Reliability of laser safety eye wear in the femtosecond regime

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Abstract: Appropriate eye protection is a prerequisite for the safe operation of ultrashort laser systems in industrial and laboratory environments. In this paper we report on the measurement of the transmission of ion-doped phosphate glass filters for pulses having a center wavelength of 800nm, a duration of 10fs to 1.2ps and a fluence range of 0.01 to 30J/cm^2. The measurements suggest, that the filter material preserves its protective features over the whole range. Saturation of absorption was only observed in the picosecond pulse duration range.

OCIS codes: (140.3360) Laser eye protection; (140.3330) Laser damage; (140.3440) Laser-induced breakdown; (160.4760) Optical properties

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References and Links

1. W. Koschinski, A. Schirmacher, E. Sutter, "Induced transmittance of eye-protective laser filters," J. Laser Applications **10**, 126-130 (1998).
2. A. Schirmacher, E. Sutter, O. Werhahn, U. Siegner, A. Nevejina-Sturhahn, "Investigation of the irradiance dependent spectral transmittance of laser filters in the nanosecond and femtosecond impulse regime in the wavelength range between 700nm and 800nm," Int. Laser Safety Conference 2003
3. M. Lenzner, J. Krüger, S. Sartania, Z. Cheng, C. Spielmann, G. Mourou, W. Kautek , F. Krausz, "Femtosecond optical breakdown in dielectrics," Phys. Rev. Lett. **80**, 4076-4079 (1998).
4. B. C. Stuart, M. D. Feit, A. M. Rubenchik, B. W. Shore, M. D. Perry, "Laser induced damage in dielectrics with nanosecond to subpicosecond pulses," Phys. Rev. Lett. **74**, 2248-2251 (1995).
5. A. Schirmacher, E. Sutter, "Induced transmittance in alexandrite laser-eyeprotectros - a survey of different types of laser filters," Optics and Laser Technology **33**, 359 –362 (2001).
6. S. Sartania, Z. Cheng, M. Lenzner, G. Tempea, C. Spielmann, F. Krausz, K. Ferencz, "Generation of 0.1-TW 5-fs optical pulses at a 1-kHz repetiton rate," Opt. Lett. **22**, 1562-1565 (1997).
7. J. Krüger, M. Lenzner, S. Martin, M. Lenner, C. Spielmann, A. Fiedler, W. Kautek, "Single- and multi-pulse femtosecond laser ablation of optical filter materials," Applied Surface Science **208-209**, 233-237 (2003).

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1. Introduction

The tremendous progress in ultrafast optics facilitates the widespread use of short pulse laser systems. Nowadays intense femtosecond laser pulses with terawatt peak power are available from commercial systems. They find application in laser micromachining as well as in industrial and medical fields. The extensive use of short-pulse laser systems calls for appropriate protective eye wear which ensures safe working conditions in all operational ranges. Among numerous absorber materials, glass filters doped with metal ions and their oxides are successfully applied in order to attenuate laser radiation to an eye-safe level. The nominal transmission and the wavelength range of the filters are controlled by the density and sort of the dopant ions, respectively. However, most of the available filter materials are well

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characterized only in terms of linear methods. Only a few measurements performed with pulses as short as some nanoseconds have been published in the literature.

Using femtosecond laser pulses several problems arise: i)ultrashort laser pulses have a large bandwidth making the usage of broadband filters essential, ii)saturation of the absorption is easily attainable with femtosecond lasers due to high pulse intensity causing reduction of the optical density, and iii) in general, the damage fluence of materials drops with decreasing laser pulse duration. In the following we will report on transmission and reflectivity measurements of a glass filter applied for laser protective eye wear. The host material of the filter is amporphous phosphate glass containing up to 70% of P_2O_5. The doping ions are Cu^+, Cu^{2+}, Ce^{3+}, and their oxides. The investigated filter material has a high linear absorption coefficient (α_0=9.43mm^{-1} @ 800nm) over a reasonable bandwidth, which enables high optical densities for usual filter thicknesses of several millimeters, making the filter ideally suited for blocking radiation from Ti:sapphire laser systems. We opted for this type of material, because similar materials are also used by numerous manufacturers of laser safety eye wear.

2. Experimental

A short pulse Ti:sapphire laser system was employed to observe the linear and nonlinear absorption behavior of the filters. The system consists of a Kerr-lens mode-locked oscillator followed by a multipass CPA-amplifier and prism compressor. The output pulses have a duration >25fs, an energy <1.5mJ, at a repetition rate of 1 kHz. By controlling the pulse picker we were able to select a single or a train of a well defined number of pulses without influencing other laser parameters. The compressed pulses were focused into a 1m long hollow fiber with an inner diameter of 250µm. The hollow fiber efficiently suppresses higher order spatial modes resulting in a fairly good TEM_{00}-mode with an M^2 <1.2. The fiber was evacuated for most of the experiments in order to act only as a spatial filter. Filling the capillary with Ne allowed the broadening of the input spectrum (60nm FWHM) up to 150nm. Using a chirped mirror compressor the pulse duration can be shortened to less than 10fs. The detailed description of the laser system is presented in [6].

The pulse duration was adjusted by varying the dispersion in the compressor by inserting additional heavy flint glass blocks into the beam path. This allowed us to keep the spectrum constant for pulse durations ≥25fs. In general, the pulse duration has been monitored with a background-free autocorrelator. Only the 10fs pulses have been characterized with a fringe resolved autocorrelator. For pulses longer than 25fs the pulse energy was adjusted by a half wave plate inserted into the beam in front of the Brewster-angled prism compressor. For pulses shorter than 25fs the energy was controlled by inserting pellicle beam splitters after the hollow fiber at different angles of incidence. This method ensures negligible modifications of the pulse duration and beam direction.

The measurement has been performed under atmospheric pressure. We focused the pulses directly by means of f# = 50 and 25 off-axis silver coated spherical mirrors onto the 0.5mm thick filter sample. The reflected and transmitted energy for each laser pulse was monitored with fast photodiodes and recorded with a digital sampling oscilloscope. Prior to the measurement the diodes have been calibrated with a pyroelectric head connected to an energy meter (MOLECTRON EPM-1000). The head (J3-09) was suitable to measure the energy of single pulses in a range between 0.4 µJ and 2 mJ. Choosing a sample thickness of 0.5mm we had comparable energy levels for both the transmitted and reflected pulses which allowed to calibrate the diodes with the same pyroelectric head, avoiding calibration uncertainties. Due to the filter's short effective length (L_{eff}=0.1mm) the transmitted fluences behind the 0.5mm-thin filter sample have been attenuated to levels where the filter acted as a linear attenuator, as it will be shown in the next section. Thus, the transmission for higher, practically applied filter thicknesses of several millimeters can be extrapolated from the thin-sample measurement. The laser spot size in the focal range has been measured by imaging the spot onto a CCD camera.

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3. Results and discussion

With the setup described above we measured the incident, transmitted and reflected energy as a function of the incident fluence, the pulse duration, and the number of shots. First of all we checked the linear transmission in order to set the reference output voltage of the photodetectors. The sample was placed off-focus and the incident energy was reduced to approximately 1mJ/cm^2 to exclude nonlinear effects. The linear transmission value obtained for 25fs pulses (FWHM-bandwidth <60nm @ 800nm) corresponds well with the calculated one. Measurements with stretched pulses yielded the same transmittivity providing further evidence of the lack of nonlinearity. Only in case of 10fs pulses having a bandwidth of >100nm @ 800nm the linear transmission was 50% higher due to the broader spectrum. A substantial amount of the energy is located in a spectral region where the absorption of the filter is weaker. Calculations confirm also quantitatively the linear origin of this effect. The corresponding spectra and the spectral transmission curve are shown in Fig. 1. Consequently, the large bandwidth of laser pulses emerges as a potential problem for the design and specification of laser protective eye wear. Therefore it is worth considering to specify not only the *optical density at the center wavelength* but also the *maximum bandwidth* for safe operation.

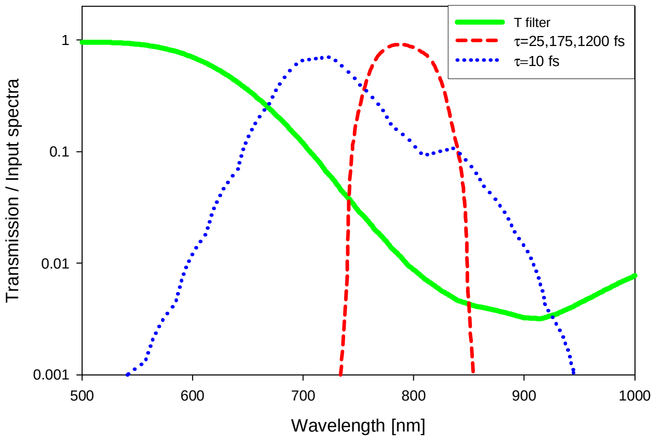

Fig. 1. Measured spectra for the pulses having a duration of ≥25fs (dashed line) and 10fs (dotted line) and the transmission curve (solid line) for a 0.5mm thick filter sample.

In the first series the single shot behavior was investigated, i.e. a fresh spot was used for each shot. The transmission measurement was performed for fluences ranging roughly from one order below to an order above the damage fluence. Recent measurements of the damage threshold of ion doped glasses [7] demonstrated, that the threshold fluence of the doped material is comparable to that of undoped glass in the sub-picosecond regime. It has been concluded that the energy required for breakdown can be transferred to the lattice in a much more efficient way by nonlinear multiphoton absorption of the lattice atoms itself than by transferring energy from the dopant to the lattice.

The obtained transmission curves as a function of fluence are depicted in Fig. 2 for pulse durations of 10, 25, 175 and 1200fs. The results present a qualitatively similar development.

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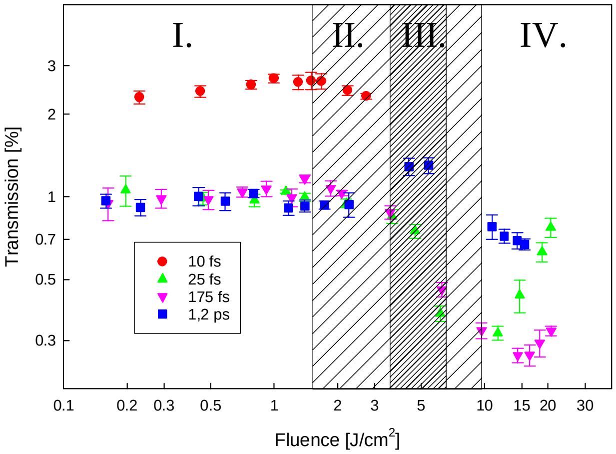

Fig. 2 Measured single shot transmission as a function of fluence and pulse duration for a 0.5mm thick sample. The total fluence range can be divided in four subranges: I) linear range, II) fluence above damage fluence and below saturation fluence, III) fluence above saturation fluence and below damage fluence (only for 1.2ps-pulses), and IV) fluence much larger than the damage fluence.

The symbols represent the mean value, while the error bars refer to the standard deviation of the transmission, respectively. For the analysis of the transmission behavior the whole fluence range has been split into four sub-ranges: I) the linear range, which is characterized by the fluence-independent transmission, II) the damage range, where the transmission lowers with increasing fluence, III) the saturation range, where the transmission increases with increasing fluence, and IV) the so called revival range, indicating an increasing transmission for fluences well above the damage fluence.

In the first, linear regime the measured transmission was the same as obtained for the linear absorption measurement. The transmission is independent of pulse duration as well as fluence over a wide range. The increased transmission only observable for the 10fs pulses is attributed to the significantly broader pulse spectrum as described previously. The results suggest that the filter operates as expected in a wide fluence and pulse duration range.

The second range is the so called damage range which is characterized by the smooth drop of the transmission curve after reaching a well defined fluence. The magnitude of the fluence at which the transmission starts to fall is in reasonable agreement with measured damage thresholds. Note that determining the damage threshold is based on the measurement of the ablated volume versus fluence in general [3]. In spite of this difference transmission measurements presented in this paper yield the same damage thresholds. Thus, the two methods are equivalent for estimating the damage threshold. The reduction of the transmission originates in several reasons: the incident energy is nonlinearly absorbed by the filter host material resulting in lattice heating and subsequently melting and irreversible damage [4]. Femtosecond laser damage is induced by multiphoton absorption mechanism dominantly, hence the threshold fluence is very precisely defined. For fluences slightly above damage threshold a moderate drop of the transmission is observable, which can be explained in terms of well localized, at the beginning very small damage spot only at the central part of the beam with a Gaussian intensity distribution. Well above the threshold the filter transmission decreases substantially. The expanding size of the damage spot with increasing fluence is obviously responsible for the observed behavior. On the other hand, monitoring the reflected energy as well as pump-probe measurements indicated an enhanced reflectivity of the spot caused by plasma generated by the leading edge of the pulse. The well defined cutoff

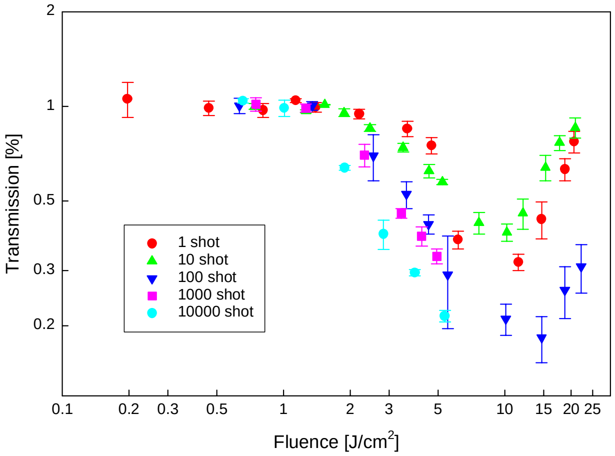

Fig. 3. Measured transmission of the 0.5mm thick filter sample as a function of fluence for a pulse duration of 25 fs and an increasing number of laser shots on the same spot.

has been observed for pulses with a duration of 10, 25 and 175fs. Only pulses longer than 1ps manifest a different behavior.

In the third, so called saturation regime, we have observed an increased transmission prior to the onset of damage for pulses longer than 1ps. This rise of the transmission is moderate, and limited by the onset of damage. The damage threshold increased from about 1.2J/cm^2 to about 3J/cm^2 for pulse durations of 10fs and 1.2ps respectively. The higher damage threshold for picosecond pulses allows to deposit more energy prior to damage. Increasing the amount of deposited energy leads to the saturation of the absorption. To determine the saturation fluence we have solved the propagation equation of the pulse for different material parameters. The best agreement between the measurement and our calculation was found for assuming a saturation fluence of about 2J/cm^2. The measurements clearly suggest, that the saturation of the absorption does not depend on the intensity and an energy-dependent saturation is only observable for pulses in the picosecond range. In conclusion, the filter maintains its protective properties for pulses in the femtosecond range for fluences up to one order of magnitude above the damage threshold. Because of the increased damage threshold for longer pulses, the energy dependent saturation of the absorption implies a severe limitation only in this range.

In the fourth range, however, an increase of the transmission for very high fluences has been observed. Thus we opted for spectral characterization to explain the observed behavior. For pulses of 25fs duration we have measured a substantial blue shift of the transmitted spectrum in the range of highest fluences. Self-phase modulation evoked by the high peak intensities is responsible for the generation of the short-wavelength-components, which, due to the high-pass characteristics, suffer lower linear absorption by the filter. Nevertheless, spectral broadening by self-phase modulation can only be observed at highest intensities. The short effective sample length, the high group delay dispersion around the absorption edge and the increasing plasma reflection all contribute to substantial intensity reduction in the sample. The increased transmission due to spectral broadening is well observable for the 25fs pulses, sets on for the 175fs pulses only in the highest fluence range and is absent for the 1.2ps pulses. This pulse length dependence yields further evidence for the proposed mechanism.

Single shot measurements are of key importance in the study of the underlying physical mechanisms. However, multishot transmission is of much more significance for practical applications. To test the materials for the corresponding safety regulations, which require to maintain protective properties of the filters as long as 10s, we treated the samples with a well

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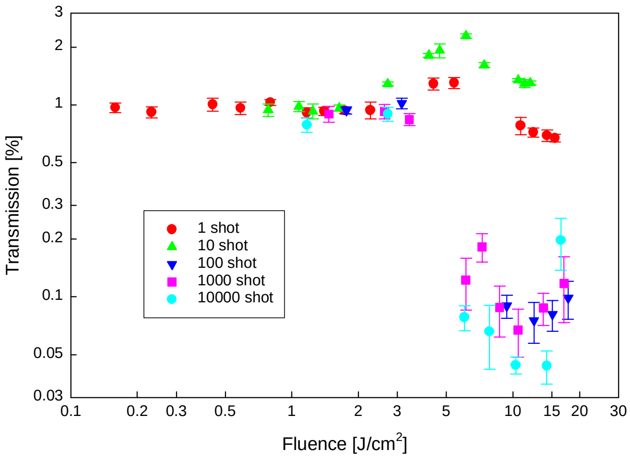

Fig. 4. Measured transmission of the 0.5mm thick filter sample as a function of fluence for a pulse duration of 1.2 ps and an increasing number of laser shots on the same spot.

defined number of pulses N, and measured the transmission of the last pulse of the train. The results for pulse durations of 25fs and 1.2ps are shown in Fig. 3 and 4., respectively. First of all, no severe degradation of the transmission has been observed in the multishot regime. Damage threshold analysis indicates decreasing threshold fluence with increasing number of shots for all pulse durations in agreement with previous measurements. For 25fs pulses the damage threshold lowered from 1.5J/cm^2 to 1J/cm^2 varying N from 1 to 10.000, respectively. Complying with prior measurements, the minimum observed transmission drops with increasing number of shots. The strong scattering of the damage spot is mainly responsible for the reduction of the transmission, confirmed by an independent measurement with a CCD camera. We have observed similar behavior for 1.2ps-pulses, only the minimum transmission was lower in this case. Microscopic analysis of the sample revealed a different damage morphology with enhanced scattering. Since the damage threshold lowers with increasing number of shots, damage occurs before the onset of saturation as observed in the single-shot regime. A slightly increased transmission is only observable at the 10-shot series, for fluences slightly above single shot damage threshold. This can be attributed to the subsequent lattice heating by previous pulses which contribute to the enhanced transmission due to saturation.

4. Summary

Transmission of ion-doped phosphate-glass filters used for laser protective eye wear have been investigated for pulses ranging from 10fs to 1.2ps and fluences of 0.01 to 30J/cm^2 at 800nm. The specified optical density is nearly maintained for all pulse durations and for fluences up to the damage threshold. Above damage threshold, nonlinear absorption reduces the transmitted energy, enhancing the protective properties. Only for fluences far above the damage threshold we have observed an increased transmission due to self-phase modulation. Latter effect implies more serious limitation of the applicability than the saturation observed only for picosecond pulses. Our measurements suggest that the filter material used for protective eye wear keeps its protective properties for sub-ps pulses without essential degradation and the presented results are directly utilizable in the design of laser protective eye wear for the femtosecond regime.

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