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Transient Radiation-Induced Absorption in Materials for the DOI Laser

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Abstract

This is the final report on a series of experiments concerned with transient radiation-induced absorption in materials for a Cr,Nd:GSGG laser. Both the Sandia National Laboratories SPR III pulsed reactor and the Hermes III pulsed X-ray machine are used as radiation sources. The time dependence and the magnitude of the induced absorption in filter glasses and in doped and undoped LiNbO₃ Q-switch materials have been measured. Gain has been observed in Cr,Nd:GSGG, the laser medium, when it is irradiated by X-rays.

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Introduction

The DOI laser program has the objective of developing a laser for direct optical initiation of explosives (DOI). Since this laser may be required to operate in a radiation environment, a knowledge of radiation effects on the laser performance is needed. Both short-term and long-term radiation effects are observed here, but the short-term effects are usually more intense and have a greater effect on the performance of the laser. This report is concerned only with transient radiation-induced absorption in the various elements of a prototype DOI laser. It is limited to induced absorption and does not address radiation effects on the electronics of the laser. The objective of this study is to develop a data base which can be used in laser models to predict the effect of radiation on the operation of the laser. Also, substitute materials for those which have large radiation-induced absorption are sought here.

Typically, transient radiation-induced absorption is greatest during or immediately after a radiation pulse. The transient absorption decays with time; usually a fast rate of decay occurs followed by a slower decay rate. In some cases, a low intensity permanent absorption (at room temperature) is observed. Generally, the permanent absorption can be removed by annealing the sample at high temperatures. The time dependence and the magnitude of the induced absorption can often be altered by adding dopants to the undoped material.

Shown in Fig. 1 is a schematic of a prototype DOI laser. As can be seen from the figure, the laser is folded. This folding requires additional elements in the laser cavity. The numerous elements in the laser cavity could give rise to radiation-induced absorption losses in the cavity. The time-dependent behavior of the various losses in the cavity and the time duration after the radiation pulse will determine the effect of the radiation on the output of the laser. A pump chamber (not shown in Fig. 1), made from KK1 filter glass and a diffuse reflector, surrounds the laser rod and the flashlamp. The pump light from the flashlamp can pass through the KK1 filter glass one or more times depending upon the path taken before being absorbed by the laser rod.

Gadolinium scandium gallium garnet doped with chromium and neodymium (Cr,Nd:GSGG) is the gain medium for the prototype DOI laser. Chromium sensitizes the laser rod to pump bands throughout the visible portion of the spectrum which matches the emission spectrum of a flashlamp.¹⁻⁶ From Fig. 2, a plot of the transmission of Cr,Nd:GSGG versus wavelength, it can be seen that absorption maxima occur at 460, 640, 750 and 800 nm. This material lases at 1061 nm and has a stimulated-emission cross section of $3.2 \times 10^{-19} \text{ cm}^2$.⁷ The large cross section of this material requires that efforts be made to prevent parasitic oscillations in the cavity by using appropriate filter glasses which absorb at 1061 nm. This material has been reported to be hard to gamma rays for doses up to 10 Mrad.⁸⁻¹⁰ It should be pointed out that those earlier studies deal with long-term effects and do not address short-term transient effects.

It can be seen that Corning 7940 is the material used for the various prisms and substrates in the cavity in Fig 1. It is radiation hard to long-term radiation effects. No long-term change in transmission for 100 Mrad doses of 1 Mev gamma rays has been reported.¹¹ Transient radiation-induced absorption measurements using a 20 ms pulse from a nuclear reactor do not indicate any absorption for 0.5 Mrad doses.¹² No radiation-induced absorption in 7940 has been measured in the present high dose rate experiments.

Only one filter glass, KK1, is referenced in Fig. 1, but two other filter glasses have been considered in this study; that is, Schott 7005 and Schott 7010 glasses. Because the two Schott glasses have nearly the same radiation properties²³ and the experimental time on the radiation sources is costly, the X-ray experiments (described below) are limited to S7010. All three of these silicate glasses are doped with samarium which absorbs at 1061 nm and prevents unwanted parasitic oscillations. The two Schott glasses differ in the amount of Samarium doping; Schott 7010 has more doping. The exact composition of these materials is proprietary, but it has been found by Rutherford back scattering (RBS), that those three materials along with M382 glass (flashlamp envelope material) contain cerium.¹³ Cerium is often added to glasses as a solarization suppressor and a UV absorber.¹⁴ For efficient operation of the laser, all four of these materials must and do pass the pump bands shown in Fig. 2.

An undoped lithium niobate element is shown in Fig. 1 as the material originally chosen for a Q-switch in the laser. This material has transient radiation-induced absorption bands which span the range 460-1100 nm.¹⁵⁻¹⁹ The half-life of the band spanning 600-1000 nm is reported to be 2.9 ms.¹⁵ Transient radiation-induced 810 nm absorption in Ti:LiNbO₃ waveguide devices has been reported to have a 100 μ s component and a longer duration 1 s component.²⁰ Another study using a Ti:LiNbO₃ waveguide device reports an initial $1/t^{1/2}$ time dependence for the decay of the radiation-induced absorption,²¹⁻²² which differs from the $1/t^{1/4}$ dependence found in previous reactor experiments.²³ In those same experiments, it has been found that MgO doped LiNbO₃ has less absorption than undoped LiNbO₃.

Experimental methods

Two Sandia National Laboratories radiation sources have been used in these studies, the SPR III pulse reactor and the Hermes III pulsed X-ray machine. The details of these machines and the dosimetry has been described before and will not be repeated here.²³⁻²⁴ The optics have also been described in detail previously, and only a cursory description will be given here. A probe beam is continuously passed through the sample, and the change in transmission is recorded during and immediately after irradiation. Three different beams are used to probe three samples during a single radiation pulse. Two of the beams are 1061 nm laser beams, and the third is a white light beam. The white light probe is used to measure radiation-induced absorption in the different filter glasses at visible wavelengths. The two 1061 nm laser beams are used

to measure radiation-induced absorption in the laser cavity elements.

Bulk 12.7 mm thick samples of optical grade LiNbO_3 and 5% $\text{MgO}:\text{LiNbO}_3$ have been obtained from Crystal Technologies Inc., and for comparison, 9 mm thick LiNbO_3 and 0.5% $\text{TiO}_2:\text{LiNbO}_3$ samples have been obtained from Virgo. The two doped LiNbO_3 samples are possible substitutes for the undoped LiNbO_3 . All of the glass samples are 12.7 mm thick except for the KK1 sample; it is 9 mm thick. The manufacturers of the KK1, S7005 and S7010, and M382 glass are as follows: Kigre, Schott, and Heraeus.

In both the SPR III reactor²³ and the Hermes III experiments, Hamamatsu Model R2368 photomultiplier tubes are used to record the 460-750 nm signals. Model HAD-1000A silicon detectors manufactured by EG&G are used in the reactor experiments, and Hamamatsu Model R406 photomultipliers are used in the Hermes III experiments to observe the 1061 nm signals. The R406 photomultipliers are faster than the HAD-1000A detectors. The reactor data has been recorded with Nicolet Model 4094C digital oscilloscopes and the Hermes III data with Hewlett Packard Model HP54542A digital oscilloscopes. The reactor data is sampled every 20 μs and most of the Hermes III data is sampled every 2 μs . The slow decay of the induced absorption in the filter glasses dictates that these materials be sampled every 200 μs in order to get accurate decay curves. These long data curves have only been observed for the Hermes III experiments. All of the time dependent data shown here has been taken on the Hermes III machine.

Results and discussion

Displayed in Fig. 3 are the peak absorption coefficients versus the absorbed dose for all of the LiNbO_3 based materials tested. The straight lines are fits to the data. Included in the analysis and plotted in the figure are the data found while using Sandia National Laboratories' SPR III pulsed nuclear reactor.²³ The slopes of the four lines are 0.0434 ± 0.0034 , 0.0357 ± 0.00073 , 0.0158 ± 0.00048 , and $0.00317 \pm 0.00024 \text{ cm}^{-1} \text{ krad}^{-1}$. The data represented by the four lines are respectively, undoped LiNbO_3 (Virgo), undoped LiNbO_3 (Crystal Technologies), 0.5% $\text{TiO}_2:\text{LiNbO}_3$ (Virgo), and 5% $\text{MgO}:\text{LiNbO}_3$ (Crystal Technologies). This figure illustrates that doping with these two materials significantly reduces the transient radiation-induced absorption. Samples with 3% TiO_2 have been purchased, but the quality of the crystals made them unusable. The undoped sample of LiNbO_3 from Virgo appears to have a slightly higher absorption coefficient than the undoped sample from Crystal Technologies, but this may be due to the limited number of data points and noise in the data for this sample. Both of these materials and the TiO_2 doped material do not exhibit saturation effects. It is difficult to determine if the MgO doped material has saturated because of the small signals.

Shown in Fig. 4 are log-log plots of the $-\text{Log}_e(T)$ versus time for the two undoped samples of LiNbO_3 from Crystal Technologies and Virgo, and the 0.5% TiO_2 doped sample of LiNbO_3 from Virgo, where T is the transmittance. A transmittance of 1

corresponds to 100% transmission, and T is less than 1 when absorption is present. All three plots can be approximated with a $1/t^{1/4}$ time dependence from .01 ms to about 8 ms. This is true for all of the dose levels of these experiments. After 8 ms, the transient absorption in the two undoped samples decays faster which indicates that the exponent on the time (t) is greater than $1/4$. The decay of the transient absorption in the 0.5% TiO_2 doped sample after 8 ms has an exponent smaller than $1/4$. Figure 5 exhibits the time dependence of MgO doped LiNbO_3 . The initial sharp absorption pulse at the beginning decays in about 20 μs to the noise level. All plots in Figs. 3 to 5 have been corrected for the small absorptions in the other optics in the system.

Previously, it has been speculated that the difference in the time behavior and the magnitude of the absorption of undoped LiNbO_3 , and Ti doped waveguide devices is due to the Ti doping.²⁴ A comparison here of the absorption coefficients (derived from both SPR III and Hermes III data) for undoped LiNbO_3 and 0.5% $\text{TiO}_2:\text{LiNbO}_3$ (see Fig. 4) indicate that the undoped material has an induced absorption coefficient of about 6 to 7 times the doped material. This is about the difference found earlier between Taylor's waveguide device^{21,22} and bulk undoped LiNbO_3 for the SPR III data.²⁴ It should be noted that Taylor probed at 1300 nm, and the probe wavelength here is 1061 nm. The TiO_2 doped bulk material has an initial time dependence similar to the undoped material; that is, it has a $1/t^{1/4}$ time dependence. This is in disagreement with the $1/t^{1/2}$ time dependence of the Ti doped waveguide devices.^{21,22} A possible explanation for this discrepancy is that in the fabrication process for waveguide devices, additional defects can be created which may alter the time dependent behavior to pulsed radiation sources. It is known that other compounds can be formed during the fabrication process, and the region of the waveguide swells above the surface.²⁵⁻²⁸ The similarity of time dependence of the TiO_2 doped and the undoped bulk materials for the first 8 ms suggests that the dopant merely reduces the number of color centers that are primarily responsible for the initial absorption, but does not alter existing centers or form new centers. The time behavior after 8 ms indicates that the nature of the decay of the color center has changed because of the TiO_2 doping. The 5% MgO doped LiNbO_3 has such a small absorption that determining a meaningful time dependence is not possible. Assuming that less MgO doping would result in a larger absorption coefficient, it should be possible to determine the time dependence of the absorption coefficient for material with less MgO.

A plot of $-\text{Log}_e(T)$ as a function of time (negative values on the graph correspond to gain) for an absorbed dose of 47.6 krad in Cr,Nd:GSGG is shown in Fig. 6, where T is the transmittance. The 20 ns X-ray radiation pulse occurs at 0 time in the figure. An exponential fit to the decay of the gain yields a time constant of 226 μs . This is less than the value given by the manufacturer, 242 μs , but close to the value, 220 μs , found by Beimowske et al.⁶ The peak of the gain in Fig. 6 occurs 20 μs after the radiation pulse indicating a delay in the excitation of the Nd ion. This suggests that the Nd excitation originates from an excited Cr ion since the delay is nearly the same as the excitation transfer time of Cr to Nd.⁶ In Fig. 7, Nd:GSGG is subjected to a 41.7 krad irradiation,

and only a slight hint of gain is noted. This further reinforces the concept that the Nd excitation primarily originates from the chromium. Pumping of Cr,Nd:GSGG by X-rays suggests that secondary electrons generated by Compton electrons are important in the excitation of Cr ions. If this is true, then electron beam excitation of Cr,Nd:GSGG is possible. The uniformity of the electron excitation would depend on the range of the electrons in Cr,Nd:GSGG. At this time, a detailed excitation pathway has not been determined.

Figure 8 is a plot of the peak value of $\text{Log}_e(T)/2L$ versus absorbed dose for Cr,Nd:GSGG, where L is the thickness of the material. The straight line fit has a $0.006874 \pm 0.0003573 \text{ cm}^{-1} \text{ krad}^{-1}$ slope. A factor of 2 is used because the probe beam double passes the sample. This quantity is the small signal gain. The small signal gain for YAG when it is vigorously pumped with flashlamps is $0.11/\text{cm}$.³⁰ For YAG with a Nd concentration of $6 \times 10^{19} / \text{cm}^3$, this corresponds to 0.6% of the Nd population being inverted. According to Fig. 8, a 20 krad dose absorbed in Cr,Nd:GSGG would correspond to a small signal gain of $0.137/\text{cm}$. Using the manufacturer supplied stimulated-emission cross section ($3.2 \times 10^{-19} \text{ cm}^2$), this corresponds to 0.2% of Nd population being inverted which is of the same order as the flashlamp YAG excitation cited above. The small signal gain under these circumstances is slightly greater than in YAG because of the higher Nd concentration (2×10^{20}).

Plots of the peak absorption coefficient versus dose for KK1 filter glass at 640 and 750 nm are given in Figs. 9a and 9b. The slopes of the straight line fits to the 640 and 750 nm data are respectively, 0.00828 ± 0.000017 and $0.00483 \pm 0.00018 \text{ cm}^{-1} \text{ krad}^{-1}$. The absorption coefficients peak at between 2 to 4 ms for both the reactor data and the Hermes data. This late cresting for the Hermes data is puzzling, since the photomultiplier tube recovers from the initial radiation noise spike in a few microseconds. The initial noise spike seen with the Hamamatsu R236 photomultiplier tube is not seen on the Hamamatsu R406 photomultiplier tube used to observe the 1061 nm laser. Figures 12a and 13a are plots of $-\text{Log}_e(T)$ versus time for an absorbed dose of 79.39 krad for 640 and 750 nm. Both wavelengths can be approximated by a $1/t^{1/12}$ time dependence for the decay of $-\text{Log}_e(T)$, which is much slower than for LiNbO_3 .

Plots of the peak absorption coefficient versus dose for M382 glass at 640 and 750 nm are displayed in Figs. 10a and 10b. The slopes of the straight fits to the 640 and 750 nm data are respectively, 0.00778 ± 0.00099 and $0.00681 \pm 0.00046 \text{ cm}^{-1} \text{ krad}^{-1}$. A straight line is not a good fit to all of the data, which implies that the absorption has saturated near 40 krad. A straight line fit to the data up to 40 krad yields a slope of 0.01154 ± 0.00011 and $0.00881 \pm 0.00050 \text{ cm}^{-1} \text{ krad}^{-1}$ for 640 nm and 750 nm, respectively. Plots of $-\text{Log}_e(T)$ versus time for an absorbed dose of 80.36 krad are shown in Figs. 12b and 13b. The decay of $-\text{Log}_e(T)$ for M382 glass can also be approximated by a $1/t^{1/12}$ time dependence.

Figures 11a and 11b are plots of the peak absorption coefficient versus dose for

S7010 filter glass at 640 and 750 nm. Straight line fits to their respective data yield slopes of 0.01339 ± 0.00071 and $0.00949 \pm 0.00029 \text{ cm}^{-1} \text{ krad}^{-1}$. Figures 12c and 13c are respectively, 640 and 750 nm plots of $-\text{Log}_e(T)$ versus time, when the sample is exposed to 80.93 krad. The decay of $-\text{Log}_e(T)$ has an approximate $1/t^{1/8}$ time dependence, which is a faster decay rate than the other two glasses. This faster decay rate may be the results of the higher samarium doping in S7010 glass.

The absorption coefficients for 640 nm radiation in KK1 and S7010 glasses are respectively, 40 and 70 % higher than at 750 nm. It is only 14 % for M382 glass if all the data is used in the straight line fit, and 31 % if only data up to 40 krad is used. This is in agreement with the general observation that the induced absorption decreases with wavelength. The differences in this ratio indicates the influence of the doping on the magnitude and time dependence of the radiation-induced absorption, since all of these materials are basically the same except for the doping.

During the Hermes III experiments data has not been taken at 440 or 460 nm. The limited available time on the X-ray machine and the difficulty in making these measurements would not allow it. The limited data taken previously with SPR III will only be referenced here.²³ Future experiments should address measurements at these wavelengths.

A few comments are given here in regards to the effect of the wide disparity in dose rate for SPR III and Hermes III experiments. The data for all of the materials tested indicate initial decay constants of the induced absorption range from 100-200 μs (LiNbO_3) to seconds (filter glasses). Since the pulse of SPR III is less than 100 μs , very little decay occurs during the pulse, so that the peak absorption due to the pulse is expected to be nearly the same as for a very short pulse of the same total dose. Also, the errors in the reactor data mask any small dose rate dependence.

Calculated effects of radiation-induced absorption in LiNbO_3 and $\text{MgO}:\text{LiNbO}_3$ (Q-switch materials) on the laser output energy are shown in Fig. 14. Radiation effects in the filter glasses have not been taken into account in this calculation. Normal Q-switch theory is used to derive the solid line³⁰, and the plotted data points, represented by squares and triangles, take into account the radiation-induced absorption in LiNbO_3 and $\text{MgO}:\text{LiNbO}_3$ immediately after and 4 ms after the radiation pulse. The decimal transmission is obtained by multiplying the transmission of the irradiated LiNbO_3 by the aggregate transmission of the other optics in the cavity (here it is assumed the aggregate transmission is 86 %). A $1/t^{1/4}$ time dependence for the absorption is assumed for calculating the decimal transmission at 4.0 ms for both undoped LiNbO_3 and $\text{MgO}:\text{LiNbO}_3$. The data point represented by an open circle corresponds to the case when radiation induced absorption is absent. It is illustrated by this plot that the effect of radiation-induced absorption can have a significant effect on the output of the laser, and that this effect can be reduced by using the substitute, $\text{MgO}:\text{LiNbO}_3$, as the Q-switch material. Also, a delay in the operation of the laser after the radiation pulse will

reduce the effects of radiation.

A similar calculation for radiation effects in the filter glasses can be made with great difficulty. Multiple reflections and multiple path lengths for the flashlamp radiation require tedious calculations in determining the effect of the radiation on the laser pumping. A possible method to reduce this effect is to minimize the thickness of the filter glass. It is estimated that the required thickness could be reduced to a few mm. Using the slope coefficient found for KK1 glass ($0.00828 \text{ cm}^{-1} \text{ krad}^{-1}$) and a 2.5 krad dose, the calculated transmission through a 1 mm thick sample is 99.8 % at 640 nm. More data is needed to determine the effect of radiation on the 460 nm pump band.

Summary and recommendations

Radiation-induced absorption can significantly effect the output of DOI laser if the laser is operated during a the radiation pulse. Because the path length through the LiNbO_3 Q-switch cannot be shortened appreciably, this material will give rise to the greatest radiation effect in the laser. Substitution of MgO:LiNbO_3 for LiNbO_3 reduces radiation effects to an acceptable level. Also, $\text{TiO}_2\text{:LiNbO}_3$ is a possible alternative material. The path length through the filter glasses can be shortened to minimize the effect of radiation-induced absorption on the 640 and 750 nm pump bands. Radiation-induced gain in the laser medium, Cr,Nd:GSGG , can be used to offset some of the effects of radiation-induced absorption in the laser. Gain is present only in the chromium doped material. Slope absorption coefficients and the initial time dependence given here for all the materials tested allow estimates of the induced absorption immediately and a long-time duration after the radiation pulse. This, in turn, permits calculations of the effects of the radiation on the laser output energy.

It is recommended that further studies be made on the time dependence of the filter glasses to explain the late cresting of the induced absorption. Also, more data is needed at 460 nm so that an accurate slope coefficient can be found for this wavelength. Additional data is needed for the M382 glass to determine if saturation occurs near 40 krad. More data is needed at 640 and 750 nm if more accurated absorption coefficients are needed.

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References

1. E.V. Zharikov, N.N. Il'ichev, V.V. Laptev, A.A. Malyutin, V.G. Ostrournov, P.P. Pashinin, A.S. Pimenov, V.A. Smirnov, and I.A. Schcherbakov, "Spectral, luminescence, and lasing properties of gadolinium scandium gallium garnet crystals activated with neodymium and chromium ions," *Sov. J. Quantum Electron.* 13(1), p82-85, Jan. 1983.
2. E.V. Zharikov, V.A. Zhitnyuk, G.M. Zverev, S.P. Kalitin, I.I. Kuratev, V.V. Laptev, A.M. Onishchenko, V.V. Osiko, V.A. Pashkov, A.S. Pimenov, A.M. Prokhorov, V.A. Smirnov, M.JF. Stel'makh, A.V. Shestakov, and I.A. Shcherbakov, "Active media for high-efficiency neodymium lasers with nonselective pumping," *Sov. J. Quantum Electron.* 12(12), p1652-1653, Dec. 1982.
3. V.G. Ostroumov, Yu. S. Privis, V.A. Smirnov, and I.A. Shcherbakov, "Sensitizing of Nd^{3+} luminescence by Cr^{3+} in gallium garnets," *J. Opt. Soc. Am. B* Vol. 3, No.1, p81-93, Jan. 1986.
4. J.A. Caird, M.D. Shinn, T.A. Kirchoff, L.K. Smith, and R.E. Wilder, "Measurements of losses and lasing efficiency in GSGG:Cr,Nd and YAG:Nd laser rods," *Appl. Opt.* Vol 25, No. 23, p4294-4305, Dec. 1986.
5. E.V. Zharikov, V.V. Laptev, V.G. Ostroumov, Yu. S. Privis, V.A. Smirnov, and I.A. Shcherbakov, "Investigation of a new laser active medium in the form of gadolinium scandium gallium garnet crystals activated with chromium and neodymium," *Sov. J. Quantum Electron.* 14(8), p1056-1062, Aug. 1984.
6. A. Beimowski, G. Huber, D. Pruss, V.V. Laptev, I.A. Shcherbakov, and Y.V. Zharikov, "Efficient Cr^{3+} and Sensitized Nd^{3+} : GdScGa-Garnet Laser at 1.06 μm ," *Appl. Phys B* 28 2/3, p234-235, 1982.
7. Data sheet supplied by Litton Airtron.
8. Yu. K. Danileiko, E.V. Zharikov, V.V. Laptev, Yu. P. Minaev, V.N. Nikolaev, A.V. Sidorin, G.N. Toropkin, and I.A. Shcherbakov, "Optical strength of gadolinium scandium gallium garnet active elements", *Sov. J. Quantum Electron.* 15 (2), p286 (Feb. 1985).
9. E.V. Zharikov, I.I. Kuratev, V.V. Laptev, S.P. Nasel'skee, A.I. Ryabov, G.N. Toropkin, A.V. Shestakov, and I.A. Shcherbakov, "Effect of UV- and γ -Irradiation on the Lasing Characteristics of Neodymium Lasers," *Bulletin of the Academy of Sciences of the USSR. Physical series* Vol 48, #7, p103.
10. S.E. Stokowski, M.H. Randles, and R.C. Morris, "Growth and characterization of

large Nd, Cr:GSGG crystals for high-average-power slab lasers," IEEE J. of Quantum Electron., Vol. 24, NO. 6, 934 (June 1988).

11. Data sheet supplied by Corning.

12. P.J. Brannon, D.E. Bodette, and D.A. McArthur, Radiation-induced Infrared Absorption in Nuclear-pumped Laser Cavity Components, SAND92-1255, July 1992.

13. G.W. Arnold, private communication.

14. J. Wong and C.A. Angell, Glass Structure by Spectroscopy, Marcel Dekker, Inc.

15. L.G. Karaseva, G.P. Bondarenko, and V.V. Gromov, " Investigation of Optical Active Centres of the Irradiated Lithium Niobate," Radiat. Phys. Chem 10, p241 (1977).

16. T.R. Volk, "Radiation-induced optical effects in oxygen-octahedron polar crystals," Optoelectronics, Instrumentation and Data Processing, #5, p1 (1988).

17. V.A. Antonov, P.A. Arsenev, B.A. Baranov, N.D. Barinova, E.F. Kustov, and I.G. Linde, "Radiation Defects Research in Single Crystals of Lithium Niobate," Crys. Res. and Tech. Vol. 9, #12, p1403 (1974).

18. E.R. Hodgson and F. Agullo-Lopez, "Displacement damage in LiNbO₃," Nucl. Ins. and Meth. in Phys. Res., B32, p42 (1988).

19. J. Rosa, K. Polak, and J. Kubatova, "ESR and Optical Studies of Impurity Centres in γ - and X-Irradiated LiNbO₃," Phys. Stat. Sol.(b) 111, K85 (1982).

20. F. Roeske, D.R. Jander, G.D. Lancaster, M.E. Lowry, G.M. McWright, R.T. Peterson, and W.E. Tindall, " Preliminary radiation hardness testing of LiNbO₃:Ti optical directional coupler modulators operating at 810 nm," SPIE Vol. 787 Optical Techniques for Sensing and Measurement in Hostile Environments, p36 (1987).

21. E.W. Taylor, "Geminate Recombination Behavior of a X-Ray Irradiated Single-Mode LiNbO₃:Ti Waveguide Operating at 1300 nm," J. Opt. Comm. Vol. 9, No. 2, pp64-66, 1988.

22. E.W. Taylor, "Radiation Effects Observed in Selected Guided Wave Devices," in Critical Reviews of Optical Science and Technology, SPIE Vol. CR-45, K.K. Wong and M. Razeshi editors, ISBN 0-8194-1005-4, pp 299-319, 1993.

23. P.J. Brannon, Sandia National Laboratories technical report, SAND93-2417 (1993).

24. P.J. Brannon, "Transient Radiation-Induced Absorption at 1061 nm in LiNbO_3 and MgO:LiNbO_3 ," IEEE Trans. on Nuc. Sci. Vol. 41 No. 3, p642-647, 1994.
25. V.G. Pan'kin, S.N. Petukhova, V. Yu. Pchelkin, V.V. Shashkin, and N.L. Shvarts, "Investigation of waveguides formed by diffusion of titanium in Y-cut lithium metaniobate," Sov. J. Quantum Electron. 8(2), pp 177-180, Feb 1978.
26. R.J. Esdaile, A.D. McLachlin, R.M. De La Rue, " New Aspects of Titanium Diffusion in Lithium Niobate," IEEE Quantum Electronics and application Society Tropical Meeting on Integrated and Guided-Wave Optics, Jan. 28-30, 1980, Incline Village, NV.
27. R.L. Holman, "The Optical Properties and Processing of Lithium Niobate Optical Waveguides," Proc. SPIE Int. Soc. Opt. Eng. Vol. 408, pp 14-20 (1983).
28. M. De Sario, M.N. Armenise, C. Canali, A. Carnera, P. Mazzoldi, and G. Celotti, " TiO_2 , LiNb_3O_8 and $(\text{Ti}_x\text{Nb}_{1-x})\text{O}_2$ compound kinetics during Ti:LiNbO_3 waveguide fabrication in the presence of water vapors," J. Appl. Phys. 57(5), pp 1482-1488, March 1985.
29. P.J. Brannon, "Gain in Pulsed X-Ray Irradiated Cr:Nd:GSGG ," to be published.
30. W. Koechner: Solid State Laser Engineering, 3rd Edition, Springer-Verlag, New York, Berlin, Heidelberg 1992.

Fig. 1 Prototype DOI laser.

Fig. 2 Absorption spectrum of Cr,Nd:LiNbO₃. Sample thickness: 6.35 mm, dopant concentrations: Nd = 2×10^{20} ions cm⁻³, Cr = 1×10^{20} ions cm⁻³.

Fig. 3 Peak absorption coefficient versus absorbed dose for undoped and doped LiNbO₃.

Fig. 4 Time dependence of $-\text{Log}_e(T)$ for a) undoped Virgo LiNbO_3 , b) undoped Crystal Technologies LiNbO_3 , and c) 0.5% TiO_2 : LiNbO_3 .

Fig. 5 A plot of $-\text{Log}_e(T)$ versus time for $\text{MgO}:\text{LiNbO}_3$.

Fig. 6 A plot of $-\text{Log}_e(T)$ versus time for Cr,Nd:LiNbO₃. Negative values indicate gain.

Fig. 7 A plot of $-\text{Log}_e(T)$ versus time for Nd:LiNbO₃. A zero value indicates no absorption or gain.

Fig. 8 A plot of peak values of $\text{Log}_e(T)/2L$ versus absorbed dose for Cr,Nd:LiNbO_3 . $\text{Log}_e(T)/2L$ is the small signal gain coefficient.

Fig. 9 Peak absorption coefficient versus absorbed dose for KK1 filter glass. a) 640 nm, b) 750 nm.

Fig. 10 Peak absorption coefficient versus absorbed dose for M382 glass. a) 640 nm, b) 750 nm.

Fig. 11 Peak absorption coefficient versus absorbed dose for for S7010 filter glass. a) 640 nm, b) 750 nm.

(a)

(b)

(c)

Fig. 12 Log-Log plots of $-\text{Log}_e(T)$ versus time for KK1, M382, and S7010 glasses at 640 nm. a) KK1 glass, b) M382 glass, c) S7010 glass.

Fig. 13 Log-Log plots of $-\text{Log}_e(T)$ versus time for KK1, M382, and S7010 glasses at 750 nm. a) KK1 glass, b) M382 glass, c) S7010 glass.

Fig. 14 Laser output energy versus one way 1061 nm transmission in the laser cavity. The effect of radiation-induced absorption in the LiNbO₃ Q-switch on the output is indicated by the symbols.

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