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Analysis of Eye Safety of repetitively pulsed laser products operating in MWIR, LWIR and FIR wavelength range

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***Abstract*—Repetitively pulsed lasers operating in the MWIR, LWIR and FIR spectral regions are increasingly used in a wide range of applications, particularly in the form of semiconductor sources valued for their stability, efficiency and compactness. Ensuring the safe use of such devices requires accurate classification in accordance with IEC/EN 60825-1 standard, a process that becomes complex when multiple emission parameters such as pulse duration, repetition rate and peak power vary simultaneously. Although the standard provides general guidance and limited examples, it does not fully address all possible parameter combinations encountered in practical systems. This work presents a simplified analysis of the safety classification of repetitively pulsed lasers with variable parameters. A MATLAB-based simulation tool was developed to explore classification outcomes within defined parameter limits and to generate classification maps as a function of peak power and pulse repetition rate. The approach offers a clearer understanding of how change of parameters influences classification and provides a foundation that can be extended to broader parameter ranges and more diverse laser systems.**

***Keywords*—laser safety; laser classification; accessible emission; accessible emission limit; IEC/EN 60825-1**

I. Introduction

REPETITIVELY pulsed lasers operating in the Medium-Wavelength Infrared (MWIR), Long-Wavelength Infrared (LWIR), and Far-Infrared (FIR) spectral regions are increasingly employed across a wide spectrum of scientific, industrial, and defense-related applications. This growing interest is primarily driven by their advantageous atmospheric transmission properties as well as by continuous technological progress in laser source development and system integration. In particular, MWIR (3–5 μm) and LWIR (8–14 μm) wavelength ranges are regarded as especially promising for free-space optical communication systems. Radiation in these spectral bands exhibits improved propagation through challenging environmental conditions such as fog, clouds, dust, smoke, and aerosols. In comparison with shorter wavelengths, MWIR and LWIR signals experience reduced atmospheric scattering, lower turbulence-induced distortion, and diminished attenuation, which collectively enhance link stability and signal quality [1, 2, 3].

Quantum cascade lasers (QCLs) have emerged as key sources capable of delivering high optical power across MWIR, LWIR, and FIR spectral regions. These semiconductor lasers can operate efficiently in both continuous-wave and pulsed regimes, thereby enabling a wide range of applications including remote sensing, surveillance, defense systems, and high-speed free-space data transmission. An important advantage of QCLs is their inherent wavelength tunability, which facilitates spectrally selective operation tailored to specific molecular absorption features. Moreover, their ability to operate at or near room temperature makes them particularly suitable for advanced sensing applications such as standoff detection and identification of explosives, chemical agents, and hazardous substances at significant distances [4, 5].

Recent advances in device architecture, epitaxial growth techniques, thermal management strategies, and packaging technologies have led to substantial improvements in output power, wall-plug efficiency, and operational stability of QCLs. As a consequence, these laser sources have become viable for portable, handheld, and battery-powered systems intended for field use, where size, weight, and power consumption are critical constraints [6, 7]. Such developments significantly broaden the range of practical applications and facilitate the deployment of infrared laser systems outside laboratory environments.

In addition to their favorable spectral characteristics, these laser sources are widely valued for their mechanical robustness, long-term reliability, output stability, relatively low power consumption, and compact design. However, the optimization and deployment of systems incorporating MWIR and LWIR lasers require careful consideration of several interrelated factors, including optical performance, thermal behavior, electrical drive conditions, and compliance with regulatory requirements. Among these considerations, laser safety is frequently the most critical aspect, particularly for systems intended for open-area or human-accessible operation.

Laser safety is of fundamental importance because exposure to high-power laser radiation can result in severe and potentially irreversible eye injuries, even for short exposure durations. To mitigate such risks, European [8] and Polish [9, 10, 11] regulations mandate that laser products comply with applicable safety standards [12, 13, 14, 15]. Wherever feasible, laser sources emitting at wavelengths longer than 1400 nm are preferred, since radiation in this range is strongly absorbed by the cornea and crystalline lens of the eye rather than being focused onto the retina. This absorption mechanism significantly reduces the risk of retinal damage, which is considered the most severe form of laser-induced ocular injury.

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Nevertheless, accurate and conservative safety classification of such laser devices remains essential to ensure safe operation under all expected conditions.

Laser product classification is inherently complex and depends on a set of emission parameters that characterize the laser output. For continuous-wave systems, classification is mainly determined by wavelength and average output power. In contrast, for pulsed and repetitively pulsed lasers, additional parameters must be considered, including pulse duration, pulse repetition rate, pulse energy, and peak power. These parameters must be measured and evaluated in strict accordance with the IEC/EN 60825-1 standard, as they define the Accessible Emission (AE) used for safety classification. Although the standard outlines a general classification methodology and includes several illustrative examples, it does not explicitly address every possible combination of laser parameters that may arise in modern laser systems.

This article aims to partially address these limitations by presenting a simplified analysis of the laser safety classification process for repetitively pulsed laser sources in which pulse duration, repetition rate, and peak power are variable. In many practical implementations, particularly for semiconductor lasers such as QCLs, system control is achieved by maintaining a constant peak power while adjusting the pulse duration and pulse repetition frequency. To analyze the influence of these parameters on safety classification, a MATLAB-based simulation tool was developed to evaluate potential classification outcomes within predefined parameter boundaries. The software enables the creation of a classification map as a function of peak power and pulse repetition rate, providing a clear and intuitive representation of classification regions.

Specific limitations on the parameter ranges were intentionally introduced in order to maintain clarity and avoid unnecessary analytical complexity. It should also be noted that laser devices vary widely in terms of their emission characteristics, operating modes, and intended applications, making it impractical to cover all possible systems within a single study. The analysis therefore focuses on representative cases that are relevant to many practical implementations. Finally, it is assumed that the reader possesses at least a basic familiarity with the IEC/EN 60825-1 laser safety standard. Once the methodology presented here is understood, it can be readily extended and adapted to other parameter sets and laser configurations beyond the limitations considered in this work.

A. Limitations and Assumptions

Reliable laser product classification requires accurate identification of the emission parameters that determine the Accessible Emission (AE) as well as the corresponding Accessible Emission Limits (AEL) applicable to a given laser device. The correctness of the classification outcome is therefore directly dependent on a proper understanding of which physical quantities influence the AE and how these quantities are evaluated within the framework of the relevant safety standard. The analysis presented in this work is intentionally restricted to laser products characterized by a specific and well-defined range of operational parameters, in order to allow for a clear and systematic discussion of the classification process.

In particular, the analysis applies to laser sources operating at wavelengths within the range of 4–100 µm, with pulse durations spanning from 1 ns to 100 ns. For this specific combination of wavelength and pulse duration, the IEC/EN 60825-1 standard defines a single expression for the applicable AEL. This significantly simplifies the classification procedure, as it eliminates the need to select between multiple AEL formulas that would otherwise depend on different wavelength intervals or pulse duration regimes. As a result, the evaluation of compliance with safety limits becomes more straightforward and less prone to ambiguity or misinterpretation.

Furthermore, the analysis assumes that all pulses within a given pulse train are identical, meaning that they exhibit uniform pulse characteristics throughout operation. In practice, this implies constant peak power, constant pulse duration, and a constant pulse repetition rate. This assumption is essential for reliable parameter derivation, as it allows the pulse energy to be directly calculated from the measured peak power and pulse duration, and the average optical power to be determined from the peak power, pulse duration, and pulse repetition rate. Without such uniformity, significant uncertainties could arise in the estimation of these quantities, complicating the classification process.

In the context of semiconductor laser products, this operating mode reflects common design practice. Laser control strategies are frequently based on maintaining a fixed peak power while varying the pulse duration and repetition rate to achieve the desired output characteristics. In such cases, the total continuous-wave power is typically measured at an early stage of the design process. Subsequently, pulse energy and average output power are calculated by systematically adjusting the pulse duration and repetition rate. This approach enables designers to tailor laser performance while ensuring that the resulting emission levels remain within the limits required for a predefined laser safety class. By adhering to these assumptions and parameter constraints, the presented analysis provides a consistent and practically relevant basis for evaluating laser product classification outcomes.

B. Determination of the Accessible Emission Limit

The Accessible Emission Limits (AEL) corresponding to individual laser classes are defined in Tables 3–9 of the standard and constitute the fundamental reference for laser safety classification. Within the wavelength range of 4–100 µm, which is relevant for the analysis presented in this work, the applicable safety classes include Class 1, Class 3R, Class 3B, and Class 4. These classes reflect increasing levels of potential hazard and define progressively higher permissible emission levels. It should be noted that the selection of the applicable AELs depends not only on the wavelength but also on the temporal characteristics of the laser emission.

For lasers operating in a repetitive pulsed regime with uniform pulse characteristics, specific evaluation requirements are defined by the standard. Uniformity of the pulse train implies that all emitted pulses have identical peak power, pulse duration, and repetition rate throughout the exposure period. Under these conditions, the classification of the laser product must satisfy two independent criteria related to both cumulative exposure and single-pulse emission.

First, the average Accessible Emission (AE) of the entire pulse train, evaluated over an emission duration equal to the specified time base $T = 100$ s (for wavelengths outside the 400–700 nm range and when prolonged intentional viewing is not inherent to the device), must not exceed the AEL defined for a single pulse of duration T, denoted as AEL_T. This requirement ensures that the integrated exposure resulting from repeated pulse emission remains below the permissible limit for the given laser class.

Second, the Accessible Emission of any individual pulse within the pulse train must not exceed the AEL specified for a single pulse, denoted as $\mathrm{AEL}_{\mathrm{single}}$. This condition addresses the potential hazard associated with high peak power or high pulse energy events and ensures that even isolated pulses remain within safe emission limits.

For the wavelength range, pulse duration, and time base considered in this study, the standard specifies the following AEL values corresponding to individual laser classes:

- Class 1:

$$\mathrm{AEL}_{\mathrm{single}} = 100\ \mathrm{J/m^2} \tag{1a}$$

$$\mathrm{AEL}_T = 1000\ \mathrm{W/m^2} \tag{1b}$$

- Class 3R:

$$\mathrm{AEL}_{\mathrm{single}} = 500\ \mathrm{J/m^2} \tag{1c}$$

$$\mathrm{AEL}_T = 5000\ \mathrm{W/m^2} \tag{1d}$$

- Class 3B:

$$\mathrm{AEL}_{\mathrm{single}} = 0.125\ \mathrm{J} \tag{1e}$$

$$\mathrm{AEL}_T = 0.5\ \mathrm{W} \tag{1f}$$

These values form the basis for determining whether a given laser product complies with the emission limits of a specific class when operating in a repetitive pulsed mode. By simultaneously satisfying both the average emission and single-pulse criteria, a consistent and conservative safety classification can be achieved for laser systems operating within the defined parameter range.

C. *Measurement and calculation of the Accessible Emission*

According to the requirements specified in the standard, when the wavelength of the laser radiation lies outside the 400 - 1400 nm spectral range, a simplified evaluation scheme may be applied for the purpose of laser safety classification. This approach is particularly advantageous because it reduces the complexity of the assessment procedure while still ensuring conservative and reliable safety evaluation. Within this simplified scheme, and specifically for laser radiation emitted at wavelengths between 4 and 100 μm, the accessible emission (expressed either as power or energy) is determined under a single, well-defined test configuration referred to as Condition 3.

Condition 3 specifies both the measurement distance and the dimensions of the limiting (stop) apertures, commonly referred to as measurement apertures. These parameters are used to define the spatial area over which the optical radiation is collected during the measurement. In general, the prescribed distances and aperture diameters depend on the wavelength of the emitted radiation and, for the wavelength range considered here, also on the emission duration t_e. By enforcing standardized measurement conditions, the simplified evaluation scheme ensures repeatability and consistency of accessible emission measurements across different laser products.

Under Condition 3, the measurement is performed at a fixed distance relative to a defined reference point of the laser source. This reference point corresponds to the physical origin of the radiation and depends on the specific type of laser system. For semiconductor lasers, such as quantum cascade lasers, it is typically identified with the location of the emitting chip. In the case of fiber-based laser outputs, the reference point is the fiber end face, whereas for conventional lasers or laser beams modified by optical elements, it is usually defined as the beam waist. If this reference point is located inside a protective enclosure and is therefore not directly accessible, and if the distance from the reference point to the nearest point of possible human access exceeds the prescribed measurement distance, the measurement must instead be carried out at the closest accessible location. This requirement ensures that the evaluated emission accurately represents the maximum exposure that a user could realistically encounter.

For laser radiation in the wavelength range of 4–100 μm, the standard specifies a measurement distance of $Dst_3 = 0$ mm. The diameter of the measurement aperture D_3 depends on the emission duration $t_e$and is defined as $D_3 = 1$ mm for $t_e \leq 0.35$ s, $D_3 = 1.5 \cdot t_e^{3/8}$ mm for $0.35\ \mathrm{s} < t_e < 10$ s, and $D_3 = 3.5$ mm for $t_e \geq 10$ s. These aperture sizes account for the temporal aspects of exposure and ensure that the evaluated accessible emission reflects both short-term and long-term exposure conditions.

As previously discussed, two evaluation requirements must be considered for repetitively pulsed laser emission: one corresponding to the emission duration equal to the time base $T = 100$ s, and the other corresponding to the individual pulse duration t_p, which lies in the range of 1–100 ns. Consequently, the appropriate measurement aperture diameters are $D_3(T) = 3.5$ mm for the time-base evaluation and $D_3(t_p) = 1$ mm for the single-pulse evaluation.

As also mentioned earlier, for pulsed emission scenarios in which the peak power P_p, pulse duration t_p, and pulse repetition rate f are constant and have been experimentally measured, the pulse energy E_p and the average output power P_{av} can be calculated using the following relations:

$$E_p = P_p \cdot t_p \tag{2a}$$

$$P_{av} = P_p \cdot t_p \cdot f \tag{2b}$$

In practical situations, the laser beam diameter at the measurement location, denoted as BD, may be smaller than, equal to, or larger than the required measurement aperture diameter. As a result, the accessible emission values must be calculated using a conditional approach that accounts for the relative sizes of the beam and the aperture. The following algorithm is therefore applied.

If $BD \leq D_3(t_p)$, the accessible emission associated with pulse energy is calculated as:

$$AE(E_p) = (P_p \cdot t_p)/(\pi \cdot \left(D_3(t_p)\right)^2 /4) \tag{3a}$$

If $BD > D_3(t_p)$, the corresponding expression becomes:

$$AE(E_p) = (P_p \cdot t_p)/(\pi \cdot BD^2/4) \qquad (3b)$$

Similarly, if $BD \leq D_3(T)$, the accessible emission associated with average power is given by:

$$AE(P_{av}) = (P_p \cdot t_p \cdot f)/(\pi \cdot (D_3(T))^2/4) \qquad (3c)$$

Finally, if $BD > D_3(T)$, the accessible emission is calculated as:

$$AE(P_{av}) = (P_p \cdot t_p \cdot f)/(\pi \cdot BD^2/4) \qquad (3d)$$

In the above expressions, $AE(E_p)$ and $AE(P_{av})$ represent the accessible emissions determined on the basis of pulse energy and average power, respectively. This methodology provides a consistent framework for evaluating accessible emission under both single-pulse and cumulative exposure conditions, forming a reliable basis for subsequent laser safety classification.

D. Classification algorithm

Following the methodology defined in the standard, the laser product classification process is carried out by directly comparing the calculated Accessible Emissions (AEs) with the corresponding Accessible Emission Limits (AELs) defined for the previously specified measurement Condition 3. This comparison constitutes the core step of the classification procedure and must be independently performed for both evaluation requirements discussed earlier, namely the assessment based on individual pulse emission and the assessment based on average emission over the specified time base.

As a consequence, the final laser class is determined by the most restrictive outcome resulting from these comparisons. To ensure compliance with the standard, both criteria must be satisfied simultaneously for a given class; if either criterion exceeds the permissible limits, a higher class must be assigned. Based on this principle, the classification algorithm can be formulated in a structured manner as follows.

If the Accessible Emission determined for the pulse energy, $AE(E_p)$, does not exceed the single-pulse AEL for Class 1, denoted as $\mathrm{AEL_{single}}$(Class 1), and at the same time the Accessible Emission determined for the average power, $AE(P_{av})$, does not exceed the time-base AEL for Class 1, AEL_T(Class 1), then the laser product is classified as Class 1.

If both $AE(E_p)$ and $AE(P_{av})$ are below or equal to the corresponding single-pulse and time-base AELs specified for Class 3R, and simultaneously at least one of these Accessible Emissions exceeds the respective Class 1 limit - i.e. $AE(E_p) >$ $\mathrm{AEL_{single}}$(Class 1) or $AE(P_{av}) > \mathrm{AEL}_T$(Class 1) - then the laser product is classified as Class 3R. This condition reflects the intermediate hazard level associated with Class 3R devices, which exceed Class 1 limits but remain below those of higher hazard classes.

For Class 3B, the evaluation requires an additional step to ensure consistency of physical units between the calculated Accessible Emissions and the AELs specified for this class. In this case, the Accessible Emissions expressed in terms of irradiance or radiant exposure are multiplied by the area of the relevant measurement aperture. Specifically, the following conditions must be fulfilled: $AE(E_p) \cdot (\pi \cdot (D_3(t_p))^2/4) \leq$ $\mathrm{AEL_{single}}$(Class 3B) and $AE(P_{av}) \cdot (\pi \cdot (D_3(T))^2/4) \leq$ AEL_T(Class 3B), while at the same time at least one of the Accessible Emission values exceeds the corresponding Class 3R limit. Under these conditions, the laser product is assigned to Class 3B. The multiplication by the aperture area ensures that the comparison with energy- or power-based AELs defined for Class 3B remains dimensionally correct and physically meaningful.

In all remaining cases - specifically, when one or both Accessible Emission values exceed the corresponding Class 3B AELs - the laser product is classified as Class 4, indicating the highest hazard category. Class 4 lasers are not subject to upper emission limits within the scope of the standard and therefore require the most stringent safety measures.

In order to visualize the classification procedure, the corresponding algorithm is shown in Figure 1.

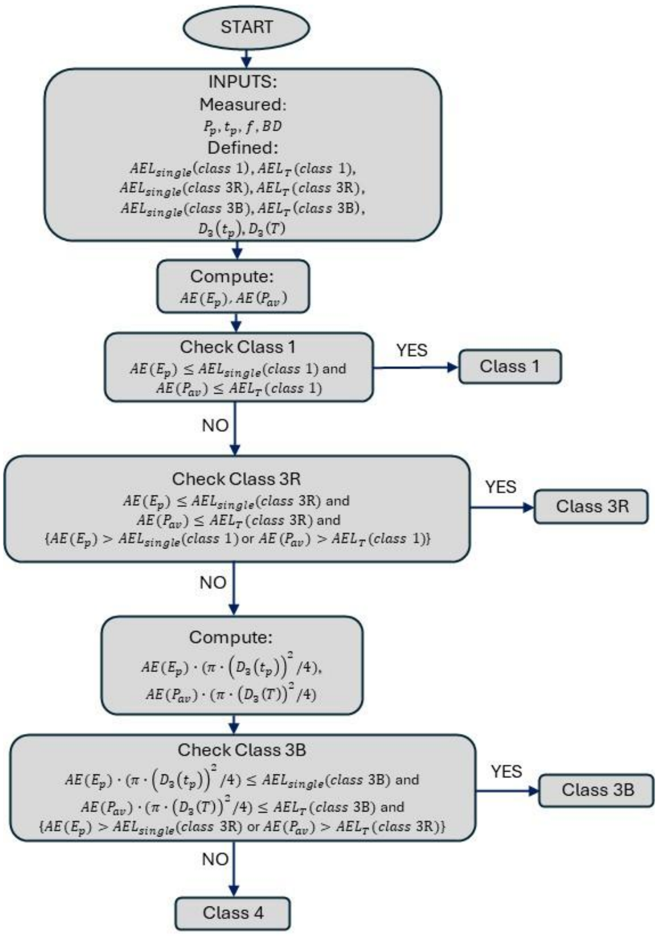

Fig. 1. Classification algorithm

E. Classification software

On the basis of the classification algorithm presented in the previous section, a dedicated MATLAB-based software tool was developed to support the practical evaluation of laser safety classes. The primary purpose of this software is to automate the classification procedure and to visualize the classification results in a clear and intuitive form. In particular, the software enables the calculation and graphical representation of a laser classification map as a function of two key operating parameters, namely the peak power and the pulse repetition rate.

To generate a classification map, the user is required to specify a set of input parameters that define the operating conditions and the parameter space to be analyzed. These inputs include the pulse duration t_p [ns], which characterizes the temporal width of an individual laser pulse. In addition, the user must provide the minimum pulse repetition rate $f_{\min}$ [MHz], defining the lower bound of the repetition rate range for which the classification is evaluated, as well as the maximum pulse repetition rate $f_{\max}$ [MHz], which sets the corresponding upper bound. Similarly, the minimum peak power $P_{p\min}$ [mW] and the maximum peak power $P_{p\max}$ [mW] define the limits of the peak power range included in the classification map. Finally, the beam diameter at the measurement position BD [mm] must be specified, as it directly affects the calculation of the accessible emission under the applicable measurement conditions.

Based on these input parameters, the software systematically computes the accessible emissions and compares them with the relevant AEL values across the defined parameter space. The resulting classification outcomes are then presented in the form of a two-dimensional map. The figures 2 and 3, shown below, illustrate an example of such a classification map generated by the developed software. Different colors are used to represent the possible laser classes, starting with Class 1 in the lower-left corner of the map, progressing through Classes 3R and 3B, and culminating with Class 4 in the upper-right corner. This visual representation allows for rapid identification of safe and potentially hazardous operating regimes.

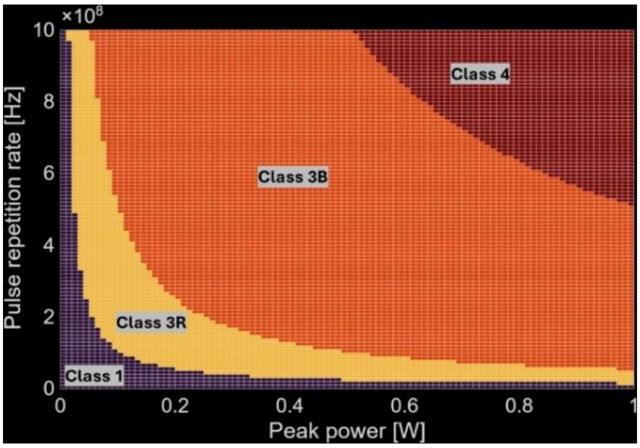

Fig. 2. Classification map for $t_p = 1\,ns$, $f_{min} = 0\,Hz$, $f_{max} = 1\,GHz$, $P_{pmin} = 0$ mW, $P_{pmax} = 1\,W$, $BD = 1.5\,mm$

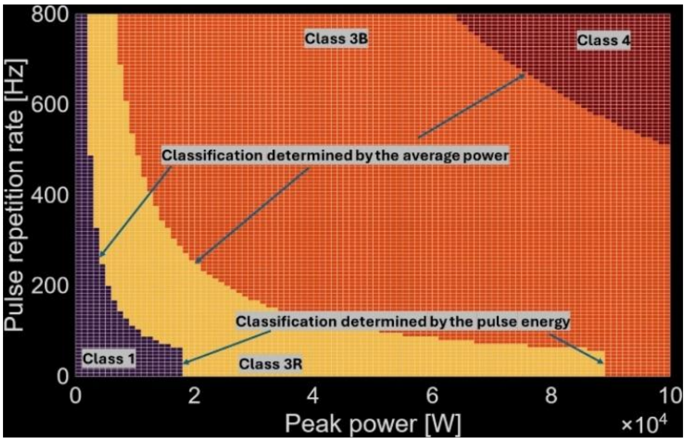

Fig. 3. Classification map for $t_p = 10\,ns$, $f_{min} = 0\,Hz$, $f_{max} = 800\,Hz$, $P_{pmin} = 0$ mW, $P_{pmax} = 100\,kW$, $BD = 1.5\,mm$

As can be observed in the presented figure, distinct regions emerge in which either the average power criterion or the pulse energy criterion becomes the dominant factor determining the laser classification. In regions governed by pulse energy, the laser product class is primarily determined by the product of the measured peak power and the pulse duration, reflecting the significance of single-pulse exposure. In contrast, in regions where average power constitutes the more restrictive criterion, the decisive quantity is the average output power, defined as the product of the peak power, the pulse duration, and the pulse repetition rate, which accounts for cumulative exposure effects over time.

The transition between these two regions - where pulse energy ceases to be the limiting factor and average power becomes the dominant constraint - can be clearly identified on the classification map. This transition line corresponds to a specific pulse repetition rate at which both evaluation criteria impose identical classification limits. As such, this boundary provides valuable insight into the interplay between pulse duration, repetition rate, and peak power, and can be used as a practical design guideline.

Figure 4 presents an example of a classification map corresponding to higher peak power values and lower pulse repetition rates. This figure highlights in particular the transition region between Class 3B and Class 4, illustrating how relatively small changes in operating parameters can result in a change of the laser safety class. Such visualization underscores the usefulness of the developed software as a design and verification tool for laser products operating in repetitively pulsed regimes.

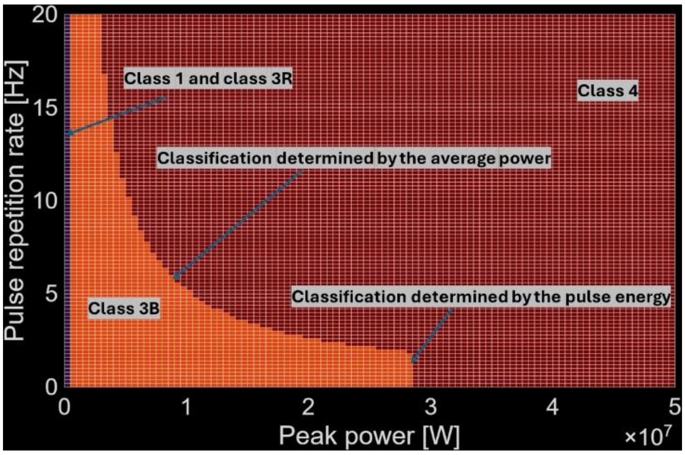

Fig. 4. Classification map for $t_p = 10\,ns$, $f_{min} = 0\,Hz$, $f_{max} = 20\,Hz$, $P_{pmin} = 0$ mW, $P_{pmax} = 50\,MW$, $BD = 1.5\,mm$

ADDITIONAL CONSIDERATION / CONCLUSIONS

The study underscores the crucial role of computational and simulation-based tools in supporting and streamlining the laser product classification process. While international standards such as IEC/EN 60825-1 provide a comprehensive and essential regulatory framework for laser safety assessment, the practical evaluation of modern laser systems often reveals a level of complexity that goes beyond the scope of purely prescriptive procedures. Real-world laser devices frequently operate under conditions that involve multiple interacting parameters, nontrivial control schemes, and trade-offs between performance and safety, which can make direct analytical assessment challenging. In such cases, simulation tools serve as an effective complement to experimental measurements, facilitating more robust, repeatable, and well-documented classification outcomes that can be more easily justified during compliance evaluation.

It should be emphasized that the representative examples presented in this article constitute only a limited subset of the wide range of possible laser configurations encountered in practice. Contemporary laser products exhibit substantial diversity in emission parameters and operational modes, including continuous-wave operation, regular pulsed emission, and more complex or irregular pulsed regimes. As a result, additional studies are required to extend the analysis to a broader library of representative cases that better reflect the diversity of commercially available and emerging laser technologies. Continued development and refinement of analytical models and simulation techniques are therefore essential to support a more uniform, transparent, and reproducible application of laser safety standards across different device categories and use cases.

The proposed methodological framework contributes to a clearer and more intuitive understanding of how variations in key emission parameters influence the resulting safety classification. By explicitly illustrating the interplay between pulse repetition rate and peak power, the approach helps identify which operating regimes are dominated by single-pulse exposure constraints and which are governed primarily by cumulative average-power limits. This insight enables designers and safety engineers to better anticipate class transitions and to optimize system parameters accordingly. Moreover, the framework establishes a solid and flexible foundation that can be readily extended to wider parameter ranges and adapted to a broader spectrum of laser architectures and operating modes, thereby supporting more comprehensive and versatile safety assessments.

One of the most important issues that should be addressed in future work is the impact of measurement uncertainty associated with key laser parameters and, consequently, with the determination of Accessible Emission and Accessible Emission Limits. Measurement uncertainties may arise from limitations in detector calibration, temporal resolution, spatial beam characterization, and environmental influences. At present, the relevant standards provide limited guidance on how such uncertainties should be propagated and accounted for in the final classification decision. This represents a significant gap, particularly in the context of accredited testing laboratories, where classification results may be subject to regulatory scrutiny or used as evidence in legal proceedings. A systematic treatment of uncertainty would therefore enhance both the technical robustness and the legal defensibility of laser safety assessments.

In application-specific scenarios such as free-space optical (FSO) communication systems, laser eye safety must be considered alongside several additional performance-critical factors, most notably atmospheric attenuation and achievable transmission range. Atmospheric attenuation has a direct and often substantial impact on the performance of FSO links. The propagation of optical radiation through the atmosphere is affected by absorption, scattering, and turbulence, all of which introduce losses and signal fluctuations. Scattering mechanisms, including Rayleigh scattering from air molecules and Mie scattering from larger particles such as dust, water droplets, and aerosols, can significantly degrade signal quality. These effects are particularly pronounced at shorter wavelengths in the visible and near-infrared spectral regions, which has led to increasing interest in the use of longer wavelengths—often beyond the commonly employed 1550 nm band—for FSO applications.

Adverse atmospheric conditions such as fog, rain, snow, and high aerosol concentrations further exacerbate signal attenuation, resulting in reduced link availability and reliability. Under such conditions, attenuation coefficients can increase dramatically, severely limiting system performance. The achievable range of an FSO system is therefore strongly dependent on transmitted laser power, beam divergence, receiver sensitivity, and prevailing atmospheric conditions. The interplay between transmitted power, beam divergence, and atmospheric extinction coefficients ultimately determines the maximum communication distance attainable under given environmental constraints. While in ideal clear-air conditions FSO systems can achieve transmission ranges of several kilometers with relatively low loss, the presence of heavy fog or intense precipitation can reduce the effective range by orders of magnitude. These considerations highlight the necessity of jointly addressing laser safety, atmospheric propagation effects, and system-level performance requirements during the design and evaluation of FSO systems.

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