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Radiation effects on laser damage in KU1 quartz glass

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Abstract

Both in-beam and post-irradiation effects on laser damage have been studied for three different materials: high purity UV grade sapphire, common glass and KU1 quartz glass. No in-beam effects have been observed. Notable changes in the laser damage sensitivity due to the accumulated dose occur in common glass and KU1 quartz glass, but not in sapphire. KU1 quartz glass becomes less sensitive with increasing dose, and one concludes that this material may be used as a window for LIDAR systems at dose rates of at least 70 Gy/s, to total doses of up to 100 MGy.

1. Introduction

Light detection and ranging (LIDAR) is one of the important promising diagnostic systems being considered for use in ITER. The system employs a high intensity laser beam which must pass along the diagnostic channel containing windows and mirrors. The window material used to transmit the high intensity laser beam must be not only highly transparent but also highly radiation resistant. If the laser intensity is too high the window material may suffer dielectric breakdown due to the high electric field associated with the laser beam, and as a consequence the window may break. In general this kind of damage initially appears in the form of craters and/or cracks near the surface, and is accompanied by light emission and noise resembling a small explosion [1–3]. A review on laser-induced breakdown in transparent dielectrics can be found in reference [4].

Damage in transparent materials does not exhibit a sharp threshold with laser intensity, but rather the sensitivity to laser damage is well characterized by curves representing the probability of damage as a function of laser beam intensity [1]. Although data on the sensitivity of different materials to laser damage exist [1,5] the effect of radiation is almost unknown. In the case of the LIDAR diagnostic system the possibility of radiation modifying the laser damage 'threshold' must be considered, as this may impose a serious limitation. The work reported here is concerned with the radiation effects on laser damage in KU1 quartz glass, a highly radiation resistant material being considered for window applications [6]. In order to obtain a more extended knowledge about the phenomenology involved, the study has also included high purity UV grade sapphire and common glass.

Both in-beam and post-irradiation effects on laser damage sensitivity have been studied. No in-beam effects have been observed in any of the three materials studied at dose rates up to 70 Gy/s. However, an increase in sensitivity with irradiation dose occurs in common glass while a decrease for KU1 quartz glass has been observed. In the case of sapphire, known to be highly radiation resistant, no radiation dose effects were observed.

2. Experimental procedure

Samples of optically polished Union Carbide UV grade sapphire, common glass, and KU1 quartz glass (kindly provided by the Russian Federation within the ITER project) were irradiated at 20°C in air at the end of the beam line of a 2 MeV Van de Graaff accelerator with 1.8 MeV electrons. A lead shielded Nd:YAG laser was installed such that its optical axis formed 45° with the accelerator axis and both axes were coincident at the sample position as may be seen in Fig. 1. The samples,

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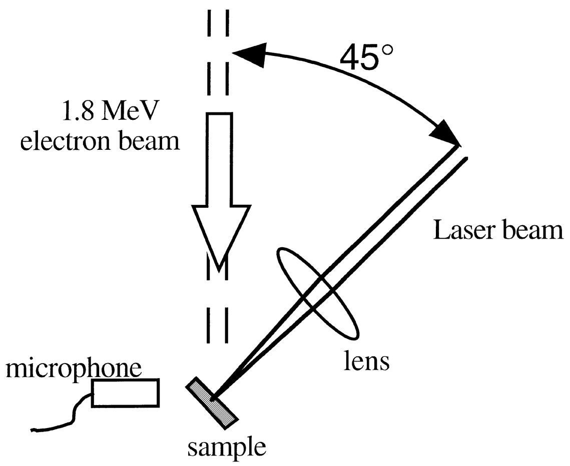

Fig. 1. Experimental set-up.

approximately $10 \times 10 \times 1$ mm^3, were mounted in a holder which could be remotely moved vertically and horizontally from the accelerator control room and the position determined to about 0.1 mm. The laser beam direction was normal to a 10×10 mm^2 sample surface and using a 50 mm focal length lens the light was focused in the bulk of the sample to be irradiated. A shielded directional microphone was placed so that if the laser beam damage occurred a typical signal produced by the noisy explosion was observed in an oscilloscope in the control room. In this way the concurrent effect of laser and electron irradiation has been studied at 70 Gy/s and 10^{-11} dpa/s, within the range of expected ionizing dose rates for LIDAR windows (10–100 Gy/s).

Measurements of laser damage were carried out in situ before, during, and after electron irradiation, at the same laser power density conditions, so that the electron irradiation effect on laser damage sensitivity could be compared. Before electron irradiation samples were laser irradiated, increasing laser power until damage was observed, then the sample was moved 0.5 mm. horizontally in the focal plane of the lens so that a new material zone could be tested. Measurements at different laser power densities were performed for 60 different positions. Once measurements before electron irradiation had been completed the sample was moved down 1 mm and then measurements during electron irradiation were carried out. After electron irradiation samples were moved down a further 1 mm and then measurements were carried out in order to study possible dose effects. Sapphire and common glass were irradiated to 0.045 MGy, while the KU1 candidate window material was irradiated to 10 MGy.

The Q-switched Nd:YAG laser used in this work generates 1064 nm wavelength pulses of 7 ns duration with a maximum energy of 330 mJ. The focal spot size on target was 30 μm, producing an equivalent power in the range 1×10^{14}–6.7×10^{16} W/m^2. Laser power and trigger were set from the control room.

3. Results

Fig. 2 shows the damage probability as a function of laser power density for unirradiated sapphire, common glass and KU1 quartz glass in the range 1×10^{14}–6.7×10^{16} W/m^2. As can be seen the probability for laser damage in sapphire is high even at low laser power density, whereas KU1 quartz glass shows a high resistance to laser damage. Sapphire and common glass show 100% probability to be damaged by 3×10^{16} W/m^2 but at this power density KU1 is not damaged at all. For KU1 it was not possible to reach a probability of damage higher than 30% even at the highest laser power density available.

In Fig. 3 damage probability curves are given for common glass before, during and after irradiation.

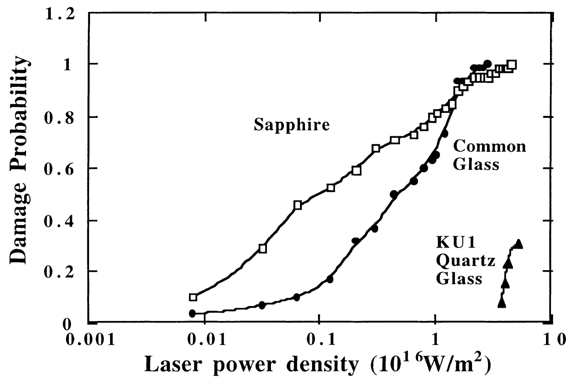

Fig. 2. Damage probability as a function of laser power density for the three unirradiated materials.

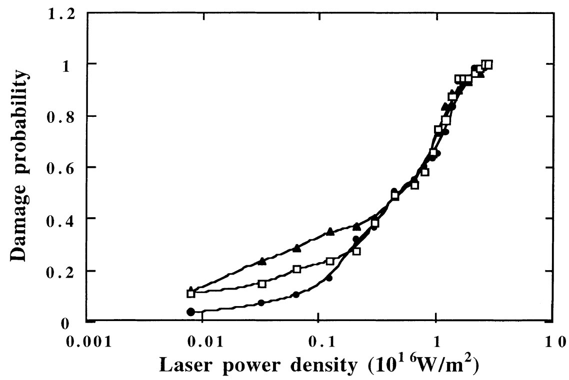

Fig. 3. Damage probability as a function of laser power for common glass unirradiated (○), irradiated up to 0.02 MGy (□) and 0.045 MGy (△).

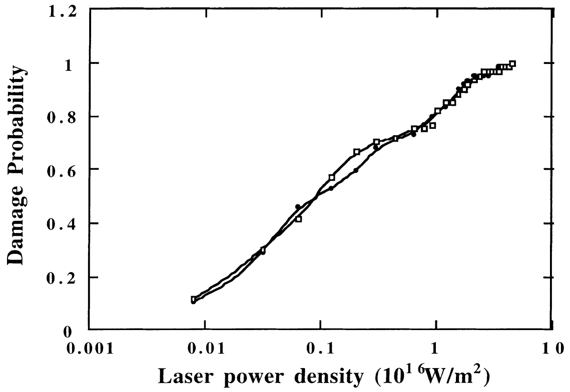

Fig. 4. Damage probability as a function of laser power density for unirradiated (○) and irradiated sapphire up to a dose of 0.045 MGy (□).

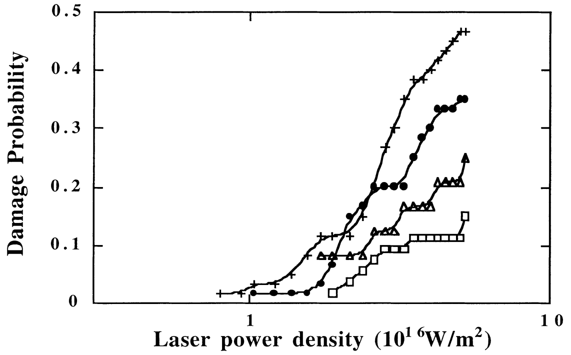

Fig. 6. Damage probability as a function of laser power for KU1 quartz glass in which the exit beam face was roughly polished. The curves are given for the unirradiated (×), irradiated up to 0.02 MGy (○), 0.045 MGy (□) and 20 h after irradiation (△).

Clearly after irradiation the material is more sensitive. The evolution with dose indicates that the increase observed during irradiation is due to the accumulated dose. The results for sapphire are shown in Fig. 4. In this case no radiation effects were observed.

As KU1 quartz glass is a candidate material to be used for diagnostic windows, it was irradiated up to 10 MGy. The results for this material can be seen in Fig. 5. After irradiation, sensitivity to laser damage was markedly less and for the highest power, damage probability was reduced to 15%. It is known that the surface condition may notably influence the material sensitivity to laser beam damage due to local electric field enhancement [4]. For KU1 it was observed that the sensitivity to damage is increased when the exit laser beam side was not optically polished, see Fig. 6. Taking advantage of this enhanced sensitivity another similar KU1 sample was irradiated. The results for this sample are shown in Fig. 6, and agree with those obtained for samples with both sides optically polished (Fig. 5) i.e. radiation decreases the sensitivity to laser damage. The decrease in sensitivity with dose is observable by 20 kGy indicating that the effect is due to ionizing radiation rather than to displacement damage processes. A slight recovery was observed 20 h after irradiation.

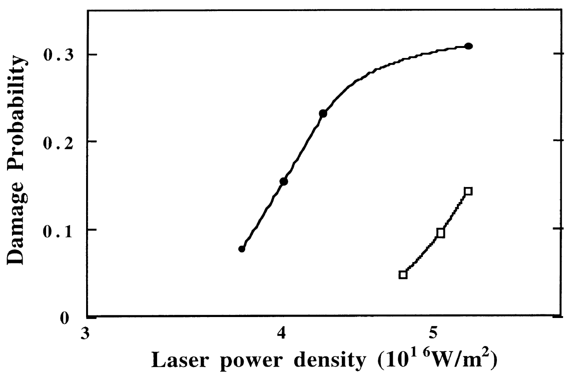

Fig. 5. Damage probability as a function of laser power for unirradiated (○) and irradiated KU1 quartz glass up to 10 MGy (□).

4. Discussion

No in-beam effects have been observed for any of the three materials studied here. Laser damage in transparent dielectrics occurs in a similar way to DC dielectric breakdown in insulators i.e. an electron avalanche process [1–5]. Excitation of electrons from the valence to the conduction band by ionizing radiation will increase the quantity of 'seed' electrons available to start an avalanche and hence the probability for laser damage should also increase. Radiation induced conductivity for UV grade sapphire at 70 Gy/s is of the order of 10^{-7}–10^{-8} S/m [7] and the conduction band electron mobility is 3×10^{-4} m^2/(V s) [8]. Electrical conductivity is given by $\sigma = qn\mu$, where q is the electron charge, n the carrier density and μ is the electron mobility. Hence n is of the order of 10^{14}–10^{15} electrons/m^3 for a dose rate of 70 Gy/s. This value is approximately one order of magnitude less than the estimated density of seed electrons necessary to start an avalanche (10^{15}–10^{17} electrons/m^3) [5]. For common glass and KU1 quartz glass there is not sufficient data on RIC and conduction band electron mobility to make a similar comparison. For sapphire, KU1, and common glass at 70 Gy/s no increase in laser damage sensitivity has been observed, hence we may conclude that the increase in density of conduction band electrons is too small to provoke dielectric breakdown. However, in the case of sapphire breakdown may occur

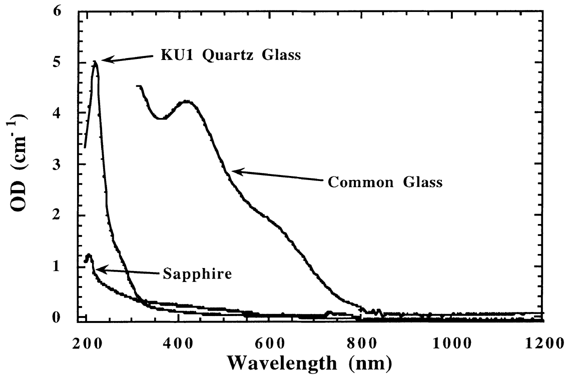

Fig. 7. Optical absorption spectra for common glass irradiated up to 0.045 MGy, and KU1 quartz glass and sapphire irradiated up to 10 and 130 MGy, respectively.

for dose rates approximately 10 times higher. This possibility is being examined.

The second aspect considered in this work is the effect of the accumulated radiation damage or dose effect. Very different responses have been observed for the three materials. While for sapphire no effect has been seen (Fig. 4), in the case of common glass and KU1 quartz glass marked changes occur. The sensitivity to laser damage increases in the case of common glass (Fig. 3) whereas it decreases in the case of KU1 quartz glass (Figs. 5 and 6). That no effect is observed for sapphire is most probably a consequence of the low sensitivity of this material to ionizing radiation. This is illustrated in Fig. 7, where radiation induced optical absorption spectra for the three materials are given. For common glass by 0.045 MGy considerable absorption is produced. In the case of KU1 even by 10 MGy (10^{-6} dpa) the absorption is considerably less and restricted to the UV region. At these dose levels the absorption for sapphire is negligible, as may be seen in the spectrum for sapphire taken from Ref. [9] for 130 MGy. This would suggest that the observed changes in the damage threshold for the glass materials are due to purely ionizing radiation. In the case of KU1 radiation induced absorption data indicates that by 10 MGy the absorption bands have reached saturation and that even by 100 MGy no further change occurs [10,11].

5. Conclusions

KU1 quartz glass may be used with confidence for LIDAR windows at ionizing dose rates of at least 70 Gy/s and doses in excess of 10 MGy, probably to at least 100 MGy, for systems operating at about 1000 nm.

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