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Laser Damage Threshold of Ceramic YAG

Jean-François BISSON*, Yang FENG, Akira SHIRAKAWA, Hitoki YONEDA, Jianren LU, Hideki YAGI[1], Takagimi YANAGITANI[1] and Ken-Ichi UEDA

Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofu-Gaoka, Chofu, Tokyo 182-8585, Japan
[1]*Konoshima Chemical Co., Takuma Works, 80 Koda, Takuma-cho, Mitoyo-gun, Kagawa 769-1103, Japan*

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Bulk laser damage thresholds of doped and undoped ceramic $Y_3Al_5O_{12}$ (YAG) materials are reported. These materials were found to resist 100 J/cm^2, 4-ns pulses at 1.064 μm wavelength. Single-crystal YAG materials of similar composition yielded similar damage thresholds. Hence, ceramic microstructure does not contribute to lower damage threshold. Beam-size dependence of damage threshold fluence was also studied by repeating the experiment using a lens with a longer focal length. The evolution of damage probability with laser fluence was found to strongly depend on the beam diameter; however, damage threshold was not found to vary significantly with beam diameter. [DOI: 10.1143/JJAP.42.L1025]

KEYWORDS: YAG, ceramics, laser, damage, microstructure, defects

Ceramic YAG laser materials have become an attractive alternative to single crystal materials because of their ease of manufacture, low cost and scalability. The ceramic YAG fabrication technology[1–3)] is now sufficiently mature to produce materials that compare favorably with the best single crystals with respect to key lasing properties.[4–7)] Because ceramic materials are easy to fabricate in large sizes, they are particularly well suited for high power applications. Such applications will require the material to withstand high fluences. For instance, design criteria for the laser fusion driver require the laser-induced damage threshold (LIDT) to be several times larger than the emission saturation fluence.[8,9)] In the nanosecond pulse-width regime, damage is known to arise from defects, such as impurities, or other imperfections that absorb laser radiation or distort the wave front.[10–12)] As shown in Fig. 1, ceramic YAG materials, unlike single crystals, are made up of several micron-size grains. Whether grain boundaries contribute to lower the LIDT has been so far an open question. This work intended to provide the first LIDT data for ceramic YAG from a Q-switched YAG laser delivering nanosecond pulses.

Pulses of 4-ns width at 1.064 μm from a Q-switched YAG laser were used for this experiment. Pulse energy was adjusted by using a variable attenuator, consisting of a halfwave plate placed between two polarizers. In order to probe the bulk material and avoid surface damage, tight focusing was required. Lenses of 5-cm or 10-cm focal lengths were used. Beforehand, calibration of the absolute energy density (J/cm^2) delivered to the sample was done and involved the following steps. First, total pulse energy was monitored by a photodiode receiving a small calibrated fraction of the pulse energy. Then, the beam profile was measured by imaging the beam profile on a CCD camera. The beam profile was found to be nearly Gaussian. Next, a pinhole was adjusted in the middle of the beam waist to measure the average energy density inside an area smaller than the beam diameter. Finally, information on the average energy density and beam profile were combined to obtain the maximum on-axis fluence. Beam quality was also estimated beforehand, by measuring the beam divergence: the M^2 parameter[13)] value was about two in the both transverse directions.

Damage was detected by using a He-Ne laser beam focused on the irradiated site: onset of damage was clearly visible since it caused most of the probe beam to be scattered. Occurrence of damage, as deduced by scattering, was confirmed afterward by observing the irradiated sites under a microscope. The range of fluence levels was chosen as to cover 0% to 100% damage probability. Because of the statistical aspect of damage at the nanosecond scale, at least 30 sites were irradiated at each fluence level, and up to 200 sites were irradiated at fluence levels yielding low damage probabilities. A damage probability at given fluence level was estimated from the fraction of damaged sites obtained at some fluence level. Each site received only one pulse, for each of which the pulse width and pulse energy were monitored. Interval between irradiated sites was 300 μm.

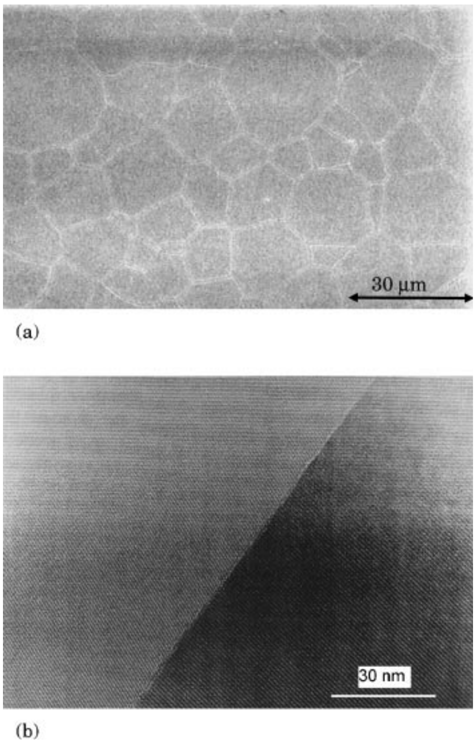

Fig. 1. Pictures of a typical ceramic YAG grain boundaries obtained by scanning electron microscopy (Fig. 1(a)) and Transmission Electron microscopy (Fig. 1(b)).

Undoped and 0.7%-Nd doped, 1-cm thick polished ceramic samples, were provided by Konoshima Chemical

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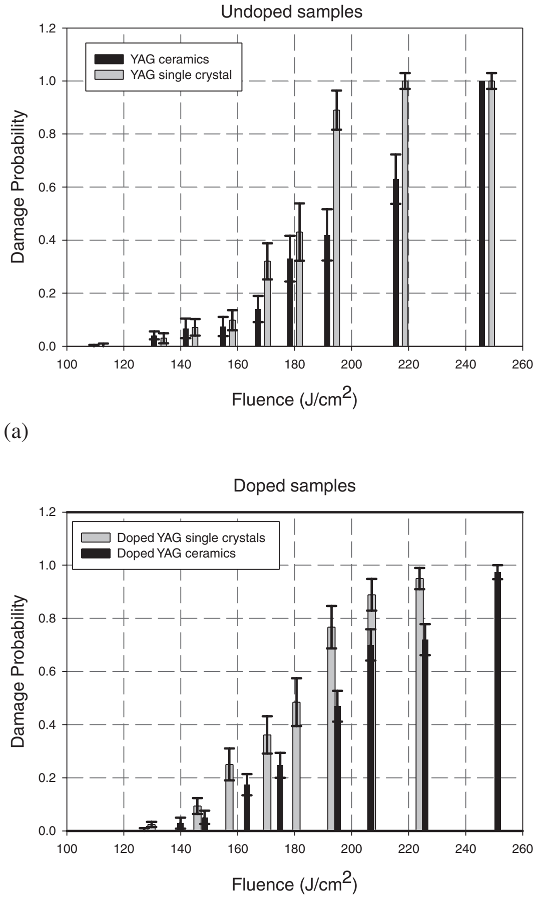
*E-mail address: Bisson@ils.uec.ac.jp

Table I. Experimental conditions used for damage measurements.

Laser	Flashlamp-pumped Q-switched YAG Continuum Surelite
Wavelength (μm)	1.064
Pulse duration (full width at half maximum) (ns)	4.5 ± 0.6
Beam profile and waist, ω. (μm)	Gaussian ($M^2 \approx 2$) $\omega_x = 18$, $\omega_y = 16$ ($f = 5$ cm) $\omega_x = 28$, $\omega_y = 29$ ($f = 10$ cm)
Polarization	Linear
Distance between tested sites	300 μm
Total number of shots	>500

Corp, whereas single crystals, of similar thickness, doping concentrations and surface quality, originated from Shanghai China Science Scarbo Opto-Electronic Materials Co. Damage experiments were also performed on fused silica Suprasil, from Shin-Etsu Chemical Co., for comparison. Experimental parameters used in this work are summarized in Table I.

The evolution of damage probability as a function of fluence, obtained for undoped ceramic and single crystal materials with the 5-cm lens, is displayed in Fig. 2(a). A similar result obtained on doped materials is shown in Fig. 2(b). The damage probability of the single crystal was found to increase more sharply with laser fluence than its ceramic equivalent; however, no significant difference in LIDT was found. Similar LIDT values were found for doped samples. Extrapolation of the low probability data to the fluence yielding zero damage probability indicates that LIDT is around 100 ± 10 and $110 \pm 10\,\mathrm{J/cm^2}$ for undoped and doped samples respectively. Damage results are summarized in Table II. Results for fused silica are also given for comparison. The LIDT of silica, $280 \pm 15\,\mathrm{J/cm^2}$, is found to be nearly 3 times as high as that of YAG samples. Published data for bulk LIDT of fused silica vary considerably from one work to the other. Recently, Natoli *et al.*[11] have found a LIDT value of $185\,\mathrm{J/cm^2}$ for 7-ns pulse duration at 1.064 μm. But other values, up to $2640\,\mathrm{J/cm^2}$ for 24-ns pulses, have also been reported.[14] Note that the threshold fluence increases approximately with the square-root of pulse duration, τ.



(a)

(b)

Fig. 2. Damage probability versus fluence obtained on undoped (Fig. 2(a)) and doped (Fig. 2(b)) ceramic YAG and single crystal.

Table II. Summary of bulk LIDT results. The LIDT value found for fused silica is given for comparison.

Material	Damage threshold ($\mathrm{J/cm^2}$)
Fused silica (Suprasil)	280 ± 15
Undoped YAG ceramics	100 ± 10
Undoped YAG single crystal	100 ± 10
Doped YAG ceramics	110 ± 10
Doped YAG single crystal	110 ± 10

The statistical nature of damage in the nanosecond regime has been successfully interpreted as the probability that some defect be irradiated at a fluence exceeding the defect damage threshold. This probability depends on defect concentration and defect intrinsic threshold fluence, as well as on the beam geometry. Mathematical expressions have been derived in the case of Gaussian beam illumination.[11,15,16] Bulk damage probability at low fluence is found to be proportional to the Raleigh volume, which is proportional to the fourth power of the beam waist, ω^4. Thus, increasing the lens focal length should reduce statistical variability and enable more accurate determination of the materials LIDT. Thus, measurements were done again by focusing the laser beam using a lens with 10-cm focal length. With such lens, only fluences yielding low damage probabilities could be used because focusing was not tight enough to avoid damage at the front surface at higher fluences.

The evolution of damage probability, obtained with the 10-cm and 5-cm focal-length lenses, is compared in Fig. 3(a) and Fig. 3(b) for undoped ceramics and single crystal respectively. Damage threshold fluence, obtained by extrapolating the damage probability results to 0, was found to be close to $100\,\mathrm{J/cm^2}$, which is similar to the result obtained with the 5-cm lens. Hence, LIDT result appears not to strongly depend on the beam size. However, damage probability above threshold was found to be about 8 times larger with the 10-cm lens, which is consistent with the $(\omega_{10\mathrm{cm}}/\omega_{5\mathrm{cm}})^4 \approx 8$-fold laser beam volume enhancement.

However, it would be risky to conclude that the thresholds reported in this work apply for large components such as those used for the laser fusion driver. Threshold mentioned herewith are the result of a statistical study performed on around 500 sites (200 for the 10-cm lens). The Raleigh volumes are $7 \times 10^{-4}\,\mathrm{mm^3}$ and $6 \times 10^{-3}\,\mathrm{mm^3}$ respectively, so

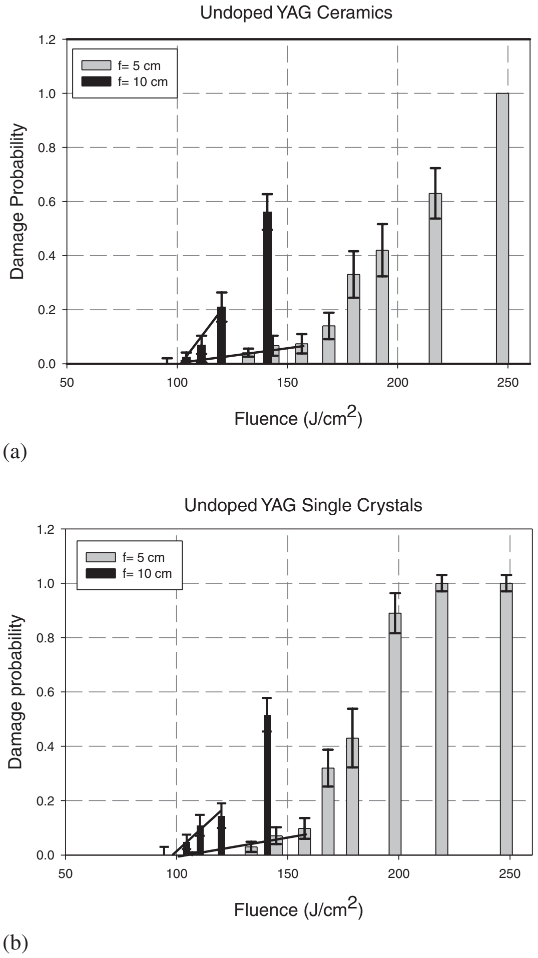


Fig. 3. Damage probability versus fluence obtained on undoped ceramics (Fig. 3(a)) and single crystals (Fig. 3(b)) using 5-cm and 10-cm focal length lenses. Zero-probability damage fluences are found to be similar in both cases. Straight lines are drawn as a guide for the eye.

that the total sample volume that was used to characterize the samples is in the order of 1 mm^3 or less. Therefore, the thresholds mentioned herewith are representative of defects that are present in concentration of the order of one part per mm^3 or more. Our measurements are not sensitive to defects that are present in concentrations significantly smaller than one part per mm^3. Defects present in very low concentrations and having lower threshold fluence would certainly impact on the performance of large components. The scaling of LIDT with beam diameter has been studied by several authors in the context of surface damage (see ref. 17 for several interesting articles); round-robin experiments performed with various experimental conditions yielded an empirical scaling law of LIDT with beam diameter 2ω, ω^{-n}, with n between 1 and 2.[18] However, the detailed dependence of LIDT with beam diameter is very difficult to predict because it depends on the defect density at each fluence.[12]

The nature of the critical defects causing damage in our experiment is not well established but the fact that the threshold values are almost the same for single crystals as for the ceramics suggests that they must be present in both single crystals and ceramics samples. Therefore, grain boundary as the main damage source appears unlikely. This may result from the fact that that grain boundaries arising from the non-press vacuum sintering method, are deprived of any secondary phase and can be as thin as one atomic layer, as can be seen in transmission electron microscope photographs in Fig. 1(b). Self-focusing is another phenomenon that may reduce LIDT for large beam diameters. Self-focusing depends mainly on the total power. As the beam diameter increases, the required power approaches the critical self-focusing power. Therefore, extrapolation of these results to large size components is at best difficult. However, this work suggests that large size ceramic YAG components would perform as well as crystal of similar dimensions, in as much as it would be possible to grow such large crystal.

In conclusion, ceramic YAG samples were found to display similar LIDT as single-crystals. Doping does not seem to affect the material resistance to high fluence. Similar threshold fluences were found for two different beam diameters but the variability of damage probability with fluence was found to be greatly reduced by increasing the beam diameter. These results are consistent with the interpretation of damage as caused by some defects randomly dispersed in the materials. Comments and discussion are welcome to help elucidate the source of damage in these materials.

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