Thermal Effects in Laser Amplifiers and Oscillators

A. E. Blume and K. F. Tittel

The causes and implications of thermally induced optical effects in solid-state laser materials are discussed. A convenient interferometric method is described for examining in a typical helical and linear laser configuration the transient optical phenomena produced by thermal expansion, change of refractive index with temperature and strain. The results obtained with a neodymium laser glass rod are presented photographically.

I. Introduction

The existence of undesirable thermal effects associated with the coherent amplification and generation of optical radiation is a basic problem in the design and operation of efficient solid-state laser devices. Heat dissipation is inherent in all existing optically pumped solid-state laser materials because the basic laser mechanism involves radiationless transition accompanying population inversion. Several important laser parameters such as fluorescence line-width, relaxation times, optical quality, and optical path length are strongly temperature-dependent. These effects with the exception of the last parameter have been considered by several investigators.[1-4] In the present paper are reported the observations of some pertinent thermally induced transient optical characteristics in solid-state laser materials. Laser performance will be affected by refractive index changes and thermal expansion in an active medium. These can be induced by both the unusable pump radiation from the light source and the radiationless lattice transitions caused by the usable radiation in either a pulsed or cw laser.

The resultant effects on laser amplifiers may be visualized as follows: a change in the average optical length is equivalent to a change of phase in traveling-wave amplifiers used in parallel, because then the outputs will be out of phase. The variation of optical length with cross section will affect the phase of the laser amplifier output in a straightforward fashion if it is a traveling-wave amplifier. The equiphase surfaces of the output will be distorted and, if the distortion is large enough, the beam divergence will increase and the intensity will decrease. If a regenerative amplifier or an oscillator is being considered the situation is more complicated. A regenerative amplifier would experience fluctuations in gain as the optical length changed. On the other hand, in a laser oscillator any distortion of the laser material will directly affect the associated cavity Q and, therefore, in turn, both laser threshold and mode behavior.

An approximate magnitude of the thermal effects can be obtained from considering the range of values of the thermal coefficient of expansion and changes of refractive index with temperature for typical laser materials. In general, thermal coefficients of expansion are in the order of 5×10^{-6} per °C.[5] Data on the index of refraction change with temperature are scarce but, judging from data on sapphire[6] and various glasses,[7] they can be either positive or negative and in magnitude they may be as high as 10 to 15×10^{-6} fractional change per °C for the visible spectrum. Furthermore, it should be noted that anomalous dispersion effects may modify the refractive index of laser materials at both emission and absorption wavelengths.[8,9] For example, a 2.5-cm long sample will increase in optical length roughly 0.05 wavelengths because of the thermal expansion accompanying 1° temperature rise. The optical length, however, may change as much as 0.5 wavelength, because of the change in index of refraction, with the same 1° temperature rise. This path-length change could be either an increase or a decrease depending on the laser material. Therefore, there may be more than 0.2 wavelength change per cm per °C. It is immediately obvious that the temperature difference within the cross section of a laser rod in a traveling-wave amplifier must not vary more than a small part of a degree for good performance, unless the change of refractive index with temperature is much less than 10×10^{-6} per °C.

The refractive index in general will be affected by

The authors are with the Advanced Technology Laboratories, General Electric Company, Schenectady, New York.
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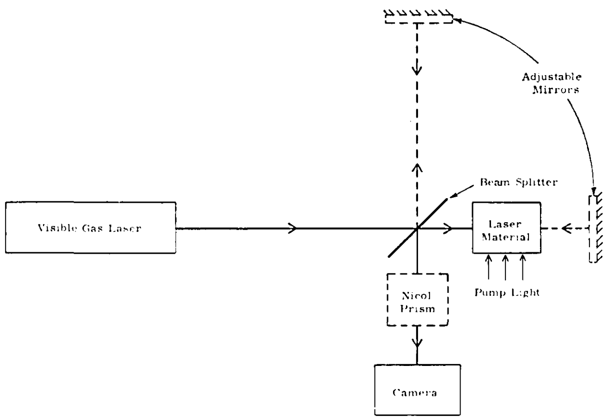


Fig. 1. Experimental interferometric arrangement for observing thermally induced optical effects in laser materials.

strain.[10] Since temperature gradients can cause strain, it might be expected that heating will cause additional changes in the refractive index because of strain.

II. Experimental Details

A series of experiments using interferometric techniques have been run to observe any changes in optical length and the presence of strain due to heating. These effects can be examined conveniently with the apparatus shown in Fig. 1 composed of a Perkin-Elmer Model 112 cw He–Ne gas laser operating at 6328 Å, a beam splitter, a camera, and a pulsed solid-state laser. The use of adjustable mirrors will be discussed below. A portion of the light from the visible gas laser is coupled by the beam splitter to an uncoated laser rod fabricated to laser tolerances and located in a standard laser head. Some light is reflected from the front surface and some from the back surface of the laser medium. These reflections form an interference pattern which in turn is coupled by the beam splitter to a camera. The number and shape of the fringes depend on the optical quality, surface characteristics (flatness and parallelism), and alignment of the laser material with respect to the incident gas laser beam. Each fringe represents a contour of constant optical path-length difference and is generally separated by one wavelength from its neighbor. For a detailed examination of the thermally induced characterisitics of the laser rod, especially during laser action, a high-speed motion picture camera is desirable. However, significant information can be obtained readily with a still camera when using a laser material of low thermal conductivity such as a good optical neodymium laser glass. Figure 2 depicts a series of interferograms showing the interference pattern from a 6.35 cm long, 0.63-cm diam Eastman Kodak neodymium glass laser rod both prior to and after optical excitation. The sequence shown in Fig. 2(a) was taken first at room temperature and then 2, 4, 6, 8, 10, and 20 sec, respectively, after the ignition of a helical xenon flash lamp. The electrical input to a PEK XE 5-5-1 lamp was 3700 J delivered in 1.5 msec. Interferograms in Fig. 2(b) were obtained from the same laser rod in a linear pump configuration at room temperature and then 2, 4, 6, 10, 15, and 20 sec, respectively, after the flash. The linear flashtube was vertically above the rod and input to an EG & G FX42 flash lamp was 550 J with a 0.5-msec pulse duration.

Since coherent illumination from the gas laser tends to show up any imperfections in optical components the use of apertures or lenses has been avoided. A faint series of closely spaced straight fringes in the interferograms is introduced by the beam splitter. Furthermore, the gas laser is adjusted to operate in a single transverse mode. The use of two additional mirrors in a Michelson interferometer arrangement is suggested in Fig. 1 as an alternative method. Such an optical setup generates high contrast fringes which can be used effectively with material of poor optical quality.

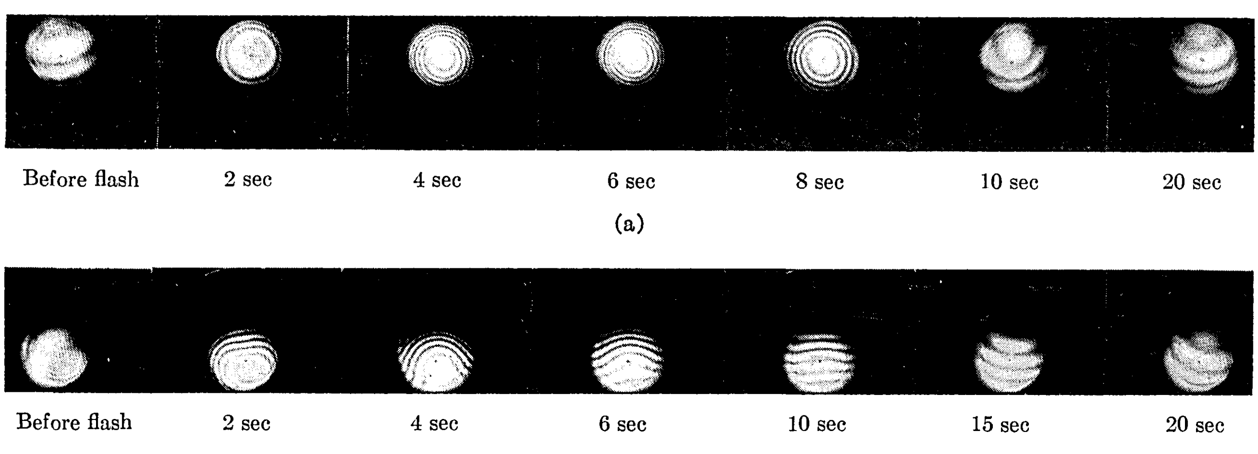
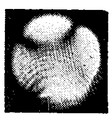


Fig. 2. Interferograms of neodymium glass laser rod in (a) helical and (b) linear optical pump configuration at various times after light excitation.



(a) (b)

Fig. 3. Effect of strain upon polarization characteristics of a neodymium glass laser rod.

In order to examine the relative importance of thermal expansion, index of refraction change with temperature, and internal strain produced by a short duration light excitation pulse, it was found necessary to isolate the effect of strain. This was done very simply by utilizing the polarization characteristics of the gas laser. An external Nicol prism, located as shown in Fig. 1, is adjusted so that its plane of polarization is normal to the plane-polarized laser beam. For such a "crossed" condition a convenient reference interferogram is obtained in Fig. 3(a). Light transmission through the prism is nearly extinguished and a 1-sec exposure was required with Type 42 Polaroid film. In contrast, optical pumping of the laser rod produced a noticeable time- and strain-dependent change in light transmission through the Nicol prism. In a forced stress condition the neodymium laser glass becomes temporarily birefringent. In this case the polarized laser beam is split into two components which vibrate in the planes of principal stress at right angles to one another. Hence the coplanar components which lie in the principal plane of the Nicol prism will now be transmitted as shown in Fig. 3(b). This photograph was taken with a 0.1-sec exposure time 3 sec after triggering the light source. In addition to a significant increase of light transmission a distinct broad dark cross is noticeable. This is due to the respective coincidence of the directions of the two laser light components in the double refracting glass and the principal plane of the Nicol prism. The lines of zero intensity are the so-called isoclinics or loci of constant stress.

The replacement of the light source by a heating coil wound directly on the laser rod was found to be a convenient method to simulate the temperature gradients produced by optical pumping techniques. Calculations indicated that, with an electrical input of about 35 W, a maximum temperature gradient would be achieved in about 30 sec with an average rod temperature rise of about 50° C. Temperature rise can be checked by counting the number of fringes that move on (or off) the face of the rod as it cools down after removal of the heat source. This procedure would seem only to be applicable if the effect of refractive index change with temperature is much greater than the effect of strain or thermal expansion.

III. Discussion

From the experimental evidence described above it is clear that the thermal effects associated with optical excitation are responsible for two distinct phenomena which determine the optical characteristics of any solid-state laser material. These are an apparent long-term effect involving thermal expansion and refractive index change and a short-term internal stress effect. The effect of strain involves heating rates and acoustic vibrations but is particularly sensitive to any non-equilibrium temperature gradients. For an electrical energy input of 550 J delivered in 500 μsec. (approximately 10^6 W) the stress forces in the neodymium glass laser rod reached a maximum value after 3 sec and disappeared after approximately 10 sec while thermal expansion effects were still clearly noticeable after 10^3 sec. For ruby much shorter times are involved,[11] presumably because of the higher heat conductivity of ruby. For the helical pump configuration a circularly symmetrical temperature gradient exists. Initially, the interference fringes move toward the center; they start moving outward when the long-term expansion effects become the predominant factor. For the linear lamp in a quasi-elliptic pump cavity this sequence of events was even more dramatic. Optical excitation is no longer rotationally symmetric, and there exists an exposed and shielded portion of the laser rod. For this case the fringes first moved down toward the cooler portion of the laser rod, and as the stress forces decreased the general motion of the fringes reversed. Motion of the fringes is opposite to the direction of heat flow after strain effects disappear. Temperature variation with radius in the glass changed its isotropic character and resulted in fringe distortion of several wavelengths. Furthermore, the increased number of fringes compared to the few that exist at room temperature indicate several wavelengths' variation in optical length.

The problem of minimizing the temperature variation requires a combination of minimum temperature rise and pumping the laser material as uniformly as possible over the section perpendicular to the direction of propagation of laser energy. The average temperature rise can be reduced to a minimum by the use of a flash lamp the output of which is only in the pump bands of the laser. The minimum would be obtained by pumping only in the pump band of longest wavelength. There will then be a certain minimum amount of energy turned into heat in the radiationless transfer to the level from which the energy transfer involving stimulated photon emission takes place. Uniform pumping to reduce temperature variation depends on the geometry of the laser material and the optical excitation scheme employed. One method that has been conceived to reduce pumping variation is the use of a composite laser rod.[12]

References *overleaf*

References

1. I. J. D. D'Haenens, J. Appl. Phys. **33**, 3201 (1962).
2. J. P. Wittke, J. Appl. Phys. **33**, 2333 (1962).
3. I. D. Abella and H. Z. Cummins, J. Appl. Phys. **32**, 1177 (1961).
4. M. Hercher, Appl. Opt. **1**, 665 (1962).
5. W. E. Forsythe, *Smithsonian Physical Tables* (Smithsonian Institution, Washington, D.C., 1954), 9th ed., p. 152.
6. I. H. Malitson, J. Opt. Soc. Am. **52**, 1377 (1962).
7. F. A. Molby, J. Opt. Soc. Am. **39**, 600 (1949).
8. A. Kastler, Ann. Phys. **7**, 57 (1962).
9. R. L. Fork and C. K. N. Patel, Phys. Rev. **129**, 2577 (1963).
10. L. F. Johnson, J. Appl. Phys. **34**, 897 (1963).
11. C. O. Alley, Univ. of Maryland, College Park, Maryland (private communication).
12. G. E. Devlin, J. McKenna, A. D. May, and A. L. Schawlow, Appl. Opt. **1**, 11 (1962).

Meetings Calendar

April

1–3 **Optical Society of America Spring Meeting, Sheraton-Park Hotel, Washington, D.C.** *M. E. Warga, OSA, 1155 16th St. N.W., Wash., D.C.* 20036

2 OSA Delaware Valley Sect. joint mtg. with SAS, Phila. Textile Inst. *H. M. Fitzgerald, Frankford Arsenal, Phila., Pa. 19137*

5–10 ACS Natl. Mtg., Phila., Pa. *ACS, 1155 16th St. N.W., Wash., D.C.* 20036

5–10 Asia-Pacific Acad. of Ophthalmology, 2nd Cong., Melbourne *R. N. Mellor, 82 Collins St., Melbourne, C1, Australia*

6–9 IEEE Conf. on Nonlinear Magnetics, Wash., D.C. *IEEE, Box A, Lenox Hill Station, New York 21, N.Y.*

7 OSA Rochester Sect., Rochester Museum of Arts and Sciences, Atmospheric Optics by S. Q. Duntley *J. H. Altman, Research Labs, Eastman Kodak Co., Rochester, N.Y. 14604*

8 OSA Chicago Sect. Mtg. *C. R. Lambrecht, 7729 N. Ashland Ave., Chicago 31, Ill.*

11–13 ISA Instrumentation Div. 4th Ann. Symp. on Measurement and Control, Tampa, Fla.

12–17 SMPTE, 95th Semiann. Conv., Los Angeles, Calif. *SMPTE, 55 W. 42 St., New York 36, N.Y.*

17–18 APS N.Y. State Sect. Spring Mtg. and Symp. on Modern Aspects of Resonance Physics, Corning Glass Center *J. T. Kerr, Corning Glass Works, Corning, N.Y.*

18 N.Y. Microscopical Soc., 87th ann, exhibition, N.Y.C. *T. G. Rochow, N.Y.M.S., Central Pk. W. at 79 St., N.Y. 24, N.Y.*

21 OSA Rochester Sect., Cutler Union, Space Simulation Techniques and the Angular Coordinate Lens System by S. Rosin *J. H. Altman, Research Labs, Eastman Kodak Co., Rochester, N.Y. 14604*

21–23 Internatl. Micrographic Cong., Phila., Pa. *C. E. Nelson, 313 N. First St., Ann Arbor, Mich.*

22–25 4th Rare Earth Research Conf., Phoenix, Ariz. *L. Eyring, Ariz. State U., Tempe, Ariz.*

27–30 APS, Wash., D.C. *K. K. Darrow, 538 W. 120 St., New York, N.Y. 10027*

27–May 1 Internatl. Conf. on Photographic Science and Engineering, N.Y.C. *W. Clark, Eastman Kodak Co., Rochester, N.Y. 14604*

28–May 2 SPSE Internl. Conf. of Photographic Science and Engineering, Americana Hotel, N.Y.C. *H. F. Nitka, Gen. Aniline & Film Corp., Bldg. 44, Charles St., Binghamton, N.Y.*

May

4–5 Inter-Soc. Color Council, Statler-Hilton Hotel, N.Y.C. *R. M. Evans, Eastman Kodak Co., Rochester 4, N.Y.*

5–9 15th Natl. Science Fair-Internatl., Baltimore, Md. *Science Service, 1719 N St. N.W., Wash. 6, D.C.*

6 OSA Natl. Capital Sect. Mtg., Georgetown U., Far Infrared Optics by R. C. Lord *H. K. Hammond III, NBS, Wash. 25, D.C.*

6-7 Electrochemical Soc., spring mtg. symp. on Optical Lasers, Royal York Hotel, Toronto, Ont.

2nd week French Soc. of Ophthalmology, 71st Cong., Paris *M.-A. Dollfus, Soc. Française d'Ophthalmologie, 27, rue du Faubourg-St.-Jacques, Paris 16, France*

10–15 Internatl. Conf. of the Soc. of Aerospace Photography Engrs. and Technicians, Palisades Park, N.J.

14–15 Soc. of Technical Writers and Publishers, San Diego, Calif. *STWP, P. O. Box 3706, Beechwold Sta., Columbus, Ohio 43214*

19–21 PTG Microwave Theory & Techniques Internatl. Symp., Internatl. Hotel, Kennedy Airport *L. Swern, Sperry Gyroscope Co., Gt. Neck, L.I., N.Y.*

19–22 German Soc. for Applied Optics, Gnumden am Traunsee, Austria *H. Volkmann, Zeppelinstr. 23, 792 Heidenheim, Germany*

20–23 Acoustical Soc. of Am. N.Y.C. *W. Waterfall, 335 E. 45 St., New York 17, N.Y.*

25–29 French Soc. of Physical Chem., 14th Ann. Mtg., Bordeaux *G. Emschwiller, Soc. de Chimie Physique, 10, rue Vauquelin, Paris 5, France*

25–June 5 Lasers—Theory, Technology, and Applications course, U. of Mich. *Engr. Summer Confs., W. Engr. Bldg., U. of Mich., Ann Arbor, Mich.*

26–28 CIBA Found. Symp. on Physiology & Experimental Psychology of Color Vision, London *41 Portland Pl., London W. 1, England*

26–28 AFIPS, Spring Joint Computer Conf., Washington, D.C. *P. Huggins, AFIPS, P.O. Box 55, Malibu, Calif.*

June

— Symp. on Quantitative Biology, Cold Spring Harbor, N.Y. *B. D. Stollar, AFOSR, Tempo D Bldg., 4th & Independence Ave. S.W., Wash., D.C. 20333*

1–12 Lasers—Masers course (H. Lyons), UCLA *Eng. Ext., U. of Calif., Los Angeles, Calif. 90024*

2–5 15th Ann. Mid-America Symp. on Spectroscopy, Sheraton-Chicago Hotel *R. I. Smick, Philips Electronic Instruments, 5535 W. Montrose Ave., Chicago, Ill. 60641*

2–6 Internatl. Optical Cong., Copenhagen *Internatl. Optical League, 65 Brook St., London, W.1, England*

7–13 European Opthalmological Soc., 2nd Cong., Vienna *J. François, 15 place de Smet de Naeyer, Ghent, Belgium*

8–10 PIB Symp. on Quasi-Optics, Statler-Hilton Hotel, N.Y.C. *L. Felsen, Polytechnic Inst. of B'klyn, 55 Johnson St., B'klyn 1, N.Y.*

15–19 Symp. on Molecular Structure and Spectroscopy, Ohio State U. *H. H. Nielsen, Dept. of Physics, OSU, 174 W. 18 St., Columbus, Ohio 43210*

15–26 AFOSR Seminar on Communications and Cybernetics, Cloudcroft *J. R. Foote, P.O. Box 1053, Holloman AFB, N.M.*

16–18 Conf. on Precision Electromagnetic Measurements, Boulder, Colo. *NBS Office of Technical Information, Wash. 25, D.C.*

21–26 Internatl. Conf. on Physics & Chemistry, Brown U. *H. E. Farnsworth, Brown U., Providence, R.I.*

21–26 ASTM Ann. Mtg., Conrad Hilton Hotel, Chicago *ASTM, 1916 Race St., Philadelphia 3, Pa.*

22–27 Internatl. Biophysics Mtg., Paris *B. D. Stollar, AFOSR, Tempo D Bldg., 4th & Independence Ave. S.W., Wash., D.C. 20333*

25–27 APS, summer mtg., Denver, Colo. *K. K. Darrow, 538 W. 120 St., New York 27, N.Y.*

29–July 2 Spectrometer Conf., Frankfurt am Main *K. Picard, c/o August Thyssen-Hütte AG, Chemische Hauptlab., 4100 Duisburg-Hamborn, Germany*

July

2–3 IP²S Spectroscopy Group Summer Mtg. on Limitations of Detection in Spectrochemical Analysis, U. of Exeter *L. Bovey, Bldg. 329, AERE, Harwell, Didcot, Berks., U.K.*

6–10 Fundamentals of Infrared Technology course, U. of Mich. *Engr. Summer Confs., W. Engr. Bldg., U. of Mich., Ann Arbor, Mich.*