encouraging and therefore a ten pound melt of this composition was made in order to provide glass of better optical quality from which a direct measurement of the induced optical distortion produced during the pumping process could be made.

Rods fabricated from this ten pound melt were submitted to H. Welling of the U.S. Army Electronics Laboratories at Fort Monmouth, New Jersey for a measurement of the change in optical thickness of the sample during pumping. Apparatus had already been constructed at Fort Monmouth to perform this specific measurement. This is an interferometric measurement using a He-Ne laser source and high speed slit and framing cameras as recording devices. A comparison was made of the change in optical pathlength at the center and at the edge of 3 inch long rods of MG-1750 glass and our standard laser glass MG-3835. These results are given in Table II.

Table II. CHANGE IN OPTICAL PATHLENGTH DUE TO PUMPING[a]

MG-1750	$\Delta P_{center} = 0.38\lambda$	$\Delta P_{edge} = 0.38\lambda$
MG-3835	$\Delta P_{center} = 1.9\lambda$	$\Delta P_{edge} = 2.7\lambda$

[a]Length of laser rod is 3 inches, λ is 6328Å, pump energy is 1000 joules.

These results are significant for two reasons. First, the change in optical pathlength is uniform across the face of MG-1750 laser rod, i.e. the change in pathlength at the center is the same as the change in pathlength at the edge. Conversely, MG-3835 shows a 40 percent greater increase in change in pathlength at the edge than at the center. This indicates that the degree of athermalization of the MG-1750 composition has been greatly improved with respect to our standard MG-3835 laser glass. Secondly, the magnitude of the change in pathlength for the MG-3835 glass is 5 to 7 times greater than that of the MG-1750 glass, thus the latter may exhibit less wavelength shift per individual laser spike.

Based on these encouraging results, a second series of 16 athermal glass compositions was melted. These compositions are modifications of the MG-1750 to see if a family of athermal glasses can be fabricated which will provide some choice in the other physical and laser properties of an athermal material.

Efforts to finalize the procedure for measuring stress-optical coefficients $B_{\perp}$ and $B_{\parallel}$ have continued. Difficulties encountered in obtaining reproducible results on a sample of MG-3835 glass of good optical quality prompted a careful reexamination of the method of measuring the change in optical pathlength due to applied stress on the sample. Results of this examination indicate that motion of the sample during the application of stress is introducing serious error in the determination of the change in optical thickness of the sample with applied pressure. This motion includes both rotation about the axis along which the pressure is applied and tilt in the plane defined by this axis and the direction of observation.

Some of the tilt problem is overcome by making measurements between two levels of applied stress rather than between an unstressed and a stressed sample, since most of the tilt seems to occur with the initial application of pressure. Rotation of the sample was reduced by removing one of the ball bearing loading points on the sample holder. This, however, made it necessary to change the sample specimen dimensions in order to obtain a portion in the sample with a uniform stress distribution to measure. With this modified system for applying stress, fairly uniform stress distributions are obtained in the central third of samples 1 cm x 1 cm x 3 cm when the stress is applied along the long axis of the sample.

The change in optical pathlength is recorded photographically as a shift in the position of interferometer fringes. This is recorded with a double exposure such that the end section of each fringe represents the unstressed state and the central portion of each fringe represents the stressed state. The light intensity of the mercury source was too low to obtain suitable photographs with reasonable time exposures. For this reason the light source was changed to a He-Ne laser with expanding optics to illuminate the whole central portion of the test samples.

Attempts to make a direct determination of the change in physical thickness, Δd, of the test sample due to applied pressure indicate that this measurement lacks sufficient sensitivity for the present requirement. Since the change in optical thickness of the sample is due to the combined effects of a change in refractive index, plus a change in the physical thickness of the sample, in order to obtain the change in refractive index due to applied pressure from the measured value of the change in optical pathlength due to applied pressure, a separate measurement of the change in physical thickness due to applied pressure must be made. The value of the change in physical thickness, Δd, may also be calculated from the following expression: $\Delta d = sd\sigma/E$, where s is the applied stress in kilograms per square centimeter, d is the unstressed geometric thickness of the sample in centimeters, σ is Poisson's ratio and E is Young's modulus in kilograms per square centimeter. The ratio of σ/E was measured directly using the Cornu-Straubel method for MG-3835 and MG-1750. It was concluded that a direct determination of σ and E by the sonic velocity method was preferable to measuring the ratio of σ/E by this method. Samples were, therefore, submitted for this measurement to Professor S. C. Moss at MIT where apparatus was already in existence. It may be necessary to make additional glass melts to provide material from which to make sample specimens for the σ and E value determinations.

Some preliminary thought has been given to the possibility of using a holographic technique to measure the change in optical thickness of striated samples. The approach would be the superposition of holograms of a stressed and unstressed sample of glass to yield information on the shift in fringes produced by the applied stress and the cancellation of the fringes due to stria initially present in the glass.