How to Assess the Eye Safety of VCSELs – Introduction

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Vertical-cavity surface-emitting lasers (VCSELs) perfectly fulfill the requirements for present and future 3D sensing applications. However, to operate VCSEL-based devices in public, the manufacturer must assure safe operation compliant with the IEC 60825-1 standard or national equivalents. As VCSELs exhibit special emission characteristics that differ from other laser sources, the safety assessment is more complex and a practical guideline does not exist. In this paper we explain the differences of VCSELs as compared to “normal” collimated, Gaussian lasers, and outline the main steps necessary for VCSEL safety assessment.

Introduction

Even though vertical-cavity surface-emitting lasers (VCSELs) have been employed in various industrial applications for over three decades, they have only recently gained great popularity and experienced rapid economic growth since the release of Apple’s iPhone X and Face ID technology. Due to their unique features such as very high conversion efficiency, a narrow spectrum, high beam quality, and low production costs, VCSEL devices are perfectly suited for 3D sensing applications, e.g. using structured light or time-of-flight technology to scan objects in 3D. On the one hand, VCSEL technology is about to have its breakthrough in consumer electronics and will become a standard part of mobile phones and AR/VR systems. On the other hand, VCSELs as part of LIDAR systems could become indispensable components for autonomous driving.

However, like all types of lasers, VCSELs can potentially harm the human eye and skin, and may cause severe health damage, such as retina destruction or skin burn. Consumer electronics and LiDAR manufacturers are therefore obliged to carry out a laser safety assessment of their products in conformance with the international laser safety norm IEC60825-1 or equivalent national safety regulations [1,2].

As VCSELs have properties different from other typical laser sources, the determination of a suitable laser class is critical: even more so, as no easily understandable guideline for the assessment of VCSEL safety has yet been published.

With our investigations, we aim to fill this gap. In this contribution, we present the results of our laser safety considerations based on the international laser safety norm specially applied to typical pulsed VCSEL arrays. This article provides the basics and discusses a general approach to this topic. A follow-up article is also to be published, discussing two hands-on, step-by-step examples of the laser class assessment of VCSEL sources.

The IEC 60825-1 Laser Safety Standard Applied to VCSELS

Laser safety norm IEC60825-1 is the international standard for laser safety assessment. It divides the potential risks of a laser into four main categories (and subcategories) ranging from laser class 1 “safe to use in public” to 4 “very harmful to eyes and skin”. It is intended to cover all kinds of lasers, and hence is generalized without focusing on the peculiarities of certain types of lasers. Guidelines on how to derive the safety class of a laser with conventional features (typically point-like light sources, Gaussian emission profile, single-mode operation) were published previously and are also cited as examples in the IEC60825-1 standard. However, compared to typical point-like, single-modal laser sources with Gaussian intensity profile, VCSEL devices have special properties that must be considered here.

Firstly, VCSELs exhibit a multimodal beam profile with longitudinal, lateral, and polarization modes competing depending on the driving current. This results in a highly irregular, dynamic intensity pattern. At different currents the spatial beam profile may therefore vary from a Gaussian to top-hat or doughnut-shaped emission. Additionally, a large divergence is typical for VCSEL sources with angular widths in the 15°-20° range for bare devices. For laser safety evaluations, the beam profile must be analyzed for its intensity “hot spots” that are not necessarily in the center of the beam (**Figure 3**).

Secondly, VCSELs designed for 3D sensing applications often come as arrays with hundreds of single emitters. In certain situations they must be considered as “extended sources” [2].

Lastly, VCSEL-based modules in 3D sensing are mostly operated in pulsed mode, and often exhibit a quite complex temporal modulation. Pulsed sources in general require a more complex safety evaluation than continuous wave lasers, and for VCSEL sources in particular it is necessary to apply assumptions and approximations when performing these evaluations.

Laser Safety Assessment Procedure

Laser class assignment follows the procedure shown in **Figure 1**. This paragraph aims to explain the flowchart step-by-step.

Determination of Safety-relevant VCSEL Parameters

The first step is to find out the safety-relevant parameters of the source. An overview of the most important parameters and the measurement devices used to determine these parameters is given in **Table 1** and **Figure 2**. These values depend not only on the optical power and wavelength but also on geometrical parameters such as the extension of the light source or the distance to the observer. For pulsed systems, pulse length, pulse energy as well as the duty cycle needs to be known.

A system that includes a fast photodiode together with an oscilloscope (e.g. pulsed VCSEL tester in **Figure 2**) is recommended for characterizing the pulse form. A near-field camera system together with a spectroradiometer is the method of choice for measuring the centroid wavelength and characterizing the size and shape of the apparent source. A far-field system (using the projection of the VCSEL source on a screen and imaging with a camera system) is recommended for the measurement of beam profile, divergence angle and power measurements. Especially for power measurement, this method is beneficial because it allows for analyzing intensity “hot spots” with the help of a camera image (see e.g. **Figure 3**). A software algorithm is used to find the pixel position with the maximal intensity after smoothing the image. Afterwards, this pixel is used as the center of the corresponding area within 7mm diameter, and the total power within the area is calculated by multiplying by the mean value.

The precision to which these values must be determined is discussed in detail in EN61040 IEC1040 [3]. All measurement errors and statistical uncertainties must be taken into account, and should be included in a measurement uncertainty budget.

Calculation of Necessary Correction Factors and Time Points

All necessary correction factors C and time points T given in Table 2 and Table 9 of IEC60825-1 must be calculated. Most of the correction factors depend on the spectral region of the emission. Furthermore, correction factors and time points may have different values if a small or large source is evaluated. A point source will be imaged to a small spot by the eye lens. Therefore, it causes higher intensities as an extended source that would cover a larger area on the retina. It is easy to understand that treating the laser source as a point source is always a worst-case assumption and hence always a valid option for the evaluation. VCSEL arrays are often extended sources. This fact can be exploited to reach a certain laser class by maintaining a certain emission power. It will depend on the individual situation whether compromising a more restricted threshold for a less complex evaluation is appropriate.

The so-called angular subtense α is used to quantify the size of the source. The angular subtense of the apparent source is determined by the smallest retinal image size that the eye can produce by adjusting the focal length of the eye lens. The two simplest methods to determine α are either using the conservative default value of 1.5 mrad, resulting in artificially low thresholds or making use of simple trigonometry to estimate the angular subtense for surface emitters. In this case, diameter d of the surface emitter and distance r between the

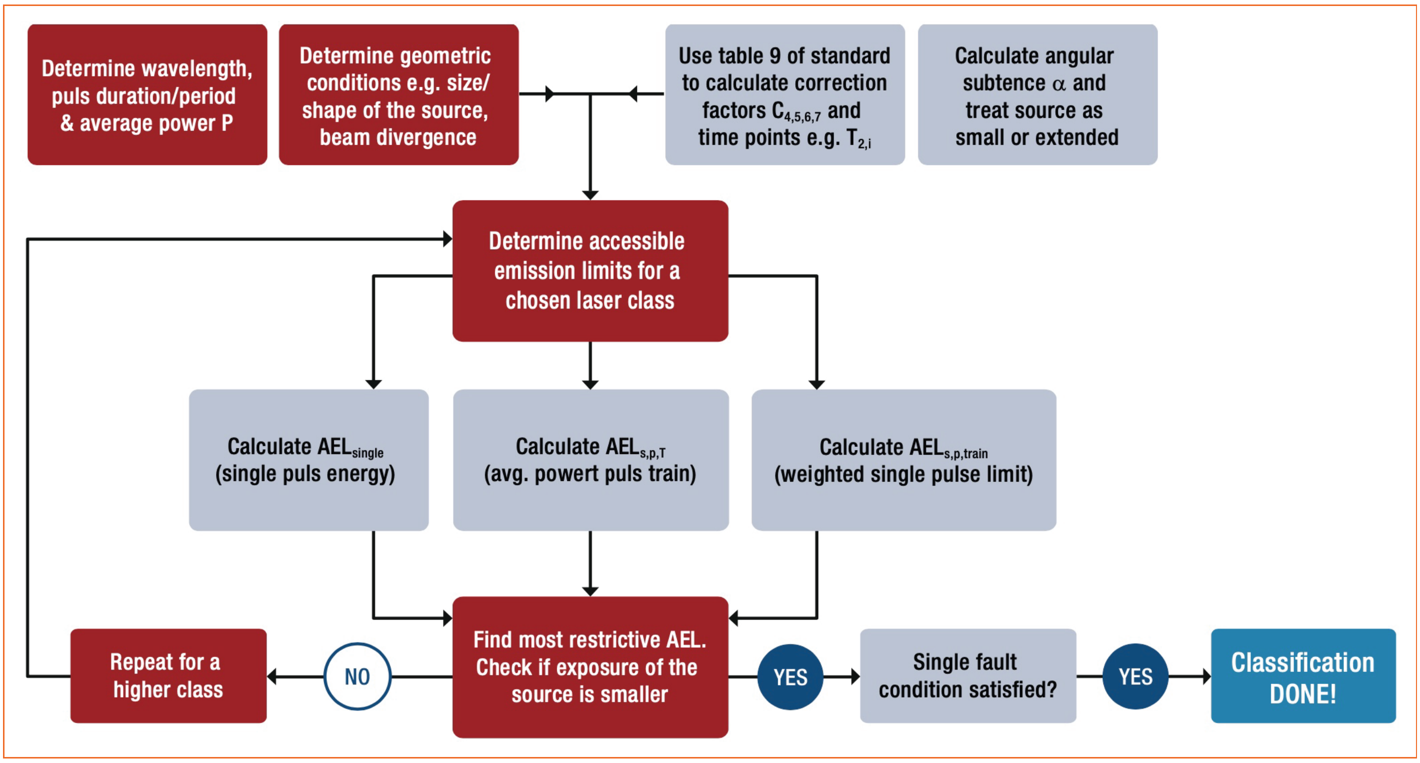

Figure 1: Flow chart for laser safety assessment according to IEC60825-1.

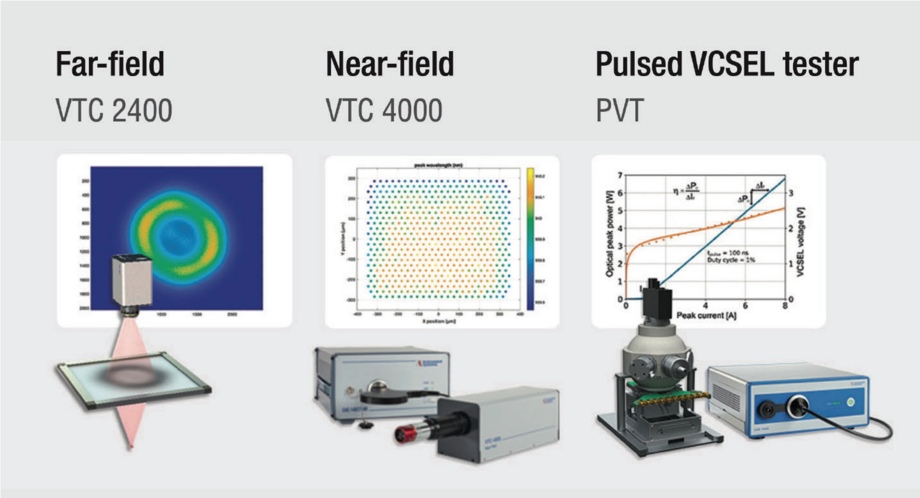

Figure 2: Measurement devices recommended for data collection.

Parameter	Measurand	Measurement device
Wavelength	Centroid wavelength	Spectroradiometer
Pulse form	Pulse width and period (group and burst if applicable)	Fast photodiode and oscilloscope
Apparent source	Size and shape of the first accessible light spot	Camera system
Beam profile	Beam profile and divergence angle	Far-field camera system or goniometric system
Beam power	Absolute average power and average power in hotspot	Far-field camera system or goniometric system

Table 1: Safety-relevant VCSEL parameters and recommended measurement devices.

emitter and the measurement aperture give the angular subtense α:

$$\alpha = 2\ tan^{-1}\left(\frac{d}{2r}\right) \tag{1}$$

With this value, it is possible to calculate the correction factors C and time points T.

Another important parameter is the emission duration to be considered for classification, called the time base. Every possible emission duration, e.g. single pulse width, within the time base must be considered for determination of a product‘s laser class. There are three possible values (0.25 s, 100 s, 500 min) for the time base, depending on the wavelength and intended use of the product. VCSEL devices used for 3D sensing applications are often designed specifically for long-term viewing. Thus, the longest time base of 500 minutes must often be used.

Calculation of Accessible Emission Limits (AEL)

For product classification, the maximum level of radiation permitted within a particular class must be determined. This so-called accessible emission limit (AEL) is valid only for a chosen laser class, and attains different values for extended or small sources. Before starting evaluation, the user must choose a laser class and refer to the appropriate table (Table 3-7) in IEC60825-1. These tables provide values of the AEL for certain ranges of wavelength and emission duration of the radiation. Often, the AEL must be calculated with the help of the correction factors C_1 – C_7.

In the case of pulsed sources, the principle applies, that the accessible emission of any group of pulses delivered in any given time must be taken into account. It is therefore necessary to find the most restrictive out of the following three requirements:

AEL for single pulse energy

The emission limit of a single pulse is called AEL_{single}. The accessible emission of any group of pulses delivered within any given time may not exceed the AEL for that given time. The assessment must consider every possible emission duration. Therefore, AEL_{single} must be evaluated not only for single pulse duration, but also for other possible temporal structures such as group or burst pulse widths.

It depends not only on the peak power and wavelength but also on the extension of the source and divergence of the laser beam.

Average power of a pulse train

The average power of a pulse train must not exceed the AEL of a single pulse of the same length. The limit for a single pulse of duration T is called AEL_T. It is mostly evaluated for the time base. For comparison reasons, the limit for average power is expressed as energy and termed $AEL_{s.p.T}$. For a regular series of pulses, the pulse repetition rate PRF is used for conversion into energy:

$$AEL_{s.p.T}(time\ base) = \frac{AEL_T(time\ base)}{PRF} \tag{2}$$

The best approach to deal with an irregular series of pulses is knowing the maximum duty factor. Under these circumstances, it can be considered as a regular series with an effective pulse repetition rate. If the irregular series contains for example groups of pulses with pulse duration t, the effective pulse repetition rate can be calculated using the duty cycle and the group duty cycle by:

$$PRF_{eff} = DC_{group} \cdot \frac{DC}{t} \tag{3}$$

For arbitrary irregular pulse trains including varying pulse amplitude and bursts, the time base must be varied from the shortest integration time T_i (see table 2 in [1]), over all relevant intervals for the different frames (e.g. bursts) to T.

Weighted single pulse limit

In the wavelength range $400–1400$ nm for comparison with thermal limits, the AEL of a single pulse must additionally be multiplied by correction factor C_5 and is called $AEL_{s.p.train}$.

$$AEL_{s.p.train} = AEL_{single} \cdot C_5 \quad (4)$$

Correction factor C_5 depends on the effective number of pulses N in the pulse train. A check must be performed to determine if multiple pulses appear within the period of T_i. In this case, the pulses are counted as a single pulse to determine N and the energies of the individual pulses are added. Depending on the situation, there are different formulae for the calculation of C_5, depending on whether the pulse duration t is smaller or larger than T_i.

Final Assessment

With the help of the calculations performed in the last paragraph, the most restrictive AEL can be identified. The exposure of the VCSEL source must be smaller than this most restrictive criterion. If this is not the case, the chosen laser class cannot be assigned to the product, and the process of finding the AEL has to be performed again using the next higher laser class.

In order to identify the exposure of the VCSEL source, the first attempt should be an "all-in-eye" approach by calculating the total laser energy per pulse using the measured peak power. If this is not sufficient, one can analyze the beam profile for off-center intensity "hot spots" (**Figure 3**). Taking the divergence of the beam and the accumulation of the human eye into account, this may lead to an exposure smaller than the AEL.

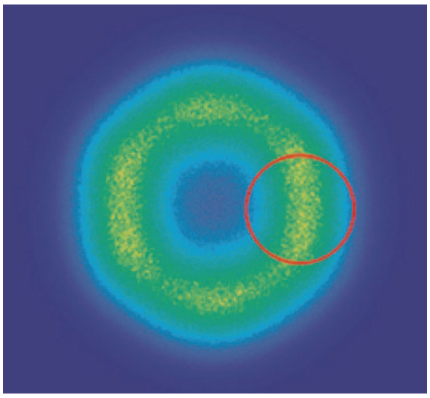

Figure 3: Beam profile with off-center intensity hot-spot.

Laser class evaluation must not only comply with all corresponding AELs, taking into account measurement errors and statistical uncertainties. It must also consider any realistically foreseeable single fault condition during operation. This means that the user must be protected from system failure such as vagabonding laser light, broken diffusors or jammed shutters. The frequency of occurrence and risk of injury are both crucial parameters that determine whether or not an event must be considered and whether security measures (e.g. interlocks) are necessary.

Conclusion and Discussion

VCSEL sources have characteristic properties that should be taken into account when performing eye safety assessment according to IEC60825-1. We have discussed these specialties and outlined a guideline to be followed for laser safety class evaluation.

In a follow-up article this general approach will be applied to two examples demonstrating the typical challenges of VCSELs. In this article we will present a step-by-step analysis on how to assess the laser safety of typical pulsed VCSELs and VCSEL arrays as often employed in consumer electronics and automotive LiDAR applications. ■

References

[1] International Standard IEC 60825-1 Edition 3.0 2014-05 Safety of laser products - Part 1: Equipment classification and requirements

[2] Technical Report IEC/TR 60825-13 Edition 2.0 2011- 10 Safety of laser products – Part 13: Measurements for classification of laser products

[3] European and International Standard EN 61040 IEC 1040:1990 Power and energy measuring detectors, instruments and equipment for laser radiation

About Instrument Systems

Instrument Systems GmbH, founded in Munich in 1986, develops, manufactures and markets all-in-one solutions for light measurement applications. Its core products are array spectrometers and imaging colorimeters. The company's main fields of activity are LED/SSL and display metrology, spectral radiometry and photometry, as well as laser/VCSEL characterization where today Instrument Systems is one of the world's leading manufacturers. The Optronik line of products for the automotive industry and traffic technology is developed and marketed at its Berlin facility. Instrument Systems has been a wholly-owned subsidiary of the Konica Minolta Group since 2012.

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