Transient radiation-induced absorption in laser materials

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Abstract

Transient radiation-induced absorption losses in laser materials have been measured using a pulsed nuclear reactor. Reactor pulse widths of 70 to 90 μ s and absorbed doses of 1 to 7.5 krad have been used. Transmission recovery times and peak absorption coefficients are given. Materials tested include LiNbO_3 , GSGG, silica substrates, and filter glasses used in the laser cavity. The filter glasses are tested at discrete wavelengths in the range 440-750 nm. Lithium niobate, MgO doped LiNbO_3 , GSGG, and the silica substrates are tested at 1061 nm.

1. Introduction

A laser exposed to pulsed radiation sources can experience a degradation of performance due to radiation-induced absorption in its optical elements. This degradation can be transient or permanent. Typically, the induced absorption is greatest during or immediately after the radiation pulse and then decays to a permanent level. This is a study of induced absorption in the laser cavity materials used in a 1061 nm GSGG laser. Sandia National Laboratories' SPR III pulsed nuclear reactor is used as the radiation source. Total doses of 1-7.5 krad and neutron fluences of 0.8 to 2×10^{13} (1 MeV Si) are used. Gamma rays are the primary source of induced absorption, but corrections for neutrons are made in the total dose.

Gadolinium scandium gallium garnet (GSGG) doped with Cr and Nd is the gain medium for this laser. Chromium has absorption bands in the spectral range 400-650 nm, and neodymium has absorption bands in the range 650-900 nm. The chromium excitation is transferred to the neodymium so that it contributes to the lasing 1061 nm neodymium laser energy.¹ This material (GSGG) has been reported to have little or no permanent radiation-induced absorption for doses greater than 10 Mrad.¹⁻³ The samples that have been used in this study were purchased from Litton Airtron Inc.

Filter glasses, that function to prevent parasitic oscillations and solarization⁴ of the laser rod, have been tested for transient and permanent absorption. These glasses are required to pass the pump bands, absorb below 400 nm, and absorb 1061 nm radiation. Commercially available materials which meet these criteria are: KK1 glass manufactured by Kigre, and S7005 and S7010 glasses manufactured by Schott. All three glasses are

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silicates and are doped with samarium which absorbs at 1061 nm. The exact compositions of these materials are proprietary, but recent tests using Rutherford back scattering (RBS) indicate cerium is present in all three glasses.⁵ Cerium is commonly added to glasses as a solarization suppressor and a UV absorber.⁴ Lasers using GSGG are commonly pumped by flashlamps because of the wide range of the pump bands. In many cases, the envelope of the flashlamp is made from cerium doped silica. An envelope material tested for this purpose is M382 glass manufactured by Heraeus. The substrate material for mirrors, beam splitters, etc. that has been chosen for this laser is Corning 7940 fused silica.

Kigre Inc., the supplier, has reported the permanent radiation-induced absorption in a 6mm sample of KK1 glass is less than 10% in the spectral range 400-1000 nm when exposed with 1 Mrad (Si) dose of Co-60 gamma rays. Greater induced absorption is noted for wavelengths below 400 nm. No radiation effects data are available from the manufacturers of the two Schott glasses and the Heraeus M382 glass. Transient measurements of the radiation-induced absorption measurements for Corning 7940 silica have been reported when using a 20 ms nuclear reactor pulse and a total dose of 0.5 Mrad.⁶ The upper bound for the peak absorption coefficient in that experiment has been determined to be 0.00158 cm^{-1} .

Lithium niobate is the material used in the laser's Q-switch. This material has radiation-induced absorption bands which span the range 460-1100 nm.⁷⁻⁹ In the range 600-1000 nm, the transient radiation-induced absorption has been reported to have a decay constant of 2.9 ms.⁷ Transient radiation-induced absorption in Ti:LiNbO₃ waveguide devices has been observed to have nonexponential decay curves which have a 100 μs component and an estimated longer duration component of about 1 s.¹⁰ In both of these studies, no permanent radiation-induced absorption has been observed for room temperature measurements. Pure and MgO doped optical grade samples of lithium niobate procured from Crystal Technologies Inc. are used in this study. Impurity levels for these materials are less than a few ppm, except for Ta, which is less than 100 ppm. The doped samples were doped with 5% MgO.

2. Experimental

The Sandia National Laboratories' pulsed SPR III nuclear reactor is the source of both neutrons and gamma rays for these experiments.¹¹ An attempt has been made to operate the reactor under the same conditions for each experiments reported here. Under these conditions the main reactor pulse width varied from 70 to 90 μs . The pulse had a low intensity tail which extended beyond 3 ms. Total dose is varied by attenuating the γ -rays with lead. The neutron energy spectrum and the corresponding fluences are varied by shielding with polyethylene.

The optics for these experiments are placed on two optical breadboards, one breadboard (B1) is 900 x 900 mm, and the other (B2) is 600 x 1200 mm. Figure 1a is schematic of B1 with its optics on it. This board is placed in the instrumentation building away from high radiation fields. The Model 124D-GSGG laser shown in Fig. 1a is manufactured by Lightwave Technology. It emits 1061 nm radiation in a single mode. Three beam splitters direct partial laser beams to 100-mm-focal-length lenses which image the laser beams onto two optical fibers and a detector to monitor the beam(see Fig. 1a). The partial laser beams imaged onto the 30-m-long fibers are transmitted to B2, which is placed in the reactor's containment building (kiva). A third leg (FO1) uses an incandescent lamp as a radiation source. Breadboard B2 is subjected to high radiation fields and has the test samples on it. Optical fibers originating from B1 are attached to the collimators on B2 as shown in Fig. 1b. Probe beams that have been passed by the fibers and the collimator propagate through the air from the collimators to the samples, pass through the sample, and then are returned by retro-reflectors along the same path to the collimators where they are re-imaged on the fibers. Upon returning through the optical fibers to B1, the probe beams are directed by the cube beam splitters to detectors which monitor the radiation-induced absorption in the entire beam path. A second beam splitter is placed in the path of the returning beam from the incandescent source. This splitter separates 440 or 460 and 640 nm, or 640 and 750 nm radiation so that two wavelengths are monitored. The signal is normalized to the level observed 200 μ s before the reactor pulse occurs. Using this method, only the change in transmission is measured. The optical fibers are shielded with lead inside the kiva to reduce the induced absorption in them. Induced absorptions due to the fibers are determined by running the experiment with and without the samples.

3. Results

Figure 2 displays $-\log_e(T)$ versus time for S7005, S7010, M382, and KK1 glasses at 640 nm, where T is the transmittance. The peak absorptions for these glasses occur in the range 1.5 to 2.5 ms which is well after the main peak of the radiation pulse. This delay is due to the long tail on the radiation pulse (which extends beyond 3 ms) and the slow decay of the induced absorption. Table I lists mathematical fits using simple exponentials to the decay curves after peak absorption. The sum of two exponentials gives a reasonable fit to the data for the four glasses and the optical fiber. Fast decay constants ranging from 5-14 ms and slow decay constants ranging from 200-1000 ms have been found for the four glasses. A single exponential with a decay constant of 244 ms also fits fiber optic data. The similarity in magnitude of the decay constants for the different glasses and fiber optics is probably related to the similarity in base materials used in their compositions. The absorption at 750

nm is smaller, but has similar time characteristics. The permanent radiation-induced absorption determined by comparing transmission before and after (several days after) irradiation is less than the measurement error.

Figure 4 is a plot of $-\log_e(T)$ versus time for "pure" lithium niobate at 1061 nm. This data is fitted best with the sum of three exponentials with decay constants of 0.189, 4.23, and 37.5 ms. The peak in the absorption occurs 40 μ s after the peak in the reactor pulse which suggest the fast decay constant of the early data is about 100 μ s. This is consistent with what has been found for the fast decay constant for Ti:LiNbO₃ waveguides¹⁰ and the fit to the data. The long decay constant (1 s) estimated for the waveguide study is considerably longer than the 37.5 ms found here. Noise caused by vibrations resulting from the reactor operation make it difficult to fit the weaker absorption in MgO:LiNbO₃ after 1 ms.

Figures 4-8 are plots of the peak radiation-induced absorption coefficients versus the total dose for the materials of this experiment at the indicated wavelengths. It appears a linear fit of absorption coefficient is good for the radiation fields used here. Figure 8 shows the comparison of the induced absorption of "pure" and MgO doped LiNbO₃. It is obvious that the radiation-induced absorption in the doped material is much less than the "pure" material. Within the measurement errors (0.02 cm⁻¹), no radiation-induced absorption has been detected for GSGG and Corning 7940 silica for the radiation levels of this experiment.

4. Conclusion

Transient radiation-induced absorption in the four glasses, KK1, S7005, S7010, and M382, have similar time characteristics. They have a fast decay constant ranging from 5-14 ms and slow decay constant ranging from 200-1000 ms. The magnitudes of the peak induced absorption for KK1, S7005 and S7010 glasses are nearly the same for comparable doses. The induced absorption in MgO doped LiNbO₃ is 6-7 times less than the induced absorption in "pure" LiNbO₃ for a dose of 7.5 krad. This material is the desirable choice for radiation environments. An expression consisting of three exponentials is required to fit the data of the "pure" LiNbO₃. The fast decay constant is 189 μ s and the long decay constant is 37.5 ms.

Acknowledgements

The author acknowledges the support of the SPR-III reactor group and the technical assistance of H.C. Richardson. He is grateful to Dr. J. Kelly for help with the dosimetry. This work was supported by the United States Department of Energy under contract DE-AC04-94AL85000.

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Table I

Mathematical fits to $-\log_e (T)$ versus time

Matl.	*Fit eq.	A	**b (ms)	C	**d (ms)	E	**f	λ (nm)	Time intv. (ms)
fiber	1 exp.	----	----	.0636	244 (237 to 250)	----	----	640	0-40
KK1	2 exp.	.064	13.7 (12.5 to 15.2)	.0839	-2341 (-919 to 4292)	----	----	640	0-76
M382	2 exp.	.0391	11.3 (10 to 12.9)	.349	841 (925 to 771)	----	----	640	0-76
S7005	2 exp.	.092	8.8 (8.2 to 9.6)	.165	287 (228 to 387)	----	----	640	0-76
S7010	2 exp.	.112	7.7 (7.5 to 7.9)	.196	336.8 (324 to 351)	----	----	640	0-76
LiNbO ₃	3 exp.	.137	4.23 (3.9 to 4.65)	.291	37.5 (36.1 to 36.9)	.189	.183 (.155 to .223)	1061	0-76

* 1 exp. - $Ce^{-t/d}$ 2 exp. - $Ae^{-t/b} + Ce^{-t/d}$ 3 exp. - $Ae^{-t/b} + Ce^{-t/d} + Ee^{-t/f}$

** The numbers in parentheses after parameter value are the 95% confidence values.

(a)

(b)

Fig. 1 Experimental setup. a) breadboard B1 located in instrument shack; b) breadboard B2 located in reactor kiva.

Fig. 2 $-\text{Log}_e(T)$ versus time for S7005, S7010, M382, and KK1 glasses at 640 nm. Radiation-induced absorption in the fiber has been subtracted off. Total dose for KK1 glass is 4.0 krad and 7-7.5 krad for the other glasses.

Fig. 3 $-\log_e(T)$ versus time for LiNbO₃ at 1061 nm. Corrections for the radiation-induced absorption in the fiber have been made. a) Total time record; b) Initial time record along with reactor pulse.

Fig. 4 Peak radiation-induced absorption coefficient versus dose for M382 glass at 440, 640, and 750 nm.

Fig. 5 Peak radiation-induced absorption coefficient versus dose for S7010 glass at 640 and 750 nm.

Fig. 6 Peak radiation-induced absorption coefficient versus dose for KK1 glass at 460 and 750 nm.

Fig. 8 Peak radiation-induced absorption coefficient versus dose for "pure" and MgO doped LiNbO_3 at 1061 nm. ● - "Pure" LiNbO_3 , Δ - MgO doped LiNbO_3 .

Fig. 7 Peak radiation-induced absorption coefficient versus dose for S7005 glass at 640 nm.

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