ICNIRP STATEMENT ON LIGHT-EMITTING DIODES (LEDS) AND LASER DIODES: IMPLICATIONS FOR HAZARD ASSESSMENT

International Commission on Non-Ionizing Radiation Protection*†

INTRODUCTION

Both visible and infrared laser diodes and light-emitting diodes (LEDs, or sometimes referred to as IREDs in the infrared) are widely used in displays and in many home entertainment systems, toys, signal lamps, optical fiber communication, and optical surveillance systems. Collectively these are referred to as diode emitters (DEs). While the higher power laser diodes have routinely been considered to be "eye hazards," traditional LEDs have been regarded as safe. However, with the recent development of higher power LEDs, there has been an effort to develop LED safety standards. There are a variety of LED types ranging from surface emitters to superluminescent diodes (SLDs). The latter have some characteristics more typical of diode lasers. Questions have therefore arisen as to whether laser or incoherent radiation exposure limits (ELs) should be applied to each type of emitter. Based upon current exposure limits, most LEDs—particularly surface-emitting LEDs—pose no clear hazard to the eye. Current surface-emitting LEDs produce exposure levels at the retina that are less than 1% of the levels that are known to cause retinal injury (WHO 1982; Sliney and Wolbarsht 1980) even when the LEDs are viewed at extremely close distances (e.g., at 10 cm) (Sliney and Wolbarsht 1980). At typical viewing distances of 0.5 to 2 m, the levels are less than 0.1% of retinal injury levels. Even lengthy exposures of the cornea and lens of the eye pose no hazards whatsoever. From a safety standpoint, LEDs have been treated both as lasers (e.g., in IEC standard 60825-1) (IEC 1998; ANSI 1988) and as lamps (CIE 1999; ANSI/IESNA 1996a,b). Because of some confusion relating to the actual risk, ICNIRP organized a panel of experts to review the potential hazards of current DEs.

Laser diodes are constructed with miniature resonant cavities with gain, produce a very narrow spectral bandwidth, can generally achieve shorter pulse durations, are not limited in radiance, and can emit much higher radiant powers than LEDs.

Light-emitting diodes of low to moderate brightness (luminance) are used in many types of visual displays as indicator lights and many related products. Higher power LEDs and IREDs are used as signal lamps and in a wide variety of domestic and industrial products, and can compete with laser diodes in limited optical communications systems, i.e., in local-area networks (LANs). They are generally not competitive with laser diodes because of different output characteristics. These differences in output characteristics define both their uses and their potential eye hazards. Most current LEDs have very limited radiance and do not pose a clear eye hazard, despite the fact that they have been included in some laser safety standards in the past few years.

LED TECHNOLOGY

What are the key differences between LEDs and diode lasers?

Laser diodes are constructed with miniature resonant cavities (with optical gain, as with Fabry-Perot structures) where stimulated emission ("lasing") occurs. As a result, they produce a very narrow spectral bandwidth, and because of heat-flow geometry and other reasons they can generally achieve shorter pulse durations than LEDs—critically important in optical fiber communications. Diode lasers—unlike most LEDs—are not limited in radiance, and can emit much higher radiant powers than LEDs. This is particularly true of surface-emitting LEDs, which have a radiance of the same order of magnitude as tungsten filaments. Edge-emitting LEDs and related structures can have higher radiances. The emission area in an edge-emitting diode laser is measured in square micrometers, but the emission surface in

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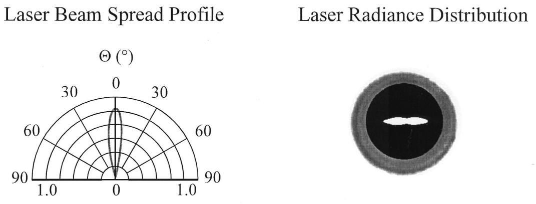
an LED is normally of the order of a square mm. If one magnifies the image of a laser diode, one sees a brilliant source, frequently oblong, sometimes a line, and sometimes nearly a point. This geometry allows the laser beam energy to be collimated, as with other lasers, to beam divergences of the order of one milliradian. By contrast, the LED emitter when magnified appears as a large disc or square area of high brightness, and if one attempts to collimate the beam, it is simply not readily possible without a large lens, as in a flashlight (hand torch). Fig. 1 compares the emission characteristics of laser diodes and light-emitting diodes (LEDs).

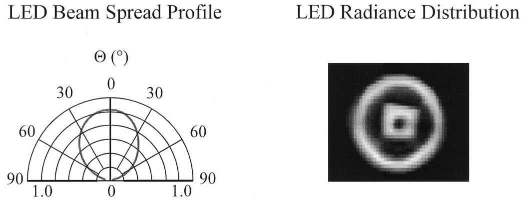
The radiance of a surface-emitting LED is limited both by semiconductor physics and device structure. At room temperature, nonradiative mechanisms often mediated by phonons (lattice vibrations) limit the likely achievable quantum efficiency to below 40%. State-of-the-art LEDs have a quantum efficiency of roughly 20%; that is, 20% of the electrons flowing through the semiconductor junction are converted into photons. As more current flows through the semiconductor junction, these nonradiative mechanisms heat the semiconductor and reduce the efficiency resulting in a self-limiting radiance. For visible LEDs, light is typically emitted only from the front facet of the device, then collected by an integral molded plastic lens. IREDs often have substrates transparent to the generated photons, resulting in a greater external efficiency—more photons escape the device before being absorbed. However, for IREDs, roughly half the totally emitted optical power emanates from the edges of the device through the transparent substrate, and is often redirected by an annular reflecting cup (Sze 1981). In all IREDs known, this annular reflection (Fig. 1) has a much larger area and a size greater than the minimum angular subtense ($\alpha_{\min}$) for extended sources, hence a lower radiance and less hazard than the front-facet die emission. This fact was taken into account when computing radiance values in Table 1. Only the highest radiance value, that of the front facet of the die, is included in the table. Because of the fundamental limitations in quantum efficiency without optical gain, the room-temperature radiance is not likely to increase by more than a factor of two in the future.

Laser Diode:


Laser Beam Spread Profile

Laser Radiance Distribution

LED:


LED Beam Spread Profile

LED Radiance Distribution

Fig. 1. Differences between diode lasers and LEDs. The beam spread is generally smaller for a laser (top) and it is clearly smaller than that for an LED. The source size of the LED (bottom, right) is much larger than that of a laser diode (top, right) as shown in the magnified near-field photographic images. In addition, the spectral bandwidth of laser diodes is far narrower than for any LED (not shown here).

The radiance of a laser is typically much more than a 1,000 times greater than that of a surface-emitting LED. Because of the limited radiance of surface-emitting LEDs, far less radiant power can be launched into optical fibers compared to lasers; therefore, their use is limited in optical fiber communications. Because of lower cost, LEDs are generally favored in applications where either an LED or a laser can be employed. An additional incentive to use an LED rather than a laser has been the lack of safety regulations applying to LEDs, as compared to the maze of regulations related to lasers.

New device types and comparisons

New developments in semiconductor technology have allowed new DE devices to be created that have led to the question whether these should be treated as laser diodes or LEDs for safety evaluations. The properties of some of these devices fall between conventional LEDs and diode lasers. A simple distinction between what a user would call a laser and an LED is no longer possible.

These device types are as follows:

1. Surface-emitting (large area) LED (SLED);
2. Micro-cavity surface emitter;
3. Edge-emitting LED (ELED);
4. Super-luminescent diode emitter (SLD);
5. Vertical-cavity surface-emitting laser (VCSEL); and
6. Ridge-wave guide laser (clearly a full-fledged laser; included for comparison).

Each of these devices will be described in the following.

Surface-emitting LEDs (or SLEDs) are the conventional LEDs which have existed for decades. In comparison to the latter types, these emit from relatively large surfaces oriented orthogonally to the axis of the emission pattern.

Micro-cavity surface emitters are SLEDs with an internal mirror and layer thicknesses tailored to act as a low-finesse Fabry-Perot cavity. These devices do not show optical gain; the cavity is added only to reduce the optical linewidth. This micro cavity also has the effect of reducing the emission half-angle, since the layer thicknesses forming the cavity reduces emission efficiency at larger angles. Assuming that device structures can be designed which reduce the half angle while preserving the total power emitted from the front facet of the device, one obtains the maximum brightness. These devices are

Table 1. Current diode emitter device types.

DE device type	Wavelength (nm)	Spectral width (FWHM)[a]	Source dimensions	Radiance (W cm^{-2} sr^{-1})	Effective 100-s-average radiance (W cm^{-2} sr^{-1})
Surface emitter	400 to 1,600	10 to 100 nm	0.3 × 0.3 to 5 × 5 mm	0.10 to 2.5	0.18 maximum
Micro-cavity surface emitter	400 to 1,600	3 to 10 nm	0.3 × 0.3 to 5 × 5 mm	0.1 to 22	1.5 maximum
Edge emitter	600 to 1,600	25 to 100 nm	3 × 100 μm, typical	6,000 max.	1.5 maximum
Super-luminescent edge emitter	400 to 1,600	10 to 100 nm	3 × 100 μm, typical	25,000 max.	6 maximum
Vertical-cavity surface-emitting laser (VCSEL)	630 to 980	0.1 nm	5 to 50 μm diameter, circular	7,000,000 max.	115 maximum
Ridge waveguide laser	400 to 1,600	0.1 nm	2 × 100 μm, typical	1,300,000 typical	220 typical

[a] FWHW: Full width at half maximum.

relatively new, and, to our knowledge, none has yet found its way into practical applications. Further, there are no reported DEs which have even approached the maximum value of radiance predicted for these devices.

Edge-emitting LEDs have a device structure similar to that of the ridge wave guide laser, with the exception that the device does not have sufficient gain to lase. Typical dimensions of the emitting stripe are 3 × 100 μm, with an active region several hundred microns long. Because of the energy density in the long active region, high radiances are achieved at the emitting facet, making it easier to launch the light into an optical fiber. Because the emitting area and geometry for this device is quite different from the SLED or the micro-cavity device, it is quite easy to distinguish from surface emitters.

Super-luminescent edge emitters are similar to edge emitting LEDs, but have cavities with a bulged ridge. That is, the central portion of the cavity is wider than the emitting facet. When properly designed, more photons generated within the device reach the emitting facet than for a uniform cross-section, standard edge emitter, hence the emitted radiance is increased. These devices are not yet commercially available, and are an active subject of research, where they are typically used in conjunction with an external cavity to make tunable, pulsed semiconductor lasers.

Another relatively new DE is the vertical-cavity surface-emitting laser (VCSEL). This device consists of two Bragg reflectors constructed from mirrors grown below and above the active region of the device. These Bragg reflectors are so efficient that the gain medium can be relatively thin (as compared to the long ridge waveguide active medium). As their name suggests, these devices emit vertically, out of the plane of the semiconductor wafer, and so are easier to package. However, because the emission area is larger than a typical ridge waveguide laser, the averaged radiance is less than that of the ridge waveguide laser.

Ridge waveguide lasers have a device structure very similar to edge emitting LEDs with one exception: the facets of the cavity are designed to be reflecting so that the cavity has optical gain. The lasing within the cavity produces very narrow optical linewidths and coherent light. Due to the high energy density in the long laser cavity and the optical gain, these devices are orders of magnitude higher in radiance than edge-emitting LEDs, which are, in turn, orders of magnitude higher in radiance than a surface-emitting LED.

Finally, SLEDs and micro-cavity surface emitters are easy to identify and cannot be confused with the other classes of emitters discussed above. They are large-area surface emitters (unlike the small-area VCSEL), they are incoherent, and have much greater spectral linewidths than lasers. In fact, any diode laser can be distinguished from an incoherent emitter by a simple two-slit interference test in the event that the device type is unknown. (Of course, more expensive optical spectrum analyzers can be used for similar coherence and linewidth determinations.)

LED specifications applicable to safety

Radiance is important for assessing the potential retinal hazards of any bright optical source that can be imaged on the retina. Radiance is generally expressed in optics with units of W cm^{-2} sr^{-1}, and, most importantly, radiance (or "brightness") is conserved and cannot be increased by any optical lensing. When examining a manufacturer's specification sheet for an LED, the "brightness" (expressed as either radiance or luminance) is not given. Instead, the radiant intensity (W sr^{-1}) or luminous intensity (cd = lm sr^{-1}) is almost always specified. If one knows what the *apparent* source size is, then one can calculate the LED radiance or luminance. The actual source size is applicable if no lens is incorporated on the LED, but, if so, the actual source size is magnified, and that apparent source size must be used in any hazard assessment.

Table 1 presents the variety of DE devices with an emphasis on their properties relevant to optical radiation safety. The optical radiation hazards of the device types range from harmless (e.g., SLEDs) to potentially hazardous (e.g., laser diodes). The approach in deriving the values in the table centered on a comparison of the radiance (column 5 of Table 1). The highest radiance of any state-of-the-art surface-emitting LEDs (SLEDs) is of the order of 2.5 W cm^{-2} sr^{-1} and is limited for fundamental reasons described above. Although the emission geometries vary, they are often nearly rectangular. Therefore, it was assumed that the effective emitting area A_{src} of the source was simply the product of the length and width of the emitting area, and the mean effective dimension (for calculating the effective angular subtense α_{src}), termed S_{eff}, was estimated as the square route of the source area. The radiant flux (power) collected by a 7-mm limiting aperture at the closest viewing distance (100 mm) could then be calculated for comparing against the published exposure limits (ELs) for a laser or incoherent source. For ease of comparison, the laser EL for 100-s viewing was used in Table 1 for all devices, as it was the most conservative value. To apply the 100-s EL (which varies with wavelength) the radiance in Column 5 of the table had to be averaged over the cone angle specified in the laser guidelines (ICNIRP 1996) and IEC Standard (IEC 1998). The proposed revision in the ELs (ICNIRP 2000) will alter the guidelines to make these less restrictive at 100 s.

From reviewing the characteristics given in the table, the actual radiances (column 5) and the "effective radiances" (column 6) of LEDs are completely different from those of LDs. (Column 6 gives the radiances as would be measured or calculated by criteria of the laser guidelines—see Appendix A for an example calculation.) While it would be desirable to have a harmonized set of optical radiation safety limits for hazard assessment for all DEs, the surface emitters are very similar to conventional lamp types and unlike laser diodes. The Regensburg group[†], which prepared the Table, considered all possible operational conditions, including pulsing, and determined that for an optimum SLED, the radiance was far below ELs. For both the pulsed and the continuous-wave (CW) case, the flux at the eye was a factor of at least an order of magnitude below the applicable laser EL. The repetitive pulse case was also an order of magnitude below ELs, as the emitted power was still restricted due to thermal effects, which limit the diode's efficiency. Appendix A provides a sample calculation. These and similar calculations led the Regensburg task group to conclude that it was not possible to imagine a SLED ever emitting a radiance near the maximum permissible exposure (MPE) since the efficiency of the devices examined was already 20%. Even if the efficiencies were to reach 100%, which is not practically possible, the calculated values would still be a safe factor below the MPE, which itself has a substantial factor of 10 to 20 below the 50% probability of detecting a minimal visible lesion on the retina (ED-50). The clear conclusion is that the SLED emitters, whether visible or IR, are more like lamps in terms of spectral bandwidth emission profile and radiance and are not like lasers; they are safe under reasonably foreseeable usage conditions when compared to MPEs. This conclusion applies equally well to visible and IR LEDs stared at for 100 s or less.

POTENTIAL BIOLOGICAL HAZARDS OF LEDS

The optical hazards of intense light sources, such as welding arcs, arc lamps, some tungsten-halogen lamps, and lasers can be grouped into at least six separate types of hazards to the eye and skin (WHO 1982; Sliney and Wolbarsht 1980; CIE 1999; ICNIRP 1997; McKinlay et al. 1988):

a. Ultraviolet (UV) photochemical injury to the cornea (photo-keratitis) and lens (cataract) of the eye (180 to 400 nm) (WHO 1982; Sliney and Wolbarsht 1980; Duchêne et al. 1991);
b. Thermal injury to the retina of the eye (400 to 1,400 nm) (WHO 1982; Sliney and Wolbarsht 1980; Duchêne et al. 1991; ICNIRP 1996; ICNIRP 1997; ICNIRP 2000);
c. Blue-light photochemical injury to the retina of the eye (principally 400 to 550 nm; unless aphakic, 310 to 550 nm) (Ham et al. 1976; Ham 1989; Sliney and Wolbarsht 1980);
d. Near-infrared thermal hazards to the lens (approximately 800 to 3,000 nm) (WHO 1982; Sliney and Wolbarsht 1980; Ham et al. 1976; Lund et al. 1996; Pitts and Cullen 1981);
e. Thermal injury (burns) of the cornea of the eye (approximately 1,400 nm to 1 mm) (WHO 1982; Sliney and Wolbarsht 1980); and
f. Thermal or photochemical injury to the skin from high irradiances (WHO 1982; Duchêne et al. 1991; Sliney and Wolbarsht 1980).

For currently available visible LED sources, only aspect (c) is of concern; whereas for IRED sources only aspects (b) and (d) are even remotely relevant, since aspects (a) and (c) can only occur from short-wavelength light and UV, and thermal injury of the skin requires optical powers in the 100 s of milliwatts-to-watts range. Therefore, only the relevant *potential* hazards need to be evaluated. Retinal hazards are dependent upon the brightness of the source, and the limited brightness (i.e., radiance) of LEDs have normally placed them in a category of "not-of-concern" in safety circles. The radiance of the brightest surface-emitting LED sources is comparable to the radiance of a tungsten lamp filament, i.e., about 2.5 W cm^{-2} sr^{-1} (25 kW m^{-2} sr^{-1}).

It should be recognized that the eye is well adapted for protection against the harmful full-spectrum optical radiation from environmental sunlight encountered in all but the most extreme natural environment. Humans have learned to use protective measures, such as hats and eye-protectors to shield against the harmful effects upon the eye from very intense UV present in sunlight over snow or sand. Bright light sources such as the sun, arc lamps, and welding arcs produce a natural aversion response by the eye. This response limits the duration of exposure to a fraction of a second (less than 0.25 s). Near-infrared sources without a significant visible component cannot offer this natural aversion response, and behavioral viewing patterns, eye fixation, and factors such as eye fatigue must be considered to determine a maximum viewing duration.

The determination of a maximum viewing duration has been a contentious point in the drafting of all laser safety standards, with extreme positions of 1 s to 8 h being proposed. As more experience has been gained from dealing with laser safety, durations of 10 to 100 s are generally recommended for evaluating hazards from ocular exposure to infrared lasers (Sliney and Wolbarsht 1980; ANSI 1988; ICNIRP 1996). Since thermal injury thresholds undergo little change with exposure durations exceeding 10 s, this debate has little significance for near-infrared laser diodes or LEDs. In 1998, the ICNIRP approved revision of its Guidelines for Laser Exposure (ICNIRP 2000) so that minimal-image laser limits are now nearly the same or identical to the incoherent guidelines for most wavelengths. These revisions were possible only after a careful study of the influence of fixational eye movements. It should be noted that if a visible or infrared source were employed in an ophthalmic instrument or a device fixed to the head for intentional lengthy exposures, these revised limits may not apply.

Applicable exposure guidelines for eye safety

Guidelines for limiting human exposure to both lasers and incoherent optical radiation have been published by many organizations (IEC, CIE, ANSI, ACGIH, CDRH) as well as the ICNIRP, and it was previously recommended that the guidelines for incoherent sources be applied to LEDs (ICNIRP 1996, 1997). At first, one would think that laser safety limits could be applied to LEDs. However, the guidelines for incoherent sources and lasers differ somewhat, although as a result of the revision of the ICNIRP guidelines for laser radiation (ICNIRP 2000) these differences have been reduced. The incoherent limits are radiance based; whereas, laser exposure limits are expressed only as radiant exposure (or irradiance) referenced to a “point-source” viewing condition.

Because the spectral bandwidth of LEDs is much greater than that of lasers, all current occupational and public health exposure limits and guidelines state that LEDs should be treated as incoherent optical sources. The Commission has in the past sometimes added additional safety factors in the derivation of laser limits (ICNIRP 1996, 1997). Separate occupational exposure limits for laser exposure of the eye and skin have been in use for many years, and today most laser standards and guidelines are reasonably in agreement world-wide (WHO 1982; Sliney and Wolbarsht 1980; IEC 1993; ANSI 1988; ICNIRP 1996; Duchêne et al. 1991; ICNIRP 2000). However, guidelines for incoherent optical radiation and for laser radiation differ for two reasons. For incoherent sources there is a need to assess several different hazards over a range of wavelengths, so the radiance criteria are the most useful for extended sources: for lasers there are concerns that their energy may cause narrow-wavelength spectral effects. Indeed, one of the reasons given for different guidelines by the Commission for applying a greater safety factor when deriving certain laser ocular exposure limits has been the concern about very narrow-band biologic effects (ICNIRP 1996).

It is reasonable to consider whether laser or incoherent-source limits are more applicable to certain types of LEDs. Conventional, surface-emitting LEDs are radiance limited, and although many eye injuries have been reported and documented for lasers, none have ever been documented for LEDs. Laboratory efforts to create ocular injury with high-power LEDs have so far been unsuccessful; whereas, laboratory studies using diode lasers did produce retinal injury (Duchêne et al. 1991; Ham et al. 1984; Lund et al. 1996; Mainster et al. 1997; Sliney and Wolbarsht 1980).

Retinal hazards

The principal retinal hazard resulting from viewing bright light sources is photoretinitis, e.g., *solar retinitis* with an accompanying scotoma which results from staring at the sun (Ham 1989). Solar retinitis was once referred to as “eclipse blindness” and associated “retinal burn.” Only in recent years it has become clear that photoretinitis results from a photochemical injury mechanism following exposure of the retina to shorter wavelengths in the visible spectrum, i.e., violet and blue light (Ham et al. 1984; Ham 1989). Prior to conclusive animal experiments, it was thought to be a thermal injury mechanism (Ham et al. 1976). However, it has been shown that an intense exposure to short-wavelength light (frequently referred to as “blue light”) can cause retinal injury (Ham 1989). The studies of Ham clearly show that blue-light injury to the retina is one thousand-fold more dangerous than 890-nm radiation (Ham et al. 1984; Ham et al. 1976). By filtering out short-wavelengths (blue light) from a white-light arc lamp, Ham et al. showed that the risk of photochemical injury to the retina could be enormously reduced.

The studies by Ham and colleagues of retinal thermal injury thresholds for a filtered xenon-arc source emitting narrow bands of infrared radiation at wavelengths bracketing the 770–950 nm IRED wavelength region showed virtually the same values at 820 ± 5 nm, 860 ± 5 nm, and 910 ± 25 nm (For the calculation of retinal exposure see Appendix B). The threshold retinal irradiances for just producing visible retinal lesions in the rhesus monkey eye were approximately 30 W cm^{-2} for 1 s, 23 W cm^{-2} for 10 s, 20 W cm^{-2} for 100 s, and 19 W cm^{-2} for 1,000 s (all for 500-μm retinal spot diameters). This compares to only 0.03 W cm^{-2} for a 1,000-s exposure to 441-nm blue laser light (WHO 1982). Thermal retinal injury has been shown to dominate at wavelengths beyond 550 nm, and the threshold for thermal injury is retinal spot-size dependent because heat flow is more efficient for smaller diameter image sizes. The 500-μm thresholds for thermal injury would be expected to be nearly twice the value for a 1,000-μm (1-mm) image. The 500-μm image size corresponds to an angle of 29 mrad. For still larger retinal image sizes, this spot-size dependence becomes less, and by 1.7 mm diameter, the threshold is virtually a constant with increasing spot size. The 1.7-mm diameter retinal image is approximately 100 mrad, and this is applied in guidelines to protect against thermal injury from both lasers and incoherent sources. Since the retinal irradiance is directly proportional to the radiance of the LED source for a fixed pupil size, the guidelines for incoherent sources are expressed as radiance (ICNIRP 1997).

Photochemically induced blue-light retinal injury is not spot-size dependent in itself if specified at the retina. However, because of eye movements, the blue-light radiance of small sources is averaged over a circular angle of 11 mrad (corresponding to an irradiance-averaging over about 190 μm at the retina) for viewing durations up to 100 s. Larger eye movements occur for longer durations, and ICNIRP provides guidance for averaging radiance over ever increasing angles with increasing duration beyond 100 s (ICNIRP 1997). Even more detailed guidance for the increasing measurement-averaging field-of-view is provided for laser guidelines (ICNIRP 2000; IEC 1998).

Viewing conditions and the near point of accommodation

Since the hazard of retinal injury varies with retinal image size, which in turn depends on the viewing distance, the exposure limits vary with the viewing distance. The closest distance at which the human eye can sharply focus upon a small object, such as a small LED, is about 10 to 20 cm. Ten centimeters is an exceptionally small value for the near-point of accommodation for the human eye—even for a child. At shorter distances the image of the small light source would be out of focus and blurred, and a relatively large retinal image is produced at such close ranges.

There is also the very unusual case of viewing an LED using an eye loupe or hand magnifier. When such an optical aid is used, several things happen: the corneal irradiance increases by as much as the square of the reduced distance if the light is not collimated and the source is an extended one. The retinal image area is increased by the same factor, with the net result that the retinal irradiance is not increased. This is the Principle of Conservation of Radiance ("brightness"). This means that the source radiance and retinal irradiance cannot be increased by the optical aid. The optical aid permits the eye to bring to focus the source at the closer viewing distances of 20–200 mm. However, despite no increase in retinal irradiance, the increasing image size can increase the retinal hazard as a consequence of the spot-size dependence of retinal thermal injury. Small eye movements redistribute optical energy in the image over a larger retinal area, greatly reducing the risk of injury for small sources, but this risk reduction factor is reduced for larger (magnified) images. This rationale applies to optically resolved (extended) sources, such as LEDs viewed by optics. Viewing by an eye loupe is only likely for persons servicing optical fiber transmission systems and highly unlikely for other LED applications. Indeed, high-magnification viewing is not a foreseeable viewing condition except for optical fiber inspections (Sliney 1997).

Viewing conditions and "use factors"

Most IREDs are not visible under normal usage conditions. Although the CIE definition of the visible spectrum extends only to 780 nm, the visual response continues at very poor sensitivity to longer wavelengths. Therefore, high-radiance sources emitting wavelengths longer than 780 nm may be weakly visible (Sliney et al. 1976). Although most IREDs emit almost all of their energy within the wavelength range from about 800 to 980 nm in the near-infrared spectral region, many IREDs are just barely visible to most individuals viewing them in the dark. If visual examination of a weakly visible red dot can be expected on occasion, even more rare—but not impossible—would be examination of an IRED red dot with a magnifying glass. In all of these close examinations, most viewing periods would probably be limited to 5–10 s at close range of 20 to 50 cm, although somewhat longer viewing distances and exposures for slightly longer periods might be expected.

Some generic safety standards assume worst-case conditions of viewing the source with optical aids for lengthy viewing durations (e.g., 100 s) and therefore will over-state the risk for all but some unusual situations. All of these exposure conditions must be borne in mind when comparing the output characteristics of LEDs with current guidelines and standards. Since a light source with a radiance equivalent to the EL guidelines for incoherent visible radiation is uncomfortably bright, lengthy viewing of visual displays of visible LEDs approaching the ELs is not a foreseeable viewing condition.

STANDARDS AND REGULATIONS

The ICNIRP (1996) laser guidelines for exposure limits (ELs), and the maximum permissible exposure (MPE) limits listed in IEC 60825-1.1 (1998) are the same for lasers emitting in the retinal hazard region (400–1400 nm) and require the use of a 7-mm aperture (simulating a dark-adapted pupil) for measurement averaging of irradiance or radiant exposure at that point of interest in space where the eye might be placed. However, the IEC accessible emission limits (AELs) for Class 1 ("eye-safe") laser and LED products have until recently required the use of a 50-mm aperture placed at a measurement distance of 10 cm from the nearest point of human access. This might appear to be a very curious method for collecting most of the energy from the source but the origin of this AEL requirement was a series of worst-case assumptions for human ocular exposure. The IEC and CENELEC standards take the worst-case assessment even further and assume an optically perfect, stabilized eye-loupe for a viewing duration of 100 s (or greater for visible sources intended to be viewed) (IEC 1998).

In the past, LED optical radiation sources or "solid-state lamps" have generally been considered quite safe, and there had been a consensus that there was no need for LED safety standards (IESNA 1996a, b; McKinlay et al. 1988). There are currently no product safety standards or regulations that expressly relate to the use of LEDs in instruments or specialized consumer electronic applications. However, there are occupational health exposure limits and guidelines used worldwide for evaluating lasers, LEDs, and other light sources in the workplace and for public exposure (IESNA 1996a, b; ICNIRP 1997; CIE 1999; ACGIH 1999). With the development of high-power IREDs for use in optical fiber communication systems, that thinking was re-examined, and in the U.S., ANSI Z136.2-1988, "Safe Use of Lasers in Optical Communication Systems (OFCS)," was issued (ANSI 1988). In 1993, the International Electrotechnical Commission (IEC) Technical Committee TC76 (Laser Products) included LEDs in the 1993 revision of their laser product performance standard, IEC 825-1-1993 (the predecessor to IEC 60825–1.1–1998) (IEC 1998). To some extent this inclusion of LEDs was to avoid confusion or the need to perform spectral measurements of OFCS emissions, but it was also favored by the laser diode manufacturers who thought it unfair to regulate laser diodes but not require similar testing and measurement of LEDs. However, in the preparation of the IEC standard, the IEC TC76 chose not to limit the inclusion of LEDs to the fiber-optic telecommunications applications, but applied it to all LED applications. Unfortunately, this decision did not adequately recognize that the overly simplified measurement methods in IEC 825-1-1993 had been developed with certain inherent assumptions relating to laser sources, and IEC TC76 had to amend the standard to correct some of these problems. Most of these problems were resolved in two stages. The 1998 Amendment 1 corrected the principal problems related to the measurement conditions for classification, and in 1998, IEC 60825-6, an application-oriented technical report, was issued with a 2-y lifetime; it dealt with LEDs (and lasers) used for displays. This report recommended that displays and similar devices be evaluated by applying ELs rather than device accessible emission limits AELs. Another technical report, IEC 60825-7, has been under development to deal with IREDs used in free-air data transmission and provides relaxations justified by this application. Still another IEC technical report, IEC 60825-9, compiled EL values for incoherent sources, and recognized the 1997 ICNIRP recommendations, but attempted changes in the recommendations with regard to measurement conditions so that the guidance was similar to the laser standard. It also addressed the determination of source-size.

It can also be argued that since the spectral output bandwidth of LEDs is much greater than lasers, LEDs should be treated as other incoherent optical sources, for which exposure limits are not so conservative (ICNIRP 1996, 1997). Finally, it should be pointed out that the same factors limiting the radiance of surface-emitting LEDs (no gain, thermal effects, large area, and hence electrical capacitance) also constrain the energy and minimum duration of light pulses emitted by the surface-emitting devices. As a consequence, the single-pulse hazard posed by these devices falls below the 100-s, quasi-CW limit in all the guidelines known to the group. This is not always the case for laser devices where significant energy can be concentrated in a single pulse.

CONCLUSIONS AND RECOMMENDATIONS

It is concluded that all surface-emitting LEDs and IREDs will be judged safe by applying the ICNIRP ELs for incoherent radiation as well as by the recommendations of CIE TC 6-38 (Lamp Safety) for realistic viewing conditions. This conclusion applies to any LED device which does not have optical gain. Only because of the extraordinary worst-case assumptions built into some current product safety standards could one reach the conclusion that an LED or IRED poses a retinal hazard. On the other hand, the use of laser ELs to evaluate LEDs could result in an understatement of the lenticular risk if the source is very large and the lens becomes overheated.

It is therefore recommended that safety evaluations and related measurement procedures for LEDs follow the guidelines for incoherent sources (ICNIRP 1997). This approach provides the most accurate assessment of incoherent sources without problems originating from certain underlying assumptions incorporated into the limits developed for collimated laser beams. Diode lasers and VCSELs clearly should be treated in all standards as lasers.

It is recognized that the determination of appropriate viewing durations and distances under different conditions of use is needed for any optical radiation hazard assessment. Unfortunately, not all safety guidelines currently recommend use of the same measurement distances and viewing durations. The future development of application-specific safety standards which may be applied to realistic viewing conditions will also contribute to reducing unnecessary concerns regarding LED and IRED safety.

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APPENDIX A

Calculations of diode emission characteristics

The formulae used in the calculations were as follows:

- Effective emitting area of the source (A_{src}):

  $$A_{src} = l \times w,$$

  where l is the length and w the width of the source in cm, and A is in cm^2;
- Mean effective "dimension" of the source (S_{eff}):

  $$S_{eff} = \sqrt{A_{src}};$$

- Angular subtense of the source (α_{src}):

  $$\alpha_{src} = \sin^{-1}(S_{eff}/10\ \text{cm})\quad (= \text{angular subtense at 10 cm});$$

- Mean emission angle of the source (Θ_{src}):

  $$\Theta_{src} = (\theta_{\parallel} \times \theta_{\perp})^{1/2},$$

  where $\theta_{\parallel}$ and $\theta_{\perp}$ are the emission half-angles in two principle planes in sr;
- Solid angle of source emission (Ω):

  $$\Omega = 2\pi[1 - \cos\Theta],$$

  where Ω and Θ are in sr.
- Radiance of the source (L_{src}):

  $$L_{src} = P_o/(A_{src} \times \Omega),$$

  where P_o is the output power in W, A_{src} is in cm^2, and L_{src} is in W cm^{-2} sr^{-1}; and
- Effective radiance (L_{eff}) averaged over 11 mrad:

  $$L_{eff} = L_{src} \times (\alpha_{src}/0.011\ \text{rad})^2,$$

  where L_{eff} and L_{src} are in W cm^{-2} sr^{-1}, and α_{src} is in rad.

Example

This is one example of the assumptions made and the results of calculation for a pulsed SLED calculation. Using a state-of-the-art Siemens pulsed SLED emitter, the specified intensity was 600 mW sr^{-1} peak power for 100 μs into a solid angle of 0.378 sr (or 20 degree half-angle) at 880 nm. Using these data, the peak output power of the LED die image would be (600 mW sr^{-1}/2)(0.378 sr) = 113.4 mW peak into 0.378 sr. The reason for the factor of two determined by the group was that 1/2 of the light comes from the LED die image, here approximately 0.8 × 0.8 mm, so its subtense is less than α_{min}. The other half of the light comes from the annular reflector cup and has an apparent size of the order of 3.3 mm (circular), hence $\alpha = 33$ mrad (i.e., greater than α_{min}). This complicates the calculations somewhat—inasmuch as by considering the die image alone gives an equal or greater hazard to taking the whole output power and using an effective image size for the whole image. Using these assumptions, a Maple routine was used to integrate the power collected through a 7-mm-diameter aperture at 100 mm distance and assuming a raised cosine angular dependence for the SLED emission, where $p = P_o(\cos^m\Theta)$, and the exponent m is about 11 for a 20-degree half-angle emitter. It was found that a

7-mm aperture at 100 mm collected a peak power of 0.84 mW (from the die image only); hence, an energy per pulse of (0.84 mW)(100 μs) = 0.084 μJ.

Thus, for the single-pulse limit:

$$EL = 18 \times C_A \times C_E \times t^{0.75} = 4.12 \times 10^{-2} \text{J m}^{-2},$$

where $C_A = 10^{[0.002(\lambda-700)]} = 2.29$ and $C_E = 1$ (ICNIRP 1996).

The calculated collected flux is 2.18×10^{-3} J m^{-2}; thus, the single-pulse emission from this diode is a factor of 19 below the EL for the single-pulse laser exposure limit.

For CW operation, where thermal effects limit the radiance of the device, the same type of LED could produce (at most) 7 mW from the die image, which corresponds to approximately 38 mW sr^{-1} (average radiant intensity) for a 20-degree half-angle device. The calculation of the EL for the CW condition gives

$$EL = 18 \times C_A \times C_E \times t^{0.75} = 1.3 \times 10^{3} \text{ J m}^{-2},$$

where $C_A = 10^{[0.002(\lambda-700)]} = 2.29$ and $C_E = 1$ (ICNIRP 1996), and t is 100 s.

The calculated collected flux is 1.34×10^{2} J m^{-2}; thus, the *CW* case yields a flux at the eye which is a factor of 10 below the *EL*. The repetitive pulse case will fall somewhere between these two limits due to thermal effects, which limit the diode's efficiency.

Visible SLEDs with 100-s averaged radiances less than 1 W cm^{-2} sr^{-1} will fall below the EL for photochemical retinal injury since the limit is 100 J m^{-2} sr^{-1} in 100 s, and all SLEDs fall below that. As mentioned above, SLEDs are unable to pose a hazard to the retina even if the efficiency of the device was 100%. The clear conclusion is that, as stated, the SLED emitters, whether visible or IR, are more like lamps, not like lasers, and are safe under reasonably foreseeable usage conditions.

APPENDIX B

Calculating retinal exposure

From knowledge of the optical parameters of the human eye and from radiometric parameters of a light source, it is possible to calculate irradiances (dose rates) at the retina. Exposure of the anterior structures of the human eye to infrared radiant energy may also be of interest; and the relative position of an external light source and the degree of lid closure can greatly affect the proper calculation of this near-infrared exposure dose in an awake, task-oriented viewing subject. The retinal irradiance (exposure dose rate) E_r (in W cm^{-2}) depends upon the radiance L (in W cm^{-2} sr^{-1}) of the LED source, the pupil size d_e (in cm), the effective focal length f (in cm) of the eye, and the transmittance of the ocular media τ (unitless, $\tau \approx 0.9$):

$$E_r = \pi L \tau d_e^2 / 4f^2,$$

which, for an adult human eye where the effective focal length is 1.7 cm, reduces to:

$$E_r = 0.27 \times L \tau d_e^2.$$

Because most major ocular structures are of the order of a centimeter, it has been customary in ophthalmic journals worldwide to use cm^2 rather than m^2. As one example, the radiance L of a measured surface-emitting LED was 1.8 W cm^{-2} sr^{-1}; hence, the retinal irradiance for a dark-adapted (worst-case) pupil of 7 mm would be:

$$E_r = 0.27 \times L \tau d_e^2 = (0.27 \text{ cm}^{-2})(1.8 \text{ W cm}^{-2} \text{ sr}^{-1}) \times (0.9)(0.49 \text{ cm}^2) = 0.21 \text{ W cm}^{-2}.$$

Note: The equation is empirical and is not dimensionally correct unless a dimensional correction factor $K = 1$ sr is inserted in the right hand numerator, but it is not conventional to show this.

This irradiance is far below any known threshold for retinal thermal injury.

■ ■