Keeping an eye on safety

Protection against laser radiation

Bundesanstalt für Arbeitsschutz
und Arbeitsmedizin

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1 Working with lasers

Lasers are an indispensable part of today‘s world. Since the experimental development of the first laser by the American physicist Theodore Maiman in 1960, lasers are increasingly gaining in importance in research and medicine, industry and commerce, in information and communication technology and in entertainment. The number of employees working with lasers is constantly increasing. There are also more and more lasers in private households. Laser printers, CD and DVD players have already been used for years; also, laser rangefinders and laser levels are part of the “arsenal” of many handymen. Laser pointers in some school bags are unfortunately not used only as a modern pointer. Given the rapid expansion of laser applications, it becomes increasingly important to be adequately informed about the safe use of lasers, both for professionals and for consumers.

In addition to general information about laser radiation, applications of lasers and possible harmful effects of laser radiation on humans, this brochure also contains the currently valid laser classification. This classification provides laser users with important information about possible hazards and protective measures.

The second part of the brochure provides an overview of three research projects initiated by the Federal Institute for Occupational Safety and Health (BAuA). The first two projects examined whether the blink reflex and aversion reactions can be regarded as sufficient protection mechanism for persons dealing with low-power lasers. The third project examined the dazzle caused by sources of optical radiation and its impact on vision. Studies on the blink reflex, aversion reactions and the dazzle were carried out under the direction of Prof. Dr. Hans-Dieter Reidenbach at the Cologne University of Applied Sciences, in the Research Department of Medical Technology and Non-Ionizing Radiation. They make an important contribution to the improvement of safety in the use of lasers.

2 What is laser radiation?

The word **LASER** is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. The term describes a physical process that leads to the generation of laser radiation. In the first step, a source of external energy is applied to atoms[1] of a laser medium ("active medium") raising them to an excited state. This process is called "pumping" (Figure 1). The active medium may be a gas, a solid or a liquid material. Depending on the active medium, the power supply can be provided by electrical gas discharges, flash lamps, an applied voltage or some other laser. After some time, an excited atom will decay back down to its ground state and emit the excess energy in the form of a light particle, a photon. If this photon encounters another atom that has been raised to an excited state, it causes the atom to decay to its ground state and to emit another photon. The new photon has identical wavelength, phase and direction as the exciting photon. Such a process, called "stimulated emission" is performed in an optical resonator, consisting of two mirrors – one highly and the other partly reflective. The photons bounce back and forth through the laser medium between the mirrors, building up more and more photons.
A small percentage of them escape through the partly reflective mirror to create a "laser beam".

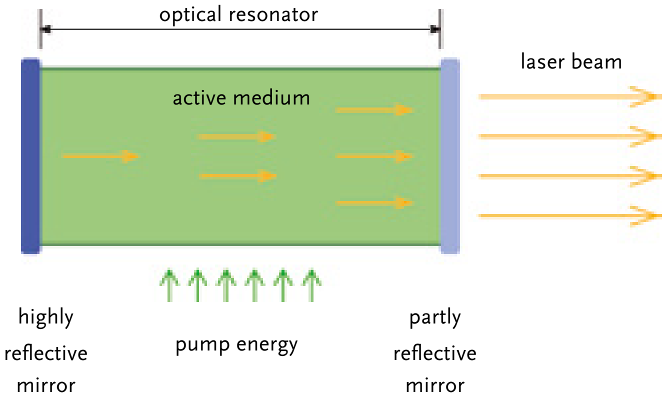

Figure 1 Diagram of a typical laser

[1] Atoms, molecules or ions, in brief hereafter denoted only as atoms.

Laser radiation differs from optical radiation of other artificial sources, such as light bulbs or light emitting diodes (LEDs), mainly due to the following properties:

– **Coherence**: the waves possess a constant phase difference, they are temporally and spatially coherent;
– **Monochromaticity**: the laser emits optical radiation of only one wavelength;
– **Parallelism**: the laser beam has an extremely low divergence.

In practice, it means a laser beam is strongly bundled and can easily be focused to a small spot. This property is, for example, exploited in every CD player, in order to read out the microscopic structures on a CD. Since laser beams allow enormous energies to be focused to a small area, very precise cutting of materials is possible.

Today, lasers are used for a wide range of different purposes and accordingly differ in their construction. The range of optical radiation covers the ultraviolet (UV), the visible (light) and the infrared (IR) regions (Table 1).There are also different types of lasers depending on the active medium: gas, solid, semiconductor and liquid lasers (Table 3). Lasers differ also in the way how the optical power is emitted: continuously or in the form of pulses. A laser operating with a continuous output for more than 0.25 s is regarded as a continuous wave laser. A pulsed laser delivers its energy in the form of a single pulse or a train of pulses, with pulse duration of less than 0.25 s.

Table 1 Wavelength ranges of optical radiation

Wavelength (nm)	Wavelength range
100 – 280	Ultraviolet C (UV-C)
280 – 315	Ultraviolet B (UV-B)
315 – 400	Ultraviolet A (UV-A)
400 – 780	Visible optical radiation (light)
780 – 1400	Infrared A (IR-A)
1400 – 3000	Infrared B (IR-B)
3000 – 10^6	Infrared C (IR-C)

Table 2 List of prefixes used in this brochure

Metric prefix	Value	Abbreviation
femto	10^{-15}	f
pico	10^{-12}	p
nano	10^{-9}	n
micro	10^{-6}	µ
milli	10^{-3}	m
mega	10^{6}	M
giga	10^{9}	G
tera	10^{12}	T
peta	10^{15}	P

3 Laser applications

Nowadays, lasers are used in many professional areas (Table 3). Fast data transfer via optical fibers as well as storage of increasing amounts of data on CD-ROMs and DVDs would be hardly conceivable without lasers. Lasers are also used in research, for example in spectroscopy or in thin-film technology. Lasers for material processing enable high precision in cutting, drilling, welding and soldering of work pieces. In measurement and testing, lasers are used for high-precision, non-contact measurements, such as measurements of distances, velocities, thicknesses and surface profiles. Lasers in tunnel constructions afford precise tunnel driving and exact meeting of two tunnel tubes. Furthermore, laser light is also used to produce holograms on credit and EC cards, as well as in barcode scanners at the checkout counters of supermarkets.

Medicine is an important scope of application as well, where clinical diagnostics and therapy have benefited from medical laser developments. For example, lasers are used for the non-invasive fragmentation of kidney stones or gallstones, or as a scalpel in surgery. Lasers enable correction of defective vision, as well as removal of pigment moles and scars.

Lasers are also part of many consumer devices. CD and DVD players, laser printers and scanners, laser spirit levels and laser rangefinders have become the rule rather than the exception. Lasers create spectacular light effects in discos and stage performances. However, the brave new laser world has its shady sides, too, when lasers are improperly handled, e.g., when teenagers spotlight themselves or others with laser pointers, thereby causing dazzling and even endangering the eyesight of others. Hazards may also arise from incorrectly classified lasers!

Table 3 Types of lasers with application examples

Laser type	Active medium	Operation wavelength	Application
Gas lasers	Helium-neon (He:Ne)	632.8 nm	Spectroscopy, holography, alignment, barcode scanning
	Argon-ion (Ar^+)	488 nm, 514.5 nm	Medicine, spectroscopy, pumping other lasers
	Carbon dioxide (CO_2)	10.6 μm	Material processing, medicine
Solid state lasers	Ruby ($Cr^{3+}:Al_2O_3$)	694.3 nm	Medicine, holography
	Neodymium: yttrium-aluminum-garnet (Nd^{3+}:YAG)	1064 nm	Material processing, medicine, research, range finding
Semiconductor lasers	Semiconductors, e.g. gallium-aluminium-arsenide (GaAlAs) and other laser diodes	660 nm – 1550 nm	Data transmission, medicine, optical disc players (CD, DVD, Blue-Ray players), printing, welding
Liquid lasers	Organic dyes	tuning range between UV and near IR	Research, medicine, spectroscopy

4 Harmful effects of laser radiation on humans

Laser radiation and optical radiation emitted by conventional sources do not differ fundamentally in their biological effects. However, since lasers emit focused beams, the high irradiance [2] achieved thereby can cause various tissue alterations. The effects of optical radiation on biological tissue vary with wavelength, irradiance and exposure time, as well as with the optical properties of the tissue itself: its absorption, reflection and scattering capability.

Wavelength dependence of the absorption is related to the different optical properties of the tissue components. Biological tissue usually contains a lot of water, which absorbs mostly in the far infrared range (IR-B and IR-C). Absorption in the UV, visible and near infrared range (IR-A) is dominated by the biological molecules hemoglobin (a protein in red blood cells that carries oxygen and regulates respiration and metabolic processes) and melanin (a pigment present in skin, hair and eyes).

[2] Irradiance (also called power density) is defined as the radiant power per unit area.

At moderate irradiances (up to 50 mW/cm^2) and exposures within the minute range, photochemical reactions in the tissue could be triggered. Absorption of optical radiation may result in the formation of highly reactive oxygen species (ROS) which can damage the genetic material deoxyribonucleic acid (DNA). Optical radiation in the UV range may also damage DNA directly. This kind of DNA damage can lead to cancer.

Laser radiation acts thermally for irradiances between 10 W/cm^2 and 1 MW/cm^2 and shorter exposures (microseconds to a second). The energy of laser radiation is transferred into heat due to absorption of photons by the tissue. Depending on the tissue temperature achieved, different effects may be distinguished: denaturation of proteins which leads to coagulation of tissue, vaporization of tissue water and carbonization (charring of the tissue).

For shorter exposures (between 10 ns and 100 ns) and higher irradiances (between 10 MW/cm^2 and 10 GW/cm^2), high energy photons break tissue molecular bonds and the tissue “evaporates” (photoablation). Further reduction of pulse duration (between 100 fs and 500 ps) together with a simultaneous irradiance increase (between 100 GW/cm² and 10 TW/cm²) leads to the formation of plasma (free electrons and positive and negative ions). Subsequent tissue ablation is primarily caused by plasma ionization itself (plasma-induced ablation).

Finally, irradiances between 100 GW/cm² and 10 PW/cm² and pulse durations between 100 ns and 100 fs lead to a plasma formation, accompanied by an acoustic shock wave that propagates and mechanically destroys the tissue. This effect is known as photodisruption.

Eye damage

The eye (Figure 2) has the property to focus light, i.e. optical radiation in the visible range, very strongly: along the way from the cornea to the retina, the irradiation is enhanced up to 200 000 times. This explains why even relatively small irradiances at the cornea can be dangerous for the eye. Damages of the retina, such as burns, can lead to considerable impairment of vision. Minor retinal burns outside the area of sharpest vision ("yellow spot") often remain unnoticed, but larger burned areas can lead to blind spots in the field of vision. Aside of the retinal damage, massive bleedings can also occur. Retinal damage in the area of sharpest vision can result in the reduction of both vision and colour vision. Finally, retinal damage in the area, where fibres of the optic nerve emerge from the eyeball ("blind spot"), can lead to a complete and irrevocable loss of sight.

Vision is limited to the visible spectrum, i.e., optical radiation of this wavelength range passes through cornea, lens and vitreous humor and is imaged on the retina. In view of potential eye damage, however, it must be taken into account that also optical radiation in the near IR region reaches the retina and can therefore cause retinal damage. On the other hand, optical radiation in the UV and far IR region does not reach the retina as it is already absorbed by the cornea, conjunctiva and lens. However, UV radiation can trigger photochemical reactions which lead to painful inflammation of the cornea (photokeratitis) and conjunctiva (photoconjunctivitis). High irradiances and repeated exposures over a prolonged period of time can lead to clouding of the lens (cataract). Cataracts are also possible in the IR range, but for wavelengths of about 2500 nm upwards only the cornea can be affected (Table 4).

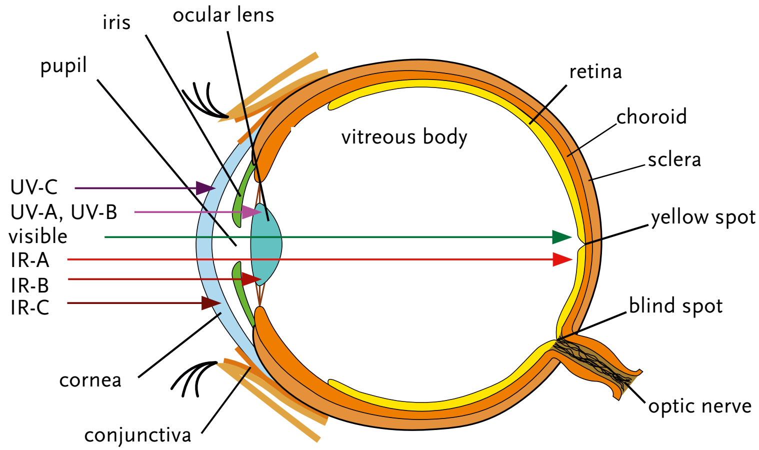

Figure 2 The human eye

Skin damage

Skin lacks the property of focusing light and reflects optical radiation stronger than the eyes. It is, therefore, less sensitive to optical radiation. Skin features a high reflectivity in the visible and IR-A range. On the other hand, it is highly absorbing at UV, IR-B and IR-C wavelengths, with penetration depths depending on the wavelength. Therefore, the skin layers are affected to different degrees (Figure 3).

The melanin granules of the epidermis absorb UV radiation and hence protect the dermis from harmful UV radiation. However, the incident radiation of high irradiance and long duration can nevertheless penetrate the protective filter of the epidermis and cause skin injury, e.g. reddening (sunburn, erythema) which presents a photochemical hazard. Chronic overexposures to UV radiation increase the risk of skin cancer. The risk of thermal injury is also present; however the exposure is generally limited due to the associated feeling of pain.

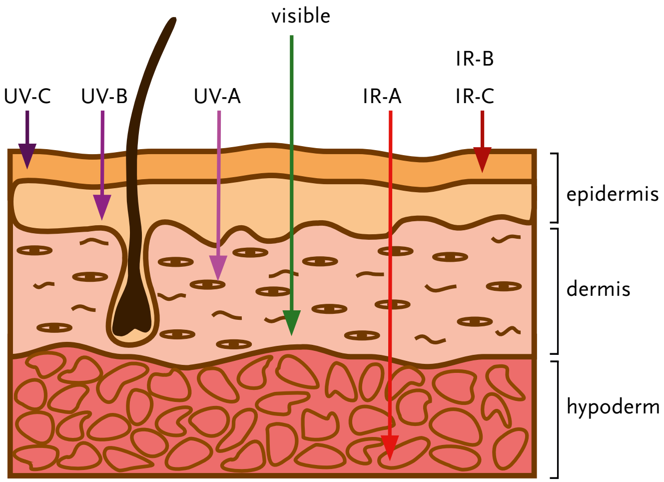

Figure 3 Skin penetration depth of optical radiation

Other hazards

In addition to direct hazards to the eye and skin from the laser beam itself, it is also important to address other hazards associated with the use of lasers. These non-beam hazards include physical, chemical and electrical hazards associated with the laser technology itself or the target material.

For instance, fire and explosion hazards threaten whenever laser beams or strong reflections impinge on combustible material or an explosive atmosphere. In material processing, harmful material degradation products in vapors, as well as UV radiation, can emerge. Furthermore, many laser dyes are toxic and can cause cancer. Lasers require electrical power for operation, so the electrical safety has to be considered as well.

Table 4 Potential harmful effects of laser radiation on eye and skin

Wavelength range	Eye	Skin
Ultraviolet C	Photokeratitis Photoconjunctivitis	Erythema Precancerosis Skin cancer
Ultraviolet B	Photokeratitis Photoconjunctivitis Cataract	Delayed pigmentation Accelerated skin aging Erythema Precancerosis Skin cancer
Ultraviolet A	Cataract	Tanning Accelerated skin aging Skin burn Skin cancer
Visible optical radiation	Photochemical and photothermal retinal damage	Photosensitive reactions Skin burn
Infrared A	Cataract Retinal burn	Skin burn
Infrared B	Cataract Corneal burn	Skin burn
Infrared C	Corneal burn	Skin burn

5
Laser classes

An obligation for a laser classification based on the International Standard IEC 60825-1 has existed for many years. Lasers are classified into seven classes according to their potential to cause biological damage. The classification scheme makes the hazardous potential of the laser beam immediately evident and indicates appropriate protective measures: the higher the class number, the bigger the potential to cause harm. It is the manufacturers' responsibility to provide the correct laser classification of their products.

Which class does a laser belong to? To assess the laser class, two limit values have to be considered. The Maximum Permissible Exposure (MPE) is the level of laser radiation to which, under normal circumstances, persons may be exposed without suffering adverse health effects. MPE is dependent on the wavelength, the exposure duration, the organ being exposed and on the size of the retinal image. The term "accessible emission" denotes the amount of accessible laser radiation a person might come into contact with. The Accessible Emission Limit (AEL) is the maximum accessible emission permitted within a particular laser class.

In the International Standard IEC 60825-1:2001, adopted as a European Standard EN 60825-1 and therefore also in Germany as DIN EN 60825-1:2001, the former laser classes 1, 2, 3A, 3B and 4 have been reclassified. New classification provides seven laser classes – 1, 1M, 2, 2M, 3R, 3B and 4 –, i.e., three new laser classes (1M, 2M and 3R) have been introduced and the laser class 3A has been canceled. Standards IEC 60825-1 and DIN EN 60825-1 (latest editions issued in 2007 and 2008, respectively) as well as the instructions relevant to the Accident Prevention Regulation BGV B2 "Laser Radiation" (2007) offer precise definitions of the laser classes.

Class 1 The accessible laser radiation poses no danger under reasonably foreseeable conditions. These lasers are safe during use, including long-term direct intrabeam viewing, even when using optical instruments. The AEL in the visible range is wavelength dependent and amounts 39 μW in the blue, up to 0.39 mW in the green to red spectral range. Class 1 also includes high-power lasers that are fully enclosed so that no potentially hazardous radiation is accessible during use, such as lasers in CD players, laser printers and scanners, as well as materials processing lasers.

Additional precautions would be necessary if the system is opened up.

Class 1M Class 1M[3] lasers produce either a highly divergent or a large-diameter beam. The accessible laser radiation has a wavelength between 302.5 nm and 4000 nm. Class 1M lasers are safe, including long-term intrabeam viewing for the naked eye. However, the AEL can be exceeded and hazards comparable to Class 3R and 3B may occur following exposure with optical instruments like magnifying glasses, lenses, telescopes or microscopes. Barcode scanners placed at the supermarket checkouts (Figure 4) are Class 1M lasers.

Class 2 Class 2 lasers emit visible radiation in the wavelength range from 400 nm to 700 nm. They are safe for momentary exposures (up to 0.25 s), but can be hazardous for deliberate staring into the beam. The time base of 0.25 s is inherent in the definition of this laser class. Additional radiation components beyond the wavelength region from 400 nm to 700 nm meet the conditions for the Class 1. The AEL for a CW Class 2 laser is 1 mW. For Class 2, in contrast to Class 2M, the use of optical instruments does not increase the risk of ocular injury. Examples are land surveying lasers, laser spirit levels, laser light barriers and laser pointers (Figure 5).

Class 2M Class 2M lasers emit visible radiation in the wavelength range from 400 nm to 700 nm. They are safe for momentary exposure of the naked eye. However, the AEL can be exceeded and eye injury may occur following exposure with optical instruments such as magnifying glasses, lenses, telescopes or microscopes. As long as the beam cross-section is not reduced by optical instruments, Class 2M lasers pose a comparable risk to Class 2 laser devices. If optical instruments are used, risks comparable to Class 3R or 3B may occur. Additional radiation components beyond the wavelength region from 400 nm to 700 nm meet the conditions for the Class 1M. Examples are laser level and alignment instruments for civil engineering applications.

[3] The "M" in Class 1M (and also Class 2M) is derived from "magnifying" optical viewing instruments.

Figure 4
A barcode scanner
Photo:Honeywell

Figure 5
A laser pointer

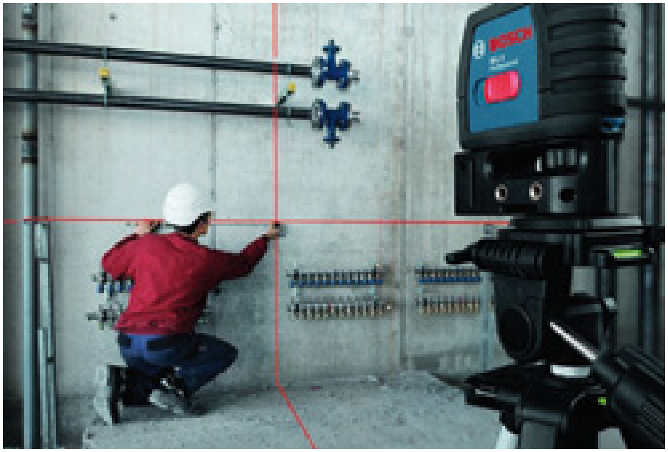

Figure 6 An alignment laser

Photo: Bosch

Figure 7 Laser cutting machine

Photo: TRUMPF Gruppe

Class 3R A Class 3R[4] laser can have any wavelength between 302.5 nm and 10^6 nm and is hazardous for deliberate ocular exposure. The AEL is within five times the AEL of Class 2 in the visible, between 400 nm and 700 nm, and within five times the AEL of Class 1 at other wavelengths. The AEL for a CW Class 3R laser is 5 mW. Examples are targeting lasers for military purposes and alignment lasers (Figure 6).

Class 3B Direct intrabeam viewing of these lasers is always hazardous. Viewing diffuse reflections is normally safe, provided the eye is no closer than 13 cm from the diffusing surface and the exposure duration is less than 10 s. Class 3B lasers may also produce minor skin injuries or even pose a risk of igniting flammable materials. The AEL for a CW Class 3B laser is 500 mW. Many lasers in research laboratories, show and disco lasers, and lasers for cosmetic applications belong to this class.

Class 4 Lasers for which intrabeam viewing and skin exposure is hazardous and for which the viewing of diffuse reflections may be hazardous. These lasers may ignite combustible materials, and thus may represent a fire risk. Examples are lasers in the materials processing (e.g. laser welding or cutting, Figure 7) and scientific laboratories, lasers for medical applications, as well as show and disco lasers. Most lasers used in the medical therapy for coagulation, vaporization, ablation and disruption of tissue are Class 4 lasers.

[4] The "R" refers to "relaxed" since this class is a relaxation of the Class 3B.

Control measures

The first step in using lasers safely is to identify the laser class and then comply with the appropriate control measures designed to reduce the possibility of exposure to the eye and skin. Suitable protective control measures depend on the laser class of the device and the application. There is a hierarchy of control measures: if any hazard is identified, priority should be given then to technical (engineering) measures since they avert danger at the outset and remove the possibility of failure of organisational (administrative) controls and personal protective equipment.

Technical controls include:
- protective housing in order to totally enclose the laser and all beam paths;
- key controls in order to prevent unauthorized persons from operating the laser;
- an emission display clearly indicating the laser operation;
- interlocks to stop the laser beam if some condition is not met, such as if a room door is opened;
- an adjustable lighting, for example for adjustment work on lasers.

Organisational controls are the second stage of the control hierarchy. They are intended to assist technical measures and ensure that employees are reliably protected from laser hazards. They include, for example:
- information, instruction and training of employees;
- safety signs to mark a controlled area to which access is restricted except to authorized persons;
- the appointment of a Laser Safety Officer (for Classes 3R, 3B and 4).

Personal protective equipment should only be used when the above measures do not provide sufficient protection. They include:
- protective eyewear (laser safety goggles);
- protective gloves;
- protective clothing.

6 Protection against laser radiation

Consumer laser products

The only lasers regarded as safe for consumers are Class 1 and Class 2 lasers. The German Product Safety Act (Produktsicherheitsgesetz – ProdSG) obligates manufacturers, importers and traders to offer only such consumer products which, when used properly, do not endanger the health and safety of either users or third parties. Class 3R, 3B and 4 laser devices are too powerful for general use and present an unacceptable risk in the hands of a consumer because they may cause eye injury under reasonably foreseeable conditions of use. For more information see the "Technical specification for consumer laser products" (Technische Spezifikation zu Lasern als bzw. in Verbraucherprodukte(n), 2010), that has originated in the initiative of BAuA and is directed at manufacturers, their representatives and importers.

Lasers in professional environment

The EU Directive 2006/25/EC on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (artificial optical radiation) fixes exposure limit values (ELVs)[5] for workers exposed to optical radiation in order to prevent short- and long-term hazards of the eyes and the skin. These limits must not be exceeded under any circumstances. The employer shall assess and, if necessary, measure and/or calculate the level of optical radiation at the workplace. If the risk assessment reveals that the ELVs may be exceeded, the employer shall devise and implement an action plan comprising technical and/or organisational measures. The Directive 2006/25/EC has been implemented into German law by the Ordinance to Protect Workers against Risks Arising from Artificial Optical Radiation (Verordnung zur Umsetzung der Richtlinie 2006/25/EG zum Schutz der Arbeitnehmer vor Gefährdungen durch künstliche optische Strahlung – OStrV) in accordance with § 18 of the German Occupational Health and Safety Act (Arbeitsschutzgesetz – ArbSchG). Technical Rules to concretize the requirements of the OStrV are currently being drafted. Compliance with these Technical Rules ensures that the relevant requirements of the OStrV are met. Until then, the Accident Prevention Regulation BGV B2 "Laser radiation" remains mandatory.

[5] It should be noted that terms "exposure limit value" (ELV) and "maximum permissible exposure" (MPE) have the same meaning.

7
Studies on laser-induced blink reflex and aversion responses of humans

The Standard 60825-1 has stated for many years that the safety of Class 2 lasers is (under reasonably foreseeable conditions) afforded by the eye blink reflex. The blink reflex is defined as an involuntary blinking of the eyelids elicited by stimulation of the cornea due to a bright light within 0.25 s (250 ms).

In the early fifties already, Gerathewohl and Strughold (1953) studied the blink reflex after exposure to flash lamp light and found the shortest time from onset of the flash light to full eyelid closure to be 180 ms. The mean value for the blink reflex, when the test subjects did not look directly into the light source, was found to be 350 ms. However, approximately 19 % of the subjects did not show any reaction.

The blink reflex time of 250 ms has been used in the International Standard IEC 825 since 1984 (now IEC 60825-1) without further investigation and has not been questioned, until investigations by Reidenbach and Wagner (1999) using a conventional photographic flash revealed that 10 % to 20 % of the subjects did not respond with a blink reflex. The question whether the same situation could happen with Class 2 lasers, i.e. if the blink reflex alone as an inherent physiological reaction provides sufficient protection against laser radiation could not have been answered without further investigations.

Project "Blink reflex"

In the research project "Examination of laser classification with regard to the eye blink reflex" it has been studied whether the blink reflex can be regarded as sufficient protection from an overexposure against the Class 2 laser radiation.

A specially designed ophthalmologic apparatus was applied both in laboratory and in field trials in order to stimulate the blink reflex (Figure 8). The subjects were informed about the intended purpose of the investigations and were placed in front of the test setup in a similar manner to an ophthalmologic examination. Due to the chin rest, which was used to fixate the optical eye axis to the direction of the laser beam, the subjects were not able to move their head freely. The laser beam was switched on by an operator and directed via a mirror and a lens centrally into the eye of the subject.

Figure 8 A test subject in front of the setup for blink reflex investigations

The project examined whether the frequency of the blink reflex depends on the wavelength, sex and age, as well as on wearing glasses. It was also examined whether blink reflex depends on the size of the retinal image. For that reason, investigations were carried out with both divergent laser beams and high-brightness light emitting diodes (LEDs). Because an LED is considered as an extended source, its retinal image is significantly larger than the one generated by a laser. A divergent laser beam was achieved either using a specially designed focussing lens system in front of the cornea or as a result of an emerging laser radiation from an optical fibre closely positioned to the eye.

The trials were done using a frequency-doubled Nd:YAG laser (532 nm), a He:Ne laser (632.8 nm), two laser diodes – GaAsP:N (635 nm) and GaAlAs (670 nm) –, and a blue (468 nm) and red (615 nm) LED.

A total of 1193 subjects were exposed to the laser and 261 to the LED radiation. The number of subjects which reacted with a blink reflex was only 17 % when exposed to a Class 2 laser, and 23 % when exposed to an LED. No dependence on gender and age of the subjects could be found. Wearing of glasses seemed to have no effect on the occurrence of the blink reflex. However, a dependency on the wavelength of the laser radiation could be detected: the frequency of the blink reflex showed an increase with decreasing wavelength from 670 nm to 532 nm.

Studies with a divergent laser beam and with LEDs showed that the frequency of the blink reflex rises with the retinal spot size. An explanation for this could be that larger images on the retina stimulate more photoreceptors. Comparison of the results from the LED and laser retinal exposure supports this explanation. This also applies to the above-mentioned study of Reidenbach and Wagner (1999), in which a conventional photographic flash was used to stimulate the blink reflex. As a result of a large-area stimulation of the photoreceptors, considerably larger number of subjects reacted with a blink reflex.

As only 17 % of subjects responded with a blink reflex under typical Class 2 laser conditions, this reflex is regarded to be insufficient as the sole protection from an overexposure against Class 2 laser radiation.

Project “Aversion responses”

The aim of the follow-up project “Human aversion response against visible laser radiation” was to clarify whether aversion responses in general, including the blink reflex, limit the duration of retinal exposure to less than 250 ms and thereby provide sufficient protection against an overexposure to Class 2 laser radiation. “Aversion responses” are defined as all reactions within 250 ms to protect the eyes from a hazard when exposed to a Class 2 laser: eye movements such as saccades, eyelid movements covering the pupil of the eye – either voluntarily (eyelid closure) or involuntarily (blink reflex) –, as well as head movements. A twitching of the eyelid, i.e. a not completely executed blink reflex is also possible.

For tests under conditions of a Class 2 laser exposure, three different experimental assemblies were established: a scanning laser line system, an adjustment system with an optical bench and an eye-tracking system. The laboratory investigations and field trials were documented by a video camera. Unlike in the previous project, the head of a subject was unrestrained.

In the scanning laser line system, the laser beam was scanned over the head of a subject, either vertically or horizontally (Figure 9). A frequency-doubled Nd:YAG laser (532 nm) was applied, since in the former project at this wavelength the highest percentage of subjects reacted with the blink reflex. In the tests with the adjustment system and an optical bench, the subject had to adjust the center of a disc by looking through two consecutively positioned apertures. A laser diode (635 nm) was used as light source. Finally, in the case of the eye-tracking system, subjects were asked to carry out a special visual task on a monitor. They had to “catch” the reflection from their own eye and to “guide” it to a stationary cross on a monitor screen. In this way the person was engaged in a visual task which required concentration, a situation similar to that during measurement activities. At the moment of coincidence, a laser beam (635 nm) was released.

Only 17 % of 2022 subjects exposed to a Class 2 laser responded either with a blink reflex or an eyelid closure, and only 6 % of 829 subjects showed other aversion responses. Therefore, the results of this project proved that aversion responses, including the blink reflex, do not ensure adequate protection when working with a Class 2 laser.

High-power LEDs were also applied as optical sources. They were used both as a single element and as a cluster – an LED array consisting of 80 LEDs, aimed at creating a situation similar to a flashlight. The studies using LEDs confirmed that the frequency of the blink reflex increases with the retinal spot size. In the tests, 29 % of subjects reacted with blink reflex or eyelid closure, significantly more often than under laser radiation. Only 7 % of subjects showed other aversion responses.

It was further investigated whether a conscious, active protective reaction can provide adequate protection against an overexposure to Class 2 laser radiation. In a comparative study, a part of the subjects were informed about the intended test procedure, while a control group remained uninformed. Additionally, the informed subjects were asked to perform an active protective reaction by closing the eyes or moving the head in order to avoid continued intrabeam viewing (Figure 10). As a result, 34 % of informed subjects reacted with an eyelid closure, 18 % showed another aversion response. In the control group significantly fewer subjects (14 % and 2 %) showed the respective reactions. Active protective reactions could protect up to 80 % of the exposed subjects against laser radiation within a period of 2 seconds. Therefore, the instruction to perform active protective reactions – closing the eyes or moving the head –, significantly increases the safety against the Class 2 laser radiation.

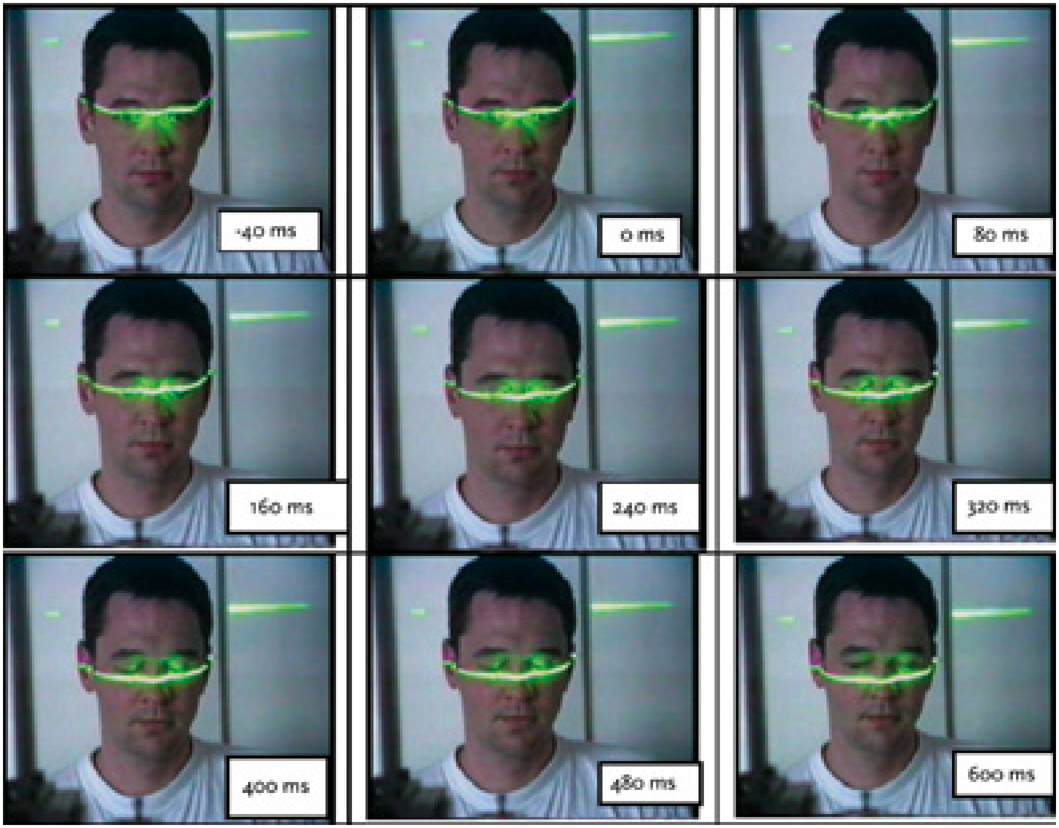

Figure 9 A laser line scanner test: vertical scanning motion of the laser line

Photo: from Reidenbach, Dollinger and Hofmann (2005)

Figure 10 A video sequence of a subject showing an active protective reaction

Photo: from Reidenbach, Dollinger and Hofmann (2005)

Based on the results of those two projects, the authors proposed to modify the safety philosophy of Class 2 lasers. A future protection concept should be based on active protective reactions, rather than on physiological reactions, such as aversion responses, including the blink reflex. As an organizational protective measure, users of low-power lasers should get instructions to perform active protective reactions, e.g., to close their eyes voluntarily and simultaneously move the head away from the beam, in case of an unintentional exposure or intrabeam viewing. The new concept would ensure the highest possible degree of safety in the use of the Class 2 lasers, both in the professional environment and as consumer products.

Impact of the studies on the blink reflex and aversion responses

The two projects revealed surprising results and had various impacts. In the updated instructions relevant to the Accident Prevention Regulation BGV B2 "Laser Radiation" (2007), the following remark was included in the definition of the Class 2 laser: "The occurrence of the blink reflex should not be assumed. Therefore, if laser radiation strikes the eye, one should close the eyes or turn away immediately." The same formulation can be found in the new edition of the Guideline "Laser Radiation" (Leitfaden "Nichtionisierende Strahlung – Laserstrahlung", 2011) of the German-Swiss Radiation Protection Association.

The laser safety concept of the 2001 edition of the European Standard EN 60825-1 for Classes 2 and 2M was based solely on aversion response reactions, including the blink reflex. Descriptions of these laser classes in the 2008 edition of this standard were amended by: "The users are instructed by labelling not to stare into the beam, i.e. to perform active protective reactions by moving the head or closing the eyes and to avoid continued intentional intrabeam viewing." For Class 3R lasers the text "Class 3R lasers should only be used where direct intrabeam viewing is unlikely" was added.

The "Technical specification for consumer laser products" (2010) also refers to the results of the studies on blink reflex and aversion responses: "When deliberately looking into a Class 2 or 3A laser beam, the risk of eye damage increases with increasing duration of exposure. Even an intense glare associated with the exposure does not necessarily cause an aversion response that limits the exposure duration. Active protective reactions, i.e. closing the eyes consciously and moving the head away from the beam significantly enhance the protection against a Class 2 laser damage."

8 Studies on glare caused by sources of optical radiation

According to the European Directive 2006/25/EC on Artificial Optical Radiation the employer shall assess and, if necessary, measure and/or calculate the level of exposure to optical radiation to which workers are likely to be exposed. In addition, the employer should consider sources of artificial optical radiation that may cause glare and afterimages. Glare is a sensation caused by bright light sources with intensity large enough to reduce vision or to cause annoyance or discomfort. Visual disturbances caused by glare can lead to an increased risk of accidents and therefore compromise the safety of employees or others in performing safety-critical operations, such as driving a vehicle or an aircraft, working at height, and operating, installing or repairing machines. According to a Federal Aviation Administration Report (Nakagawara et al. 2004), in recent years several hundred incidents were reported in the United States, including those that may have had serious consequences. Pilots in civilian and military aircraft as well as in police and rescue helicopters were struck by a laser beam during the flight. They reported the glare, flash-blindness and the formation of afterimages.

In the recommendation “Glare by natural and new artificial light sources and related risk” (2006), the German Commission on Radiological Protection (Strahlenschutzkommission, SSK) points to risks of glare caused by artificial optical sources such as Class 2 and 2M lasers and recommends various measures to avoid or minimize them. The “Technical specification for consumer laser products” (2010) also warns of potential risks of glare: “Even Class 1 lasers pose potentially high secondary hazard risk due to their blinding effect. As well as after viewing other bright light sources, such as sun or headlights, temporarily limited visual acuity and afterimages can lead to an irritation, annoyance, inconvenience and even cause accidents. Degree and duration are not easily quantifiable. They mainly depend, however, on the difference in brightness between the dazzling source and environment, and the exposure parameters like power density (irradiance) and the exposure duration.”

The indirect effects, such as glare, are addressed in the new edition of the European Standard EN 60825-1:2008 as well. In the informative description of Class 2 lasers, the standard indicates: “However, dazzle, flash-blindness and afterimages may be caused by a beam from a Class 2 laser product, particularly under low ambient light conditions. This may have indirect general safety implications resulting from temporary disturbance of vision or from startle reactions. Such visual disturbances could be of particular concern if experienced while performing safety-critical operations such as working with machines or at height, with high voltages or driving." Hints on glare can also be found in the descriptions of the Classes 1, 1M, 2M and 3R.

In order to get reliable quantitative data concerning the influence of glare, flash-blindness and afterimages, the goal of the research project "Dazzle caused by sources of optical radiation" was to investigate various parameters which determine the impact on vision.

Low-power lasers and various high-brightness LEDs were applied in specially developed test setups in order to determine the duration and progression of colours in afterimages, the disturbance of visual acuity, as well as the impairment of colour and contrast vision as a function of the applied wavelength, optical power and exposure duration. A total of 191 subjects were tested in 1736 trials during the project.

Due to the fact that the retina exhibits variable sensitivity, a dependency of the duration of an afterimage[6] of the site of the laser spot on the retina (dependent on glare angle) was expected. A Class 1 He:Ne laser (632.8 nm) was mounted on a movable assembly where the respective beam direction relative to the line of sight (glare angle) could be adjusted. Measurements of the afterimage duration were carried out for exposure durations of 1 s, 5 s and 10 s at the power of 5 µW, 10 µW, 20 µW and 30 µW. For the determination of the duration of the afterimage, the moment when the afterimage disappeared and could not be retrieved, not even by squinting, was taken as stop criterion. Additionally, a reading test on a computer monitor was applied after laser irradiation. Special notice was given to the fovea, located in the centre of the macula region with the highest concentration of cone photoreceptors. It is responsible for sharp central vision, which is necessary for any activity where visual detail is of primary importance. The position of the blind spot, the place lacking photoreceptors, was also identified.

Concerning the duration of an afterimage, the results show a strong dependence on the glare angle and on the exposure duration. The bar graph in Figure 11 shows the afterimage duration as a function of the glare angle and the exposure duration for a subject when the laser output power was adjusted to 30 µW. It should be pointed out that very similar curves for different subjects have been documented. The particular location of the fovea and the blind spot (located at about 15 degrees nasally) is clearly depicted. In the blind spot no afterimage could be seen. Afterimage durations up to 300 s were found if the fovea was irradiated for 10 s with a laser beam of 30 µW output power. If the fovea was irradiated for 5 s and 1 s, afterimage

[6] The afterimage is defined as follows: "A visual image that persists after the visual stimulus causing it has ceased."

durations shortened to three-quarters and half of the value at 10 s, respectively.

Following dazzling by a laser beam, two further tests were carried out: a test for determining the inability to read due to the disturbance produced by afterimages, and another one for determining the impairment of the visual acuity[7]. Reading disability lasted between 35 s and 70 s, and the visual acuity was strongly reduced during 60 s to 90 s. This means that the visual function impartment takes about 10 % to 30 % of the total afterimage duration.

[7] Visual acuity is defined as the sharpness of vision, which is the ability of the eye to see and distinguish fine details.

Furthermore, a frequency-doubled Nd:YAG laser (532 nm) operated as a scanning laser was applied as a dazzling light source. After exposure of 250 ms duration and 0.8 mW laser power, 64 % of subjects perceived the exposure as bright, 51 % felt dazzled and 58 % reported afterimages. Those who perceived an afterimage, described it predominantly as a green dot.

If a dark-adapted eye is stimulated by a bright light, a sequence of afterimages of different colours follows. In order to determine the flight of colours, investigations were done with high-brightness LEDs. A computer assisted measuring system was developed in order to determine the dependency on various parameters like colour, optical power and exposure duration of the

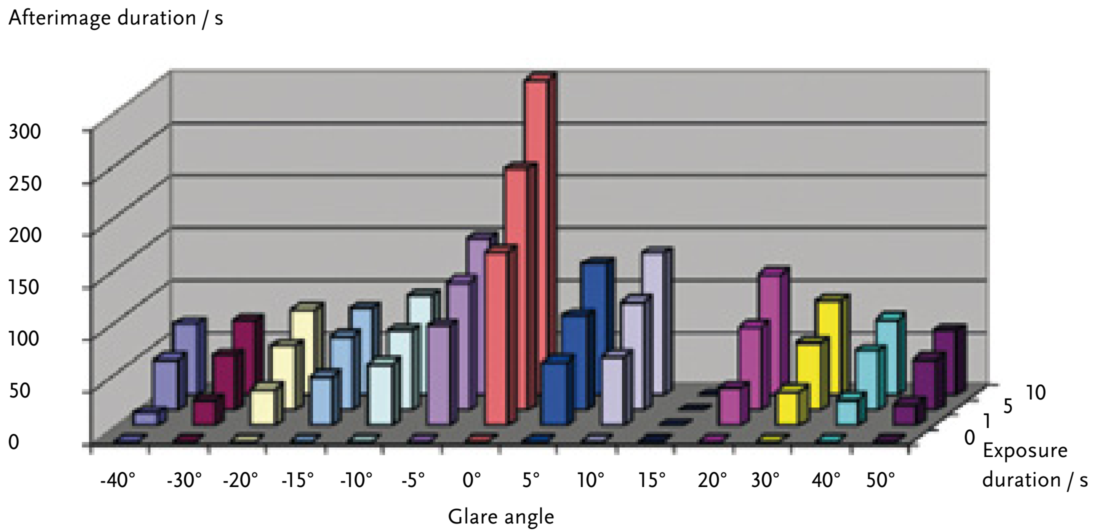

Figure 11 Afterimage duration as a function of the glare angle and the exposure duration for a laser power of 30 µW
Based on Reidenbach, Dollinger, Ott, Janßen and Brose (2008)

stimulating LED. The time-dependent change of the afterimage colours was determined for 4 dominant wavelengths (455 nm, 530 nm, 590 nm and 625 nm) in the optical power range between 0.05 mW and 0.5 mW and for exposure durations between 0.5 s and 5 s. The tests showed that the stimulating colour was dominant in the perception during the first 50 s up to 100 s. A similarity in the perceived colours could be derived for all subjects, but an unambiguous progression of the colours of an afterimage did not exist.

The influence on colour contrast capability was investigated with test charts based on the so-called Pelli-Robson contrast with coloured Landolt C-rings. Glare increased the identification time of respective Landolt C-rings for about 16 s. Tests with pseudoisochromatic plates showed that colour vision was impaired for periods between 27 s and 186 s, depending on the applied colour plate and respective LED colour. Concerning the colour of the applied LED, the contrast vision was most disturbed after an irradiation with a green LED, but the difference to the other colours was small.

The authors propose to classify light sources according to their temporary blinding effect into classes B0, B1 and B2. Whereas class B0 would mean no blinding effect or a dysfunction of vision up to maximum of 2 s, Classes B1 and B2 would indicate the dysfunction lasting up to 10 s and longer than 10 s, respectively.

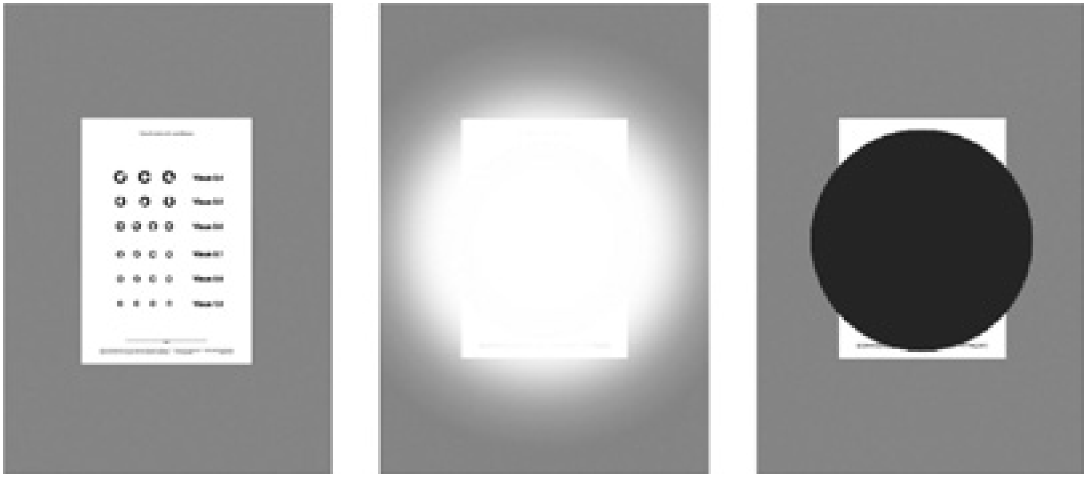

Figure 12 Glare and afterimage

9
Rules of conduct on the safe use of lasers

Class 2 lasers – such as laser pointers, laser spirit levels and laser alignment instruments – are already widespread as consumer products. They are used by persons who in most cases are totally unaware of the biological effects of laser radiation and the associated hazards. All the more important are the results of the studies presented in this brochure, stating that there is no inherent physiological reaction (aversion responses including the blink reflex) providing sufficient protection against a Class 2 laser and that the glare can cause prolonged visual impairment. For lasers as consumer products, user manuals should clearly and unambiguously specify the class-specific behavior and give instructions according to the state of the art (see “Technical specification for consumer laser products”). All professional users of Class 1M, 2 and 2M lasers as well as users of the laser adjustment eye-protectors shall be instructed about the risks of a direct view into the laser beam. When adjusting a laser, the probability of a direct view into the laser beam is particularly high. Laser adjustment eye-protectors reduce the respective laser radiation to values of Class 2 lasers, for which no adequate safety by aversion responses including the blink reflex can be ensured.

The following rules are of particular importance:

- **Never point the laser beam at anyone’s eyes!**
- **Do not look directly into a laser beam!**
- **If the laser light accidentally strikes your eyes, close your eyes and immediately move your head out of the laser beam.**
- **Do not use any focusing optical device to look at the laser beam while working with Class 1M and 2M lasers.**

Further information

Some of the following information is available in German language only.

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