Excelitas Technologies Corp. 1 Fortune Drive | Billerica, MA 01821, USA Tel: (+1) 978-262-0049 | www.excelitas.com	Document No. OM0035	Revision A
	Title ***1060nm VCSEL Swept Source Engine IEC Laser Safety Classification***	Sheets: 1 of 9

Revision History

Rev.	ECO #	Description/Summary	Chg'd By	Date
A	8611	Initial Release	B. Goldberg	5/31/24

Contents

1.0 Introduction and Summary

The following is a summary description of the application of the IEC International standard for Laser Eye Safety IEC60825-1:2014 Edition 3.0 to Axsun branded 1060nm VCSEL laser engines. The following analysis applies to laser engines shipped using both Gen1 and Gen2 Azmyth laser driver boards using VCSEL lasers with an integrated SOA booster amplifier.

According to IEC60825-1:2014 §1, "Laser products sold to other manufacturers for use as components of any system for subsequence sale are not subject to IEC 60825-1, since the final product will itself be subject to this standard". However, the information in this document may be useful to Excelitas' customers who may also follow IEC 60825-1:2014 to determine classification of their integrated product, and to determine appropriate engineering controls to ensure conformance.

In addition, classification of a laser system is critically dependent on the characteristics of the optical beam divergence, which is the responsibility of the system integrator. As such, the laser classification of the Axsun OEM swept source VCSEL engine only applies to the case of bench top or laboratory testing of the unit as part of our customer's evaluation or testing in a stand-alone configuration, and not installed as part of the customer's systems.

If Excelitas were to fully classify our OEM VCSEL laser engine as a standalone product per IEC60825-1:2014, the laser engine would be classified as 3B.

System integrators are responsible for analysis of the safety classification of their completed system as it pertains to user safety.

1.1 List of Acronyms

VCSEL: Vertical Cavity Surface Emitting Laser
IEC: International Electrotechnical Commission
OEM: Original Equipment Manufacturer
MEMS: Micro-Electro-Mechanical System
TEC: Thermo electric cooler
FMEA: Failure mode and effects analysis
OSA: Optical Spectrum Analyzer
AEL: Accessible Emission Limit
SOA: Semiconductor Optical Amplifier

2.0 Classification of stand-alone OEM swept source engine

Per IEC60825-1:2014 §4.3, *"The product shall be classified on the basis of that combination of output power(s) and wavelength(s) of the accessible emission (laser radiation) over the full range of capability during operation…"*

Of note, by design, Axsun swept source laser engines emit over a multitude of wavelengths and powers during normal operation. As such, Excelitas has developed a procedure to apply IEC 60825-1:2014 §4.3b, Radiation of multiple wavelengths, by using spectrally resolved power data measurements. Data is obtained primarily from an OSA and an integrating sphere power meter for normalization during normal operation and reasonably foreseeable single fault conditions.

To meet a particular classification, the following inequality must hold:

$$\sum_{\lambda_n} \frac{P(\lambda_n)\, w(\text{condition}; \lambda_n)}{AEL(\text{class}; \lambda_n)} < 1$$

where λ_n is the nth spectral component, $P(\lambda_n)$ is the emitted optical power for the nth spectral component, $w(\text{condition}; \lambda_n)$ is a weighting function describing the fraction of emitted power that is accessible given the relevant viewing conditions and wavelength, and $AEL(\text{class}; \lambda_n)$ is the accessible emission limit of the nth spectral component for the considered classification.

As a stand-alone swept source, the configuration of normal use is with the output fiber connector installed and connected through a bulkhead to a second fiber patch cord. Thus, in normal use the swept source engine does not have any free space beam and is not intended for use with aided viewing or collimated beams. As such, to determine the weighting function, we use Condition 3 per IEC60825-1:2014 §5.4 which applies to the “unaided eye”.

The weighting factor details can be found in our internal classification procedure, P7.5-10. The main inputs are the fiber optic mode field diameter and the source wavelength.

Per the IEC standard, the AEL as a function of wavelength for the most conservative time base is shown in Figure 1. However, using the weighting function as described above, one can define a weighted AEL equivalent to the where the accessible emission level equals the class AEL limit under the defined viewing condition. This is shown in Figure 2. Note the weighted AEL is almost a factor of 10 higher than the un-weighted AEL.

Further, we define the class margin as the ratio of the accessible emission level to the AEL after integration across all observed wavelengths, reported on a dB scale. A negative value indicates a unit does not meet the class of interest; a class margin of 0 dB indicates a unit is exactly at the class limit; and positive value indicates the unit has margin to the class limit.

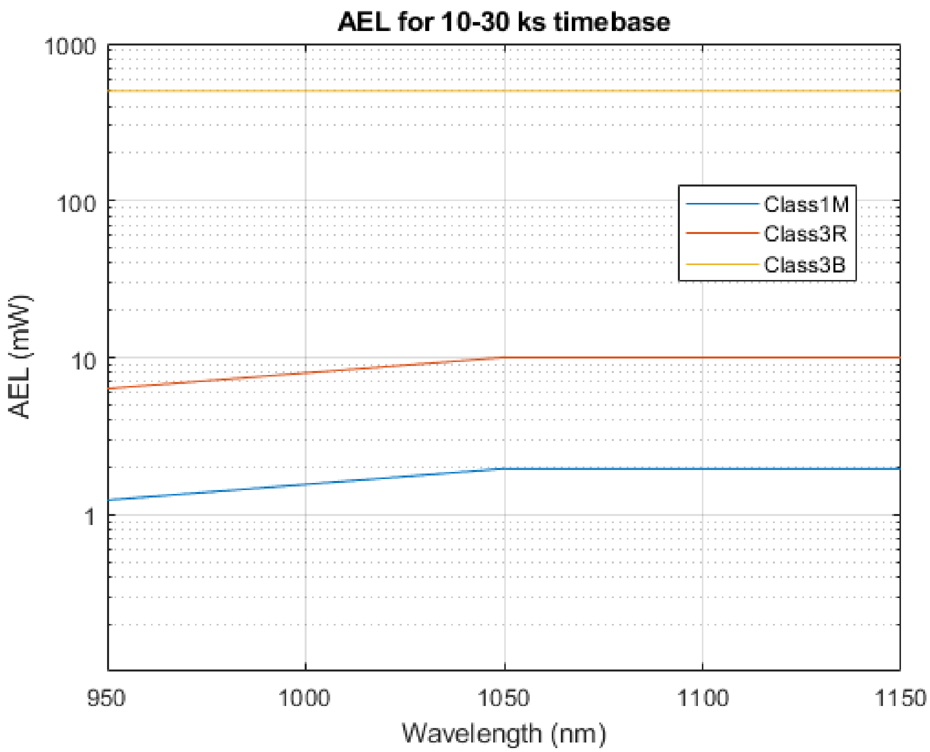

Figure 1: AEL limit for relevant wavelengths per IEC60825-1:2014

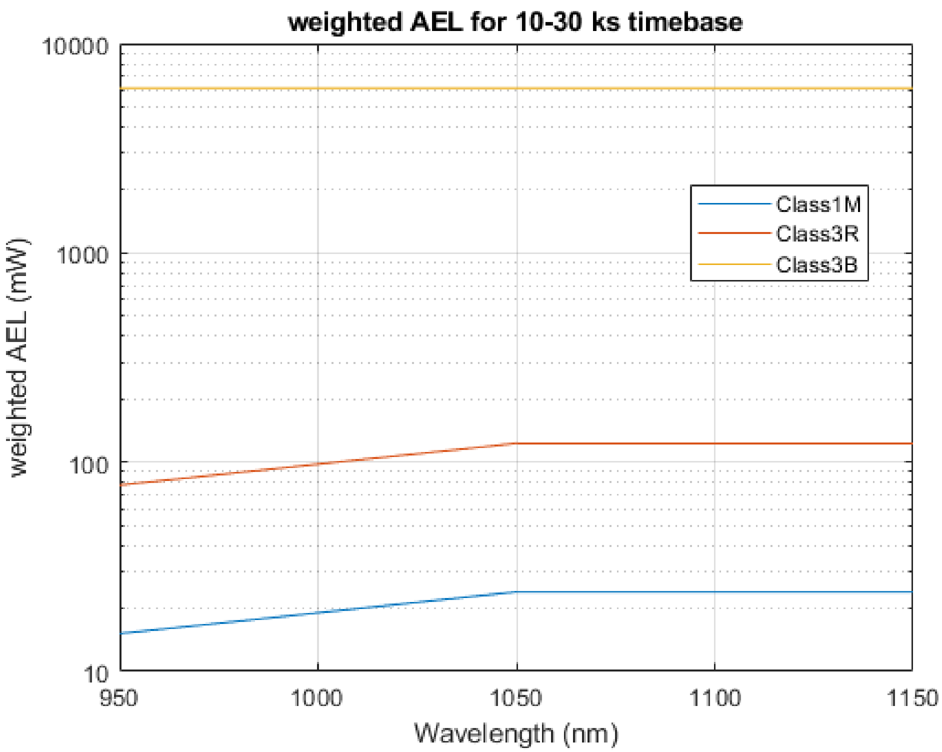

Figure 2: Weighted AEL using single mode HI-1060 fiber as output fiber type

2.1 Normal Operation

During normal operation, the 1060nm VCSEL swept laser engine could reasonably be classified as a 3R source.

Center Wavelength	Tuning Range	Average Power	Margin: Class 1M	Margin: Class 3R	Margin: Class3B
1040 -1065 nm	> 85 nm	15 – 45 mW	[-6,-4] dB	[0.8, 5.4] dB	[18, 22] dB

Table 1: Normal operation class margin. N > 50 units

Note the normal operation class 3R limit margin gets worse (closer to zero) with increasing nominal average power. Roughly speaking, the class 3R limit is reached at 45 – 50 mW of nominal power. The classification margin is not correlated with center wavelength over the range identified in Table 1.

However, the IEC standard requires classification based on capability during normal AND any reasonably foreseeable single-fault conditions (see IEC 60825-1:2014 §5.1). Thus, a full 3R classification is not supported.

2.2 Single Fault Conditions

The set of reasonably foreseeable single-fault conditions have been identified through FMEA. While there are several single-fault conditions that result in loss of power, only relevant faults that contribute to excess power will be discussed in this report.

2.2.1 Stuck or Uncontrolled Optical Filter

The wavelength tunable element in the VCSEL laser is a MEMS based optical filter designed and fabricated at Excelitas. Tunability is achieved by applying a time-dependent voltage waveform across the MEMS device. The MEMS device is susceptible to electrical overdrive, and design controls are in place to prevent electrical overdrive in the field during all modes of operation. Nonetheless, if electrical overdrive were to occur, it's possible the MEMS filter could snapdown and become stuck in an unknown state leading to lasing at an unknown wavelength. In addition, there are electrical failures that could lead to loss of control over the MEMS optical filter which could also lead to lasing at an unknown wavelength. In this failure mode, the other critical drive circuits are assumed to be in working operation (nominal optical pump and nominal booster SOA). To simulate this failure mode, Excelitas parked the optical filter across a range of voltages to achieve stuck filter lasing at all obtainable wavelengths. In addition to classification as described above, we report the ratio of stuck filter power relative to the nominal unstuck condition as described in 2.1.

Fault Condition	Power Ratio	Margin: Class 1M	Margin: Class 3R	Margin: Class3B
Stuck Filter	< 3x	[-8.5,-4] dB	[-1.5, 3] dB	[15, 20] dB

The class margin drops by approximately 2-3dB for each class limit. The power ratio of < 3x is a class agnostic measurement which can be used by the system integrator.

2.2.2 Drive Current short circuit of SOA

The VCSEL laser module contains a booster SOA to amplify the low power light coming directly from the VCSEL laser. Generally speaking, the power is converted from low single digit mWs to several 10s of mWs. A possible single-fault failure condition that could result in an over-power condition is a failure in short-circuit mode of the output transistor for the SOA drive.

Even in a short-condition, the drive circuit contains design controls to limit the maximum current drive to the SOA. The failure mode can be simulated by maximizing the control signal to the SOA as well as modifying the hardware to provide for a short circuit at the appropriate point in the circuit. Once again, the laser engine is classified as described in 2.1 and we report the class agnostic power ratio (power at fault condition : nominal working power).

Fault Condition	Power Ratio	Margin: Class 1M	Margin: Class 3R	Margin: Class3B
Short-Circuit SOA*	< 5.5x	[-10.5,-5.5] dB	[-3.5, 1.5] dB	[14, 18.5] dB

**Note: Applies to Gen1 driver boards. Earlier versions of the Gen2 Azmyth driver board could result in 10x power failures under a SOA short-circuit. This has been corrected for shipments after May-2024*

2.2.3 Drive Current short circuit of Pump

Similar to a short-circuit of the SOA, a short circuit of the optical pump can affect the optical power output. Within the accessible pump drive current limits, even under a short circuit fault condition, the output power does not increase beyond ~1.2x the normal operation as described in 2.1.

2.2.4 Control Failure

In the case of the Axsun branded swept source, the most important single-fault condition for the laser engine after it is integrated into a system is the case of a failure in the control circuit of the laser engine. While the control circuit controls the MEMS filter, SOA, and pump, through separate electrical outputs, it is difficult to separate them from an FMEA point of view under a failure of the control circuit. For the purposes of this report, we consider the scenario where the control circuit gets stuck at the worst case SOA, pump, and filter locations simultaneously and report excess power ratio and classification in that state. Generally, this represents the worst case excess power fault condition.

Fault Condition	Power Ratio	Margin: Class 1M	Margin: Class 3R	Margin: Class3B
Control Failure	< 10x	[-12,-9] dB	[-5,-2.5] dB	[12, 15] dB

It should be noted that the power ratio value can be influenced by the nominal normal operation power setpoint. The control failure power ratio of < 9x applies to laser engines with nominal powers in the 22 – 26mW range. Higher nominal powers can result in lower fault condition ratios, whereas lower nominal power values may increase this result.

3.0 Summary

When treated as a stand-alone OEM engine, the Axsun branded VCSEL swept source engine should be classified as 3B per IEC60825-1:2014 Edition 3.0. As our OEM source is not required to be classified under the standard based, information is given to the system integrator on various reasonably foreseeable single fault conditions. A summary table is listed below.

System integrators using the Axsun swept source must take the potential over-power condition into consideration when designing safety protocols for the manufacturing line and for product safety. For safety interlock design, it is important to consider the response time between the presence of an overpower condition and the blocking, attenuation, or interlock shut-down of the laser output. For this treatment, the laser output can be considered as a single pulse, for which the IEC standard defines the dependence of the Allowable Exposure Limit (AEL) and the Maximum Permissible Exposure (MPE) in total energy increases as a function of time as t^0.75 for exposure times up to 10 seconds. This corresponds to a decrease in the AEL peak power limit as t^-0.25.

Based on this time dependence, we can define the maximum safety interlock delay time to prevent the overpower condition from presenting an increase in the eye hazard level relative to the CW condition (defined by the standard as >=10s exposure). These calculations are summarized in the table below. For interlock/countermeasure response times above those indicated, an additional safety margin in output power should be provided.

Nominal Avg Laser Output power	Fault Condition	Worst-case Power increase under single fault condition	Maximum Interlock response time to prevent increase in hazard level relative to normal average power
22-26mW	Stuck Filter	3x	123ms
	SOA short-circuit	5.5x	10.8ms
	Control Failure	10x	1.0ms

Note: Interlock response time on Excelitas driver boards < 100 usec or better