Comparative test of bulk laser-induced damage of experimental crystals at 0.85 μm

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ABSTRACT

Comparative tests of bulk laser-induced damage of some experimental crystals having prospects for laser applications were performed for evaluation of exploitation reliability of elements made from these crystals. A number of fluoride and oxide crystals doped with ions of Ce, Cr, Ti, and Zr were studied in these measurements. BK7 glass was tested under the same experimental conditions as a comparison. Pulses from a single transverse mode, Cr: LiSAF laser ($\lambda = 0.85$ μm, $\tau \sim 60$ ns) were used in these experiments. The laser radiation was focused to a small spot size (2 μm) in the bulk of these crystals to exclude the influence of inclusions and inhomogeneities on the results. Absorption spectra of these crystals were measured to be sure that there is no strong absorption in the region of the irradiating wavelength. The possible effects of dopant ions on the laser-induced damage thresholds of the crystals studied is discussed.

Keywords: crystal, dopant ion, bulk laser-induced damage, self-focusing.

1. INTRODUCTION

A very large range of crystals, both pure or doped with different ions, are used in many areas of modern laser technology. They are used as lasing elements and amplifiers of radiation in wide ranges of wavelengths (from UV up to IR) and pulse durations (from femtosecond pulses up to cw), for harmonic generation, for parametric oscillation and other applications. In most cases the optical elements made from these crystals are used for long time exposures to high-power laser radiation. Under these conditions, the main process that limits the lifetime of these elements is laser-induce damage of crystals, leading to the appearance of irreversible modifications of their bulk and surface. Crystals that are used for lasers contain dopant ions, and it is therefore important to know the effect of the dopant ion on the laser-induced damage. There are many processes in doped materials that can lead to optical radiation induced damage. Firstly, the dopant ions can combine and create small inclusions. Laser radiation is then absorbed and the consequential heating of these inclusions leads to large damage sites. Secondly, the dopant ions increase the absorption coefficient of the crystal, which can then lead to the thermal destruction of the material arising from exposure to radiation and direct heating. In addition, the heating process can also lead to a decrease of the thermal self-focusing threshold, which will also cause damage. Finally, the dopant ions, in substituting for ions of the matrix, can modify the crystals parameters, and therefore change the damage threshold of crystal. The explanation for the reduction in damage threshold with ion concentration in the first two cases is well understood [1-4]. The objective of the work is to measure the bulk laser-induced damage thresholds of several experimental crystals doped with different ions under conditions that exclude the influence of inclusions and uniformly distributed absorption, and to evaluate the possible effect of dopant ions on the damage threshold.

2. EXPERIMENTAL

The majority of samples used in this study were grown at the Center for Research and Education in Optics and Lasers. The $LiSrAlF_6$, $LiCaAlF_6$, and Ti: Sapphire samples were provided by Virgo Lightning Optical Corporation and Union Carbide. The samples were in the form of thin plates with a thickness of ~ 1 mm. These samples were originally used for a study of the spectroscopic properties (absorption, emission spectra, and fluorescence decay times) of the dopant ions in both oxide and fluoride hosts [5]. The absorption measurements were made using a Perkin-Elmer spectrophotometer.

A Q-switched, flashlamp-pumped Cr: LiSAF laser was used to irradiate the crystals in these studies. The laser produced pulsed energies of up to 15 mJ in a 60 ns (FWHM) pulse duration at a frequency of up to 10 Hz. The beam profile of the output of the laser was approximately Gaussian. It is well known that a Cr: $LiSrAlF_6$ crystal has a very broad gain bandwidth [6]. The laser oscillated with multiple longitudinal modes with a smooth temporal profile. This feature leads to a low statistical variance of the instantaneous power of each laser pulse and allowed us to measure the damage thresholds with an accuracy of ~ 20 % [7].

Since all the samples had a small thickness, the damage thresholds of these crystals were measured under conditions of a very tightly focused laser beam thereby excluding surface breakdown. The spot size of focused laser beam was ~2 μm. Optical damage was detected by the usual methods: (a) by the appearance of a spark in the bulk of the sample, (b) by observing the scattering of a coaxial beam of a green He-Ne laser (λ=0.63 μm), and (c) by the visual observation of a damage region with a Nomarski microscope. Specially care was taken to ensure to absence of a spark on both front and rear surfaces of the samples during experiment. When was necessary, the temporal shape of transmitted laser pulse was also measured to detect the moment of damage during the laser pulse.

3. RESULTS AND DISCUSSION

The absorption spectra of each sample was measured to be sure that there was no significant linear absorption in the spectral region of the irradiating laser. It was found that each of these crystals had very low absorption losses in the 0.85 μm region. Usually the absorption is concentrated in the absorption bands of the dopant ions. As an example, the absorption spectra of Ce^{3+} ions in different matrixes are shown in Fig.1. One can see that all absorption is concentrated in the visible and UV spectral regions. No losses were registered in near IR region. As can be seen the statistical variance of the laser-induce damage thresholds did not exceed 20%. We conclude therefore that damage threshold measured was that of these crystals themselves, and not inclusions. Additional evidence for this was obtained from experiments on the temporal truncation of the transmitted pulses and from the morphology of the damage area.

Photographs of the damaged sites in the bulk $Cr:LiSrAlF_6$ crystal are shown in Fig.2. The damage site in Fig.2a was obtained with laser radiation focused to a spot size of 2 μm. One can see that it has a selective direction and consists of two separated points. Damage sites in the bulk of BK7 glass had an analogous appearance under similar conditions. A study of the temporal shape of the transmitted pulses in this case showed that when the pulse energy slightly exceeded the threshold energy, the damage occurred a few nanoseconds after the peak of the pulse (Fig.3a). Similar data were obtained for all the crystals studied. When damage occurs as a result of breakdown associated with inclusions, the damage sites had a characteristic appearance (Fig.2b), that was observed in one of the first papers devoted to inclusion breakdown [1]. In this case the damage area obscured a small part of the laser beam and thus there was no sharp truncation of the temporal shape of the transmitted pulse (Fig.3b). The data for a spot size of 10 μm are shown in Fig.2b and 3b. A 10 μm spot size was used instead of a 2 μm spot size due to the difficulty in finding inclusion sites.

Thus, in summary the laser-induced optical damage of the crystals studied is similar to the optical damage occurring in BK7 glass and had following features:

- only a small variation of the damage thresholds (< 20 %) from one point to another was observed for each sample;
- damage occurred on the same depth from the front surface for each sample;
- the morphology of the damage sites were similar for all damaged regions;
- the damage sites had a similar form for all crystals and for the BK7glass;
- at threshold transmitted pulses were truncated in a few nanoseconds after the peak of laser pulse for all materials, and the threshold irradiance at the moment of damage increased when the time of the interaction was decreased;
- the central part of the damage site always had a distinctive direction.

A similar investigation performed earlier with K8 glass [8] showed that this set of characteristics is associated with damage resulting from self-focusing.

A summary of the data on laser-induced damage thresholds of the crystals studied and of BK7 glass is shown in Fig.4. The values of the damage thresholds are also given in Table 1. A few conclusions can be drawn from this data. A comparison of rows 4 and 5 in Table 1 shows that the concentration of the dopant ions does not have a strong effect on the damage threshold of the crystal. Moreover, it is believable from rows 6, 7 and 9 that the damage threshold remains constant for different types of dopant ions in the matrix if the dopant ions substitute for the same ion in the matrixes (as for the cases of Ti, Ce, and Zr ions substituting for Y ions). On the other hand, rows 10 and 15 show that if the dopant ions substitute for different ions of the same matrix, the damage threshold for this crystal can differ (Ce ions substitute Sr ions, and Cr ions substitute Al ions) substantially. These characteristics demand further study.

4. CONCLUSIONS

A comparative test of bulk laser-induced damage of many fluoride and oxide crystals doped with ions of Ce, Cr, Ti, and Zr under irradiation of focused nanosecond radiation from a Q-switched Cr: $LiSrAlF_6$ laser at 0.85 μm wavelength has allowed us to make the following conclusions:

- laser-induced damage of these crystals is a result of self-focused laser radiation;
- there is no significant dependence of the damage thresholds of these crystals on the concentration of the dopant ions or their type if the ions substitute for the same ion in the matrix;
- significant differences in the damage thresholds of crystal doped by different ions are observed if these ions substitute for different ions in the same matrix.

Two last conclusions demand further study.

5. REFERENCES

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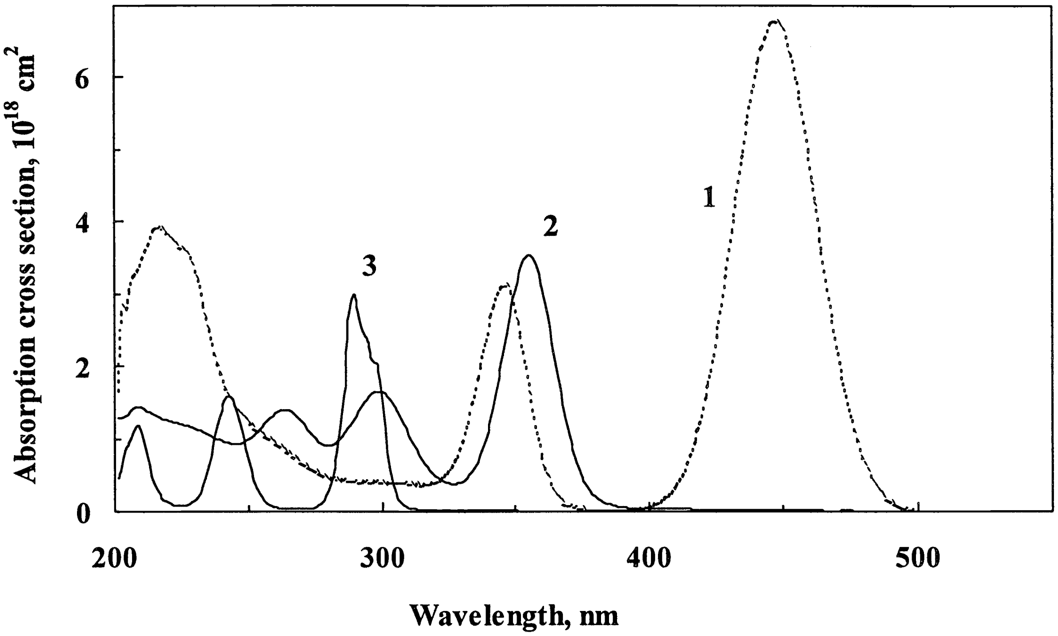

Fig.1. Absorption spectra of Ce^{3+} ions in different matrixes: 1- $Lu_3Al_5O_{12}$; 2– Y_2SiO_5; 3– $LiYF_4$.

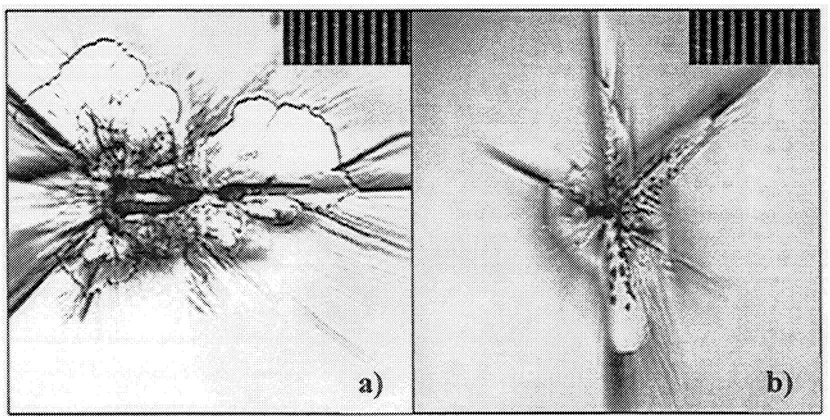

Fig.2. Pictures of damage sites in Cr:$LiSrAlF_6$ crystal bulk (scale division – 10 μm):

a) damage as a result of self-focusing;

b) damage as a result of inclusion breakdown.

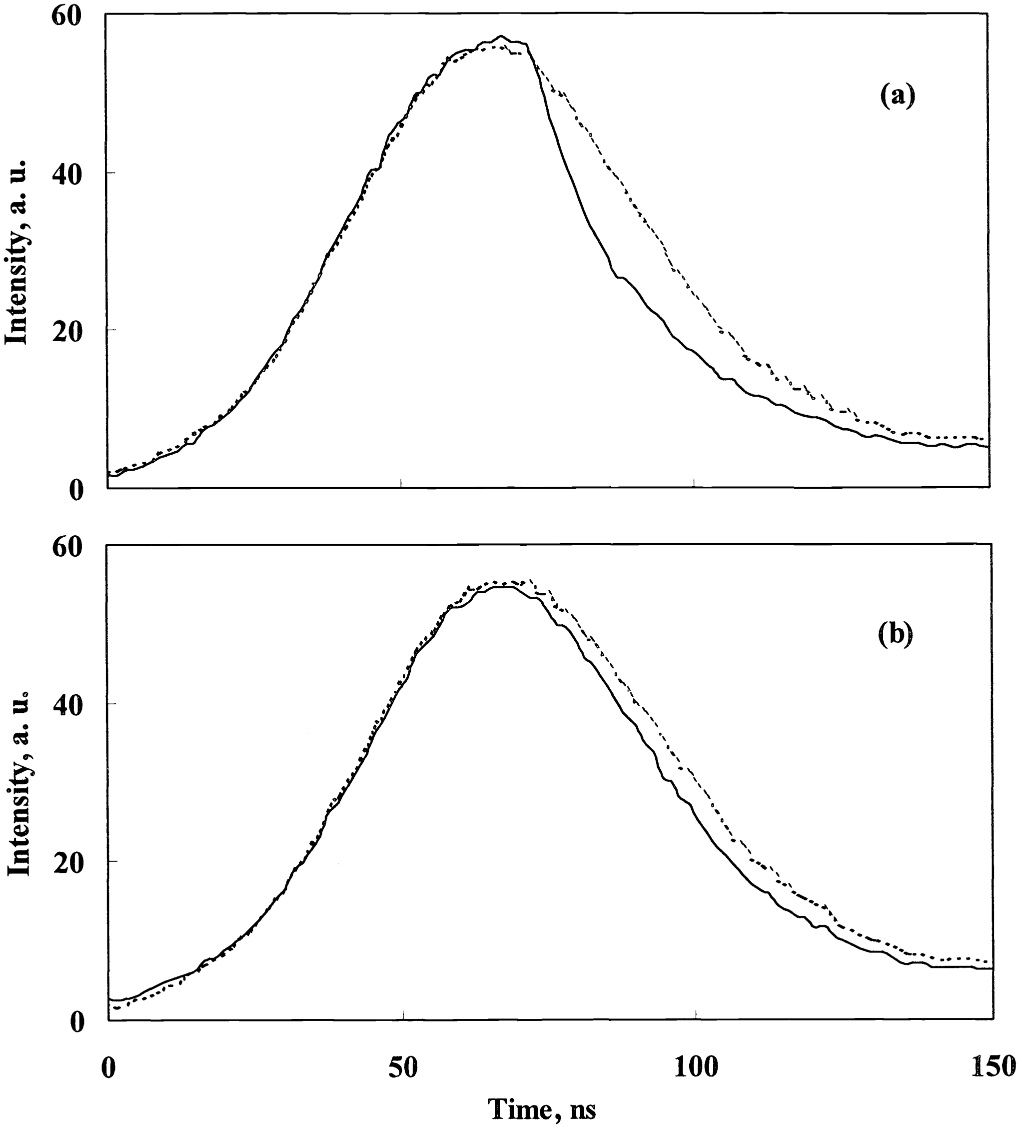

Fig.3. Temporal shape of laser pulses transmitted through Cr: $LiSrAlF_6$ crystal bulk (dash lines – no damage):

a) damage as a result of self-focusing ($d_f = 2$ μm);

b) damage as a result of inclusion breakdown ($d_f = 10$ μm).

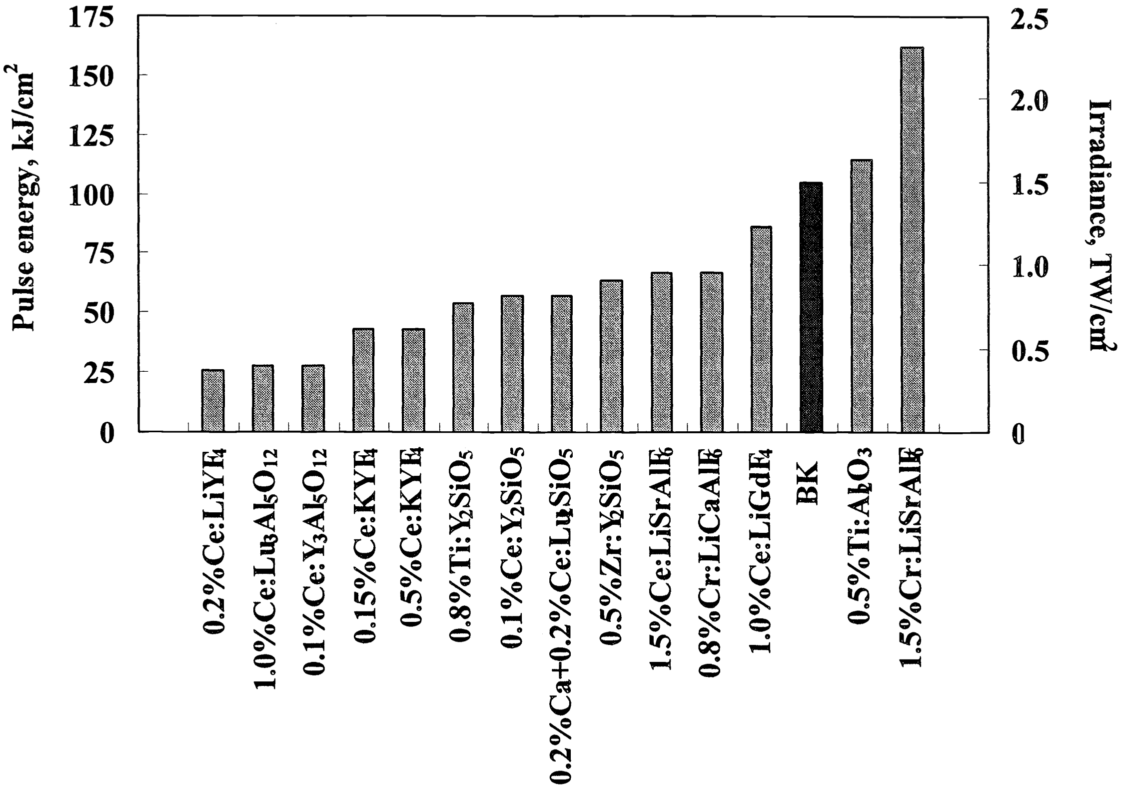

Fig.4. Laser-induced damage thresholds of experimental crystals and BK7 glass.

Table 1.

##	Matrix	Dopant	C, %	E, mJ	W, kJ/cm^2	I, TW/cm^2
1	$LiYF_4$	Ce	0.20	0.81	26	0.37
2	$Lu_3Al_5O_{12}$	Ce	1.00	0.86	27	0.39
3	$Y_3Al_5O_{12}$	Ce	0.10	0.86	27	0.39
4	KYF_4	Ce	0.15	1.35	43	0.61
5	KYF_4	Ce	0.50	1.35	43	0.61
6	Y_2SiO_5	Ti	0.80	1.70	54	0.77
7	Y_2SiO_5	Ce	0.10	1.80	57	0.82
8	Lu_2SiO_5	Ce, Ca	0.20 + 0.20	1.80	57	0.82
9	Y_2SiO_5	Zr	0.50	2.00	64	0.91
10	$LiSrAlF_6$	Ce	1.50	2.10	67	0.96
11	$LiCaAlF_6$	Cr	0.80	2.10	67	0.96
12	$LiGdF_4$	Ce	1.00	2.70	86	1.23
13	BK7	boro-silicate glass		3.30	105	1.50
14	Al_2O_3	Ti	0.50	3.60	115	1.64
15	$LiSrAlF_6$	Cr	1.50	5.10	162	2.32