Vixar Application Note

Eye Safety with NIR VCSELs

Contents

Note: This application note is only an introductory guide to the mechanisms and calculations that determine laser safety classification. It is not meant to be a resource for laser module evaluation and should not be used for end-product evaluation. Each laser application will have its own specific driving conditions and operating environments that need to be considered. All laser products should be tested to meet eye safety standards through the assistance of a certified laser safety consulting firm.

1 Introduction

Vertical Cavity Surface Emitting Laser (VCSEL) arrays have emerged as an important technology for applications within the consumer, industrial, automotive, and medical industries. Regardless of the application, laser sources need to be integrated with laser safety in mind. Laser safety is a factor that is dependent on many factors including wavelength, divergence, and pulse conditions.

This application note introduces the safety considerations for lasers with a focus on VCSEL sources available from Vixar. The theory behind laser safety limits are explained based on academically acknowledged maximum permissible exposure limits. Laser safety classes are also described in terms of relevance and scale, along with proper handling processes used for evaluating VCSEL components. Laser safety levels stated in this application note are written in reference to the IEC laser safety standard IEC 60825-1:2014, and laser classification levels may change with future revisions to the IEC standard. In addition, multiple laser safety standards exist, and each industry and country may utilize a different standard with different power levels and classification methods that may not match those in the IEC 60825 standard.

2 Laser Hazards

Semiconductor lasers emit nonionizing optical radiation, which can be a hazard to the human body. While laser radiation can affect all human tissue, the main concern for laser safety is the human eye due to its sensitivity. The human eye collects lights from the environment for visual perception. The lens collects incoming light, focuses the optical power, and creates a focused image on the retina. The iris acts as an adjustable aperture is in front of the lens and controls the amount of light the lens can collect. The cornea acts as an outer covering. The pieces of the eye work together to efficiently to image visible light (400 nm – 700 nm) and allow animals to see their surroundings. However, each wavelength will interact differently with the various eye tissues and will impact the laser power threshold limits.

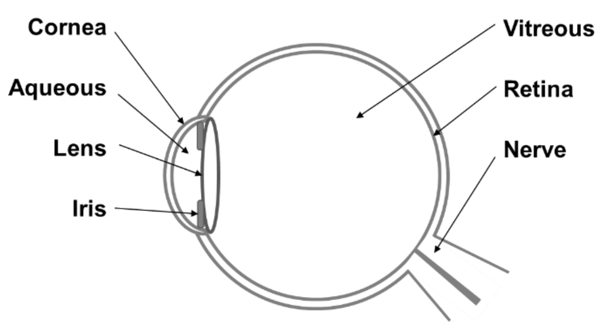

Figure 01: A cross-section illustration of the human eye's anatomy.

2.1 Ultraviolet Radiation

UV radiation is commonly known to cause sunburn for skin exposure, and the same is true for ocular exposure. Actinic UV wavelengths (180 nm – 315 nm) are quickly absorbed at the cornea and can burn the outer layer of the eye, a condition called photokeratitis.

Near UV radiation (315 nm – 400 nm) is transparent to the cornea and is transmitted into the eye. After passing the aqueous humour, these wavelengths are quickly absorbed by the proteins in the lens. Excess absorption in the lens will cause the len's proteins to denature, causing the lens to become permanently opaque and unable to transfer light to the retina. This is known as a cataract, and surgery is required for lens removal and replacement to recover one's ability to see.

2.2 Visible Radiation

The human eye mostly consists of water contained in the aqueous and vitreous humour and is highly transparent at visible wavelengths. This allow visible light (400nm – 700 nm) to be transmitted and focused to the retina. While beneficial for everyday application, this becomes a disadvantage to eye safety when working with visible laser sources. When the eye focuses on a laser source, it creates near perfect image of the object with up to a 20,000x magnitude in optical power density. Excess amounts of focused laser energy will cause photoreceptor cell damage. This can destroy retinal cells that cannot regenerate and result in permanent vision loss.

The silver lining with visible radiation is that laser radiation can easily be detected when it hits the retina, and victims can react to the perceived laser beam (blink) before additional damage can occur. The typical blink response time is 0.25 seconds, and it used for laser safety classes specifically for visible radiation.

2.3 Infrared Radiation

While invisible to the rod and cone cells in the retina, near infrared (NIR) radiation [700 nm – 1,400 nm] can still pass through the eye and focus on the retina. This poses an additional hazard compared to visible radiation, as victims cannot blink to laser radiation they cannot perceive.

Short wave infrared (SWIR) radiation [>1,400 nm] is opaque to the eye and is quickly absorbed by the cornea and aqueous humor. While UV radiation damage at the cornea is photochemical, damage with SWIR absorption is thermally induced. Thus, significantly more SWIR power is required to cause permanent damage the eye. This region is considered the most eye safe, but significant exposure levels can still lead to corneal burn or aqueous flare.

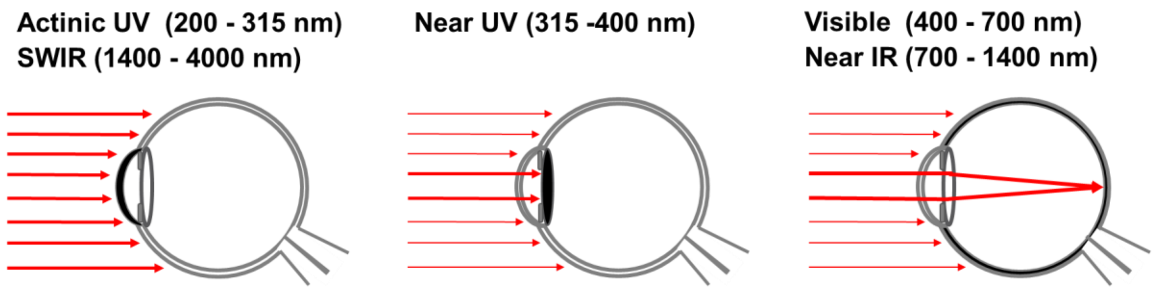

Figure 02: Optical absorption of the eye at different wavelengths, with the most absorbing tissue highlighted in black.

Table 03: The expected biological damage possible with laser radiation at different wavelengths.

Wavelength	Spectrum Name	Potential Damage
180 - 315 nm	Actinic UV [UV-B, UV-C]	Photokeratitis Cornea "sunburn"
315 - 400 nm	Near UV [UV-A]	Photochemical cataract Lens clouding/damage
400 - 780 nm	Visible	Photochemical damage to the retina Retinal burn
780 - 1400 nm	Near IR [NIR]	Cataract (heating) Retinal burn
1400nm – 1mm	Short Wave IR [SWIR]	Corneal burn Aqueous flare

3 Maximum Permissible Emission

To determine what level of laser power is considered safe, maximum permissible emission (MPE) limits are utilized. The MPE limit is the amount of laser radiation biological tissue can be exposed to without negative long-term effects, either in the form of total power (retinal damage) or power density (cornea and lens damage). MPE limits are based on the best available information gathered from numerous experimental studies. These limits help set the standard in terms of laser classification. Regardless, these values are not meant to be a dividing line between safe and hazardous, and laser radiation exposure should always be as low as possible.

The main factors in safety limits are wavelength and pulse conditions. High power pulsed lasers are more likely to cause thermal effects, which need to consider the tissue's ability dissipate thermal energy absorbed from laser radiation. Long exposures at even low irradiance levels are more likely to cause photochemical effects. Thus, both pulse energy and average power need to be considered for safe laser handling.

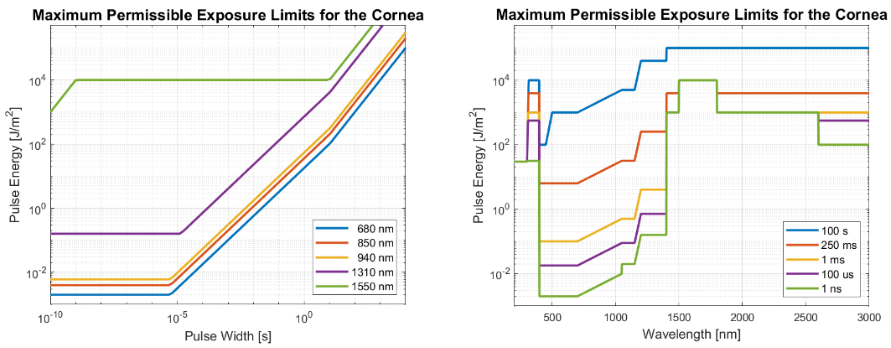

Figure 04: Maximum permissible exposure limits (IEC 60825:1-2014) of the cornea in terms of pulse energy density as a function of pulse width (left) and wavelength (right).

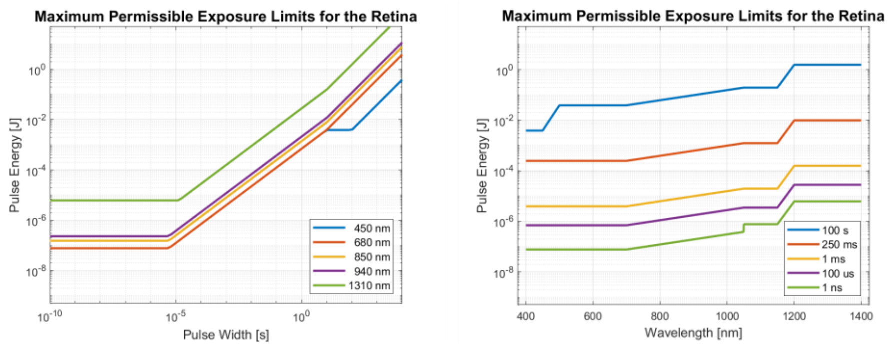

Figure 05: Maximum permissible exposure limits (IEC 60825:1-2014) of the retina in terms of pulse energy as a function of pulse width (left) and wavelength (right).

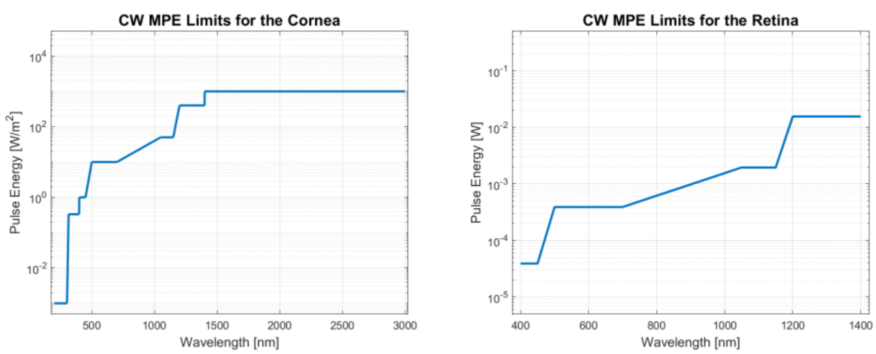

Figure 06: Maximum permissible exposure limits (IEC 60825:1-2014) for continuous wave (CW) power at the cornea (left) and the retina (right).

3.1 Cornea Damage

Actinic UV and SWIR wavelengths are directly projected on the eye and absorbed by the cornea. Due to the thermal and photochemical mechanisms behind laser damage, MPE limits for the cornea are set in terms of power density over the exposed tissue area. The lens is affected in the similar fashion, with the exception that the iris does restrict the total amount of energy that is incident on the lens, but the power density of near UV radiation projected on the lens remains mostly unaffected.

For typical semiconductor lasers, including VCSELs, longer wavelengths are generally more eye safe. In addition, shorter pulse widths are obviously more eye safe, as a shorter pulse duration delivers less total radiation to the eye.

3.2 Retina Damage

Laser power in the visible and NIR spectrum are focused on the retina. Laser power from a collimated light source can be focused by the lens down to a spot size as small as 10 µm. While the power density at the lens may be quite low, it becomes difficult to scale power density limits on the retina. Assuming laser light focuses down to a single point on the retina, setting the MPE limit in the terms of total power is more appropriate. This allows laser classification limits to be easily calculated from retinal hazard limits.

Similar trends for eye safety energy limits are observed for retinal limits, which are defined from the power density delivered to the cornea and transmitted through a fully dilated iris (7mm). The retina also exhibits a high sensitivity for blue radiation, commonly known as blue light hazard, that occurs over long exposure periods.

4 Acceptable Emission Limits

Acceptable emission limits (AEL) are maximum power levels from the laser module and are derived both from MPE limits and the known laser source parameters, which include wavelength, laser illumination area, beam divergence, pulse width, and duty cycle.

For a continuous wave (CW) laser, there is typically a single calculated AEL. For pulsed lasers, there are multiple thresholds that need to be considered, including pulse energy and average power thresholds. A high-speed pulse train of low power laser pulses can quickly accumulate thermal energy on exposed tissue and destroy living cells. In contrast, a single high-speed pulse operated at a low duty cycle could have enough energy to cause ablation, vaporizing molecules and causing explosive rupturing of tissue material. Both parameters need to be evaluated to determine if a laser source is safe. In general, a pulsed laser source is considered safe if it doesn't exceed limits on (1) single pulse energy, (2) cumulative pulse train energy, and (3) average pulse train power.

While MPE values are based on power incident on the eye, this must be translated to an AEL of power that is emitted from the laser. For retinal damage, IEC 60825 sets a minimum distance of 10 cm, the closest distance the lens of a typical human eye can focus on an object. Any objects closer or farther way would thus result in a reduced power density on the retina. An aperture size of 7 mm is used to model the maximum opening of a dilated pupil in order to convert from the maximum MPE limits on the retina to the AEL emitted from the laser.

For wavelengths that are outside the eye's range of transparency [400 nm – 1,400 nm], the measurement guidelines used to determine AEL will vary with wavelength and defined operating conditions. This is due to the tissue's specific sensitivity to power density levels, and exposure limits will vary for each use condition. Due to complex nature of laser radiation, a certified laser safety consulting firm can evaluate laser modules, set up the appropriate test conditions, and measure the power and energy output to determine laser safety classification for each application.

5 Laser Classifications

According to the International Electrotechnical Commission's Safety of Laser Products (IEC 60825.1-2014), there are four main laser classification levels: Class 1, Class 2, Class 3, and Class 4. These classifications are based on laser radiation and do not consider the additional non-beam hazards, including thermal, chemical, and electrical hazards. There are other sub classifications for specific scenarios that will not be covered in this application note, including non-ocular tissue exposure and viewing with telescopic optics.

5.1 Class 1

A Class 1 laser product is considered safe for extended viewing without the need for any eye protection. This is the main require for most consumer, industrial, and automotive products equipped with semiconductor lasers, since they cannot produce sufficient hazardous radiation levels to cause temporary or permanent damage in any use case. In addition, a higher power class laser may be classified as Class 1 if it is fully contained so no radiation exposure is possible.

5.2 Class 2

A Class 2 laser product only pertains to systems that emits visible wavelengths [400 nm – 700 nm]. The human body is able to reduce exposure limits through the blink response, which consists of closing the eye, constricting the pupil, and turning the head away. This is assumed to happen in roughly 0.25 seconds. This allows visible laser to be classified at a distinct power level with a continuous wave (CW) power AEL limit of 1 mW. Exposure levels under Class 2 limits may cause temporary flash-blindness, but typically do not cause long term damage unless under intentional long-term exposures.

5.3 Class 3

Class 3 laser products exceed Class 1 limits or Class 2 limits for invisible or visible radiation respectively. Class 3 lasers require manufacturing requirements and control measurements to be available to the user to reduce risk of eye damage.

There are two subsets in the Class 3 laser category: Class 3R and Class 3B. Class 3R is considered the more eye-safe subset with the probability of injury of a Class 3R laser being relatively low, but not impossible. The AEL limit for Class 3R limits is set at five times the Class 1 or Class 2 threshold limits for invisible and visible radiation limits respectively. Class 3B laser products are significantly more powerful. The direct viewing of a Class 3B laser system is considered hazardous with a high chance of permanent eye damage.

5.4 Class 4

The Laser 4 class is for laser products that exceed all Class 3 limits and can be very dangerous to operate. Direct laser beam exposure from a Class 4 laser system are hazardous to both the eye and skin. Radiation energy reflected off of a diffuse source, including white paint, can be high enough to cause permanent eye damage. The radiation output density could also ignite the air it passes through and create a fire hazard while creating unwanted air contaminants and plasma radiation. A Class 4 laser system requires sufficient control measures in place to reduce the potential exposure to hazardous radiation and to mitigate non-beam hazards of the laser.

6 VCSEL Laser Safety

VCSELs are essential for many consumer, industrial, medical, and automotive applications that require Class 1 laser safety limits for everyday use. For example, 3D camera methodologies require a high bandwidth pulse train to be delivered to the environment. Higher peak powers can detect farther distances and darker materials, and longer pulse trains can improve detection resolution and accuracy. Both factors reduce the laser’s ability to maintain power levels under the Class 1 laser safety limits.

For semiconductor lasers, the properties and applications of VCSELs allow for features that can improve eye safety concerns compared to their edge emitting laser (EEL) counterparts. In addition, VCSEL products come in many forms from single aperture low power die for proximity sensing to high power die with >1000 apertures. In addition, VCSELs can be packaged with either collimation optics or wide field of view (FOV) diffusers based on their end application.

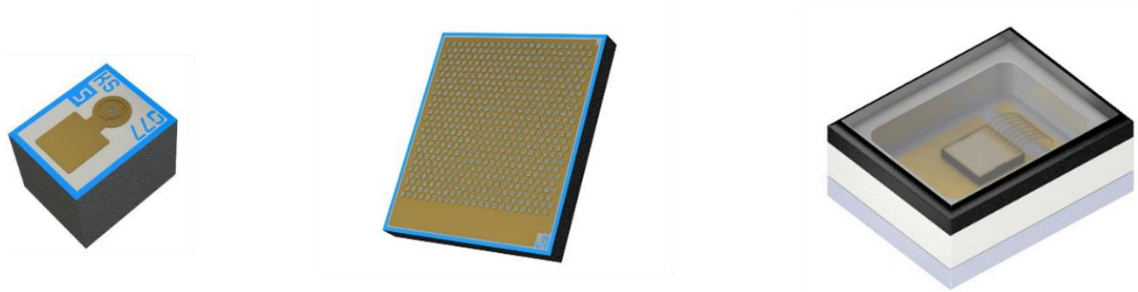

Figure 06: VCSEL components may consist of singe aperture die (left), power array die (center) and packaged die integrated with a diffuser (right).

6.1 Single Aperture VCSELs

The IEC 60825-1:2014 standard states that a collimated, point source laser at 900 nm is considered Class 1 if its CW output power output is less than 1 mW. Thus, it's not difficult to overcome this safety threshold with a single aperture (SA) VCSEL designed for low power output. A 900 nm SA VCSEL with a slope efficiency of 1 W/A would have to stay under 1mA of constant current. Proximity sensors can maintain Class 1 safety levels through pulsed operation using peak powers within standard limits, but the average radiation power must maintain levels below 1 mW.

While SA VCSELs can be modeled as a point source, the raw VCSEL laser beam is not collimated and can have a FWHM beam divergence between 10° – 25° depending on the epi technology and aperture diameter. A wider beam reduces the max energy the eye can collect and focus on the retina, increasing AEL limits for VCSEL laser sources. For many mobile and wearable products, a wider beam allows for larger tolerances in consumer safety and improves signal detection for close distance detection. However, if a VCSEL beam is collimated, such as in a long-distance range finder, all laser radiation must be assumed to be fully collected by the eye to determine proper AEL limits.

6.2 Power Array VCSELs

To deliver higher power, it is most efficient to build a VCSEL die with a large quantity of small apertures in contrast to a larger single aperture. The far-field of the entire of apertures develops a similar beam profile shape similar to a SA VCSEL. Due to the tight arrangement of apertures, it is difficult to collimate the laser beam without advanced optical systems. In addition, the large array of apertures reduces the etendue, and the laser doesn't have to be treated at a point source. While this slightly decreases the eye's overall ability to focus the light into a single point on the retina, this only marginally increases AEL limits in determining laser safety classification.

The advantage of VCSEL power arrays comes in the application of flash LiDAR. Flash LiDAR fully illuminates a target field with a single laser pulse, and a diffuser optic is used to spread the power over a wider FoV. Vixar supplies high power VCSELs packaged with diffuser optics of various FoVs from 60°x45° to 110°x80°. The diffuser further decreases the etendue and significantly increases AEL thresholds.

7 VCSEL Eye Safety and Handling

As stated by IEC 60825-1:2014, "Laser product that are sold to other manufacturers for use as components of any system for subsequent sale are not subject to IEC 60825-1, since the final product will itself be subject to this standard." VCSEL products delivered by Vixar are not fully operational laser modules, and thus need additional effect to create laser radiation. Thus, it is possible to exceed laser safety limits with VCSEL die and modules if powered with excess electrical input, and care must be taken into consideration to avoid potential eye damage.

When designing a test bench setup for VCSELs, engineering controls are recommended to reduce the hazard of the laser. They are the first line of defense against laser hazards and may include enclosures, interlocks, visual warning devices, labelling, and protective barriers. Collecting optics such as microscopes used during laser diode evaluation should have appropriate controls such as filters and interlocks to mitigate unintentional viewing during laser operation.

Administrative controls are the next method of mitigating laser hazards, and include standard operating procedures, output emission limitations, authorized personnel, and education and training for laser users and spectators. Laser safety training should be required for all personnel that handle and evaluate laser components.

Personal protective equipment (PPE) is the last line of defense against laser hazards that protects the user from hazardous direct or diffusely reflected beams by absorbing the laser wavelengths. The optical density of laser safety eyewear determines the attenuation of the radiation passing through the glasses, and the necessary optical density for the application can be calculated using the maximum laser power from the laser source. It is recommended to inspect laser eye protection annually for damage and imperfections in the attenuation or reflecting materials, and to carefully clean the surface without damage to the protective coatings.

8 Conclusions

Laser sources produce radiation levels that can be hazardous to the eye depending on laser classification and power output as defined by maximum permissible emission (MPE) limits. To meet MPE limits for eye safety, all laser parameters and operating conditions need to be taken into consideration to calculate acceptable emission levels (AELs). While multiple class levels exist, most commercial products must remain under Class 1 AELs.

VCSEL products come in a wide variety of power levels and package designs, and each product must be individually analyzed for laser safety classification due to the range in output power, beam divergence, and pulse characteristics. Due to the component nature of Vixar products, laser classification can't be guaranteed for these products as safety consideration is dependent on driving conditions created in the assembly of laser end products.

A certified laser safety consulting firm can evaluate laser modules and help laser module manufacturers develop the proper operation conditions to meet their target laser safety classification. Safety considerations should be incorporated by customers of VCSEL components during laser module development and evaluation including safe test stations, proper laser safety training, and mandatory laser safety PPE.