Femtosecond Laser Technology in Use: Safety Aspects

A Detailed Study compares different Materials for Eye Protection

In recent years, femtosecond lasers matured from sensitive research setups to turnkey systems for an increasing number of applications. Now that running an ultra-short pulse laser system needs no longer a specialized scientist, safety issues become more crucial. Ultrashort laser pulses have extremely high peak powers and even scattered radiation may possess severe risks to the unprotected eye. Accordingly, special protection schemes are necessary for these unique laser systems.

Introduction

Ultrashort-pulse lasers are the most important experimental tools for investigating fast evolving atomic and molecular dynamics in physics, chemistry, and biology. Our understanding of the relaxation of elementary excitations in condensed matter, carrier dynamics in ultrafast semiconductor devices, or the temporal evolution of chemical reactions has been dominantly formed by experiments performed with picosecond (1 ps = 10^{-12} s) and femtosecond (1 fs = 10^{-15} s) optical pulses. Moreover with the availability of high-power ultrashort pulses down to 10 fs in duration from solid state laser systems using the chirped-pulse amplification concept has opened up entirely new regimes of light-matter interactions. For instance, when a high-power femtosecond pulse is focused into a gas, electrons will be accelerated in the laser field, resulting in a vast number of fascinating new physical phenomena, including x-ray generation. On the other hand femtosecond laser micromachining has excited vivid attention in various industrial fields and in medicine owing to the advantages of ultra-short laser pulses compared to long-pulse treatment. These are mainly the reduction of the laser fluence needed to induce ablation and the improvement of the contour sharpness of the laser-generated structures.

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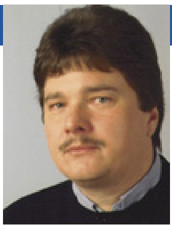

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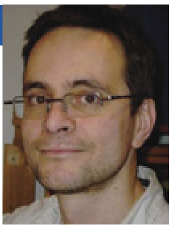

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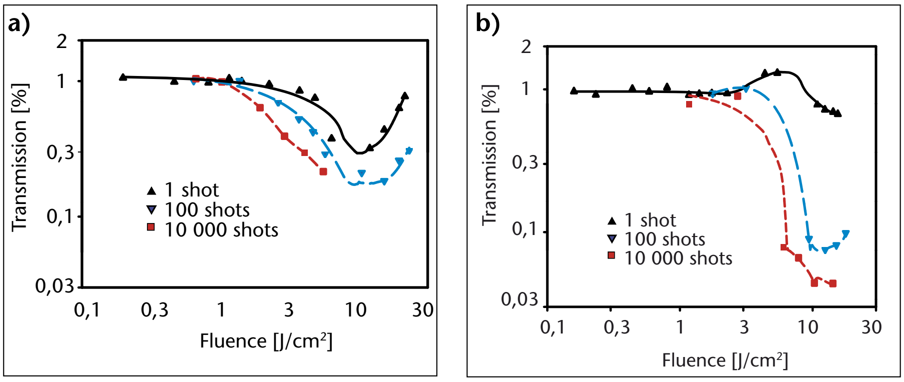

FIGURE 1: **Transmission of a 0.5 mm thin ion-doped glass filter sample as a function of the incident fluence for different numbers of shots and pulse durations. a) τ_p = 25 fs and b) τ_p = 1.2 ps. For the shorter pulses no protection-degradation of the filter can be observed. Slight saturation of the filter can be found in the single-shot case for longer pulses.**

However, the high peak intensities and the broad bandwidth of the laser pulses provided by short-pulse systems raise special, sometimes counteracting requirements for optical materials applied for radiation protection. I.e. the nominal optical density of a filter has to be maintained for a wide range of fluences and pulse durations, while out of the absorption bandwidth the filter should be as transparent as possible. In this paper we present a short overview about possible hazards when operating lasers and summarize representative results of our comprehensive characterization of protective materials especially for eye protection.

Primary and Secondary Hazards of Laser Radiation, General Remarks

Hazards resulting from the use of laser equipment can roughly be grouped into two categories:

1. primary hazards which are optical radiation hazards to the eye and the skin,
2. secondary hazards as device related or application related hazards.

Device related hazards are electrical hazards (e.g. by using high-voltage laser power supplies), chemical hazards (e.g. caused by laser dyes and gases), and danger by pump radiation. Application related hazards can be e.g. fire hazards, emission of harmful substances or particles, and generation of secondary radiation with wavelengths different from the primary optical radiation. The most important hazard is the radiation damage to the eye and far less likely the injury to the skin [1].

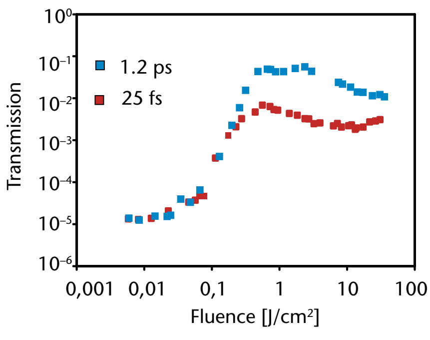

FIGURE 2: **Transmission of dye-doped polycarbonate filter samples as a function of the incident fluence for single-shot excitation and pulse durations of τ_p = 25 fs and τ_p = 1.2 ps. The transmission depends substantially on the pulse duration and incident fluence.**

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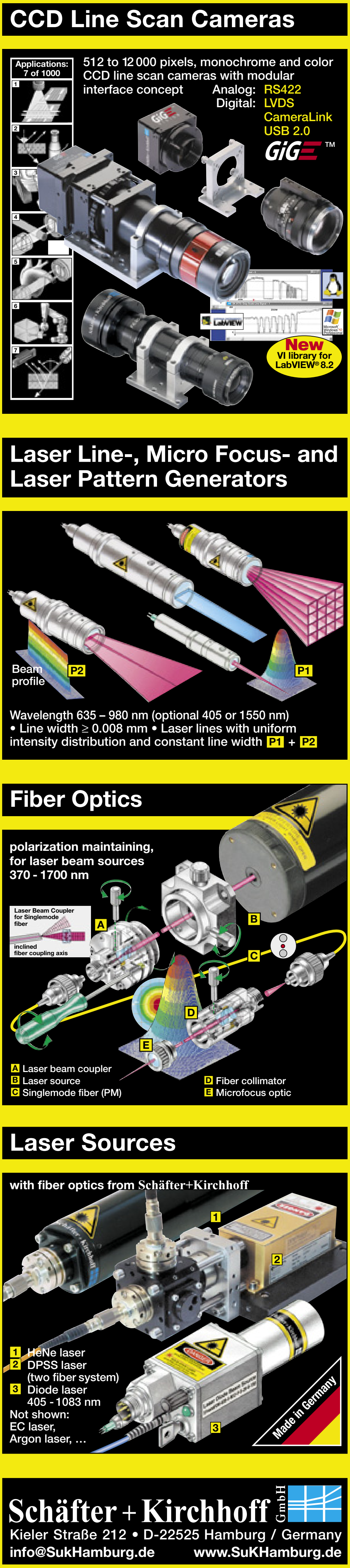
The BAM Federal Institute for Materials Research and Testing is a technical and scientific senior federal institute under the authority of the German Federal Ministry of Economics and Technology. The guideline of the institute is "Safety in technology and chemistry". BAM's working group "Pulse laser technology, laser safety" is experienced in the application of short laser pulses for micro-structuring and cleaning purposes of different materials and questions of laser safety.

Depending on the wavelength different parts of the eye can be injured due to a different absorption behavior. Cornea and lens of the eye absorb ultraviolet light with wavelengths < 400 nm and infrared light (> 1400 nm). Above critical laser intensity values, burn injuries and cataract can be induced. In the wavelength range of 400 to 1400 nm, light passes through the cornea and the lens of the eye and is focused onto the retina. A comparatively low radiation power (per area) can lead to a severe damage of the retina due to the fact that the light intensity at the entrance of the pupil can be amplified by a factor of the order of 10^6 resulting in tremendous intensities at the surface of the retina. The damage effect on the retina is more or less thermal. An illumination of the skin with sufficiently high exposure levels results in a burning of the skin.

Lasers are categorized with respect to their hazardous potential in four classes. The classification bases on the concept of accessible emission limits (AEL). These maximum power (W) or energy (J) levels in dependence on wavelength range and pulse duration are defined for each laser class. Class 1 means no hazard during normal use and class 4 corresponds to a considerable hazard for eyes and skin. Even a diffuse reflex of a powerful class 4 laser can be hazardous to the eye. The basic standard containing the classification system of lasers and the maximum permissible exposure (MPE) is IEC 60825-1. MPE values specify the highest laser fluence (energy density, J/cm^2) or intensity (power density, W/cm^2) of a laser that is considered safe. MPE values are different for the exposition of eye and skin and depend on wavelength and exposure time (pulse duration).

The current international standards concerning important aspects of laser safety namely



- IEC 60825-1:1993 + A1:1997 + A2:201, Safety of laser products – Part 1: Equipment classification, requirements and user's guide,
- IEC 60825-4:1997/A2:2003, Safety of laser products - Part 4: Laser guards,
- DIN EN 12254:2002-12, Screens for laser working places – Safety requirements and testing,
- DIN EN 207:2002-12, Personal eye-protection – Filters and eye-protection against laser radiation (laser eye-protectors),
- DIN EN 208:2002-12, Personal eye-protection – Eye-protectors for adjustment work on lasers and laser systems (laser adjustment eye-protectors)

are primarily concerned with continuous wave lasers and pulsed lasers down to the nanosecond range. The shortest pulse length respected in an international standard so far is 100 fs. The field of laser safety, especially eye protection, for pulses shorter than 100 fs is briefly reviewed in this paper.

Protection of the Eyes Against Femtosecond Laser Radiation

For practical use of lasers it is of key importance to achieve reliable laser protection. Laser guards and curtains are widely used in an industrial environment, and their protective properties in the femtosecond range have been extensively studied [2,3]. Laser goggles are the most important devices for the protection of the eyes against laser radiation, so we restrict the discussion in this paper only to this topic.

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The research interests of the research group Experimental Physics 1 at the University of Würzburg are concentrated on studies of the dynamics of elementary excitations in atomic and solid state physics. Our methods include femtosecond laser techniques (pump-probe, transient absorption, et cetera), photoelectron spectroscopy, and time-resolved x-ray spectroscopy. The different ultrafast techniques allow to characterize various material systems in basic and applied science.

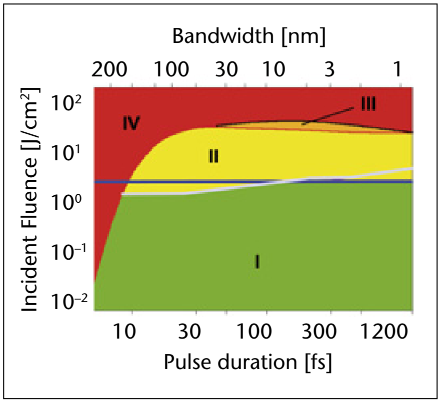

FIGURE 3: **Operation chart of an ion-doped glass filter: I, safe operation range. Absence of any nonlinear effects such as saturation. II, damage range, onset of single-shot surface damage, but the filter keeps its protecting properties. III, saturation regime, the single-shot damage threshold exceeds the saturation limit. IV, danger range: the transmitted energy exceeds the eye-safe limit. The white line and blue line correspond to the single shot damage fluence and absorption saturation fluence, respectively.**

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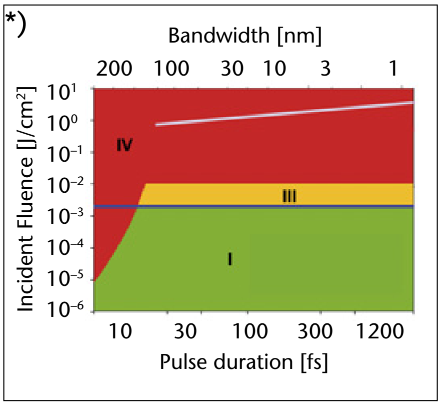


FIGURE 4: **Operation chart of a dye-doped polycarbonate filter: I, Safe operation range. III, saturation regime. Saturation occurs, however, due to the high nominal optical density of the filter (OD=5). The regime can be considered (with restrictions) as eye-safe. IV, danger range: the transmitted energy exceeds the eye-safe limit. Above saturation fluence the transmission increases until reaching the damage threshold. The white line in region IV corresponds to single shot damage fluence, and the blue line separating region I and III corresponds to the absorption saturation fluence.**

Two classes of absorbing laser protection filters are mainly established namely ion-doped glasses and dye-doped polymers. The protective filters must attenuate the transmitted laser pulse energy to levels well below MPE for a wide range of laser pulse parameters including pulse duration, energy, spot size, number of pulses, etc. To decide whether filter materials are suitable for eye protection the following experiments must be performed:

- linear absorption (optical density) for the desired wavelength range, keeping in mind the broad bandwidth of femtosecond laser pulses,
- nonlinear absorption/bleaching behavior, i.e. the transmission should be independent of laser pulse duration and fluence in a wide range,
- laser-induced damage thresholds, i.e. the filter must maintain its protective properties for at least 10 seconds, even if surface damage occurs.

Experimental Results

Results of femtosecond laser interaction with some representative filters of both categories will be presented in the following. All experiments were performed with Ti:sapphire femtosecond lasers emitting 800-nm-center-wavelength pulses with bandwidth-limited pulse durations ≥ 10 fs at a repetition rate of 1 kHz. As a first measurement the energy transmission of the ion-doped glass and the dye-doped polycarbonate filters was characterized.

The single- and multi-shot transmissions for a glass filter featuring a sufficiently broad linear absorption spectrum [4] are summarized in Fig. 1 for pulse durations of 25 fs and 1.2 ps. The symbols represent the mean values of the measured transmission, the lines serve for guiding the eye. Below the pulse duration dependent damage threshold of about 1 to 3 J/cm^2 the transmission is independent of the incident fluence and the pulse duration. Damage threshold experiments were performed on doped glass samples with a varying number of pulses per spot. For all pulse durations the ablation threshold fluence decreases with increasing number of pulses per spot by a factor of two only. However, the onset of damage causes generally a decrease of the transmission in the full laser parameter range, enhancing the optical limiting properties of this type of filter.

The single shot transmission-evolution for a polycarbonate filter is depicted in Fig. 2 for 25 fs and 1.2 ps-excitation [5], respectively. Only for very low fluences (linear range) no degradation of the filter is observable. For somewhat higher fluences the optical density of the filter is significantly reduced and may be dangerous. In general, saturation of the

*) Diese Abbildung wurde nach Veröffentlichung nochmals korrigiert.

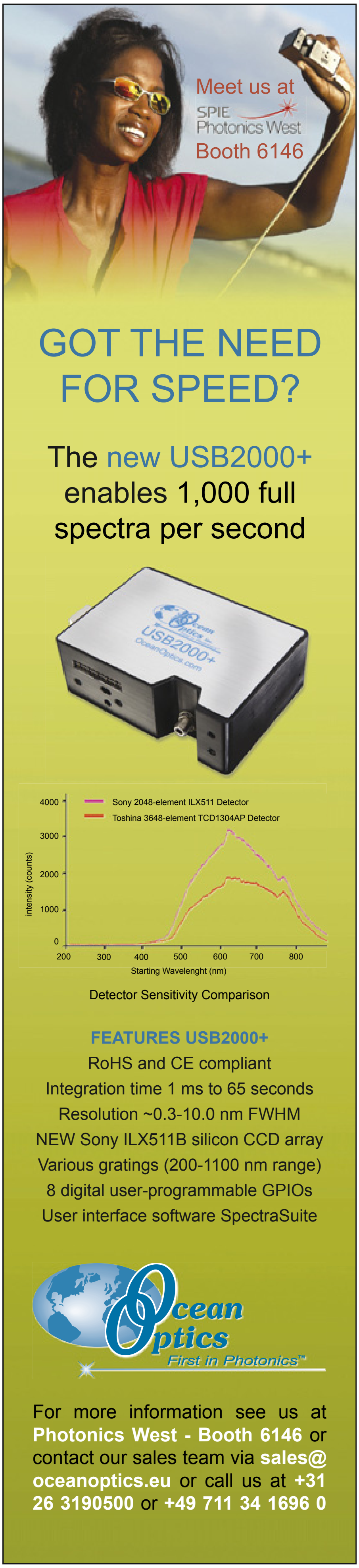
absorption takes place in every absorbing material if the incident fluence exceeds the saturation fluence. For the current sample the transmission increases by approximately three orders of magnitude independently of the pulse duration, i.e. the saturation depends only on the incident pulse energy. This suggests that the saturable behavior of this filter can be described by means of the simple slow saturable absorber model. For other dopants and polymer host materials a strong pulse duration dependence in the saturation regime was observed. The transmission-increase ranges approximately two orders of magnitude for picosecond pulses, and it amounts only to a factor of three in the case of 25 fs-pulses, respectively.

The single-shot damage thresholds have been estimated to 3 J/cm^2 and 0.5 J/cm^2 for 1.2 ps and 25 fs pulses, respectively. Applying more pulses at the same spot with a constant fluence resulted in a severe damage of the filter and drilling a hole through the 3-mm-thick filter material. Safety standards require that the material must maintain its optical density for about 10 s. The measured threshold meeting this requirement is only about 3 mJ/cm^2 and independent of the pulse duration [5]. These results suggest that melting far below the single shot damage threshold is initiated purely by thermal processes, which depend merely on the deposited heat and are independent of the pulse duration. The melting process extends over a large volume in the filter material leading to deep-crater formation substantially reducing the optical density. The significant lower multi-shot damage threshold for polycarbonate filters is a severe risk factor.

Several mechanisms have significant impact on the evolution of the transmission: i.) damage, which generally contributes to the reduction of the transmission by enhanced nonlinear absorption but degrades the surface, ii.) saturation, which has a negative impact on the protective properties of the filters and can be present (especially for polycarbonate filters) for fluences far below damage threshold, iii.) spectral broadening, which causes an increase in the transmission only for extremely high fluences (above 10 J/cm^2) and short pulses, iv.) the wings of the spectrum of ultrashort pulses can be easily extend to ranges where the linear absorption of the filter is no longer sufficient. Subsequently, for a multi-shot excitation scheme, heating and incubation effects can degrade the long-term usability of the filter. Almost all these transmission-influencing effects can be summarized and illustrated in a so called operation chart which allows an easy decision whether the filter works properly for a given set of laser parameters. The operation chart for a 2 mm thick sample of an ion-doped glass filter is depicted in Fig. 3. For a given pulse duration and laser fluence the transmitted energy was calculated using a model accounting for the above-mentioned effects. The calculation of the filters' transmission requires parameters such as saturation fluence and damage threshold which have been extracted from measurements published in detail elsewhere [5]. After this calculation it was checked whether the transmitted energy is above or below the eye-safety limit. For the eye-safety limit the ICNIRP-recommendation, which prescribes a maximum allowable fluence of 10^{-7} J/cm^2 for a single sub-picosecond laser pulse entering at the cornea, was applied. This is approximately one order of magnitude below retinal damage threshold. As a result, different operational ranges were identified which are following: I) safe operation range, II) damage range, III) saturation range, IV) danger range.

For very short pulses ($\tau_p \le 10$ fs) the bandwidth of the incident radiation restricts the applicability of the filter, i.e. the bandwidth of the pulses exceeds the filter's linear absorption bandwidth. At the top of the operational chart we have added the bandwidth assuming Fourier-limited Gaussian pulses at a center wavelength of 800 nm. For pulses in the range of 10fs $< \tau_p \le$ 200fs the damage threshold sets upper limits for the safe application. Exceeding the damage threshold leads to permanent surface damage of the filter (range II), however, the protective properties are not affected up to attaining range IV. Thus, the damage threshold itself does not contain substantial information about safety properties of the filter. For pulses longer than 200 fs the damage threshold exceeds the saturation fluence, i.e. in range III saturation takes place before damage occurs. However, the maximum allowable incident fluences for the 2 mm-thick filter are limited in effect by range IV.

The operation chart of the polycarbonate filter is shown in Fig. 4. Bandwidth limit, saturation fluence, single-shot damage threshold and the measured safety limit (MSL) determine the different operation ranges represented in the picture. The MSL represents the maximum safely applicable incident laser fluence, where the measured transmitted energy does not exceed the eye-safety limit. For longer pulses, the eye-safe range I is limited by the saturation regime



III. Despite of saturation, range III may be considered (however with restrictions) as eye-safe, according to the measured data. The gap between saturation limit and single-shot damage threshold is typical for polycarbonate filters and it opens a way for the effective saturability. This has obviously a negative impact on the optical density, hence on the protection effect.

Summary

In summary a representative transmission characterization of eye-protective filter materials in the sub-picosecond regime is described. As a conclusion, ion-doped glass filters are advantageously applicable to protect against laser radiation from short-pulse Ti:Sapphire laser systems. Due to the relatively high saturation limit and low damage threshold they can be considered as eye-safe in a wide range of fluences and pulse durations. For polycarbonate-host filters saturation sets in for all materials at relatively low fluences reducing the absorption up to four orders of magnitude. Their low melting temperature results in a large-volume melting for rather low fluences for multi-shot operation. As a conclusion, the applicability of the polycarbonate filters in the ultrashort pulse range can be recommended only after careful considerations and at strict assurance of certain laser parameters.

The unusual laser parameters such as very high peak intensities or broad bandwidth make the comprehensive survey of the nonlinear behavior of optical materials applied for eye-protection indispensable. Thus, we suggest the implementation of standardized characterization procedures for the eye-protective materials such as transmission characterization in a standardized fluence and pulse duration range. Furthermore, we recommend the extension of the current safety standards with operation charts, which represent on the one hand the impact of the most relevant physical parameters on the transmission and enable a simple overview of them on the other hand.

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