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Final Report Thermal Optic Distortion Report Period: 16 June 1965 to 1 October 1966 Contract NOnr - 4874 (00) ARPA Order No. 306 Project Code 4730 Prepared for OFFICE OF NAVAL RESEARCH Washington, D. C. Westinghouse General Order WGD-38538-KD Project Supervisor: Mr. I. T. Basil Authors: E. P. Riedel G. D. Baldwin This research is a part of Project DEFENDER under the joint sponsorship of the Advanced Research Projects Agency, the Office of Naval Research, and the Department of Defense. P.O. Box 1897 Westinghouse Electric Corporation Baltimore, Md. 21203 MDE 1198

ABSTRACT Γ I The Final Report on Contract Nonr-4874(00) "Thermal Optic Distortion" quantatively describes the optical distortion in neodymium doped glass which is induced by pump radia- tion. We have observed optical distortion at 6328Å and have found the optical path length dependent on four primary effects: 1) Change in physical length 2) Change in refractive index due to temperature rise 3) Change in index resulting from stress 4) Change in index associated with an excited state population of neodymium ions. Section I presents the experimental techniques used and the results obtained through- out this contract Included in this section are measurements of optical path length variations, pump-induced birefringence, change in physical length, change in refractive index, bulk temperature rise, and the deflection of a light beam. In Section II, the theory of thermal optic distortion. is developed for the first time to include Fermat's principle. This approach leads to equations defining both the slope and trajectory of rays through the material. The resulting equations are employed to predict ray refraction, beam divergence, and the optical path length through the material as a function of radius, time, and polarization. Section III compares the results of Sections I and II. Good agreement between theory and experiment is achieved provided a new term is added to the expression for the change in refractive index. This term arises from the fact that the polarizability of the neodymium ion ground level. The inclusion I in its excited "F. level is different from its value in the 3/2 19/2 I of this new term in the expression for the change in refractive index implies that large optical distortions can exist in "athermalized" glass. I =

The objective of the contract was to formulate a mathematical model of pump-induced optical distortion in neodymium-glass laser rods and to verify this theory through experiment. The experimental measurements made during the course of this contract included interferometer measurements of optical path length variations, pump-induced birefringence, change in length and refractive dex, bulk temperature rise, and the deflection of a light beam. The general approach taken during this contract was to first measure pump-induced birefringence and the change in length of the laser rod. From this data, the temperature of the laser rod as a function of radius and time was calculated. This temperature distribution was then used to theorethically predict the results of interferometric measurements, re- fractive index change, bulk temperature rise, and the refraction of a light beam. Three major sections comprise the body of this report. Section I deals with the experiments performed and the results obtained, Section II is concerned with the development of a theoretical model, while the final section shows the correlation which exists between the experimental results and the theory. ili/iv

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SECTION I. EXPERIMENTAL TECHNIQUES AND RESULTS

A. INTRODUCTION

This section of the Final Report or Contract Nonr-4874(00) is concerned with the ex- perimental techniques used and the experimental results obtained throughout this contract. The most important product of the experimental work was quantative data which was used to test the theory developed in Section II. The ability to obtain reliable and usable quantative data rests primarily on the achieve- ment of good radial symmetry in the optical path length gradients across the rod diameter during the optical pump cycle. Without radial symmetry, the effect of pu np-induced stress and resulting strain cannot be determined, while all other data obtained would be extremely difficult to interpret. This section will, therefore, be concerned with two major topics. The first deals with achieving radial symmetry and the associated physical problems, while the second is con- cerned with the measurements of the laser rod's dynamic optical properties when exposed to a pump source. 1.

B. ACHIEVEMENT OF RADIAL SYMMETRY

Optical Pump Geometry The source used to optically pump the glass rods, which were 3/8 inch in diameter by 3 inches long, consisted of a 6-inch long xenon-filled helical lamp. The helical lamp had an inside diameter of 1. 15 inches, and an outside diameter of 2.2 inches, with 9-1/2 coils along its length. Close coupled to the inside diameter of the lamp was a frosted pyrex sheath with a. 06-inch wall thickness, while the outside diameter of the lamp was in contact with a heavy aluminum foil reflector. The purpose of the frosted Pyrex sheath was to prevent solarization of the Ndo rod and to diffuse the pump light before it fell on the laser rod. The aluminum reflector served to increase the total pump energy falling on the rod. The laser rod was supported in the center of the Pyrex sheath. There were several reasons for choosing a 6-inch long helical lamp to pump a 3-inch long laser rod. Perhaps the most important was that the 6-inch lamp provided more even illumination along the length of the laser rod than a shorter lamp. An additional advantage was that the lamp (capable of dissipating 20,000 joules) was excited to a fraction of its maximum rating, thus providing very reproducible data throughout the experimental program. 1-1

The laser rod and cavity were air-cooled between firings with sufficient time allowed between shots for the rod to return to room temperature equilibrium. 2. Effects of Residual Stress* If the residual stress in a laser rod is large compared to the stress induced during optic) pumping, the measurement of the latter may be difficult or impossible. This is particularly true if the residual stress does not possess radial symmetry with respect to the rod axis. A study was therefore undertaken to determine the distribution, and where possible the magnitude, cf residual stress existing in a number of glass rods and to observe the effect this residual stress had on the optical path length through the laser rod during the pump cycle. This investigation is covered in detail in Appendix A. It was observed that those rods which did not possess radially symmetric residual stress exhibited non-radial optical path length gradients and non-radial stress during the pump cycle. However, those rods which did have radially symmetric residual stress exhibited radially symmetric stress and optical path length gradients during the pump cycle. In general, the achievement of radially symmetric optical distortions was dependent on the laser rod possessing either radially symmetric residual stress or zero stress. In addi- tion, there were only two cases in which the residual stress appeared to be as large as the pump induced stress, while for all of the other glass rods tested, the residual stress appeared to be considerably less. The results of this study were used to select a rod (AO-2) which contained only radially symmetric residual stress and of magnitude small compared to the pump induced stress. This rod was used to take the quantitative data contained in this report. Laser Rod Support Effects 3. Prior to determining the effects of residual stress it was found necessary to determine the distortion of the laser rod optical path caused by the laser rod supports. Basically, two types of distortion were observed. The first arose from air, which was heated at the laser rod surface, flowed around the end of the laser rod, and perturbed the optical path in the vicinity of the end of the rod. The mechanism of the second type of distortion is not yet known; however, it manifested itself by modulating the refractive index of the laser rod and appeared to originate at the point of contact between the laser rod and the rod support. The details of this investigation are to be found in Appendix B of this report. Residual Stress is defined as that stress present in a laser rod when the rod is at equilib- rium room temperature. 1-2

After a thorough investigation of the distortion produced by several types of rod sup- ports, a new support was designed and tested It was found that the new rod support intro- duced no observable distortion. 4. Conclusion The attainment of radially symmetric optical path length variations in a neodymium glass ser rod requires that three conditions be satisfied. It is necessary that the optical pumping cavity be so designed as to ensure uniform distribution of pump energy over the surface of the laser rod. One of two conditions with respect to residual stress must be met: Residual stress must be small, or (1) (2) the residual stress must possess radial symmetry. Finally, it is imperative that the laser rod supports introduce no d. tortion. All three of these requirements have been met during this contract, thus enabling reproducible quantita- tive data to be obtained. 1. C. QUANTITATIVE OPT.CAL DISTORTION MEASUREMENTS Operating Range of Laser Rod It was deemed necessary to demonstrate that the pump energies and pump cavity used to obtain the thermal-ortic distortion data produced gain in the laser rod which was comparable with the gain being generated in operational laser systems. To this end, laser rod AO-2 (See Appendix A) was placed in a resonant cavity composed of a 70% reflecting front mirror and a 99%+ reflecting rear mirror. The laser rod was pumped at various energies, and the output energy in joules was recorded. Throughout this contract the light output from the lamp was temporally in the form of an unshaped pulse with a 3 db intensity duration of approxi- mately 600 microseconds. The shape of the pump pulse is shown in figure 1-1, while figure 1-2 shows a plot of output versus input energy for rod AO-2. The low slope efficiency of . 31% is not unusual considering the type of pumping cavity employed. Of major importance, however, is the fact that at the pump energies used to record the dynamic optical distortions (6400, 8800, and 11, 500 joules), the laser rod possessed considerable gain. 2. Optical Path Length Variation The dynamic optical path length variations in rod AO-2 were measured on a Mach- Zehnder interferometer and recorded by means of a Beckman and Whitley Model 350 high- speed framing camera. The experimental diagram is the same as that shown in figure A-2. The framing camera was run at a speed of 35,900 frames per second. This speed yielded a * Appendix A * 1-3

Figure 1-1. Temporal Shape of Pump Source (200 µs/div.) frame separation of 28 microseconds with a frame exposure time of 3 microseconds. Figure 1-3 shows some typical photographs obtained for 6400, 8800, and 11, 500 joules into the helical lamp. The film strip on which the fringe patterns were recorded was Kodak Shellburst Film. This film was developed in Kodak HC-110 developer at 68°F for 5 minutes. The film was calibrated so that relative intensity could be obtained by means of microdensitometer traces. The phase change, measured from the center of the rod to the edge, was obtained from the microdensitometer traces in the following manner. In general, the fringe intensity at a fixed radius for the Mach-Zehnder Interferometer is given by 1 (I. 1) $I(r) = f(r) [1 + k g(r) + 2 \sqrt{k} g(r) (r)] \cos 8 (r)$ where $I(r)$ is the fringe intensity, $f(r)$ is the intensity in the arm of the interferometer not containing the laser rod, k is an intensity loss factor $(0-k\leq1)$ introduced by the laser rod in one arm of the interferometer, $g(r)$ is a loss factor which accounts for the depolarization ef- fects of stress, and 8 (r) is the fringe phase angle. The maximum fringe intensity is given by (1.2) $I \max(r) = f(r) [1 + kg(r) + 2 \sqrt{kg(r)}]$ while the minimum intensity is given by (I. 3) 1-4 $I\min (r) = f(r) [1 + k + k g(r) - 2 \sqrt{k} g(r)]$.

OUTPUT ENERGY IN JOULES 38 36 34 32 30 28 26 24 22.2 j- 22 22 18 16 14 12 10 6 2 T 14.6j- SLOPE EFFICIENCY = .31%. AO-2- 6400 i 8800 j 2 4 5 6 7 8 9 10 12 INPUT ENERGY IN KILOJOULES Figure 1-2. Output vs. Input Energy for Rod AO-2 1-5

C GOMs 180μS ■■ 300μS 4205 -Pottom- -Bottom- -Bottom- O 600MS -Bottom- 780μs -Bottom- 96045 -Bottom- 1260MS -Bottom- Figure 1-3(a). Mach-Zehnder Fringe Pattern Photographs for Rod AO-2 - (6,400 Joules) O GOMS Bottom- 180μ' 300μs -Bottom- - Bottom- 42045 -Bottom- C 600μs -Bottom- 780us -Bottom- 96045 -Bottom- 126045 " -Ittom- Figure 1-3(b). Mach-Zehnder Fringe Pattern Photographs for Rod AO-2 - (8,800 Joules) 1-6

-Bottom- acous T -Bottom- 31045 -Bottom- 42gus C Tagus Bellam Figure 1-3(c). Mach-Zehnder Fringe Pattern Photographs for Rod AO-2 - (11,500 Joules) m'x' min For our experimental results it was found that I (r) and I (r) remained essentially con- stant from r = 0 to r = R. In addition, by running the microdensitometer traces parallel to the direction of the polarization of the He-Ne beam the value of g(r) was 1. Since was therefore taken for radially polarized radiation, we shall write 8 (r) as 8 (r) from now on to denote this fact. By next defining the quantity σ as the ratio I ¸(r)/I¸ (r) and requiring that the value of I x(r) be normalized to 1, the phase angle 8 _ (r) can be expressed as max (I. 4) where -1 8(r) = COS (I. 5) k = min max (r) - [P16) $ (1-4)] 1+ $\sqrt{\sigma}$ vα [:] 2 (I. 6) S= 1 1 + k + 2 $\sqrt{k}$ and ■ (r) is defined as the ratio I(r)/I (r). max 1-7

Using equations (I. 4), (I. 5), and (I. 6) the phase angle across the rod radius was calcu- lated for rod AO-2 at 11, 500 joules pump energy for all frames between time t equal to zero (start of pump cycle) and t = 1600 microseconds (approximate end of pump cycle). Figure 1-4 shows this phase angle, normalized to zero at the center of the rod (r/R = 0), at selected times as a function of normalized radius r/R. In addition to the relative phase angle across the rod, the high-speed photographs were used to give the total phase angle change at r/R = 0 as a function of time. First, the fringe intensity variation at r/R = 0 versus time was plotted, and from this curve the total phase angle change was determined. Figure 1-5 shows the intensity variation for 11, 500 joules pump energy, while figure 1-6 shows the total phase angle change recorded at three separate pump energies for the doped AO-2 rod and at one energy for the undoped AO-3* rod. It is in- teresting to note that when the shape of the curves for the total phase angle change (figure 1-6) are compared to the shape of the curve for the percent of total light emitted from the flash lamp, figure 1-7, there is excellent agreement. To determine the effect of the glass host on the observed optical distortions, an undoped AOlux rod (AO-3) was placed in the pumping cavity. A set of selected Mach-Zehnder fringe pattern photographs recorded at 11, 500 joules is shown in figure 1-8. When comparison was made between the relative phase angle across the radius recorded for the doped rod (AO-2) with that for the undoped rod, there appeared to be no great difference between them. Thus, one must conclude that the relative phase angle across the radius as observed for the doped +3 laser rod is primarily caused by the glass host. Although the addition of Nd to the host did not greatly effect the relative phase angle across the radius induced by the pump, the total phase angle change was much greater for the doped rod. It can be seen from figure 1-6 that the maximum phase angle change for the doped rod is x2. 7 greater than that observed for the host. The optical path distortions noted for the undoped rod were probably caused by absorp- tion of the U. V. pump radiation which passed through the pyrex sheath. This effect was ag- gravated for the AOlux host because its UV absorption band appeared to extend well into the visible blue region. By analyzing the fringe patterns of the host in the same way as for the doped rod, the effect of the Nd oncentration alone could be determined. Four times were selected for comparison purposes. The total phase angle change for the undoped rod as a function of r/R was subtracted from the total phase angle change for the doped rod as a function of r/R, the resulting curves being shown in figure 1-9. In figure 1-10, the relative phase angle for Nd*³ * See Appendix A 1-8

RELATIVE PHASE ANGLE, 8, (r)-8,(o), IN RADIANS 18 16 14 12- 10-- 10 3■ 51/2 2A 1=1380 $\mu\varepsilon$ 3A2 t=1048 μs 1 = 745 $\mu\varepsilon$ 13 469 $\mu\varepsilon$ t=303 μs- +=138μs- 0.2 0.4 0.6 0.8 1.0 r/R. 1/2 Figure 1-4. Radial Optical Path Length Variation for Rod AO-2 at 11,500j Pump Energy (all curves normalized to zero at r/R = ·0) 1-9

1-10

Figure 1-5. Fringe Intensity Variation at r/R = 0 for Rod AO-2 at 11,500) Pump Energy

NORMALIZED FRINGE INTENSITY: 1.2 1.0 1.2 1.4 1.6 1.8

TIME IN MILLISECONDS: 0.2 0.4 0.6 0.8

11-X27 10 Figure 1-6. Total Phase Change at r/R = 0 for Rods AO-2 and AO-3 1-11 TOTAL PHASE ANGLE CHANGE IN RADIANS " AO-2, 11,500 j AO-2, £800 j AO-2, 6400j AO-3, 11,500j 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 TIME IN MILLISECONDS

1-12 100 -06 PERCENT OF TOTAL LIGHT EMITTED 30 30- 50 40 Figure 1-7. Percent Total Pump Energy Dissipated as a Function of Time 20 20 10- 5 2 G. 6° 1.0 1.1 TIME IN MILLISECONDS → 1.3 1.8 1.7

6945 -Botten- 18gus -Botton- 309-8 -Bottom- 42gus -Bottom- bogl - Bottom- agats -Bottom- Megas -Bottom- Figure 1-8. Mach-Zehnder Fringe Pattern Photographs for Rod AO-3 at 11, 500j Pump Energy 1-13

1-14 TOTAL PHASE ANGLE CHANGE DUE TO Nd *3, IN RADIANS 6.5 6.0 X2 πT 5.0 3.5. 3.0° 2.5- t = 1600 p's t = 993 ps t = 717 ps t = 303 µs 2.0 0 123456766- 1.0 r/R -> +3 Figure 1-9. Total Change in Phase Angle attributed to N■ in Rod AO-2 at 11,500j Pump Energy 2

RELATIVE PHASE ANGLE RADIANS 3.0 . 1600 p LEGEND: **HOST • Ne's 20+ x2 1.0 10- t-993 10+ X2IT °. t = 7i7ys 10+ x21 °- 1.303 ps 3. x2π 10 Figure 1-10. Comparision Between Radial Optical Path Change Due to Nd+3 and Host in Rod AO-2 at 11,500; Pump Energy. Nd+3 Plus only is compared with that for Nd +3 plus the host. It is obvious that elimination of host absorp- tion would noticably reduce the optical distortion. 3. Birefringence Measurements To assess depolarization effects and to acquire the necessary quantative data to use in Section III to calculate the temperature rise in laser rod AO-2, the pump-induced birefrigence was measured. The experimental arrangement for measuring the time resolved birefringence is shown in figure 1-11. Figure 1-12 shows selected photographs in the time development of the birefrigence in rod AO-2 at 11, 500 joules. As in case of the Mach-Zehnder photographs end B of the laser rod was focused at the focal plane of the camera. The film used, develop- ment procedure, film calibration data, framing speed, and frame exposure was essentially identical to that used for the Mach-Zehnder measurements. The equation used to calculate the phase angle between the radial and tangential polarization components was equation (A. 1)*. We shall call this the stress phase angle. The stress phase angle for an azimuthal angle 0 of 45 degrees is shown as a function of normalized radius and time in figure 1-13 for a pump *Appendix A 1-15

BEAM EXPANDING OPTICS POLARIZER NO.I POLARIZER NO. 2 100% MIRROR SPECTRA-PHYSICS MOD. 112 He-Ne LASER END B APERTURE LASER ROD 8 PUMP CAVITY FOCUSING LENS SHUTTER- CORNING RED FILTER' " LIGHT SHIELD -PINHOLE APERTURE BECKMAN & WHITLEY MOD 350 HIGHSPEED FRAMING CAMERA Figure 1-11. Experimental Diagram: Measurement of Pumo Induced Birefrigence. 1-16 Figure 1-12. Stress Development in Rod AO-2 at 11, 500j Pump Energy (Direction of incident polarization 7/352) 45°

STRESS PHASE ANGLE IN RADIANS -8 (r. 1) 3.5 3.0+ 2.5- N 1.5 1.0+ 0.5- * FOR CLARITY EXPERIMENTIAL ERROR HAS NOT BEEN SHOWN. ======== 0.1 0.2 0.3 04 0.5 0.6 0.7 0.8 r/R 0.9 1.0 t= 684 us t=443us t=382 us t = 262 us t = 201 us -t=141 us -t = 80 us Figure 1-13. Radial Stress Angle in Rod AO-2 at 11, 500j Pump Energy 1-17

1-18 (Sr-So) IN Kg/cm 0.10 10.0+ 1.0F * MAX. STRESS AT 11,500) PUMP ENERGY PUMP INDUCED (11,500j) STRESS* RESIDUAL STRESS 1 0.01 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 /R 1.0

Figure 1-14. Comparison Between Residual and Pump Induced Stress in Rod AO-2 1

energy of 11,500 joules. Within experimental error (not shown in figur: 1-13) there was no change in the stress phase angle between t = 684 microseconds and t = 1600 microseconds. The mean value of the data, however, indicated that the stress phase angle decreased slightly after 800 μseconds. r To illustrate the degree of stress induced by the pump in rod AO-2 at 11,500 joules, the stress (S S) before the pump, and at its peak value during the pump, was calculated from the data and equation (A. 3)*. This is shown in fig re 1-14. As can be seen from this curve, the pump-induced stress is better than an order of magnitude greater than the residual stress. The undoped laser rod AO-3 was also tested for birefrigence during the pump cycle. Although no quantative data was extracted from the photographs. there was little qualitative difference between the birefrigence patterns for rods AO-2 and AO-3. 4. Change in Length and Refractive Index The experimental technique used in this part of the work allowed us to determine not on- ly the change in physical length, but also the degree of physical distortion in the flatness of the rod ends and the change in refractive index. 2 The laser rod was aligned with the He-Ne Beam, as in figure 1-15, so that the ends of the rod formed an interferometer. End B of the laser rod was imaged on a target in front of a photomultiplier tube. Directly in front of the photocathode surface was a . 05-inch diameter pinhole. The position of the target and P. M. tube was changed to establish a value of r/R and data was taken at each position. The movement of fringes past the pinhole was recorded during the pumping cycle for the "rod-end" interferometer. By using the data obtained with ** the "rod-end" and Mach-Zehnder interferometers, the change in length {sf (t)} change in index {^n(t)} for the laser rod could be calculated as follows. and Consider the diagram of a Mach-Zehnder interferometer shown in figure 1-16. The phase differential between paths L■ + L2 and L3 + L4 prior to the pump cycle is given by: 2π 8ø■ = 2 [{(×■■) + 1 + 12} - (L■+14)] (1.7) 80. However, (1.8) X■ + x2 + 10 = L■. *Appendix A **Pinhole much smaller than fringe width 1-19

BEAM EXPANDING OPTICS MOD 112 He-Ne LASER 1-20 APERTURE mo ■■■ 60% 100% TARGET FINE PINHOLE -IMAGING LENS END B m LASER ROD P.M. TUBE G PUMP CAVITY TO CATHODE RAY OSCILLOSCOPE Figure 1-15. Experimental Diagram: "Rod End" Interferometer He Ne LASER BEAM (6328Å) M LASER 50% ROD L3 Ma 100% La 100% '50% Figure 1-16. Mach-Zehnder Interferometer

Thus: (1.9) 8 Ø■ = 27 [f(n-1) + (L■■+L■) - (L3+L■)] During the pump, equation (1.7) is modified such that (1.10) 802 = 2π A 2 * [×■' + x2' + { I■ +^l«t} {n+^n(t)+L■ - (L■+L■)] Again, (1. 11) Thus: ×■' + ×2' + [I■ +ôƒ«)] = 4. (1.12) 802 = 2 [{ +Al (t)} {n■+An(t)-1} +(L■+L■■)-(L■■+L4)] 1 The difference between equations (1.9) and (1. 12) gives the actual phase variations observed during the pump cycle. Thus, (1. 13) Since lo 2π ^ø■(t) 27 [An(t) {l+Al(t)} +Al() {-1}] >>A & (t), equation (1.13) becomes (1.14) A■(t) = 2π λ An(t) + (n-1) A l (t)] Next, consider the "rod-end" interferometer as shown in figure 1-17. Prior to pump- ing, the phase difference between rays traversing the path OA -> AO and those reflected di- rectly from M1 is given by: (1.15) 803 = 47 (lon). 4π A During the pump cycle the phase difference is given by 4π (1.16) 8(t) = {l +Al (t)} {% + An(t)} . Again, & >>^l (t), and the observed phase change during pumping is given by the difference 1-21

Me-No LASER BEAM (6328 Å) M, (~4%) M■ (~4%) 0 A Figure 1-17. "Rod - End" Interferometer between (1. 15) and (1. 15). This phase change is 4T (1.17) A2 (t) = [1 An(t) + n^l (t)]. Equations (1. 14) and (1. 17) can be used to solve for ▲ n(t) and Al(t). These solutions are: (1.18) Al(t) (1.19) = 4π ½ 02 (t) - Ø ()]), An(t) = [(t) ° Thus, by recording A■(t) and A/2 (t) at a fixed value of r/R, the change in physical length and refractive index can be determined. Figure 1-18 shows the phase change obtained at r/R = 0 for the Mach-Zehnder and "rod- end interferometers at 6400, 8800, and 11,500 joules pump energy. In spite of the large number of fringes recorded for the "rod-end" interferometer, the data was found to be extre- mely reproducible from shot to shot. Figure 1-19 shows ^l (t) as obtained from this data, while figure 1-20 shows An(t). . The value of (t) was also obtained at 11,500 joules for r/R = 44 and r/R = . 72. This was done to determine whether any physical distortions to the ends of the laser rod occurred during the pump cycle. A plot of ^ 1 (t) at r/R = 0, .44, and. 72 is shown in figure 1-21. Within experimental error there was no change r/R = . 72 up to t = 1.1 milliseconds. After t = 1. 1 ms there end flatness from r/R = 0 to still no distortion be- = = 0 tween r/R = 0 and and r/R . 44, but distortion definately does exist between r/R = 44 and r/R . 72. At 1.6 ms this distortion in end flatness has increased (between r/R and .72) to approximately 1/4 per end. Ignoring all internal refractive index gradients, this distortion alone will cause the laser rod to act like a negative lens. 1-22

OBSERVED VALUES OF 2 x A4, (1) AND A 2(t), IN RADIANS 80+x27 56 52 11,500) -"ROD END" 48- 44 40 9,800 "ROD END" $\Delta\Phi$, (1) 2 36 32 28- 24 20 16- 12+ 6,400; "ROD END" $\Delta\Phi$, 197 11,500) - 2 × ×¢,(1) 8,800)-2×44(1) x 6,400) -2x44 (1) .? 1.0 1.1 1.2 1.3 1.4 1.5 16 1.7 1.8 1.9 TIME IN MILLISECONDS Figure 1-18. 2 × ×■(t) and ■Ø■ (t) vs. Time at r/R = 0, for "Rod-End" and Mach-Zehnder Interferometer at 6400, 8800, and 11,500 joule Pump Energies 1-23

1-24 25 24+ 23- 22- 21- 200 19 18 17 16- 15 14 13 12- CHANGE IN PHYSICAL LENGTH, Al(t),IN VALUES OF A■ Wo* 6.328 × 105 CM) 3 2 /* /R=0, 11,500 j /R=0, 6400j T T /R=0,8800] ° α_ι 0.2 0.3 04 0.5 0.6 0.7 0.8 0.9 1.0 TIME IN MILLISECONDS 1.2 1.3 1.4 1.5 1.6 1.7 1.8 Figure 1-19. Change in Physical Length for Rod AO-2 vs Time at 6400, 8800, and 11, 500j Pump Energies

CHANGE IN REFRACTIVE INDEX, An(t) 18-X10-6 16+ 14 12- 10+ /R=0,6400 j "/R=0,11,500j /R=0,8800] .2 .3 4 .5 .6 .7 8 .9 1.0 1.1 1.2 1.3 TIME IN MILLISECONDS 1.4 1.5 1.6 1.7 1.8 Figure 1-20. Refractive Index Change (experimental Error not shown) vs Time for AOlux Rod AO-2 at r/R=0, and 6400, 8800, 11, 500j Pump Energies 1-25

CHANGE IN LENGTH NO_OF A λ = 6. 328 × 105 CM 13 17 18 16- 15 14 11 11,500■,7R 72 'll, 500],'/R.44 11,500 j,'/R= (+ ERROR FOR /R =O CURVE ERROR FOR '/R=44 CURVE ERROR FOR '/R: 72 CURVE ° OI 02 03 04 05 06 07 08 09 10 12 13 14 15 16 17 18 TIME IN MILLISECONDS 19 2.0 Figure 1-21. Change in Physical Length for Rod AO-2 at 11,500j Pump Energy and for r/R = 0, r/R = .44, F/R = .72 1-26

5. Thermocouple Temperature Rise Determination To obtain an experimental check on the calculated temperature rise of the laser rod, a tnermocouple was used to measure the temperature rise after the pump cycle was terminated. A .1 inch diameter hole 5 inch deep was drilled in the center of the end of rod AO-1. A thermocouple was inserted into this hole and contacted he glass. Initially, a low thermal mass thermocouple, manufactured by RdF Corporation, was placed in the laser rod. It was hoped that accurate temperature rise data could be obtained at least after 10 milliseconds. Unfortunately, the thin (.0003 inch thick) RdF thermocouple evaporated when exposed to the pump radiation. A new thermocouple was constructed, from .01" diameter chromel-alumel wire, and tested. This unit withstood repeated flashes at 11,500 joules. The time after e ilash that was required to obtain the temperature rise in the rod was approximately 20 seconds with this new unit. The time of 20 seconds might at first seem too long for meaningful data to be obtained. However, for glass with its low thermal conductivity, the temperature rise rê- corded at 20 seconds should be a reasonable approximation to the equalized temperature rise in the rod. If the temperature at a certain length of Consider an infinite length cylinder at a uniform temperature T the outside surface is suddenly increased and held at a temperature T■, *ime will be required for the cylinder to assume a uniform temperature. By defining a time constant r "t as the time required for the temperature at the center of the rod to rise to 63% is given by of its final value, the value of "t (1.20) = 26 YC R² 2 It K ■ ■■ t where Y is the density, c the specific heat, K the thermal conductivity, and R the radius of the cylinder. For rod AO-2 and AO-1 the value of 12 seconds. Although the idcalized case il- lustrated above is not strictly true for an optically pumped laser rod, particularly since the outside of the rod is not constrained at a fixed temperature, the value of the rod temperature 20 seconds after the flash should be a close approximation to the equalized temperature rise in the rod induced by the pump. Additional experimental verification of this assumption is found in the fact that the temperature rise recorded by the thermocouple remained constant within 1°C from 15 seconds to at least 1 minute after the flash. Correlation between the equalized rod temperature and that calculated theoretically from birefringence and change in physical length data can be obtained by integrating under the calculated temperature distribution curve at the end of the pump cycle (1600 microseconds) to obtain the total heat absorbed by the rod. This heat deposited uniformly in the laser rod 1-27

should result in approximately the same temperature rise as measured by the thermocouple. It is to be expected that the temperature measured by the thermocouple may be slightly high- er than that predicted by the heat content of the rod at the end of the pump cycle. This ad- ditional temperature rise occurs by absorption of heat from the hot flash lamp and other com- ponents within the cavity after the flash. The temperature rise measured by the thermocouple as a function of pump energy is shown in figure 1-22.

6. Small Diameter Light Beam Deflection

The theory to be presented in Section II predicts the refraction suffered by a light ray within the rod. To determine the validity of this prediction, an experiment was set up to mea- sure the deflection of a small diameter light beam for various values of r/R. The experiment- al arrangement is shown in figure 1-23. After passing the probe beam throug. the laser rod at a fixed value of r/R, the far field pattern of the probe beam was photographed by the high-speed camera. The angle the probe beam makes after emerging from the rod with the direction of the probe beam before it enters the rod is converted to a translational movement of the far field image in the focal plane of the camera. Figure 1-24 shows this angle of the probe beam as a function of time, recorded for rod AO-2 at 11,500 joules pump. The angle of the probe beam was always zero for r/R = 0. In addition, as r/R was increased, the probe beam angle increased in the direction of bend- ing the probe beam away from the rod axis. Both of these characteristics are in quantitative agreement with the theory as will be shown in Section III.

7. Mach-Zehnder Optical Path Length Variation with Nonex Sheath

All quantative measurements of thermal-optic distortion were made with a Pyrex sheath surrounding the laser rod. During the course of these measurements it was found that the large optical path length gradients across the rod diameter were largely caused by absorption of pump radiation by the glass host. It has been postulated that absorption of U. V. radiation, passing through the Pyrex sheath, is responsible. It was also shown that if the host absorp- tion could be eliminated, the resulting optical path gradients would be substantially reduced. To confirm this the frosted pyrex sheath was replaced by a frosted Nonex sheath (Corning Code No. 7720 glass). The short wavelength cutoff of Nonex is much closer to the visible than that of standard Pyrex and was expected to decrease the amount of energy absorbed by the host. Unfortunately, direct comparison of the effects of the two glasses could not be made. This was due to the fact that the standard size of the Nonex in stock was different from the pyrex. The pyrex tube had a .06" wall thickness with a . 98" i. d. while the Nonex had a . 09"

1-28

BULK TEMPERATURE RISE IN C 19 18 17- 16- ROD AO-I IDENTICAL MATE TO 15- ROD AO-2 14 13- 12 117 10 5- 4 3- 2 2 3 4 5 6 7 8 9 10 12 PUMP ENERGY IN KILOJOULES

Figure 1-22. Bulk Temperature Rise in Rod AO-1*as a Function of Pump Energy

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1-30 SMALL MOVABLE BEAM APERTURE APERTURE 114" FL. LENS MOD 112 He- Ne LASER EXPANDING OPTICS Figure 1-23. Experimental Diagram: Measurement of Light Beam Deflection PROBE BEAM (0.06"DIAMETER) LASER ROD AND PUMP . HIGH SPEED BECKMAN & WHITLEY CAMERA SHUTTER CORNING "RED"FILTER! FOCAL PLANE OF CAMERA - ■

0.6 PROBE BEAM ANGLE IN MILLIRADIANS Figure 1-24. Plot of Probe Beam Angle vs. Time for Rod AO-2 at 11, 500 Joules Pump Energy 1-31 2 x O + T + + + r/R = 0.9 /R = 0.5 V/R = 0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.0 TIME IN MILLISECONDS 0.1 0.2 0.3 04 0.5 0.6 0.7 0.8 0.9 6'1

wall thickness with a .84"i. d. Pictures were obtained of the optical path distortion with the Nonex sheath at a pump energy of 11,500 joules. By comparing these with those in figure 1-3(c) it was found that the optical path length gradients were less for the Nonex sheath. 8. Measurement of a n-n where n is the refractive index of the glass 0 n 1 $\Delta\eta$ The term a$*$ is defined as η ΔT, $\Delta\eta$ and is the total change in the index due to uniform temperature rise. It was found nec- AT essary to measure a since its value at 6328 A was not available. The value of a was determined by uniformly increasing the temperature of the laser rod over a range AT, deter- mining the change in optical path length which occured, and subtracting the effect of rod ex- pansion from the observed path length change. n The experimental approach was to place a thermocouple in contact with the surface of rod AO-2. The rod was then wrapped with a layer of asbestos cloth leaving the ends exposed. Approximately twenty windings of nichrome wire were wound around the inner layer of cloth and covered by a second wrapping of asbestos cloth. This thermally insulated assembly was placed in a cardboard container, considerably larger than the rod, which was located in one arm of a Mach-Zehnder interferometer. As the temperature of the rod changed, the fringe shift at the center of the rod was counted by means of a photomultiplier connected to a re- corder. The experimental arrangement is illustrated in figure 1-25. The rod was first al lowed to stabilize at room temperature. Then, current was applied to the nichrome winding, $\Delta\eta$ and the rod allowed to stabilize at its final temperature. The value of was then calculat- AT ed from (24) $\Delta\eta$ AT $\mathrm{N}\Lambda$! 4T - (n-1) a where N was the number of fringes which passed the center of the rod, λ the He-Ne wave- length, 1 the length of the rod, AT the temperature rise, no the refractive index, and ° ■■ a the expansion coefficient. The range of AT was held to approximately 20° C for each ■ experimental run. The value of at 6328 Å was found to be -1.25 +. 66 x 10-6 a n per °C. Most of the uncertainty in this figure arises from the uncertainty in the value of a. (See Ap- pendix F.) *See Section II 1-32

11 COLLIMATED He-Ne LASER BEAM(6328A) THERMOCOUPLE NO. 1. 50% 100% VARIABLE DC POWER SUPPLY THERMOCOUPLE WATER AT O°C 100% CARD BOARD BOX LASER ROD ASSEMBLY CARDBOARD TARGET 50% FOCUSING BRIDGE + THERMOCOUPLE NO.2 P.M. 1000V DC TUBE LENS 0.05" PINHOLE CHART REORDER Figure 1-25. Experimental Diagram: Measurement of a n 9. Conclusions The most important results obtained from the experiments described in this section are in the form of reproducible data which could be used to obtain correlation between theory and experiment. This will be done in Section III. There are, however, important observations which give a better qualatitive understand- ing of the optical properties of American Optical AOlux glass laser rods when exposed to an intense pumping sour :e. For clarity, these will be listed below in outline form as they refer to each experiment. 1) Operating Range of Laser Rod Rod AO-2 exhibited considerable gain at 11,500 joules pump energy. 2) Total Phase Angle Change a) The total phase angle change at the center of the rod increased at a rate pro- portional to the total pump energy deposited in the rod up to the time of obser- vation. b) The relative phase angle across the rod diameter is primarily due to host ab- sorption. 3) Birefringence Measurements a) Within experimental error the pump-induced stress phase angle reached a steady 1-33

1. 2. 3. 1-34 state approximately 700 microseconds after the start of the pump cycle. b) The pump-induced stress differential (S_--S) was better than an order of magni- tude greater than the residual stress differential. 4) Change in Physical Length and Refractive Index. Physical distortion to the flatness of the rod ends (dishing) is evident for times greater than 1 millisecond, and for values of r/R greater than .5. 5) Thermocouple Temperature Rise Determination - Equalized temperature rise in the laser rod was approximately 18°C at 11, 500 joules pump energy, 16° at 8,000 joules, and 12°C at 6400 joules. 6) Small Diameter Probe Beam Deflection a) There was no deflection of the probe beam when passed through the center of the rod (r/R = 0). As the probe was moved in the direction of increas- ing r/R, probe beam angle increased to a maximum value (for 11,500 joules in- put) of .4 milliradian at r/R = .90 and t = 1600 microseconds. b) The probe beam was bent away from the axis of the rod as was predicted by the Mach-Zehnder interferometer fringe patterns. These show that the optical path length increases as r increases. 7) Measurement of a n c - The measured value of a at 6328 A was $1.25 \pm .66 \times 10^{-6}$°C. n

D. REFERENCES - SECTION I Born & Wolf, Principles of Optics, Pergamon Press (1959), pg. 258 A. Y. Cabezas, L. G. Komai, and R. P. Treat, Appl. Optics, Vol. 5, No. 4, April, 1966, Pg. 647 H. S. Carslaw & J. C. Jaeger, Conduction of Heat in Solids, Oxford University Press (1959), pg. 200 34

II. THEORETICAL CONSIDERATIONS A. INTRODUCTION Thermal optical distortion in isotropic laser materials such as glass stems from temperature gradients which arise as a result of energy dissipated as heat in the 1,2,3,4 material. Two separate types of optical distortions arise from such temperature gradients. The first is caused by a non-zero index of refraction change with temperature of the material. The second is caused by a change in index of refraction of the material with stress which in turn arises from temperature gradients within the material. Both of these effects are important in most glasses. The neglect of the stress optical effect in American Optical 3835 glass (AOlux) leads, for example, to the prediction that a glass rod of this material will act as a positive lens when the temperature increases from the center of the rod outward while, in fact, it acts as a negative lens. In the following analysis the distortion suffered by an initially plane wave in passing through a glass rod of radius R and length & will be considered for the case where the temperature of the rod is a function only of the radial coordinate r and the time t. This will be done by obtaining the equation for the ray trajectories (or paths) by requiring that Fermat's principle be satisfied and then computing the optical path length along these ray paths. These results will then be used to predict the results of a Mach-Zehnder interferometer experiment, a birefringence experiment, and the refraction suffered by a small diameter light beam in passing through the rod. The latter will lead to the formulation of an expression for an average beam divergence angle for laser amplifiers. In Section III of this report, it will be demonstrated that this theoretical description is in quantitative agreement with the experimental results described in the first section. B. RAY TRAJECTORIES 5 Suppose a plane wave traveling parallel to the axis of a rod of length & and radius R falls on one end of the rod as shown in figure 2-1. We define light rays in the usual way' as the orthogonal trajectories to the geometrical wave-fronts. For clarity, the wave-fronts have been omitted within the rod. We first ask what are the equations of these trajectories. Consider a ray which enters the rod at point P at a radial distance from the axis of the 0 2-1

E R RAY PATH S To ROD ° To' Figure 2-1. Ray Path Geometry rod r = r travels through the rod and emerges from the rod at point P■ at radius ■■ and at angle with respect to the normal to the rod at P. P1 as shown. The optical path length S along this ray between P and P, is P1 (II. 1) s of " n(r) √■. dz 0 6 where n(r) is the index of refraction at r, and the prime denotes differentiation once with respect to z. Fermat's principle now requires that S be a minimum (i.e., that a solution be found for the variational problem 8 S = 0). The mathematical formulation for this problem is well known. In our case the solution is the solution to Euler's differential equation (II. 2) F ar - dz (OF) = 0 where F is $n(r) \sqrt{1 + r'^2}$. Using this function for F we obtain from equation (II. 2) (II. 3) r' (1 + r■2,2 dn(r) 2-2 - n(r) (1 + r'²)r" + n(r)r'²r" = 0

$\dfrac{d^2r}{dz^2}$ Now let $r' = p$ and $r = p$ We then find from (II. 3) (II. 4) $n(r)\ p$ or $-(1 + p^2)\ 2\ dn(r)$ Integrating once yields = 0 (II. 5) $-1/2\ (1 + p^2) = \ln[C\blacksquare\ n(r)]$ The $C\blacksquare$ is found from equation (II. 5) to be where $C\blacksquare$ is a constant and must be determined by the boundary condition that dr/dz zero at $r = r$. $r = r_o$ (II. 6) $C\blacksquare = n(r)\ \sqrt{e}$ From (II. 5) and (II.6) we find that the slope of the ray is (II. 7) $= \pm - \ln n(r)\ n(r\ 0'$ $\ln n(r)\ n(r e = p$ is where the positive sign in front of the square root is used when $dn(r)/dr \geq 0$, and the negative sign when $dn(r)/dr < 0$.* To obtain the equation for the ray path, equation (II. 7) must be integrated. Rearranging and integrating we have (II. 8) $\pm \int \dfrac{1}{\ } dr = z + C\ 2$ $2\ \ln[n(r)/n(r)] = 0$, $r = r$ r_o' where C_2 is a constant to be evaluated by the boundary condition that when 7 Before the left-hand side of (II. 8) can be evaluated we must assume an explicit function for $n(r)/n(r)$ over only the range of values of r covered by the ray which enters at $r = r$ We choose the function to be (II. 9) $n(r)/n(r) = e^{a(r-r_o)}$ $50°$ The use of equation where a is chosen to be $n(r)/n(r)$ and where the dot denotes differentiation once by r. This choice of a makes the first two terms of the power series expansion of $e^{a(r-r_o)}$ identical with the first two terms of the power series expansion of $n(r)/n(r)$ about r, (II. 9) will be justified so long as the range of values of r covered by a ray which enters the rod at r and leaves at $r\blacksquare$ is smaller than the range of r for which the exponential is a good * Here $n(r)$ is assumed to be either monotonically increasing or decreasing throughout the range r_o to 1 inclusive.

2-3

fit to n(r)/n(r). This condition is satisfied even under the most intense pumping conditions of Aolux rods described in this report because of the small values of r■-r and the slowly varying character of n(r). Although this condition should always be checked before the theory is applied, it is expected to hold in all cases for glass rods where the optical pumping conditions are sue that the temperature depends only on the radial coordinate and the pumping is fairly uniform. Inserting (■.9)into(II. 8), integrating and evaluating C■ to be zero by the boundary condition, yields za (N. 10) ± 1½ {$\sqrt{}\sqrt{}2$■(r-r■) $\sqrt{}\sqrt{}$1-2a(r-r_) + sin ¨¹ $\sqrt{}$2a(r-r) } = -1 = Z 10-5 as the required equation for the ray path. We note that since for glass the index change is or less per degree temperature change, we have (II.11) 2a(r-ro) ≈ 2 An n Arc 10-4 for all practicable pumping conditions of glass rods. In view of (II. 11) we may write an approximate form of (II. 10) which will be adequate for our purposes: 2 az (II.12) r-ro = C. OPTICAL PATH LENGTH Now that the equation for the ray path through the material is known, we are in a position to evaluate the optical path length S. This is given by equation (II.1) provided that the integration is carried out along the ray path. We therefore rewrite equation (¡I. 1) using equations (II.5) and (II. 6). The result is (II. 13) S = n(r) dr $\sqrt{}$ In [n(r)/n(r)] where r, is the value of r at P, in figure 2.1. With the aid of equation (1.9) and the variable change P1 (II. 14) y' y2 = a(r-ro) 2-4

equation (II. 13) may be written as (II. 15) S = or $\sqrt{}\sqrt{}\sqrt{}2$ n(r) a a(r■-ro) ° 270 dy n(r)$\sqrt{}$2a(r■-■) (II.16) S = a [1 + 1/3 a(r■-xo) + terms of order {a (r■■)} 2]. Using equation (II. 12) and noting that z■ == 80 (1 + €22) where & ■■ is the length of the rod before pumping begins and e is the strain in the z direction, equation (II.16) becomes ZZ (II. 17) S = n(r) & ■ (1 + € zz) {1.1 1/6 [n(rc) to n(r) 2 where the terms of higher order in (II. 16) have been dropped. If we require S to be correct to 1/10 we may calculate the largest value of 1 for which the last term in (II. 17) may be neglected. The condition is ° 2 n(r) o (II.18) n( ) ■ (1/6) = n(r A typical value of ■(r) which we obtained experimentally in pumping AOlux glass rods is -5 5 x 10 cm¨¹. We find the value of & from (II. 18) with n(r) = 1.5 and λ = 6.3 x 10-5 0 cm to be about 28 cm. Therefore under these conditions, the last term in (II. 17) is important in determining S for rods longer than 28 cm. The last term arises from the fact that the ray paths through the rod are not straight lines. If straight lines are assumed for the ray paths, only the first term in (II. 17) appears. The inclusion of Fermat's principle in the theory is therefore important in computing optical path length differences between different rays through the rod at least under some conditions. In addition, the refraction suffered by a pencil of rays in traversing even the 3-inch long rods used for this report cannot be predicted by considering only straight rays. In fact, as will be shown later in this section, the slope of the ray already given in general terms by equation (II. 7) will lead to an equation for the average team-divergence angle to be expected for glass-laser amplifiers. 2-5

D. MACH-ZEHNDER ANALYSIS

In figure 2-1, the optical path length at radius ■2 between plane m and n before the material is heated, i.e., at time t = 0, is (II.19) P(■2,0) = b b + no lo + d where n is the initial index of refraction of the material. At some time t after the heating ■■ begins, the path length is (I.20) P(r■, t) = $ + bo - ■■ 80/2 + - (d■ - 2/2)/cos 8 ■■ The change in path length AP(r,t) which exists at time t is therefore (II. 21) AP(r■, t) = S - no I■ - 10 zz (1 € + sec 0)/2 - d (1-sec 0). ° We now assume that the temperature rise, T, of the rod is a function only of the radial coordinate r and the time t. We set T = 0 at t = 0. For an isotropic material with no externally applied stresses the stress-strain relations under these conditions are° 8 R (II.22) σ …(r,t) = B T(r,t)r dr - (II.23) σ (r,t) = B II. 24) σ zz (r,t) T(r,t) r dr r +] I T(r,t)r dr + R = B T(r,t)r dr - T(r,t) (II. 25) . ■■ (r,t) = (20</R²) R T(r,t)r dr r 0 T(r,t)r dr T(r, where E/(1-v), ✓ is the linea) thermal expansion coefficient, E. Young's modulus, and Poisson's ratio. These equations give the correct stress-strain values for a temperature T(r,t) which is changing slowly enough so that in a time interval equal to the characteristic mechanical time t✓ = d/ve it changes by an amount which is small compared to the total temperature rise at the beginning of the interval. t. M 9,10 Here d is a

2-6

characteristic dimension of the material and v. the longitudinal sound wave velocity. Since e ✓ for glass is about 6 x 105 cm/sec, t✓ is about 10-6 seconds for 3/8-inch diameter rods. e For the pumping conditions employed in this report, the rod temperature rises about 15°C -3 in 10° second or only about 0.015°C in 10-6 seconds. We expect therefore that after about the first 10 μ seconds after the beginning of the pump pulse equations (II. 22) through (II. 25) should be valid for the experimental conditions studied in this report. The indices of refraction for light polarized perpendicular and parallel to the direction of stress are in general different. The propagation of light in a rod stressed as in equations (II. 22) through (II. 25) must therefore be described by the indices of refraction at a given radius r and time t. The index for light polarized parallel to the radial direction n(r,t) and that for light polarized perpendicular to this, i.e., parallel to the direction no (r,t) may be written as (II. 26) n_(r,t) = no + d (II.26) (II.27) nÅ(r,t) ■■ = no + at where (II. 28) and (II. 29) # 0 an = T + JT " σ = 0 T = 0 an = σ = 0 an + dol (σ €9 σzz) T = 0 an + 00 + 8011 _ð n dol (σrr + ozz) T = 0 T = 0 and where the temperature rise T = T(r,t) is assumed small compared to the temperature of the rod at t = 0. Here ■■ 0 = 0 | 41 is defined as the change in index with respect to an 8011 T = 0 an do1T= 0 as the change in index with as the change in index with temperature at constant stress equal to zero, respect to a change in stress at constant temperature where the change in stress is directed parallel to the direction of polarization, and respect to a change in stress at constant temperature where the change in stress is directed perpendicular to the direction of polarization. Using the definitions (II. 30) an ■■ nα J = 0 ° n 2-7

(II. 31) 0011 n = -B || T = 0 (II. 32) an Job = -B T = 0 and equations (II. 22), (II.23), and (II. 24), the indices may be written as (II. 33) ■ (r,t) = n■ + [no% + 2B■B] T(r,t) + B(B,, -B. r -B (3B■ + B) R T(r,t)rdr (II. 34) n(r,t) = n■ + [no)] B + B (B■, + B■)] T(r,t) +8 (B■ -B,,) · - B(3B + B,,) R T■r, t)rdr T(:, t)rdr T(r,t)rdr This result was first obtained by Quell?. With the determination of the two refractive indices given by equations (U. 33) and (II. 34), we are now in a position to develop equation (II. 21) for both directions of polarization. We note first that the tangent to the ray at P1 in figure 2-1 inside the rod = 8 (r■,t). For the radial polarization we have 0 = 0 (r,t) and has slope dr r =r1 (II. 35) n (r,t) sin𝑋_ (r1r,t) = nair sine _ (r1r, i) r r where for radial polarization becomes r. ■r. r1 1r' r (r,t). Using equations (II."), (II. 9), and (II.12) and setting n = 1, for small angles equation (II. 35) becomes air (1.36) (1 " 8 ¸, t) = &…Å¸(■¸,t) . 2-8 = = = F

Expanding the sec 0 for small angles, equation (II. 21) becomes with the aid of (II. 36) and (II. 17) (II. 37) AP✓ (12) = {(n-1)e 2r % ■■ + n(rot)-n + [1 + 3nd/]²(r,t)}. From figure 2-1, r2 the radius of the ray at Pis (II. 38) ■2 = r +r. 0 1 - r■ + (do -€/2) tan 0. 4Z 525 1 = 1 2r (r,t). We have with the aid of For the radial polarization, r2 is defined as r. equations (1I. 36 and (II. 12) (II. 39) 2 (t) = + [1 +4] ñ¿‹r¸,t). r For light polarized in the 0 direction equations (■. 36), (■. 37) and (II. 39) become (II.40) = (1) long(r,t), (II.41) AP (± 2, t) = l■ {(n−1)e¸ + n¸(r,t)-n ,—,— [1 + 3n_d¸/ 8] ñ,ª«r«,t)} and ■■ (II.42) F■ø (F¸, t) = r¸ + [1º + 4] &¸ñi¸(r,t) . d E. BIREFRINGENCE EXPERIMENT ANALYSIS If we wish to know the difference in path length between radially and tangentially polarized rays at the point P■ in figure 2-1, we cannot simply subtract equation (II. 41) from equation (II. 37). The reason for this is that if both rays enter the rod at the same point and r. "10 Fir at radius r they leave the rod at different radii r. TO given by equations (II. 39) and (II. 42) respectively (d set equal to zero). Therefore, to find the path length difference at point rie between radially and tangentially polarized rays, AP re (18,t), we must compute the path length difference between a radially polarized ray which enters the rod at r = r, and emerges at r = Γ10 and a tangentially polarized ray which enters at r = r and emerges =% That is, we must find at r = r. 10° (II. 43) AP(1) = AP (■ 10, t) -AP (■16,t) . r m 2-9

We have (1.44) AP (r,t) AP (Ft) - { // AP (r,t)} Arire r where r = r Fir 2 (II.45) Arire Fir = F10 [i■(r,t) - (r,t)] . do Inserting (II. 44) and (II. 45) into (II. 43) and using equations (II. 37) and (II. 41) with d set equal to zero yields (II.46) $AP_s(F10,t)$ = &■ {n(r,t)-n_s(r,t) + 2 [h² (r,t)-n² (r,t)] - 2n i■(r,t) [1 b + ï(■_s,t)] [i■(r,t)-ñ_s(■ro,t)] } where the double dot denotes differentiation twice with respect to r and where from (II.42) 2 (0.47) ■10 = ■ 10 (■o, t) = r r. + ng(pt). F. SMALL DIAMETER BEAM REFRACTION AND AMPLIFIER BEAM DIVERGENCE ANGLE Equation (II. 36) gives the angle at which a radially polarized ray emerges from the rod (see figure 2-1). In the next section we use this equation to calculate the angle at which a radially polarized beam 1.5mm in diameter emerges from the rod. We find good agree- ment with experiment. It seems reasonable therefore to use equation (II. 36) to compute an. average beam divergence angle & (r,t) for a radially polarized beam of diameter 2r on propagating once through a rod. The beam is assumed to be concentric with the longitudinal rod axis. We have (II.48) (r,t) 0 2 w■⁰±(■¹µ, t)G(■_s, t)e■(r, t)dr rlr' 2☞■G(r,t)(r,t)dro 2-10 * 1 = 1 = 1

1 r where G (r,t) is the single pass rod gain at r. and t, and I (r,t) the intensity of the input T_0 beam at r F_0 Using equation (II. 36) we have (II.49) (r,t) 1 [* r h■ (r, t) (r,t), (r■, t) dr ■G(r,t)I(r,t)dr■ A similar equation holds for & (r,t) and is obtained from (II.49) by replacing the subscript r by 0. It should be noted that equation (II. 49) neglects diffraction effects and therefore holds only when (r,t)>>>&, i.e., only when the beam divergence is considerably larges than expected from diffraction effects alone. G. CONCLUSIONS E Inclusion of ray path geometry, in the derivation of the basic equations which predict the effects of thermo-optic distortion, not only increases the range of applicability of the theory but also leads to results which are not obtainable when only straight ray paths are considered. The deflection of a small diameter probe beam and an average beam divergence angle for laser amplifiers can be calculated directly when ray paths are included. In addition, for long laser rods and under certain experimental conditions for short rods, consideration of ray paths is absolutely necessary to predict the effects of thermal-optic distortion. H. REFERENCES 1. H. Welling & C.J. Bickart, J. Opt. Soc. of America, Vol 56. No. 5, May 1966, pg.611 2. A. P. Veduta, A. M. Leontovich, & V. N. Smorchkov, Soviet Physics JETP, Vol. 21, No. 1, July 1965, pg. 59 3. A.E. Blume & K. F. Tittel, Appl. Opt., Vol. 3, No. 4, April 1964, pg.527 4. S.P. Sims, A. Stein, & C. Roth, Appl. Opt., Vol. 5, No. 4, April 1966, pg. 621 5. M. Born & E. Wolf, Principles of Optics, The Macmillan Co., New York, (1964), pg. 114 6. Reference 5, Pg. 128 7. F. W. Quell, Jr., Appl. Opt., Vol. 5, 1966, pg. 633 2-11

* 8. B.A. Boley & J. H. Weiner, Theory of Thermal Stresses, John Wiley & Sons, Inc. (1960), Sec. 9-10 9. Reference 1 10. Reference 8, pg. 51 2-12 ■■■■

III. COMPARISON OF THEORY WITH EXPERIMENT A. INTRODUCTION This section will be concerned with a quantitative comparison of the theoretical pre- dictions of Section II with the experimental results presented in Section I. This comparison will be divided into two major parts. The first part will discuss only the radial dependence of the parameters. The second part will compare the experimental and theoretical results only at the center of the rod. It will be seen that the agreement between theory and experiment for the radial de- pendence of the parameters is within experimental error. However, when the experimental value of the absolute magnitude of the change in index of refraction along the center of the rod is compared to the value expected from the theory in Section II, agreement does not exist within experimental error. This discrepancy has led to an important new term which must be added to equations II. 33 and II. 34 for the change in refractive index. This term arises from the existence of an excited neodymium ion population. The theoretical and experimental evidence for the exist- ence of this term is discussed. B. COMPARISON OF THEORY WITH EXPERIMENT: RADIAL DEPENDENCE To see if the theory can be correlated with experiment, we first find the tempera- ture T(r,t) by using the data given in figure 1-19 for the change in length A (t) and the data given in figure 1-13 for the stress phase angle 8 (r, π/4). The temperature is given by 1 R 1 F(r,t) 2 - F(r,t) rdr + (III. 1) T(r,t) = a BR Δρ (t) & 0 where (M.2) F(r, t) ΞΔP re (r,t) + S 0 AP (r,t) dr re r 3-1

and (III. 3) a Elo [B■. B-B]. B = T-T The path length difference between the radially and tangentially polarized components, ΔP (r,t), is of course 1/2 times the stress phase angle. We note that in the derivation re of equation III. 1, the rays through the rod have been considered to be straight lines. This is a good approximation for path length differences measured in the birefringence experiment since the rod length used in our experiments was only 3 inches (See the discussion follow- ing equation II. 18 in Section II.). T(r,t), as calculated from III. 1, is shown in figure 3-1 for rod at 11, 500 joules pump energy. * bulk temperature rise can be obtained from the value of T(r, t) at the end of the pump cycle (assuming no additional heat flows into or out of the rod after this time). The amount of heat deposited in the laser rod is given by R (III. 4) Q(t) = 2 ■■ T(r,t)rdr ° where Q(t) is the heat deposited, C the specific heat, and & the density. Since the bulk temperature rise is defined as that temperature the rod would assume if Q(t) calories were deposited uniformly in the rod at the end of the pump pulse (t = 1600 microseconds), the bulk temperature rise (TB) is given by (III. 5) TB = 2 R R T(r, 1600) rdr . 0 ** TB was calculated to be 16.8 ±1.9 °C for rod AO-2 at 11,500 joules pump energy. The temperature rise recorded by the thermocouple measurements in Section I.C.5 for the same experimented conditions was 18°C. According to the theory presented in Section II, once the temperature is known all other parameters may be calculated. We proceed therefore to use the results shown in figure 3-1 to compute the change in refractive index n (r, t) - n nr no' the probe beam angle r @(Fir' t), and the relative phase angle & ✓ (r,t) -8 (o, t). We then compare these results r r with the experimentally determined values given in Section I. *See Section I. C. 5 **Includes spread in experimental data for 8 (r, 1/4) and (t) plus spread in material constants (see Appendix F). 3-2

19 17. 15' 13+ T (r,t) IN■C 11+ -- 9-- F- * TYPICAL ERROR RANGE t = 1.6 ms 1.0 ms t = .7 ms (~= ±5% ERROR) t = .38 ms * Indicated uncertainty includes only the spread in 7 the experimental data for 8 (r, 1/4) and Al(t). Uncertainty in material constants have not been in- cluded in this graph. 5- ° t = .2 ms t = .08 ms 1 2 3 4 5 6 7 8 r/R 1.0 Figure 3-1. Calculated Value of the Temperature Rise, T (r,t) for Rod AO-2 at 11, 500j Pump Energy 3-3

Using equation II. 33 with n a 0 n = -2.14 x 106/°C, we find the results shown in figure 3-2 for the change in refractive index for radially polarized radiation at two represent- ative times. We note first of all that the index change at the center of the rod shown in figure 3-2 does not agree with the measured values given in figure 1-20 of Section I. We shall return to discuss this discrepancy in the last part of the present section. We shall assume for the present, however, that the radial dependence of the refractive index given in figure is correct. 3-2 [1.e., n (r, t)-n (o, t)] 0 r = From figure 3-2 we may determine the value of ■ (r, t) at r/R = 0.5 and 0. 9. Using these values and equation II. 36, with r = r ≈ r. and o Flr 7.62 cm, we may compute the angle 6 (r,t). The calculated results are shown in figure 3-3 compared to the measured values found in Section I, figure 1-24. We see that good agreement exists between experi- ment and theory and that the rod acts like a negative lens. r Finally, with the aid of equations II. 25 and II. 37, we compute the relative phase again at two representative times. angleð (r, t)-8 (o, t) = 27 [AP A³ (r, t) -■³ (0, t)] r r r ' In these computations, we have set d equal to zero in equation II. 37 to correspond to the fact that the camera used in the Mach-Zehnder experiment was focused on the end of the glass rod. In addition, we have again assumed r=r0=1r. The results of these computa- tions are compared in figures 3-4 and 3-5 to the experimentally measured values given in Section I (figure 1-4). Again, the theoretically computed values agree with the experi- mentally determined values within the experimental error. We have seen in this first part of Section III, therefore, that if the stress phase angle and change in physical length experiments are used to determine the temperature, then this temperature and the theory of Section II successfully predicts the radial dependence of the remaining experimental results. The magnitude of the change in refractive index at the center of the rod does not, however, agree with experiment. We consider now this dis- crepancy. C. REFRACTIVE INDEX CHANGE DUE TO EXCITED NEODYMIUM ION POPULATION Consider first a direct comparison between the experimentally determined refrac- tive index change at r = 0 and that calculated from equation II. 33 and the temperature rise data of figure 3-1. Both quantities as a function of time are shown in figure 3-6. Curve A in this figure is that curve which when added to n (o, t) -n yields the experimentally 3-4

7r (r,t)-70 CHANGE IN REFRACTIVE INDEX ×10-5 O - 0.2 -0.4 -0.6 -0.8 -1.0 -1.2 -14 -1.6 - 1.8 t = 0.38 MS -2.0 -2.2 -2.4 - 2.6 t = 1.0 MS -2.8 - 3.0 -3.2 -3.4 - 3.6 * MEAN VALUE OF DATA ; EXPERIMENTAL ERROR NOT SHOWN - 3.8 0.1 0.2 Q3 Q4 0.5 0.6 0.7 0.8 0.9 1.0 r/R- Figure 3-2. Calculated Change in Refractive Index* vs. r/R for Radially Polarized Radiation (Rod AO-2 at 11, 500j Pump Energy) 3-5 1

3-6 $\theta_r(r,t)$ IN RADIANS 0.8 × 10-3 0.7 0.6 0.5 ö ESTIMATED ERROR CALCULATED POINTS IN ESTIMATED ERROR IN EXPERIMENTAL POINTS 0.3 CALCULATED POINTS AT t = 1.0 MS ++ CALCULATED AT 1 = 0.38 MS POINTS 0.2 0.1 EXPERIMENT: t = 1.0 MS a 0.1 EXPERIMENT: t = 0.38 MS + 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 "/A k-

Figure 3-3. Calculated and Experimental Probe Beam Angle $\theta(r,t)$, for Rod AO-2 at 11,500j Pump Energy

r 11 3

9.0 8.0 7.0 PHASE ANGLE, εr (r,t) - εr (0,†)=- 2T (A P, (r,t) - A P, (0,1, IN RADIANS RELATIVE 5.0 4.0 LEGEND 1) RANGE OF EXPERIMENTAL DATA 2) CALCULATED FROM HIGH STRESS PHASE ANGLE DATA 3) CALCULATED FROM LOW STRESS PHASE ANGLE DATA * } * -- I }-- © 3.0 * SPREAD IN CALCULATED POINTS OCCURS FROM THE SPREAD IN THE STRESS PHASE ANGLE DATA. NO OTHER SOURCES OF ERROR HAVE BEEN INCLUDED. 20 2.0 1.0 ■ I ✕ tot 0 0.1 0.2 0.3 0.4 0.5 0.6 "/R - 10 0.7 0.8 0.9 1.0 Figure 3-4. Calculated and Experimental Relative Phase Angle for Radially Polarized Radiation vs. r/R at t = .38 ms for Rod AO-2 at 11, 500 j Pump Energy 3-7

3-8 PHASE ANGLE, &r (r,t) - Sr (0,1) = : 8r (0,1) = 2π [A P,(r,t) – AP, (0,11]. , IN RADIANS RELATIVE ■ 2 LEGEND 1) RANGE OF EXPERIMENTAL DATA 2) CALCULATED FROM HIGH STRESS PHASE ANGLE DATA 3) CALCULATED FROM LOW STRESS) PHASE ANGLE DATA * SPREAD IN CALCULATED POINTS OCCURS FROM THE SPREAD IN THE STRESS PHASE ANGLE DATA. NO OTHER SOURCES OF HAVE BEEN INCLUDED. ERROR I * * i ° 0.1 0.2 0.3 Q4 0.5 0.6 0.7 0.8 0.9 1.0 "/R - to 13 RADIANS Figure 3-5. Calculated and Experimental Relative Phase Angle for Radially Polarized Radiation vs r/R at t = 1.0 ms for Rod AO-2 at 11, 500j Pump Energy

REFRACTIVE INDEX CHANGE × 10-5 +4.8 +4.4 +4.0 CURVE A +3.6 +3.2 +2.8 +2.4 +2.0 CURVE B +1.6 +1.2 +0.8 EXPERIMENTAL INDEX CHANGE +0.4 -0.4 CALCULATED INDEX CHANGE [7, (0,1)-70] -0.8 -1.2 -1.6 -2.0 -2.4 -2.8 -3.2 -3.6 -4.0 -4.4 -4.8 ° 0.1 02 0.3 0.4 0.5 I 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 TIME IN MILLISECONDS → Figure 3-6. Refractive Index Change at r/Ro vs. Time for Rod AO-2 at 11,500 Pump Energy 3-9 1

determined curve. Any proposed mechanism to account for Curve A must, therefore, have the same time behavior, approximately the same magnitude, and in addition be essentially independent of radius. The latter requirement is implied by the successful calculation of the angle (r, t) and the relative phase angle described in the first part of this section. r The only mechanism we have found which satisfies all three requirements arises from a change in the polarizability of the neodymium ion when it is excited to the metastable 4F 3/2 level. In order to gain a relation which describes the expected index of refraction change with excited neodymium ion population, we first note the well known relation[2] (III.4) 2. $\eta - 1 = 4\pi\alpha$ 2 provided n-1<<1. Here n is the index of refraction, a the polarizability of the at m, and N the number of atoms per unit volume. Let the concentration of neodymium ions in the ground level at a given time t be N■ (t) while the number in the excited 4:19/2 Then assume the total concentration N to be 4. levei be 3/2 N_3 (t). (III. 5) N = 1 N■ (t) + N■ (t). Now if the polarizability of the neodymium ion is a■ in the ground level and a, in the '1 metastable level, it is easy to show that the change in index of refraction An(N_3) which arises as a result of a finite excited state population N_3 (t) is (III. 6) An(N_2) = 2π (α 3 -α■) N_3 (t) The electronic polarizability at angular frequency wis given by (III. 7) α == e m Σ j wij 4 where e, m, fij and wij between are respectively the electric charge, mass of the electron, oscillator strength for a transition from state i to state j, and the energy difference states j and i divided by K. The difference α 3 -α■ may therefore be written as E_i -E_i (III.8) 03-1 = m { ■3j Σ Σ j L where Σ runs over all of the excited states of Nd +3 j and runs over the ground state and all excited states except the metastable state. Because of the small oscillator strengths for 4f - - 4f transitions compared to those for the allowed 4f 5d transitions and because of 3-10

[5 ' the impor- the much larger number of 4f 5d transitions compared to 4f $\rightarrow\rightarrow\rightarrow$4f transitions tant contribution to the polarizability difference $\alpha_3 - \alpha_1$, arises from 4f5d transitions. We therefore neglect the contributions to $\alpha_3 - \alpha_1$ from all transitions except 4f $\rightarrow$5d. We further replace the 5d band by one state at $w_■$t above the ground state and assume that the oscillator strength $f_■$ to this 5d state is the same from either level 3 or level 1. This should be a good approximation since these are all allowed 4f 5d transitions. Equation III.8 then becomes - (III. 9) $\alpha_3 - \alpha_1 \dfrac{e^2 4}{} = m W_3 - W_1$ where level 1. $W_3 = -_{13}$ and where $_{13}/■$ is the energy of the excited level 3 above the ground $-_3 2$ We next calculate an effective value of $e^f_■/m$ in front of equation III. 9. The re- fractive index of the unpumped rod changes by $An = - 6 \times 10$ at frequency $w_\_$ (corresponding to the sodium D line) when the concentration of Nd^{+3} ions is changed from $N^1 = 1 \times 10^2$ to $N_{11} = 6 \times 10^{20}$ (m. 10) $An = $ we have (II 11) $1 = cm 2\pi\alpha_1 -_3(6) \bullet$ Since $(N^1 - N^{11})$, $An 2 (N_1 N_{11}) W_■ f_■ 2 2 3-$ Using equation III. 11 and replacing w_3 by $w_■ - W_{13}$, equation III. 9 may be written as (III. 12) $3-0 1 = W_{13} 2 3- An w_■3$ (w1" 2) S (2w1 $-W_{13}'$ 2 2π $(N^2 - N^{11})$ $(w_■^2 - 2 w_■ w_■3 + w_■3^2 -w^2)$ $(w_■^2 -w^2)$ Inserting the appropriate values in this equation yields a $-a = 0.8 \times 10$ The refractive index change then becomes $-_{24} 3$ cm . $20 -3$ cm (III.13) $An (N_3) = 2\pi (\alpha_3 -\alpha_■) ■ 3 -a = * 10-24 N_3 (t).$ 18 The required peak value of $An (N_3)$ is shown in figure 3-6 (curve A) to be approxi- mately 3.6×10^{-5}. From equation II. 13 this would imply a value of N_3 max of 7×10 cm^3. This is a reasonable approximate value for N_3 max at this pump energy since it falls between the upper and lower bounds for N_3 which may be estimated from the following 3-11

threshold considerations. First, let us consider the upper bound for N3. As will be dis- cussed shortly, we have observed the 1.06μ radiation along the axis of the rod during the pump period with no reflectors on the rod (except of course the Fresnel reflection at each end). No laser action is observed. Therefore N■ must be lower than the minimum population N■μ required for laser threshold under these conditions. The minimum popula- tion inversion ▲ N required for laser threshold with the Fresnel reflectivities of the ends 7 1 = 2 = .04 is 3 max n (ΠΠ. 14) ΔN = N 521 N3μ 2 - N■ = 2π C 81 TAX {-In [F■■] } 4 ■ ■ cm -3 -3 • Now let us consider the lower where is the lifetime of level 3 due to spontaneous emission of radiation by a transition be- tween levels 3 and 2, ▲ is the wave length in vacuum at the peak of the Lorentzian spontaneous emission line with a full width at half-height of Aλ, and C is the speed of light. Using con- 19 stants supplied by the American Optical Corporation, * we find AN = 1.3 x 101 cm 19 Since we may take N■ to be zero, N■μ = 1.3 x 10 bound for N. We may safely take this to be the population inversion N3 obtained at 1650j pump energy. This is the pump energy necessary to achieve laser operation with r■ = 99 and r. ■2 = .70 (see section C. 1, figure 1-2. The value of N. N32 obtained from equation III. 14 18 with the above values of r■ and r■ is 0.7 x 10 cm • A, -3 3. • It has been shown theoretically that the magnitude of ▲n (N3) can account for curve figure 3-6. Next, it is necessary to show that the temporal variation of N3 (t) falls within the experimental error limits imposed on the same curve. Consider a simplified two energy level model to estimate the time dependence of N3 (t). The rate equation for this system can be written in this form 8 (III. 15) N3 = -N■ = P(t) N■ (t) - 1 - N3 (t) W (t) N3 (t) *32 732 is the measured florescent time constant of the where P(t) is a pumping function, ■. 3/2 metastable level, and W (t) is a function accounting for stimulated emission. Substi- tuting N = N■ (t) + N3 (t) into III. 15 yields 0 αN 3 (III. 16) dt = P(t) [No N■ (t)] - N3 (t) [11/12 32 + W (t)] *See Appendix F 3-12

20 For laser rod AO-2, $N = 4.6 \times 10$ ■ ions/cc, and the maximum value of N 3. (t) can be 19 assumed from the previous threshold calculation to be less than 1.3 x 10/cc. Thus, the approximation can be made that N3 (t) <<N. Equation III. 16 then has the solution (III.17) N3 (t) == e -Y(t) *** No t e r(t) P(t) dt where (III.18) X(t) ° f t/ W(t) dt + 32 ° The function P(t) can be assumed to be proportional to the pump intensity (See figure 1-1). The function W(t) has yet to be determined. An experiment was set up in the laboratory to determine the time variation of W(t) by observing the axial emission of radiation at 1.06μ (11, 500 joules pump energy) from the laser rod. This experiment is diagramed in figure 3-7. By means of a series of tests it 1.06 INTERFERANCE FILTER S-I SUFACE P.M.TUBE LENS PUMP CAVITY LASER ROD ADDITIONAL GLASS FILTERS TO PASS ONLY 1.06 u NOTE: CENTER OF ROD AO-2 IMAGED ON PM TURE - ONLY LIGHT EMITTED FROM CENTER OF ROD INCIDENT ON PHOTOMULTIPLIER TUBE. Figure 3-7. Experimental Diagram: Measure of Temporal Variation in W(t) 3-13

was determined that almost all of the radiation observed (light sum curve) was due to stimulated emission. Therefore, the temporal variation of the light sum curve measured in this experiment is that of $W(t)$. Normalized curves of $W(t)$ and $P(t)$ are shown in figure 3-8. Using figure 3-8 and equations III. 17 and III. 18 with parameters $W(t)$ peak peak = 100 sec -■■ $P(t)$, = 50 sec¹, $N_3(t)$ may be determined with a peak value of 6.3×10^{18} cm³. Using this curve for $N_3(t)$ and equation III. 13, curve B shown in figure 3-6 has been drawn. D. CONCLUSION It is now clear that within experimental error a new term can legitimately be added to equations II. 33 and II. 34, and that it has the form given in equation III. 13. This result is extremely important since it illustrates that pump induced optical distortions in Nd +3 doped glasses are not solely determined by temperature and temperature gradients, but are strongly influenced by the magnitude and distribution of inversion within the laser rod. The addition of this new term to the refractive index equations modifies the theory in Section ■ only to the extent of changing equations II. 33 and II. 34. Adding this term equally to the radial and tangential refractive index has no effect on the deter:ination of $T(r, t)$ from the stress phase angle and change in physical length data. It does, however, effect the calculation of 8 (r, t) -8 (o, t), and § (r, t) as carried out in section III. B. Since the radial dependence calculations in Section III. B were completed r r r without the addition of the term $\Delta n [N_3(t)]$, and reasonable correlation was still obtained, one must confide that the radial dependence of $N_3(t)$ was not very great in our experi- ments. This is consistant with the fact that the total phase angle change due to the neo- dymium ions, shown in figure 1-9, is a constant within about ten percent across the rod diameter. 3-14

3-15 Figure 3-8. Temporal Variation of P(t) and W(t) for Rod AO-2 at 11, 500j Pump Energy

RELATIVE AMPLITUDE 10 10 B 0.3 T 0.2|-- ro 0.1 P(t) O 0.1 0.2 0.3 0.4 0.5 0.6 0.7 w(t) T 1.1 1.2 1.3 1.4 1.5 1.8 1.9 0.8 0.9 1.0 TIME IN MILLISECONDS

E. REFERENCES 1. First Semi-Annual Report, "Thermal Optic Distortion", Contract NOnr-4874(00), pgs. 2-4 & 2-5, 2. M. Born & E. WI, Principles of Optics, Pergamon Press (1959), pg. 95. 3. E. Snitzer, "Neodymium Glass Laser", Presented at 3rd International Symposium on Quantum Electronics, February 1963, Paris, France. 4. C. Kittel, Introduction to Solid State Physics, John Wiley & Sons, Inc. (1957) pg. 166. 5. G. H. Dieke and H. M. Crosswhite, Appl. Opt. 2, 675 (1963). 6. Data Sheet on Rare Earth Laser Glass Rods issued by the Eastman Kodak Company (October 1962). 7. E. P. Riedel, Westinghouse Research Report 62-112-259-RI, pg. 5 (1962). 8. K. Shimoda, Proceedings of the Symposium on Optical Masers, New York, 1963, Polytechnic Press, Brooklyn, New York, pg. 95. 3-16

IV. SUMMARY The present report is a theoretica and experimental study of optical distortions induced in neodymium-doped glass by pump radiation. The report is divided into three major sections. The first and second sections describe respectively the experimental and theoret- ical work while the third section is used to quantitatively compare the results of the first two sections. The aim of the experimental work presented in the first section is to obtain quan- titative data which can be used to check the theory. Before this cont be done, however, two separate experimental investigations had to be performed. The fire of these consisted of a study of the static optical distortions present in the 3" long rods. was shown that for some rods, these static distortions were so large and of such low symmetry as to prevent their use for obtaining & antitative data. The results of this study led to the selection of rods which possessed static distortions small enough to be ignored in the dynamic experiments. The second investigation consisted of obtaining radially symmetric optical distortions throughout the dynamic period. This was achieved by using a helical lamp, a frosted glass tube between the rod and lamp, and a specially designed rod holder. This was a critical part of the expe- rimental work since it appears that the only tractable theoretical description of the index of refraction is based on the assumption of a radial temperature distribution within the rod. Once these two preliminary investigations were completed, the data to be used in checking the theory was obtained. Measurements were made of the optical path length as a function of radius, time, and polarization and the change in physical length as a function of time and radius. In addition, the index of refraction along the rod axis as a function of time was measured, as was the refraction, as a function of time and radius, of a small diameter probe beam passing through the rod. In Section II, Fermat's principle is used for the first time in the analysis of the dynamic optical problem to gain expressions for the slope and trajectories of the rays through the material for a plane wave input. These results are then used to predict ray refraction, beam divergence, and optical path length through the material as a function of radius, time, and polarization. Effects associated with the fact that the rods are not very long compared to their diameter have been ignored. In the third section, the experimental and theoretical results are compared in two parts. In the first part, the change in the measured parameters with the radial coordinate is compared to the theoretical predictions. This is done by first using the measurements of 4-1 wh

the optical path length difference between the radially and tangentially polarized components and the change in physical length of the rod to determine the temperature of the rod as a function of time and radius. This temperature is then inserted into the theoretical expression for the optical path length change and for the refraction angle of radially polarized radiation. Good agreement is found for the variation in the measured and calculated parameters with radius. In the second part of the third section, the correlation between experiment and theory is considered only along the axis of the rod. It is first observed that the measured refractive index change does not agree with the theory, However, this discrepancy can be removed by the addition of a new term to the expression for the change in index of refraction. This term is proportional to the population of neodymium ions in the metastable *F, level 3/2 and takes into account the fact that the polarizability of the neodymium ion is different in the level than in the ground level. The importance of this new term cannot be overempha- sized since it implies that even if a glass is "athermalized", large optical distortions can arise as a result of a non-uniform population inversion. 3/2 4-2

V. RECOMMENDATIONS FOR FUTURE WORK

Further investigation of the refractive index change due to the population of neodymium ions in the 4F. level is needed. Index of ref action measurements at 6328Å similar to those made in this report should be made along with a measurement of population in the 3/2 level. A satisfactory quantitative check of this index term at 6328 Å would complete a 3/2 successful description of optical phenomena in glass rods at this wavelength. To quantitatively understand the far field pattern obtained with a given input wave to the glass amplifier, measurements similar to those made in this report should be made at 1.06μ in conjunction with a determination of gain and excited level population. Due consideration shuld again be given to dispersion phenomena. This study should first be con- ducted with the same 3-inch rods used in the present report. After a satisfactory under- standing is achieved with these short rods, similar work should be done using long rods; again with due attention directed toward the achievement of the critical requirement of low static stress and radially symmetric dynamic distortions. Perhaps the best way to achieve 1 uniform pumping for long rods at high energies is to employ a coaxial lamp developed at the Westinghouse Research Laboratories. The successful conclusion of the above work would place one in a favorable position to consider the problem of quantitatively describing the output of a glass oscillator. Whether or not this complex problem can be treated in such a way as to yield a discription which will be of use from a practical point of view is, however, not clear at the present time. J. P. Lesnick and C. H. Church, IEEE, J. of Quantum Electronics, Vol. QE-2, Pg. 16, 1966. 5-1/2

APPENDIX A EFFECTS OF RESIDUAL STRESS To qualitatively determine the effect of residual stress in glass laser rods, several types of laser rods were analyzed in a plane polariscope. A diagram of the polariscope is shown in figure A-1. BEAM EXPANDING OPTICS GLAN-LASER POLARIZER NO. 1 GLAN-LASER POLARIZER NO. 2 SHUTTER FILM PLANE MOD. 112 SPECTRA- PHYSICS He-Ne LASER ✓ LASER RCD FACE B APERTURE (TEM OO MODE) FOCUSING LENS NOTE: POLARIZER NO. I ALIGNED WITH AXIS PARALLEL TO OUTPUT POLARIZATION OF He-Ne LASER POLARIZER NO. 2 CROSSED WITH RESPECT TO POLARIZER NO. I Figure A-1. Polariscope Diagram The pattern recorded on the film plane is the pattern of the light transmitted through the second polarizer as it exists at face B of the laser rod. Several pictures were taken as the rod was rotated approximately 45° between each picture. By rotating the rod all regions which possess residual stress could be observed. Most rods tested did not possess radial symmetry of residual stress; and for these quantitative data was not obtained. For those which did possess radial symmetry, the difference between the radial and tangential stress vectors was calculated. Several of the rods tested in the polariscope were also placed in the pumping cavity and inserted into one arm of a Mach-Zehnder Interferometer. A diagram of the experimental arrangement is shown in figure A-2. The interferometer was initially adjusted so that the entire field covering the laser rod was uniform. The focusing lens served to image end B of the laser red on the film plane of the high-speed framing camera, Photographs of the pump-induced optical distortion in the laser rod were recorded during the pump cycle, and were compared with the previously obtained residual stress patterns. A-3

MOD.112 SPECTRA-PHYSICS He-Ne GAS LASER APERTURE M■(50%) BEAM EXPANDING OPTICS M2(100%) L END B' LASER ROD & PUMP CAVITY M3(100%) M4(50%) FOCUSING LENS SHUTTER CORNING"RED" FILTER WHITE LIGHT. SHIELD PINHOLE APERTURE BECKMAN & WHITLEY MOD. 350 HIGH SPEED FRAMING CAMERA Mg(100%) Figure A-2. Mach-Zehnder Experiment Table A-I shows the laser rods tested in the polariscope, while figure A-3 shows the pictorial results of these tests. The ruby rod tests are included for comparison pur- poses. It is interesting to note that of all the rods tested, the 6-inch long P. P.G. rod appeared to have the least residual stress. The stress present was different from that observed in all of the other glass rods in that it appeared to be principally aligned in one direction across the rod diameter. The three Kodak rods showed varying degrees of stress but exhibited similar stress patterns. Common to all Kodak rods was the concentration of stress near the outer surface of the rod coupled with large stress gradients. Rod K-2 originally had a polished surface while rods K-1 and K-3 had frosted surfaces. The most probable reason for the high stress near the surface of the Kodak rods seems to be that surface stresses were introduced when the rods received their frosted surfaces at the factory. The first American Optical laser rods tested in the polariscope were the clad rods AO-4, AO-5, and the undoped rod AO-3. The clad rods were taken from the same melt. It was four that the clad rods possessed extremely high residual stress. In addition, the stress in the clad rods appeared to be equal in magnitude to that observed in a Linde 0° ruby. A-4

Figure A-3a. Polariscope Patterns Rod K-1 A-5 J Rod K-2

A-6 Figure A-3b. Polariscope Patterns Rod K-3 Rod PPG-1 =

■■■■ Figure A-3c. Polariscope Patterns Rod AO-1 ■■■ A-7 Rod AO-2

Rod L-1 C axis // to polarization (:) Rod L-2 C axis at 45° to polarization ($) Figure A-3e. Polariscope Tests Polarization (1) 1 to C axis 1 C axis parallel // polarization ($) to Rod M-1 Rod L-3 Rod L-4 Figure A-3f. Polariscope Patterns Polarization () II to C axis 2 : C axis 45° to polarization ($; A-9

TABLE A-I. LASER RODS TESTED

MANUFACTURER ROD DESIGNATION	MANUFACTURER	COMMENTS
K-1*	Kodak	Type ND-10 Kodak Laser Glass Used on Contract Nonr-3922(00) (See Appendix C.)
K-2**	Kodak	Experimental Rod 3/8 x 6 inches obtained from Westinghouse Re-search Laboratories
K-3*	Kodak	Specially Annealed Laser Rods (See Appendices D and E.)
P.P. G.-1*	Pittsburgh Plate Glass	Undoped glass host (See Appendix D.)
AO-1■*	American Optical	1/2 x 3 inch clad laser rods (See Appendix D.)
AO-2*	American Optical	
AO-3* ("control")	American Optical	
AO-4** AO-5**	American Optical An:erican Optical	
L-1*	Linde Co.	3/8 x 3 inch, .05%Cr'
L-2*	Linde Co.	3/8 x 3 inch, .05%Cr' 60° ruby +++
L-3*	Linde Co.	0° ruby ' +++
L-4*	Linde Co.	+++
M-1**	Muller Co.	3/8 x 3 inch, .05%Cr 0° ruby

*frosted surface finish **polished surface finish

Rod AO-3 ("control" rod) is apparently a typical example of the residual stress to be found in unclad 3/8 x 3 inch Alux. laser rods. Under the criteria that the rods to be used to obtain quantitative data have either small or radially symmetric residual stress, it was obvious that rods AO-1 and AO-2 were the only rods which satisfied one of these requirements. Rods AO-1 and AO-2 were specially prepared by American Optical for this contract; the details of their preparation are given in Appendix E. r Since rods AO-1 and AO-2 possessed radially symmetric residual stress, the value of the difference between the radial and tangential stress components (S-S8) could be determined. Assuming that the stress present is uniform along the length of the laser rod, the phase angle between the radial and tangential polarization components passing through the rod is given in cylindrical coordinates by:

[1] E. V. Condon & H. Odishaw, Handbook of Physics, McGraw-Hill (1958), pg. 3-86

A-10

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(A. 1) $\delta(r, 0) = \cos^{-1} \frac{I(r, e)}{2 I_1(r, 0)} \sin 2\theta$ where $I(r, 0)$ is intensity transmitted with polarizers crossed, $I(r, 0)$ is intensity transmitted with polarizers uncrossed, and 0 is azimuthal angle between the first polarizer axis and r along which $\delta(r, 0)$ is being determined. The relation between the stress, refractive index, and stress optic coefficients is given by: 1 (A.2) $S_r n - n_0 - S = r B B$ ■ where subscript r represents the radial direction, 0 is the tangential direction, and $B_. - B$ is the difference between the stress optic coefficients. 11 If the length of the rod is 1. and the wavelength λ, the difference in phase between the radial and tangential components is given by $\frac{2\pi l_0(n - n_0)}{}$: then equations (A. 1) and (A.2) can be combined to give: (A.3) $\Delta S(r, 0) = S_r(r, ¤) - S_\AA(r, ð) r = 2 .1 \cos 1 (5,0) I_,(r, ■) [1] \sin 2\theta$ A plot of $\Delta S(r, 0)$ as a function of r for rods AO-1 and AO-2 is shown in figure A-4. Rod AO-2 exhibited a more uniform stress di tribution than AO-1; thus it was chosen as the test rod for this contract. Three glass rods were checked in a Mach-Zehnder Interferometer to determine what correlation existed between residual stress and dynamic optical path length changes during the pump cycle. These were K-1, K-2, and K-3. Figure A-5 is a pictorial comparison between regions of highest residual stress and regions of maximum distortion to the optical path for each rod. Two conclusions may be drawn: 1) Those regions of maxinium residual stress correspond to those regions of maximum optical path length distortion; 2) The greater the residual stress, the greater is the optical path length distortion. It is interesting to note that for radially symmetric stress as in rod AO-2 there were no optical path distortions traceable to residual stress. This is not to say that radial residual stress has no effect on the optical path length through the rod during the pump cycle, but A-11

A-12 As(r,e) IN KILOGRAMS/CM² 0.10 1.0+ 10.0 AO-1. AO-2 0.02 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 NORMALIZED RADIUS -/R Figure A-4. Plot of AS (r, 0) vs. r/R for AOlux Rods AO-1 . AO-2

STRESS PATTERN ROD K-1 F B FRINGE PATTERN DISTORTION ROD K-1 FRINGE PATTERN PHOTOGRAPH ROD K-1 Figure A-5a. NOTE: REGION MARKED C IS BURNED SPOT ON ANTI-REFLECTION COATING STRESS PATTERN ROD K-2 FRINGE PATTERN DISTORTION ROD K-2 B C FRINGE PATTERN PHOTOGRAPH ROD K-2 Figure A-5b. A-13

STRESS PATTERN ROD K-3 FRINGE PATTERN DISTORTION ROD K-3 Figure A-5c. that the effect is not identifiable when the optical gradients induced by the pump are also radially symmetric. In addition to the Mach-Zehnder measurements, rod K-1 was placed in a plane polariscope and the pump-induced birefrigence recorded by a high-speed framing camera. As in the case of the optical path length measurements, the birefrigence pattern of rod K-1 was distorted in those regions of maximum residual stress. The birefrigence pattern ob- tained is illustrated in figure A-6. A-14 Figure A-6. Dynamic Birefrigence in Rod K-1 !

In conclusion, there seems to be little doubt as to the effect residual stress has on the optica quality of a glass laser rod during the pumping period and that the resulting per- turbations to the optical path length are quite important. This is particularly true when it is necessary to extract quantative information from physical measurements of pump-induced birefrigence and optical path length variations. A-15/A-16 ∎

[■ ■ APPENDIX B LASER ROD SUPPORT B-1/B-2

APPENDIX B LASER ROD SUPPORT It has been found that the design of a laser 1od support is quite important if it is necessary to observe only those distortions in the optical quality of a laser rod which are in- duced by direct absorption of pump radiation. Several support geometries were tested during the course of this contract, the object being to eliminate distortions to the laser rod optical quality which were directly traceable to the rod supports. After various supports were tested, the knowledge gained was used to design a support which introduced no observable distortions. The first laser rod support tested was of all-brass construction, as illustrated in figure B-1. The Mach-Zehnder fringe patterns during the pump cycle were recorded for rod K-3* and were found to possess no radial symmetry. The developments of the distortion in the rod is illustrated in figure B-2a while figure B-2e shows the fringe pattern for rod K-3 in the absence of holder distortion. Careful observation of the fringe development in figure B-2a indicated that the dis- tortion appeared to originate at the area of contact (see figure B-1) between the brass and the laser rod. It appears that the most probable source of this distortion is that at the brass- glass interface the pump introduces an instantaneous temperature differential between the two materials due to unequal absorption of pump radiation. The second design employed neoprene rubber O-rings to contact the rod equally around its circumference. The O-rings were recessed and shadowed to protect them from direct pump light irradiation. Figure B-3 shows the holder design, while figure B-2b shows the development of Mach-Zehnder fringes during the pump cycle. When the support was dis- assembled it was found that the neoprene O-rings had not been shielded from the pump light to as great a degree as had been hoped. The O-rings were badly burned in the region of contact between the O-rings and the laser rod. Again the distortion appeared to originate from the support-glass interface, which included the entire rod circumference. *At the time of these tests rod A0-1 and A0-2 had not been received from the Americar. Optical Company. B-3

BRASS (UNPOLISHED) LASER ROD POINTS OF CONTACT BETWEEN ROD AND SUPPORT TOP BOTTOM Figure B-1. Brass Laser Rod Support A third type of holder was designed to take advantage of the small temperature rise experienced by fused quartz when placed in the pump cavity. This low temperature rise was attributed to the broad pass-band of fused quartz to pump radiation, and to the fact that the pyrex sheath removed the bulk of radiation which would have been absorbed by the quartz. Figure B-2c shows the development of the Mach-Zehnder fringe pattern while figure B-4 B-4 18gus -Bottom- 36gus -81- 480us -Bottom- ■■■■ 66gus -Bellom- 900,s -Bttom- Figure B-2a. Fringe Patterns Obtained with Brass Laser Rod Support

Peak of white Light -- Bettom- ■ 120us 240us ■ - Bottom- - Bottom- Sogus - Bottom- 36045 -Bottom- 960,45 →Bottom- c' 1 78045 -Botton.- 66948 -Bottom- d Figure B-2b. Fringe Patters Obtained with Neoprene O-Ring Laser Rod Support Peakof white Light -Button- 24045 - Bottom- E 36045 -Bottom- E 42gus -Bottom- 0 48045 -Bottom- 54045 -Bottom- B 78045 Bottom - 16ous Bottom Figure B-2c. Fringe Patterns Obtained with Quartz Laser Rod Support B-5

B-6 Peak of white 180us 360us 240MS Light F F - Kattone- F -Boltem- -Bottom- F -Botto- 30045 -Bottom- F 420us - Bottom- 72045 96045 F F -Bottom- F - Bottom - Figure B-2d. Fringe Patterns Obtained with Needle Laser Rod Support Peak of wate Light B. Tom- 120us -Bottom- M 24gus -Bottom- M 36945 -8.- M 489M5 -Bottom- M 54gus -Bottom- 60gus -Bottom- M 84045 M -B.m Figure B-2e. Fringe Patterns Obtained with "New Holder" Design Laser Rod Support

BRASS RETAINING RING LASER ROD TOP Fuzz NEOPRENE "O" RING. BOTTOM Figure B-3. Neoprene O-Ring Laser Rod Support "O" RINGS TOP -FUSED QUARTZ TUBE LASER ROD BRASS POINT OF CONTACT BETWEEN QUARTZ AND LASER ROD BOTTOM Figure B-4. Quarts Laser Rod Support shows the holder design. It is interesting to note that the distortion was greatly reduced over that shown in figure B-2b; however, it was not completely eliminated. As before, the distortion ap cared to originate from the region of contact between the rod and support. After analysing the results obtained with. three previously described holders, all holders being characterized by a reasonably large area of contact between the support and rod, it was decided to support the rod on fine polished needle points. This approach led to the observation of optical path distortions which originated from heated air flowing across the face of the laser rod. Figure B-5 shows the support design while figure B-2d shows the development of the fringe pattern. As can be seen in figure B-5, the optical path in front of both ends of the laser rod was shielded from direct irradiation by the pump. In spite of this precaution, large distortion was observed. By means of a series of tests it was determined B-7

END VIEW BRASS TOP LASER ROD NEEDLE SUPPORTS' BOTTON. -LASER ROD BRASS NEEDLE SUPPORTS SIDE VIEW Figure B-5. Needle Laser Rod Support that the distortions were caused by air being heated at the rod-air interface in the pumping cavity, flowing along the rod surface, and over the ends of the rod. These tests indicated that the air path in front of the laser rod must not only be blocked from direct pump irradia- tion but also from the air contained in the interior of the pumping cavity. The final and successful rod support was designed on the basis of the information gained from the previously described experiments. A drawing of the complete design. is shown in figure B-6. Figure B-2e shows the Mach-Zehnder fringe development, with holder-induced distortion being conspiciously absent. The only remaining distortion is that which is traceable directly to the residual strain in rod K-3. It was felt that the reason this design was successful in eliminating support distortions was that the Sylgard No. 182* O- rings are transparent and exhibit good thermal stability when partially exposed to pump illumination. Very little absorption of pump radiation takes place with a consequent small rise in temperature of the O-ring. In addition there is little if any alteration of the pump energy distribution in the vicinity of the O-rings. The Aluminum spacers (see figure B-6) were included so that the O-rings could be recessed varying amounts behind the end caps to prevent over-exposure of the O-rings to the pump illumination. For the maximum pump

*Dow Corning Trade Name → => 4# B-8

energy used throughout this contract, this holder allowed only .2 inch of each end of the rod to be shadowed. ■ A BRASS HOUSING WITH MILLED "AIR ESCAPE"SLOTS B BRASS RETAINING RING TO SUPPORT PYREX SHEATH G PYREX SHEATH LAMP COILS ALUMINUM REFLECTOR LASER POD POLISHED ALUMINUM SUPPORT BODY POLISHED ALUMINUM SPACERS SYLGARD #182 "O" RINGS POLISHED ALUMINUM END CAPS AND "O" RING SHIELD Figure B-6. Final Design of Laser Rod Support B-9/B-10

T I 1 I 340 APPENDIX C PROPERTIES OF EASTMAN KODAK COMPANY NEODYMIUM GLASS LASER RODS C-1/C-2

f APPENDIX C PROPERTIES OF EASTMAN KODAK COMPANY NEODYMIUM GLASS LASER RODS A. MATERIAL IDENTIFICATION: Kodak Laser Glass, Type ND-10 B. OPTICAL PROPERTIES: 1. Glass 2. Doping 3. Emission Wavelength Eastman Kodak Rare Earth Optical Glass 1% and 3% by weight of neodymium oxide 1.06 microns, ±.01 micron approximately 150 Angstroms see attached curve, Figure C-1 4. Line Width 5. Absorption 6. Index of Refraction ND = 1.6970 with 1% doping (ranges as high as 1 7030, depending on the concentration of neodymium) "F - "C n "D- "A' ne - nc "F-D n g h - "F - n g 7. 7. Index Variation vs. Temperature* 483222024 100 .01241 .00803 .00675 .00874 .00673 .00559 AND (X10-5) °C AND (X10-5) 11. 8 -60 +1.2 8.0 -80 +3.0 5.0 -100 +5.2 2.7 -120 +7.5 1.1 -145 +10.5 0.0 -170 +13.3 -0.5 -194 +15.7 0.0 *F. A. Molby, JOSA, 1. 39, NO. 7, July 1949 C-3

C-4 Figure C-1. Absorption Spectra of Kodak ND-10 Laser Glass 100 90 80 70 TRANSMITTANCE - PERCENT 60 50 40 TRANSMITTANCE: I WT. PERCENT Nd 203 IN EK-110 GLASS THICKNESS-5.6 MM 30 357 20 10 ° 680 475 430 300 320 350 400 523 500 580 WAVELENGTH -MILLIMICRONS 880 740 800 700 1000 1500 2000

C. PHYSICAL PROPERTIES 1. Specific Gravity 2. Coefficient of Expansion 3. Water Solubility 4.1 gm/cc -6 (25°C - 125°C) 6.4 x 10¯ Stains slightly after 8 hours in standard humidor test (100°F, 90% r.h.) Berger Class 5 4. Acid Solubility 5. Littleton Softer:ing Point 701°C (107.6 Poise) 6. Littleton Anneal Point 628°C 13.0 (10' Poise) 7. Littleton Strain Point (1014.5 610°C Poise) 8. Thermal Shock 9. Thermal Conductivity (1% doping) Rods have been immersed from ambient room temperature into liquid nitrogen. After temperature stabilization, the same rods have been returned to am- bient room temperature. No apparent damage has been observed. Thermal Conductivity ¸-2 °C¨¹ cm) Temperature (Cal Sec -1 Cm 52°C .0019 69°C .0021 91°C .0021 114°C .0022 138°C .0023 164°C .C023 196°C .0024 C-5

10. Modulus of Rupture (1% doping) Temperature Modulus of Rupture (psi) 25°C 100°C 250°C 11. Modulus of Elasticity (1% doping) Temperature 25°C 100°C 250°C D. END SURFACE COATINGS 17,600 20,500 18,20 Modulus of Elasticity (psi x 105) 14.4 15.0 16.6 1. Either dielectric coatings or anti-reflection coatings can be supplied. Dielectric coatings are optimized performance at 1.07 microns. Because of the low loss coefficient of this glass, special low-absorption dielectric coatings are required. Silver coatings are not recommended. 2. Standard anti-reflection coatings should be applied to rods intended for use with external mirrors. E. LASER PERFORMANCE 1. Loss Coefficient 2. Efficiency 0. 16%/cm C-6 3. Threshold 4. Power Output 5. Fluorescence Time Constant 0.5 to 2.5%, dependent on rod and flash tube geometry and coupling. Threshold is dependent upon many vari- ables, and specific values cannot be stated. Type ND-10 Glass is characterized by low threshold. Figures ranging around 4 joules have been reported. Greater than 1 joule per cubic centimeter of glass. Type ND-10 Glass has a fluorescence life- time of about 60 microseconds. ' 4 4

6. Beam Divergence 7. Low Temperature Operation Output divergence from a Type ND-10 rod, 2" long x 1/4" diameter, has been meas- ured at less than 2 milliradians. This can be reduced with remote external mirrors or external mode selection. Cooling may be desirable to maintain am- bient conditions at high repetition rates. However, the fluorescence transition re- sponsible for laser action terminates well above ground state and this laser gla does not require refrigeration for its operation. SPECIFICATIONS AND AVAILABILITY F. 1. Sizes 2. Kodak laser rods, finished, are available in sizes up to 3/4" diameter x 30" long. Configurations a. Rods can be supplied with flat ends, spherical ends, chisel-tipped internally- reflecting ends, Brewster's angle, or any combination of these. b. They are not presently offering clad rods of this material. 3. Standard Size Tolerances a. Diameter b. Length +.000", -.005" +.000", -.020" 4. Finish Tolerances a. End flatness held to 0.1 wave. b. End parallelism held to 6 seconds of arc. C. The cylindrical surface is normally finished to an optical shine, but can be supplied with a more precise optical polish, or fine ground, on a custom basis. C-7

C-8 5. Laser Rod Testing a. Every finished laser rod will be optically tested, using a Twyman-Green in- terferometer with a gas laser source, checking optical homogeneity of the material as well as end flatness and parallelism. With multi-layer dielectric end coatings, this can be done after the rod is coated and at any time during its useful life. b. Every finished rod will be lased before shipment, but with no guarantee on the nature of its performance, since there is so much variation between optical heads and pump systems. 6. Delivery a. Certain smaller rods will be stocked for immediate delivery. b. Special orders and custom configurations can usually be shipped in 30 to 60 days. If a special glass melt is necessary, delivery will be 60 to 90 days. (All of the above material is from specifications supplied by Eastman Kodak Company.) F

F APPENDIX D PROPERTIES OF AMERICAN OPTICAL AOLUX NEODYMIUM GLASS LASER RODS D-1/D-2

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CENERAL SPECIFICATIONS Solid and Clad AOlux Laser Rods Length ±0.20" Diameter End Specification: Material ±0.005" (up to 1/4" diameter) ±0.010" (up to 20" length) ±0.020" (over 20" length) Flatness Perpendicularity Parallelism Brewster Angle 56° 30') 19 = B Parallelism between Brewster faces Roof ends centering Physical Properties Laser Properties 1/10 wave at 1.06 microns 90° ±2 min. to rod axis 10 sec. arc (up to 1/4" diameter) 6 sec. arc (over 1/4" diameter) B ±30 min. arc 8 min. arc to axis 15 min. to normals ±. 003" (under 1/4" diameter) ±. 005" (1/4" diameter) ±. 008" (over 1/4" diameter) Typical Properties of AOlux Nom. 5 wt.% Nd203 in barium crown optical glass ■■ = 1.519 n1.06 1.509 Strain point = 450°C V = F 6.6 Linear Expansion Coeff. (50-300°C.) = 10.3 x 106/C° Density = 2.63 qm/cm³ Water Solubility 0.053 microns (powder test) Thermal Conductivity = .002 cal/sec/cm/°C. Number Nd ions/cc = 4.6 x 10 Wavelength = 1.06 microns Fluorescent 'ine width: at 1.06 microns = 180 Å at 77°K. at half width = 250A at 300 K. Lifetime 0.57 milliseconds = Specific gain/cm/joule stored/cm³ = .08 D-3

D-4 100 90 80 70 60 50 40 Figure D-1. Absorption Spectrum of AOlux Sample Thickness: 6.4 mm 4 THEORETICAL TRANSMITTANCE DUE TO FRESNEL LOSSES = 92.2% 300 400 300 600 700 800 900 1000 1100 WAVELENGTH (MU) " "

INTENSITY RELATIVE FLUORESCENT 8 7 7 6 10 -180°A- 300° K 1.02 1.04 1.06 1.08 1.10 1.12 WAVELENGTH (MICRONS) Figure D-2. Flouresence of AOlux (5% Nd■■ 03) D-5

D-6 RELATIVE THRESHOLD 6 1 0 OUTPUT SLOPE ABOVE THPESHOLD (NORMALIZED TO 1) 0 1.8 1.6 1.4 1.2 1.0 .8 2 4 60 8 10 12 14 16 18 20 010 WT OF Nd 203 Figure D-3. Relative Threshold vs % Wt of Nd 203 .6 4 .2 0 0 10 20 30 10 40 50 60 70 80 90 100 110 LENGTH / DIA OF ROD 120 Figure D-4. Output Slope Versus Rod Length/Diameter Ratio

= APPENDIX E ANNEALING PROCEDURE USED FOR RODS AO-1 AND AO-2 E-1/E-2 -

APPENDIX E ANNEALING PROCEDURE USED FOR RODS AO-1 AND AO-2 ■ T Processing Steps

After drawing from the melt, the rod temperature was dropped from the annealing point to the strain point at a rate of approximately 1°F per hour. The rods were fabricated from the rough boule:

1) Machined to final dimensions (3/8 x 3") 2) Rough ground surface finish applied 3) Ends ground and polished to specifications. (See Appendix D.) The rods were reannealed by holding the rod at the annealing temperature for 20 hours, and dropping the temperature at a rate of .25°F per hour until the strain point was reached. After final annealing, the flatness of the ends was checked, and the rods were re-polished (not reground) to meet specifications. American Optical suggested that the laser rods not be anti-reflection coated, since previous experience had shown that strain can be introduced if proper precautions are not taken during the vapor deposition process. E-3/E-4

APPENDIX F PHYSICAL CONSTANTS FOR AOLUX ROD AO-2 F-1/F-2

APPENDIX F PHYSICAL CONSTANTS FOR AOLUX ROD AC-2*

1) E (Young's Modulus) = 6.98 x 105 kg/cm²
2) ✓ (Poisson's Ratio) = .225
3) a = 1.25 ± . 66 x 106, n
4) ■■ =
5) B = 10-7 1. 515 (estimated value at 6328 A°) 3.5 ± . 6 x 10 ■■? 2/kg
6) B|| = .42 ± 13 x 10⁻7 cm²/kg
7) a (Expansion Coefficient) = .905 ± .05 x 10' 10-5/°C (at 25°C)
8) C (Specific Heat) = 15 cal/gm/■C (at 25°C)
9) ■■ K (Thermal Conductivity) = .002 cal/sec/cm/°C
10) Y (Density) = 2.63 gm/cm' cm³
11) 31 τ (Flourescent Time Constant) == 585 ± . 015 x 10-3 seconds
12) N (Nd +3 Ion Density) ° n a 2P
13) q + ° V V ° 0 Jn
14) JT
15)
16) /cc] = 5.2 ± 1.2 x 106/°C -6 = 3.3 ± 1.1 x 106/°C 2. (Length of Rod) = 7.62 cm R = .476 cm = 4.6 x 1020
17) ■■ = 1.06 × 10-4 cm
18) Δλ (1.06μ flourescent line 1/2 width) = 2.5 x 106 cm

* (American Optical 3835 glass, 5% Nd+3 doping) used during this contract.

F-3/F-4

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ABSTRACT The Final Report on Contract Nonr-4874(00) "Thermal Optic Distortion" quantatively describes the optical distortion in neodynium doped glass which is in- duced by pump radiation. We have observed optical distortion at 6328A and have found the optical path length dependent on four primary effects! (1) Change in physical length E . 2) Change in refractive index due to temperature rise 3) Change in index resulting from stress, 4) Change in index associated with an excited state population of neodymium ions. Section I presents the experimental techniques used and the results ob- tained throughout the contract. Included in this section are measurements of optical path length variations, pump-induced birefringence, change in physical length, change in refractive index, bulk temperature rise, and the deflection of a light beam. In Section II, the theory of thermal optic distortion is developed for the first time to include Fermat's principle. This approach leads to equations defin- ing both the slope and trajectory of rays through the material. The resulting equations are employed to predict ray refraction, beam divergence, and the DD FORM 1473 1

optical path length through the material as a function of radius, time, and polarization. Section III compares the results of Sections I and II. Good agree- ment between theory and experiment is achieved provided a new term is added to the expression for the change in refractive index. This term arises from level the fact that the polarizability of the neodymium ion in its excited 4F3/2 is different from its value in the 41 9/2 ground level. The inclusion of this new term in the expression for the change in refractive index implies that large optical distortions can exist in "athermalized" glass.